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The NASA Hypersonic Experimental Aerothermodynamics Capabilities (HEAC) Study: A Vision for Technical Excellence in Hypersonics

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Table of Contents

Abstract 1
HEAC Executive Summary 2
  Assumptions 2
  Findings 3
  Recommendations 5
Introduction 8
Overview of the Current State of National Hypersonic Testing Capabilities 9
  Perspectives on NASA Hypersonic Ground Testing Capabilities 9
  Perspectives on Hypersonic Ground Testing Capabilities in Industry and Academia 15
  Perspectives on Computational Fluid Dynamics 15
  Future State of NASA Hypersonic Ground Testing Capabilities 17
Overview of the HEAC Study 18
  The Value-Based Justification Process 18
  Adapting the IDA Methodology to HEAC 18
  HEAC Team Structure and Products 19
    HEAC Team Organization and Tasks 19
    HEAC Data Sources 19
    The HEAC Database 20
HEAC Team 1: Vision and Goals 21
  Contextualizing HEAC 21
  Vision and Goals Team Analysis 22
  Vision and Goals Team Products 23
HEAC Team 2: Programs, Objectives, and Requirements 26
  HEAC Team 2 Overview 26
  Team 2 Programs List 27
    Hypersonic Entry, Descent, and Landing Theme 27
    Hypersonic Atmospheric Flight and Access to Space Theme 34
    Hypersonics Tools and Methods Theme 40
  Team 2 Database Objectives and Test Requirements 45
HEAC Team 3: Technical Capability and Logistical Capacity Gaps 54
  HEAC Team 3 Overview 54
  Technical Capability and Logistical Capacity Gaps List 54
  Technical Capability and Logistical Capacity Gaps Analysis 59
  Gap Closure and Mitigation Alternatives Analysis 74
  Gap Consolidation, Reevaluation, and Categorization 77
  Gap Prioritization for Investment Recommendations 80
HEAC Team 4: Investment Recommendations 82
  Tier 1 Large Investment Closure Recommendations 83
    Construct a Hypersonic, High Reynolds Number Tunnel 83
  Tier 2 Moderate Investments Closure Recommendations 85
    Repair and Maintain Existing NASA Hypersonic Facilities 85

Construct a High Enthalpy Flow Field Laboratory 86
Upgrade the LaRC Unitary Plan Wind Tunnel to Mach 5+ 87
Tier 3 Small Investment Closure Recommendations 88
Modernize the Ames EAST Facility 88
Convert the LaRC Mach 6 Nozzle Test Chamber into a Hypersonic Quiet Tunnel 89
Convert the LaRC 15-Inch Mach 6 Tunnel into a Hypersonic Ludwieg Tube 90
Summary and Conclusions 91
Forward Action Items 92
Acknowledgments 93
Contributors to HEAC Team 1: Vision, Goals and Objectives 93
Contributors to HEAC Team 2: Programs, Objectives, and Requirements 93
Contributors to HEAC Team 3: Capability and Capacity Gaps Assessment 94
Contributors to HEAC Team 4: Gap Closure Investments Recommendations 94
References 95
Appendix A Socialization and Advocacy 99
Appendix B Responses to Vision and Goals Team Survey Questions 110
Appendix C Database for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human Rated Exploration 120
Appendix D Database for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration 168
Appendix E Database for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Technology and Architecture Development 213
Appendix F Database for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development 297
Appendix G Database for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support 349
Appendix H Database for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support 414
Appendix I Database for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation 449
Appendix J Database for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development 526

List of Figures

Figure 1. Hypersonic Flight Programs Supported by NASA Ground Test Facilities. 10
Figure 2. Declining Productivity of the LAL Wind Tunnels. 13
Figure 3. Declining SME of Experimental Hypersonics Workforce. 13
Figure 4. Hypersonics Challenges in the 21st Century. 22
Figure 5. Pareto Analysis of EDL Technical Gaps. 71
Figure 6. Pareto Analysis of HTP Technical Gaps. 72
Figure 7. Pareto Analysis of CFD Technical Gaps. 73
Figure 8. Hypersonic High Reynolds Number Tunnel (HHRNT). 84
Figure 9. Current NASA Hypersonic Test Facilities. 85
Figure 10. Schematic of HEFFL Shock Tunnel. 86
Figure 11. Langley Unitary Plan Wind Tunnel. 87
Figure 12. Ames Electric Arc Shock Tube (EAST). 88
Figure 13. LaRC Mach 6 Nozzle Test Chamber. 89
Figure 14. Ludwieg Tube Conversion of 15-Inch Mach 6 Air Tunnel. 90

List of Tables

Table 1. Historical Roster of NASA Hypersonic Wind Tunnels. 11
Table 2. EDL Theme: Customer Types and Program Categories. 30
Table 3. EDL Programs – Focus on Program Category 3.1 HIAD Technology Development. 33
Table 4. Hypersonic Flight & Access-to-Space Theme: Customer Types and Program Categories. 36
Table 5. Hypersonic Atmospheric Flight & Access to Space Programs – Focus on Category 6.1 Defense Fundamental / Applied R&D. 39
Table 6. Hypersonic Tools and Methods Theme: Customer Types and Program Categories. 41
Table 7. Hypersonic Tools and Methods Programs – Focus on Program Category 7.6 Thermophysical and Radiative Properties. 44
Table 8. EDL Programs – Focus on Database Objectives for Program 3.13 HIAD: Launch Vehicle Booster Recovery. 48
Table 9. EDL Programs – Focus on Test Requirements for Program 3.13 HIAD: Launch Vehicle Booster Recovery. 52
Table 10. EDL Programs – Focus on Capability and Capacity Gaps for Program: 3.13 HIAD: Launch Vehicle Booster Recovery. 57
Table 11. Gap ID, Description, and Frequency. 61
Table 12. SME Ranking of EDL Gap Criticality. 65
Table 13. SME Ranking of HTP Gap Criticality. 66
Table 14. SME Ranking of CFD Gap Criticality. 67
Table 15. EDL Technical Gaps Frequency and Criticality. 68
Table 16. HTP Technical Gaps Frequency and Criticality. 69
Table 17. CFD Technical Gaps Frequency and Criticality. 70
Table 18. EDL Programs – Focus on Gap Mitigation and Closure for Program 3.13 HIAD: Launch Vehicle Booster Recovery. 76
Table 19. Consolidated Rankings of Actionable Gaps. 78
Table 20. Consolidated Rankings of Supporting Gaps. 78
Table 21. Consolidated Rankings of Diagnostics Gaps. 79
Table 22. Categorization and Prioritization of Actionable Gaps. 80
Table 23. HEAC Gap Closure Recommendations. 91
Table 24. Programs List for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration. 120
Table 25. Database Objectives for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration. 123
Table 26. Test Requirements for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration. 135
Table 27. Gaps List for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration. 146
Table 28. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration. 155
Table 29. Programs List for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration. 168
Table 30. Database Objectives for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration. 171

Table 31. Test Requirements for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration. 183
Table 32. Gaps List for Theme: Hypersonic Entry, Descent, and Landing, Customer: NASA and Partners Robotic Exploration. 194
Table 33. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration. 202
Table 34. Programs List for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development. 213
Table 35. Database Objectives for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development. 218
Table 36. Test Requirements for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development. 241
Table 37. Gaps List for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development. 261
Table 38. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development. 277
Table 39. Programs List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development. 297
Table 40. Database Objectives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development. 299
Table 41. Test Requirements for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development. 314
Table 42. Gaps List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development. 326
Table 43. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development. 336
Table 44. Programs List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support. 349
Table 45. Database Objectives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support. 352
Table 46. Test Objectives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support. 371
Table 47. Gaps List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support. 387
Table 48. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support. 398
Table 49. Programs List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support. 414
Table 50. Database Objectives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support. 416
Table 51. Test Requirements for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support. 428
Table 52. Gaps List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support. 435

Table 53. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support. 441
Table 54. Programs List for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation. 449
Table 55. Database Objectives List for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation. 455
Table 56. Test Requirements for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation. 479
Table 57. Gaps List for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation. 497
Table 58. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation. 511
Table 59. Programs List for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development. 526
Table 60. Database Objectives for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development 529
Table 61. Test Requirements for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development 536
Table 62. Gaps List for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development. 539
Table 63. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development 542

Acronyms and Abbreviations

Numerous acronyms and shorthand abbreviations are used throughout the HEAC report for agencies, groups, programs, facilities, test techniques, codes, etc. Definitions for these are given below, although some "one-off" usages may have been missed.

Acronym	Definition
AAVP	Advanced Air Vehicles Program (of NASA ARMD)
AEDC	Arnold Engineering Development Complex (of the USAF)
AETC	Aerosciences Evaluation and Test Capabilities (portfolio of NASA ARMD)
AFRL	Air Force Research Laboratory
AHSTF	Arc-Heated Scramjet Test Facility (of NASA LaRC)
ALHAT	Autonomous Landing Hazard Avoidance Technology
ARC	Ames Research Center
ARMD	Aeronautics Research Mission Directorate
BAM6QT	Boeing/AFSOR Mach 6 Quiet Tunnel (of Purdue University)
BOLT	BOundary Layer Turbulence (flight test program)
CFD	Computational Fluid Dynamics
Cmq	aerodynamic pitch damping derivative
CUBRC	Calspan University of Buffalo Research Center
DoD	Department of Defense (deprecated)
DoE	Department of Energy
DoW	Department of War
DCSTF	Direct Connect Scramjet Test Facility
DES	Detached Eddy Simulation
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DSMC	Direct Simulation Monte Carlo
EAST	Electric Arc Shock Tube (of NASA Ames)
EDL	Entry, Descent, and Landing
EEV	Earth Entry Vehicle (of Mars Sample Return mission)
ESM	Entry Systems Modeling project (of NASA STMD)
F&M	Force and Moment
FLDI	Focused Laser Differential Interferometry
FSI	Fluid-Structural Interactions
FTSI	Fluid-Thermal-Structural Interactions
GCD	Game Changing Directorate (of NASA STMD)
GRC	Glenn Research Center
HEAC	Hypersonic Experimental Aerothermodynamics Capabilities
HEFFL	High-Enthalpy Flow Field Laboratory
HFFAF	Hypervelocity Free-Flight Aerodynamic Facility (of NASA ARC)
HHRNT	Hypersonic High Reynolds Number Tunnel
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HIFiRE	Hypersonic International Flight Research Experimentation (flight test)
HPC	High Performance Computing
HSWT	High Speed Wind Tunnel (of Lockheed Martin)
HTP	Hypersonic Technology Project (of NASA ARMD)
HVSI	Hypersonic Vehicle Simulation Institute (of the USAF Academy)
HWT	Hypersonic Wind Tunnel (of Sandia National Laboratories)
HYMETS	Hypersonic Materials Environmental Test System (of NASA LaRC)
IDA	Institute for Defense Analyses
JCP	Journal of Chemical Physics
JHTO	Joint Hypersonics Transition Office (of the DoW)
JSC	Johnson Space Center
JSR	Journal of Spacecraft and Rockets
LAL	Langley Aerothermodynamics Laboratories
LaRC	Langley Research Center
LAURA	Langley Aerothermodynamics Upwind Relaxation Algorithm
LEO	Low Earth Orbit
LES	Large Eddy Simulation
LHEML	Laser-Hardened Materials Evaluation Laboratory (of AFRL)
LOFTID	Low-earth Orbit Flight Test of an Inflatable Decelerator
MAV	Mars Ascent Vehicle (of Mars Sample Return mission)
MMOD	Micro-Meteoroid and Orbital Debris
MRV	Mars Return Vehicle (for Mars Sample Return)
MSFC	Marshall Space Flight Center
MSL	Mars Science Laboratory (mission)
MSR	Mars Sample Return (mission)
MWIR	Mid-Wavelength Infrared (spectra)
PSWT	Polysonic Wind Tunnel (of Boeing)
RCS	Reaction Control System
S&T	Science and Technology
SBLI	Shock-Boundary Layer Interaction
SLDT	Supersonic Low Disturbance Tunnel (of NASA LaRC)
SMD	Science Mission Directorate (of NASA)
SME	Subject Matter Expert
SRL	Sample Return Lander (of Mars Sample Return mission)

Acronym	Definition
SSTO	Single-Stage to Orbit
STMD	Space Technology Mission Directorate (of NASA)
SWBLI	Shock Wave - Boundary Layer Interaction
TAMU	Texas A&M University
TBCC	Turbine-Based Combined Cycle
TRL	Technology Readiness Level
TSTO	Two-Stage to Orbit
UHTC	Ultra-High Temperature Ceramic
UPWT	Unitary Plan Wind Tunnel (of NASA LaRC)
USAF	United States Air Force
VKF	Von Karman gas dynamics Facility complex (of AEDC)
VST	Vertical Spin Tunnel (of NASA LaRC)
VUV	Vacuum Ultra-Violet (spectra)

Abstract

The NASA Hypersonic Experimental Aerothermodynamics Capability (HEAC) study was a data-driven, Subject-Matter-Expert led team effort to forecast NASA demands for hypersonic ground testing over the next 25+ years. Based on the identified expected demands, the HEAC team assessed the technical capability and logistical capacity of NASA's hypersonic ground testing infrastructure to meet program objectives and test requirements. Multiple critical gaps were identified in the hypersonic ground testing infrastructure which jeopardize the Agency's ability to contribute to the safe and successful performance of NASA's own ambitious 21st century exploration missions and goals, let alone support those of its national partners in the Defense and Commercial sectors. These gaps are traceable to decades of insufficient funding directed to the sustainment of existing logistical capacity and the lack of investment in new technical capabilities. Furthermore, these gaps have directly contributed to the decline of subject matter expertise in NASA's hypersonics workforce. To address these critical gaps in NASA's hypersonic ground test infrastructure, the HEAC team developed a set of investment recommendations for both the construction of new hypersonic ground test facilities and upgrades or modification to existing facilities. These recommendations provide a roadmap to restoring NASA's technical competency and ensuring its preeminence in the discipline of hypersonics.

HEAC Executive Summary

The Hypersonic Experimental Aerothermodynamics Capabilities (HEAC) study was chartered to conduct a forward-looking assessment of demands on NASA's hypersonic ground testing infrastructure and its role in supporting the safe and successful conduct of future NASA programs as well those of its National partners in the commercial and Defense sectors. Specifically, the HEAC team was asked to address four topic areas:

1) Develop a **Vision and Goals** for the role of NASA's hypersonic experimental aerothermodynamics capabilities in meeting NASA, Defense, and Commercial requirements for future programs.

2) Consistent with the **NASA Vision and Goals**, what potential **Programs** of National intertest could NASA be called upon to support over the next 25+ years for customers including NASA itself, as well as Defense and Commercial partners and customers? For this set of **Programs**, what are the hypersonic **Database Requirements** and **Test Objectives** that will help ensure their safe conduct and successful outcome?

3) Assess the ability of NASA's suite of hypersonic ground testing facilities to provide the **Technical Capability** (operational ranges) and **Logistical Capacity** (available testing hours and cost) to meet the set of **Database Requirements** and **Test Objectives**. Evaluate and rank the importance of any **Critical Gaps** in NASA's hypersonic ground test infrastructure

4) How can the **Critical Gaps** in NASA's hypersonic ground testing infrastructure be mitigated or closed?

A team of subject matter experts and program leaders from multiple NASA centers was assembled to perform the HEAC study. Beginning in late 2018, the HEAC team spent approximately three years assembling, analyzing, and documenting an extensive database to address the questions above. This phase took a considerable length of time because the HEAC study was conducted as a "white-space" activity in the team members' free time above and beyond their assigned duties. From 2022 – 2025, the HEAC results were "socialized" internally through leadership at NASA Centers and the NASA Mission Directorates at Headquarters, as well as externally at various conferences and workshops. A list of HEAC briefings and a sample briefing package are included in Appendix A

This final report is being released now to fully document the HEAC results during a time when National priorities, including NASA's human exploration plans for the moon and Mars, the commercial development of a space-based economy, and Defense applications, are all increasingly dependent on hypersonic technologies. The recommendations presented herein are intended to provide a NASA roadmap for 21st century technical excellence in the field of hypersonics that will enable National Civil, Commercial, and Defense goals

Assumptions

The HEAC study team relied on certain fundamental assumptions about the discipline of hypersonics as being axiomatic. These axioms provide the starting point for the HEAC analyses:

Axiom 1: **Hypersonics is a challenging flight regime**. The design of hypersonic vehicles, which include systems for ascent (e.g. rockets), sustained flight (e.g. missiles and winged vehicles) and entry, descent, and landing (capsules, decelerators, and retro-propulsive stages) is arguably the most challenging

aerospace discipline. Hypersonic flight produces a myriad of complex physical phenomena, collectively referred to as *aerothermodynamics*, which include shockwaves, aerodynamic heating, shock-layer radiation, high-temperature gas reactions, boundary-layer transition, thermal protection system ablation, rocket and thruster plumes, etc., all of which may interact both with each other and with the vehicle itself. These challenges are multiplied by the fact that NASA's mission set encompasses not just hypersonic systems for use in the Earth's atmosphere, but also in the diverse and exotic atmospheres of rocky planets like Mars and Venus (mainly carbon dioxide), planetary satellites like Titan (mainly nitrogen) and the gas giants Jupiter, Saturn, Neptune and Uranus (mainly hydrogen).

Axiom 2: **Hypersonic analyses rely on ground testing, flight experiments, and computational simulations:** Information on hypersonic flight phenomena can be obtained through flight experiments, ground testing and/or computational simulations. Each approach has its own advantages and disadvantages, and the most robust hypersonic analyses rely on a combination of data from each of the three tools sets. For any given hypersonic vehicle design, the balance between flight experiment, ground test, and computational simulation is dependent on the complexity, risk, and budget profile of the program. For example, the Mars Insight robotic lander, a small, low cost "Discovery-class" mission that landed a seismometer on Mars in 2018, relied on heritage flight and ground test data from previous Mars missions, supplemented by a limited set of computational simulations. In contrast, the ongoing development of the human-rated Orion capsule that will return a crew to Earth from the Moon at an entry speed of greater than Mach 30, has relied on data generated from two uncrewed orbital flight tests, more than 100 ground-based wind tunnel tests, and thousands of computational simulations.

Axiom 3: **Hypersonics is a core capability required by both NASA and its external partners**. NASA plays a key role in the development of hypersonic systems both for its own missions and also in support of external partners and customers in the Defense and Commercial sectors. NASA has and will continue to conduct crewed and robotic missions and technology development programs that employ hypersonic systems, such as the Space Shuttle, which transported astronauts and payloads to and from low-earth orbit, the Mars Science Laboratory capsule, which landed the Curiosity rover on Mars, and the Hyper-X research vehicle that pioneered hypersonic airbreathing propulsion technology. NASA also has and will continue to support the development of commercial systems through activities such as the Commercial Crew Program under which the SpaceX Dragon and Boeing Starliner capsules were funded. And NASA has and will continue to support National Defense activities, such as the Air Force's HIFiRE and BOLT technology development flight test programs.

Findings

The HEAC team's assessment produced multiple findings on the future needs for hypersonic ground testing in support on National priorities in the Civil, Defense, and Commercial sectors and NASA's ability to conduct such testing.

Finding 1: The future demand for hypersonic ground testing is strong. To extrapolate the future demand signal for hypersonic ground testing, the HEAC team collected inputs from a large, inter-center pool of NASA Subject Matter Experts and program leaders on possible NASA projects for the next 25+ years. The team also gathered "open source" information (e.g. press releases, websites, trade journals, government policy statements, etc.) on future Defense and Commercial sector activities. From these inputs, a list of more than 170 potential hypersonic flight missions, vehicle acquisition programs, and technology development projects was generated. This list was the basis for the HEAC team's assessment of the logistical capacity and technical capability of NASA's hypersonic ground testing facilities to meet future demands.

Finding 2: **NASA's legacy hypersonic ground test facilities have fallen into a critical state of disrepair**. Over the last 30 years, the productivity of the hypersonic wind tunnels in the NASA Langley Aerothermodynamics Laboratory (LAL) has fallen by a factor of ten, primarily because of lost operational capacity due to deferred/insufficient maintenance and repair funding, exacerbated by the age of the facilities' infrastructure. Currently (early 2026), all three wind tunnels of the LAL are off-line due to mechanical issues, as are the high supersonic Mach number Langley Unitary Plan Wind Tunnel (UPWT) and the Langley 8-ft High Temperature Tunnel hypersonic propulsion test facility. Similar difficulties have been experienced in the Ames Electric Arc Shock Tunnel, which provides fundamental gas kinetic and radiative data at hypersonic conditions. Because of this productivity decline, major test programs for both internal NASA projects and external Defense, Commercial, and Academic partners have experienced substantial delays or cancellations, causing adverse impacts to these customers. NASA is also failing to capitalize on new business opportunities due to its inability to allocate test time to potential customers.

Finding 3: **NASA's legacy hypersonic ground test capabilities cannot meet critical technical requirements of current and future test programs**. NASA's hypersonic wind tunnels were designed and entered into service in the 1950s and 1960s, during the heyday of the "space race" when the discipline of hypersonics was in its infancy. Data from these facilities was used in the development of major hypersonic systems, such as the Apollo capsule and the Space Shuttle Orbiter. As the state-of-the-art of the hypersonics discipline advanced, outdated facilities were closed; however, NASA failed to invest in newer facilities with more advanced capabilities. As a result, there are critical performance requirements which the few remaining facilities cannot meet, the most important of which are turbulent flow over hypersonic vehicle geometries, high-temperature flow with sufficient energy to cause shock-layer chemistry and radiation effects, and an overlapping high-supersonic / low-hypersonic Mach number range aerodynamics testing capability.

Finding 4: **NASA cannot rely on external, non-NASA hypersonic ground test capabilities**. In the past, NASA has relied on limited access to external Commercial or Defense hypersonic test facilities to mitigate critical capacity and capability gaps in its own hypersonic testing infrastructure. However, the availability of these external facilities for NASA test programs has been declining for more than a decade due to surging demands from Defense-related programs. This surge is unlikely to abate in the near future, as evidenced by substantial, long-term investments by the Department of War to repair, modernize, and construct facilities to meet its own testing demands.

Finding 5: **NASA cannot rely on Computational Fluid Dynamics to replace ground testing.** Despite making great strides over the last 50 years, there remain many physical phenomena for which computational fluid dynamics models are non-existent, unvalidated, or impractical. Computational subject matter experts on the HEAC team identified numerous such challenges relevant to hypersonic systems, including boundary-layer transition and turbulent flow, unsteady wake flow, shock-shock interactions produced by complex vehicle geometries, flow field and/or vehicle surface interactions with propulsion system and thruster jets and plumes, high-energy shock layer radiation characteristics, magneto-hydrodynamics, and aero-optical effects. The development and validation of computational models for such phenomena will rely on experimental data obtained from a combination of flight experiments and ground testing. And in addition to these technical shortfalls in modeling and simulation capabilities, the capacity of NASA's supercomputing assets on which numerical simulations are performed is ranked well below other national and international systems.

Recommendations

As evidenced by the HEAC team's findings, there are critical gaps between the projected future National demands and requirements for hypersonic ground testing and the ability of NASA's legacy infrastructure to provide those capabilities. These gaps are discussed in detail in the body of this report. A set of technical and programmatic recommendations has been generated to close these gaps and deliver a 21st century vision for NASA technical excellence, as given below.

Technical Recommendation 1: **Repair and modernize critical existing NASA hypersonic facilities**. NASA's legacy hypersonic testing facilities have fallen into an unacceptable state of disrepair that endangers NASA's ability to support its own mission commitments, let alone those of its partners and customers in the Defense, Commercial, and Academic sectors. Additionally, critical subject-matter-expertise is being lost because of the lack of opportunities for researchers and engineers to actually perform hypersonic testing. Funding should be allocated to repair, replace, and/or modernize failing or outdated systems and components in the facilities themselves, as well as in the supporting infrastructure such as electrical distribution, high-pressure air supply, and the fundamental integrity of the buildings in which these facilities are housed. Even if the recommendations discussed below for construction of new facilities are accepted, the existing facilities would still be needed for the next 25+ years, both to maintain testing capabilities and expertise while new facilities are being developed and to continue providing extra capacity to accommodate the projected rising demand for hypersonic testing.

Technical Recommendation 2: **Construct a new Hypersonic High Reynolds Number Tunnel (HHRNT)**. A new hypersonic ground test facility should be constructed that would produce data on convective aeroheating augmentation at turbulent conditions. This conventional blow down wind tunnel would incorporate multiple, interchangeable nozzles to produce hypersonic test conditions from Mach 6 to Mach 12. In comparison to existing NASA wind tunnels, this Hypersonic High Reynolds Number Tunnel would feature a larger test section to accommodate bigger test articles and operate at higher Reynolds numbers, which together will provide NASA the capability of producing turbulent flow over all hypersonic configurations of interest.

Technical Recommendation 3: **Construct a new High Enthalpy Flow Field Laboratory (HEFFL)**. A new hypersonic ground test facility should be constructed that would produce high temperature data on non-equilibrium thermochemical effects on hypersonic vehicles. This high enthalpy, short run duration impulse tunnel would have a dual-mode configuration enabling operation as a reflected shock tunnel for hypersonic atmospheric flight conditions or as an expansion tunnel for hypersonic atmospheric entry conditions. These high temperature, hypervelocity operating conditions would provide a unique new NASA capability for producing data on the effects of shock-layer reacting gas chemistry on hypersonic vehicle performance.

Technical Recommendation 4: **Upgrade the Langley Unitary Plan Wind Tunnel (UPWT).** The existing Langley UPWT should be upgraded to allow operations in the Mach 5 – 6 range. This increase beyond its current operational maximum of Mach 4.6 would provide NASA with a bridge between its current supersonic and hypersonic testing capabilities and allow collection of vehicle performance data in this regime of interest for hypersonic atmospheric flight systems.

Technical Recommendation 5: **Upgrade the Ames Electric Arc Shock Tube (EAST).** The existing Ames Electric Arc Shock Tube should be modernized to improve throughput and reduce facility downtime. The facility currently relies on 60-year-old control and high voltage electrical systems that are no longer serviceable. Rebuilding these systems will improve facility reliability and guard against future testing gaps

that may last for months or longer. Modernizing the facility instrumentation with new laser absorption and emission spectroscopy systems will enable measurement of flight-similar chemical and radiative processes, increase data throughput and reduce downtime for configuration changes.

Technical Recommendation 6: **Convert the LaRC Nozzle Test Chamber into a Hypersonic Quiet Tunnel.** The existing LaRC Nozzle Test Chamber should be converted into a quiet-flow hypersonic tunnel through installation of a specially designed new nozzle. This conversion would provide NASA with a unique new capability for gathering information on boundary-layer transition in a controlled, noise free environment. These data would be used in the design of hypersonic atmospheric flight systems and the development and validation of boundary-layer transition models for numerical modeling and simulation codes.

Technical Recommendation 7: **Convert the LaRC 15-Inch Mach 6 Air Tunnel into a Hypersonic Ludwieg Tube.** The existing LaRC 15-Inch Mach 6 Air Tunnel should be converted to a low-cost, high-productivity Ludwieg Tube. This converted facility would permit intensive and fast-paced development of advanced new measurement and diagnostics techniques for use in all NASA hypersonic and supersonic ground test facilities. Such work has become extremely limited due to the declining productivity of NASA ground test facilities and the prioritization of programmatic testing for their limited availability.

Programmatic Recommendation 1: Commit to sustained maintenance funding of NASA's hypersonic facilities. The decline in productivity of NASA's ground test facilities and accompanying loss of hypersonics subject matter expertise are directly traceable to NASA's prioritization of short-term mission goals over long-term investments in sustaining capabilities. Because of this prioritization, NASA has essentially allowed many of its facilities to fall into the "run-to-failure" category because of the lack of funding for annual maintenance and repairs. Sustained maintenance funding for both the new facilities recommend herein and the highest-priority legacy infrastructure should be mandated to ensure that they remain viable throughout the 21st century in order to recoup their capitalization costs.

Programmatic Recommendation 2: **Reinvigorate NASA's hypersonics subject matter expertise**. Investments in the physical infrastructure for hypersonic ground testing should be complemented by investments in workforce training and development. "Hands-on" subject matter experience in hypersonic ground testing can only be acquired by *doing* hypersonic ground testing. However, the opportunities for NASA personnel to develop expertise have become increasingly limited due to both the declining productivity of NASA facilities and to the emphasis on mission-focused test programs of limited scope and duration. NASA should allocate funding for engineers and technicians to engage in fundamental and applied research and development test programs, as well as for facility calibrations, diagnostics, and test-technique development which will contribute to the development of a wide base of subject matter expertise at NASA. Such testing also affords opportunities for workforce training partnerships with the Department of War and Academia that benefit the National interest in developing a robust hypersonics workforce.

Programmatic Recommendation 3: **Support NASA's computational tool development**. The development of new hypersonic ground testing facilities is a complementary goal to the development of new numerical tools and methods for hypersonic flow field simulations. Because advanced computational model development and validation efforts will require experimental data from wind tunnel testing, NASA should commit to the sustained support and funding of computational development programs. Limited activities in this area are being conducted within existing NASA programs, e.g. the STMD Entry Systems Modeling (ESM) Project, the ARMD High Speed Flight (HSF) Project, and the ARMD Transformational Tools and Technologies (TTT) Project. Although these projects address different mission goals and flight regimes, communication and collaboration between them should be encouraged, as well as coordination

with the hypersonic ground testing community. Greater funding for computational development efforts such as these will be required, which should include ground-test programs targeted specifically at obtaining high-fidelity data for computational model validation exercises.

Programmatic Recommendation 4: **Socialize the HEAC results**. Implementation of the above list of recommendations will require time, funding, and leadership. These are all finite resources and the direction and prioritization of them towards fulfilling these goals can only be accomplished through communication, outreach, and socialization. The HEAC findings should be shared to the fullest possible extent with NASA's hypersonics stakeholders, which include NASA itself, especially Mission Directorate and HQ leadership; the Department of War and its service branches, particularly the Air Force, Space Force, and Navy; the commercial sector, including vendors directly supporting NASA and/or DoW missions, as well as those active in the development of space-based economy; and the Academic community.

Introduction

The NASA Hypersonic Experimental Aerothermodynamics Capabilities (HEAC) study team, consisting of numerous subject matter experts and program leaders from across the Agency, was chartered to formulate a future vision for technical excellence in NASA's ground based hypersonic aerothermodynamics testing capabilities. A detailed discussion of the HEAC study methodology, results, and recommendations will be presented herein. The guiding principle of the HEAC process was that it would produce a "data-driven" product rather than an opinion paper. As such, an extensive database of inputs from the HEAC study team is documented in the Appendices.

The analysis of this database provides the basis for the HEAC assessment of future NASA (and partner) program needs for hypersonic information, gaps between program objectives and requirements and NASA's hypersonic ground test capabilities, and recommendation for investments to close those gaps. However, before presenting the details of this study, a few notes on the organizational boundaries, technical scope, and personnel and financial resources are necessary.

First, with respect to organizational boundaries, the HEAC study was a *NASA* study, focused on NASA roles, missions, and needs. The key consideration in all analyses was "how does this affect NASA?" That being said, NASA does have a role supporting National interests in the Defense and Commercial sectors and the team was asked to consider that role as well. However, in order to ensure the public distribution of this report, no inputs were requested from any military or corporate entities on their potential requirements, although representatives of the Defense hypersonic testing community did provide limited reviews and comments on aspects of this work. Furthermore, any information presented herein on potential NASA test support for commercial or Defense programs represents only informed speculation based on open-source information, including press releases, policy statements, websites, and technical publications.

Second, the technical "control-volume" of the HEAC study encompasses only *external* hypersonic aerothermodynamics — that is, the physical phenomena of the flow around a hypersonic vehicle, including shockwaves, chemistry, radiation, heat-transfer, aerodynamic forces, etc. The control volume excludes internal phenomena such as combustion processes, mechanical-structural responses to aerodynamic loads, material thermal response to external heating, etc. Thus, ground testing facilities such as arc-jets, scramjets and propulsion test facilities, which provide data on these phenomena, were not considered in the HEAC study.

Finally, with respect to resources allotted to the HEAC study, they were constrained. With the exception of a support contract with the Institute for Defense Analyses (IDA) to provide process-related guidance and facilitation for the study, there were no direct expenditures or procurements. NASA subject matter experts contributing to this task worked in their "white-space", i.e. time outside of their assigned duties. These constraints contributed to the extended duration of the activity from its genesis in 2018 to publication of this final report.

Overview of the Current State of National Hypersonic Testing Capabilities

The results of the HEAC study are intended to provide recommendations and guidance on the future of NASA hypersonic aerothermodynamics capabilities. But before presenting the full details of the HEAC study, it is a useful starting point to provide some background on the current state of national capabilities for hypersonic ground testing. Thus, perspectives are given below for NASA, Defense, Commercial, and academic experimental ground testing capabilities, as well as for the complementary field of hypersonic computational fluid dynamics.

Perspectives on NASA Hypersonic Ground Testing Capabilities

Since the creation of NASA in 1959, its ground testing capabilities have provided invaluable data on the hypersonic aerothermodynamics performance of numerous atmospheric flight and entry, descent and landing systems developed by NASA for its own missions, as well in support of Defense applications, commercial partners, and academia. A partial list of important programs and activities is illustrated in Figure 1.

Examples of major programs that required wind tunnel data include the ground-breaking X-15 hypersonic flight aircraft in the 1950s; the Mercury, Gemini, and Apollo crewed entry capsules during the "Space-Race" of the 1960s; and the development of Space Shuttle Orbiter in the 1970s. During the 1980s-1990s, NASA performed hypersonic ground testing on many "X-vehicle" concepts such as the X-30 National Aerospace Plane, the X-33 reusable launch vehicle, the X-34 reusable space plane, and the X-38 crew return vehicle, as well as the X-43 Hyper-X hypersonic airbreathing propulsion testbed.

In the 2000's, NASA hypersonic facilities supported the development of the X-37A reusable space plane (the precursor to the USAF X-37B Orbital Test Vehicle), the Mars Science Laboratory and Mars 2020 entry systems, the Orion Crew Exploration Vehicle (CEV), and the Genesis solar wind and Stardust comet sample return capsules. During this period, NASA facilities also played a vital role in the Columbia accident investigation and the Shuttle Return-to-Flight program. Since the 2010s, testing has been conducted for the IRVE-3 and LOFTID inflatable aerodynamic declarator flight demonstration missions and for the Earth Entry System capsule of the Mars Sample Return Program, as well as continuing work on the Orion CEV.

NASA hypersonic test facilities have also supported multiple Defense-related projects, including public activities such as the HIFiRE and BOLT series of hypersonic flight tests, as well as other missions. And in the commercial sector, test programs were conducted for Blue Origin, Boeing, Kistler, Lockheed-Martin, Rocket Lab, Sierra Nevada / Sierra Space, SpaceX and other customers.

And finally, in addition to test programs that supported defined missions and customers, NASA has also conducted hundreds of fundamental and applied research programs in its suite of facilities that have contributed to the advancement of the state-of-the-art of national hypersonic capabilities. Topics of these programs have included boundary-layer transition, surface roughness effects, advanced configuration and concept evaluation, separated wake flow characterization, aerodynamic control effectiveness, and reaction-control-system (RCS) thruster performance, as well as various test technique development and demonstration activities. Many of these activities were performed in collaboration with students and professors from various Universities.



Figure 1. Hypersonic Flight Programs Supported by NASA Ground Test Facilities.

These ground test campaigns were enabled through a once-large roster of hypersonic aerothermodynamics wind tunnels developed and operated by NASA (Ref. 1), which is listed in Table 1. The nation's first hypersonic wind tunnel was the Langley 11-Inch Hypersonic tunnel, which entered service in 1947 and was actually developed by NASA's predecessor, the National Advisory Committee for Aeronautics (NACA). This tunnel was followed by several dozen hypersonic blow down wind tunnels, impulse facilities, and ballistic test ranges developed and operated by NASA during the 1950s – 1960s, primarily at the Ames and Langley Research Centers.

However, NASA has not commissioned a *new* hypersonic facility into service since the Langley Mach 6 High Reynolds Number Tunnel was brought online in 1967 (discounting the 1972 conversion of an older existing facility into the LaRC 20-Inch CF4 tunnel). To put that date into perspective, many of the *parents* of the young engineers being hired today by NASA to conduct hypersonic research had not yet been born when NASA last put a new hypersonic facility into operation.

Of the many hypersonic aerothermodynamics facilities once operated by NASA, only the three hypersonic blow down tunnels of the Langley Aerothermodynamics Laboratory (LAL): the 31-Inch Mach 10 Air Tunnel, the 20-Inch Mach 6 Air Tunnel, and the 15-Inch High Temperature Mach 6 Air Tunnel, along with the Ames Hypervelocity Free Flight Aerodynamic Facility (HFFAF) and Electric Arc Shock Tube (EAST), remain in operation today. Additionally, the 8-Foot High-Temperature Tunnel at NASA LaRC is still active; however, that is a hypersonic propulsion test facility, which falls outside the scope of this report.

Table 1. Historical Roster of NASA Hypersonic Wind Tunnels.

Facility	Location	In-Service	Type	Application	Status
1-Foot Hypervelocity Shock Tunnel	ARC	1960	impulse facility	high-temperature gas kinetics effects	Demolished 1972
Electric Arc Shock Tube (EAST)	ARC	1965	impulse facility	high-temperature shock-wave radiation effects	Active
Hotshot Tunnel	LaRC	1962	impulse facility	high-temperature gas kinetics effects	Damaged 1969 and demolished
6-Inch Expansion Tube	LaRC	1967	impulse facility	high-temperature gas kinetics effects	Government excess 2000's, transferred to Purdue
Atmospheric Entry Simulator	ARC	1958	ballistics range	free flight aerodynamics/aeroheating	Demolished 1967
Pressurized Ballistic Range	ARC	1958	ballistics range	free flight aerodynamics/aeroheating	Decommissioned 1990
Hypervelocity Free-Flight Aerodynamics Facility	ARC	1966	ballistics range	free flight aerodynamics/aeroheating	Active
10 x 14-Inch Hypersonic Tunnel	ARC	1950	blow down tunnel	aerodynamics/aeroheating	Decommissioned 1963
Hypersonic Helium Tunnel	ARC	1960	blow down tunnel	aerodynamics/aeroheating	Demolished 1971
3.5-Foot Hypersonic Tunnel	ARC	1961	blow down tunnel	aerodynamics/aeroheating	Decommissioned 1999, Demolished 2015
Mach 50 Helium Tunnel	ARC	1965	blow down tunnel	aerodynamics/aeroheating	Demolished 1970
21-Inch Hypersonic Wind Tunnel	JPL	1957	blow down tunnel	aerodynamics/aeroheating	Standby 1975, decommissioned 1998, demolished 2007
11-Inch Hypersonic Tunnel	LaRC	1947	blow down tunnel	aerodynamics/aeroheating	Transferred to Virginia Tech 1973
37-Inch Mach 10 Helium Tunnel	LaRC	1952	blow down tunnel	aerodynamics/aeroheating	Closed 1990s, demolished 1998
60-Inch Mach 18 Helium Tunnel	LaRC	1952	blow down tunnel	aerodynamics/aeroheating	Closed 1990s, demolished 1998
Mach 6 Pilot Quiet Tunnel	LaRC	1955	blow down tunnel	aerodynamics/aeroheating	transferred to Texas A&M 2005
20-Inch Mach 6 Air Tunnel	LaRC	1958	blow down tunnel	aerodynamics/aeroheating	Active
15-Inch Mach 6 High-Temperature Air Tunnel	LaRC	1959	blow down tunnel	aerodynamics/aeroheating	Active

Facility	Location	In-Service	Type	Application	Status
18-Inch Mach 8 Variable Density Tunnel	LaRC	1960	blow down tunnel	aerodynamics/aeroheating	Standby 1980s, mothballed 1990s after failed conversion
22-Inch Mach 20 Helium Tunnel	LaRC	1960	blow down tunnel	aerodynamics/aeroheating	Closed 2003, demolished 2007
20-Inch Mach 8.5 Air Tunnel	LaRC	1961	blow down tunnel	aerodynamics/aeroheating	demolished 1980
20-Inch Mach 17 Nitrogen Tunnel	LaRC	1964	blow down tunnel	aerodynamics/aeroheating	Closed 1990's, demolished 2007
31-Inch Mach 10 Air Tunnel	LaRC	1964	blow down tunnel	aerodynamics/aeroheating	Active
12-Inch Mach 6 High-Reynolds Number Air Tunnel	LaRC	1967	blow down tunnel	aerodynamics/aeroheating	Closed 1998, demolished 2007
Hypersonic Helium Open-Jet Leg	LaRC	1969	blow down tunnel	aerodynamics/aeroheating	Closed 1990s, demolished 1998
20-Inch Mach 6 CF4 Tunnel	LaRC	1972	blow down tunnel	aerodynamics/aeroheating	Standby 2011, Demolished 2017
42-Inch Hypersonic Test Facility (HTF)	GRC	1969	blow down tunnel	propulsion system testing	Intermittent operations, mothballed 2006
8-Foot High-Temperature Tunnel	LaRC	1965	blow down tunnel	propulsion system testing	Active

In addition to the lack of investment in new testing facilities, NASA's budget for maintenance and repairs of its existing facilities has long been insufficient (e.g. National Academies assessment in Ref. 2). As a result, its remaining facilities have experienced a long-term decline in productivity. An example of this decline is shown for the wind tunnels of the Langley Aerothermodynamics Laboratories in Figure 2. From the mid 1990s to the mid 2020s, the number of weeks of testing each year in the LAL wind tunnels has dropped by a factor of ten. While surges in demand can be traced to high-priority projects such as the Columbia accident investigation, this decline is attributable mainly to tunnel availability, not a lack of customer interest. An extrapolation of this trend suggests that by 2050, there will be no testing capacity available in the LAL wind tunnels.

The lack of testing capacity has had, and will continue to have, adverse effects on the ability of NASA to execute its missions or support its partners. As this report is being prepared, more than 20 test programs have been delayed by 1-3 years because of operational capacity issues in the NASA hypersonic tunnels. Because of these delays (or outright cancellations) of ground test programs, missions that intended to rely on these tests have been impacted by schedule slippage, increased costs for simulations and analysis to replace ground test data, and/or acceptance of more conservative design safety margins.

And obviously, as facility productivity consistently drops and fewer actual wind tunnel tests are conducted, subject matter expertise in hypersonic experimental testing is not being developed. The impact of this loss of opportunities to develop and maintain subject matter expertise in hypersonics on NASA's workforce is illustrated in Figure 3. This plot shows the actual accumulated testing experience of experimental hypersonics researchers at senior career (1997 hire), middle career (2013 hire), and junior career (2022) levels at the present date. Extrapolating their relative career experiences weighted for the declining facility productivity shows that in 30 years from entering service, the mid-career researcher will have accumulated only 50% of the subject matter experience of the baseline senior research and the junior-career researcher will have accumulated only 30% of that experience.

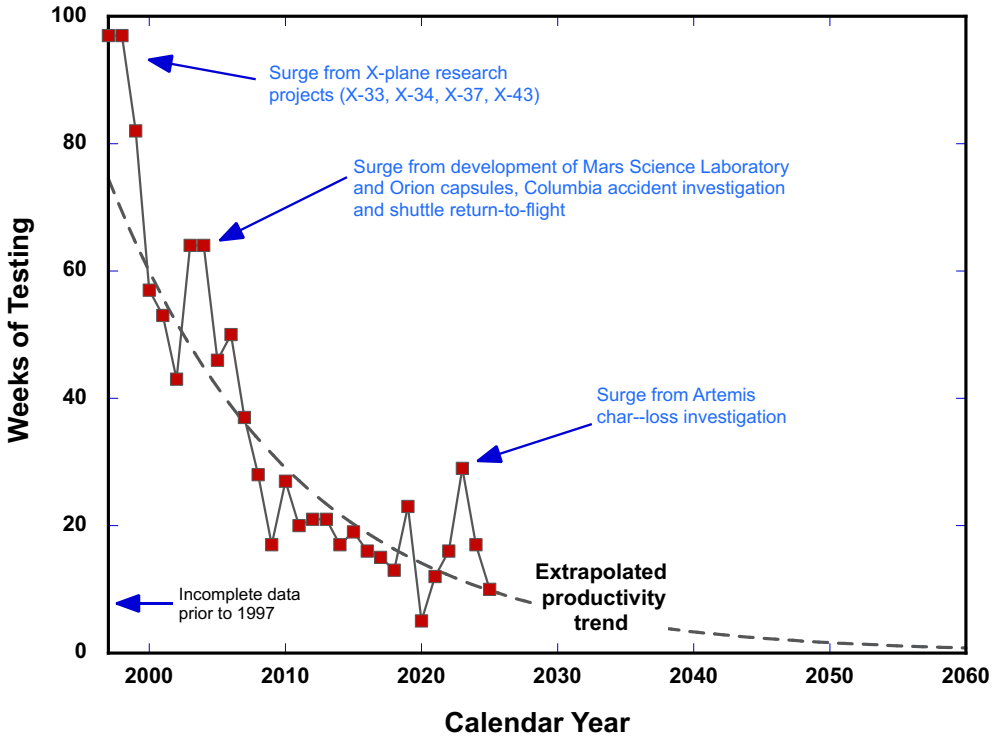


Figure 2. Declining Productivity of the LAL Wind Tunnels.

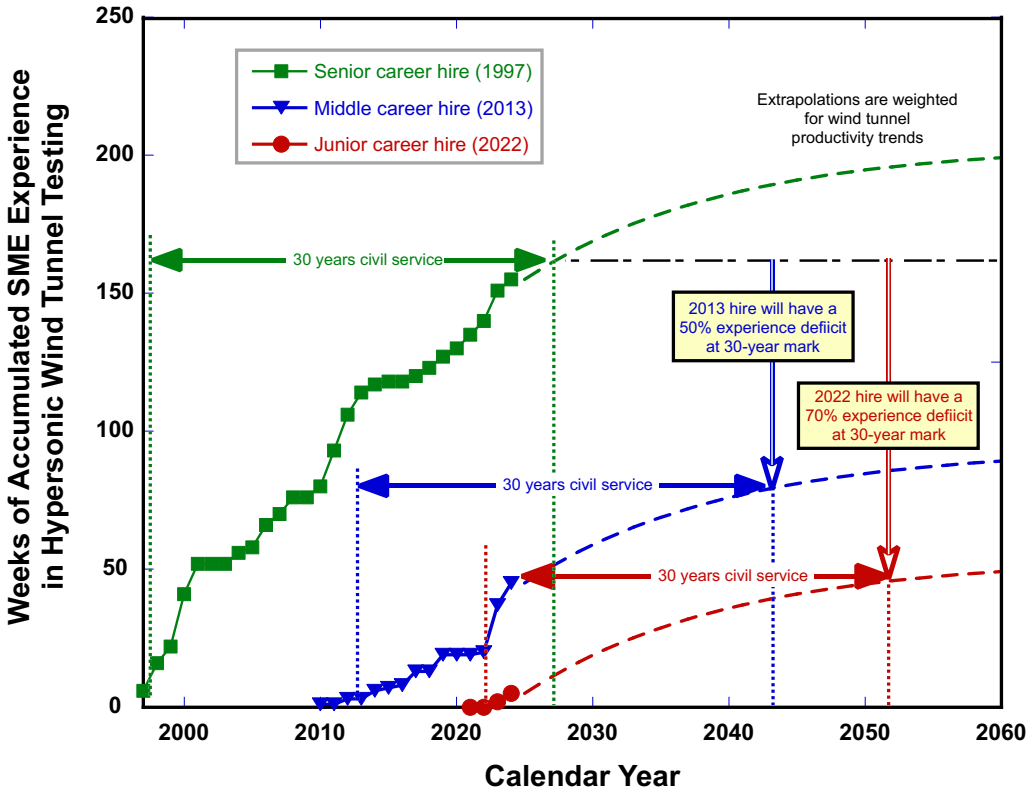


Figure 3. Declining SME of Experimental Hypersonics Workforce.

Perspectives on Defense Sector Hypersonic Ground Testing Capabilities

The Department of War[1] (DoW) operates a large suite of aeronautical ground testing facilities covering the entire speed range. With respect to the hypersonic regime, DoW assets include the Von Karman Gas Dynamics Facilities complex in Tullahoma, TN and Hypervelocity Tunnel 9 in White Oak MD, both of which fall under the purview of the United States Air Force Arnold Engineering Development Complex (AEDC). Additionally, the Air Force Research Laboratory (AFRL) operates the Mach 6 High Reynolds number tunnel at Wright Patterson Air Force Base in Ohio.

In contrast to the lack of funding by NASA for testing infrastructure, the DoW has been investing heavily in its own ground testing capabilities for aerospace applications for more than a decade. These investments are directed at both maintenance and upgrades to aging legacy facilities and the construction of new facilities. While detailed information on Defense-related spending is, for obvious reasons, not always available for public release, there are some citable data on this topic. In Ref. 4, a total investment of $98M for the period of 2007 to 2013 is given for investments in testing infrastructure at the Arnold Engineering Development Complex in Tullahoma, TN, the Air Force's main center for aerospace testing. More recently, a fiscal year 2022 appropriation of $47.5M for hypersonic test infrastructure at AEDC is cited in Ref. 5. And again, these are only the open-source, publicized investments by the DoW. In short, the DoW is investing a large amount in its aerospace testing infrastructure to improve its technical capability and logistical capacity.

This comparison between NASA and DoW investments in ground test infrastructure is not intended to suggest that the NASA budget for hypersonic aerothermodynamics applications should be proportional to DoW investments for military applications; NASA and the DoW have different roles, responsibilities, and missions. Rather, the conclusion to be inferred is that these large levels of DoW spending are necessary because its facilities are insufficient to meet its own current demands. Furthermore, if DoW capabilities and capacity for ground testing are insufficient to meet DoW requirements, then it is a logical conclusion that those DoW facilities are not now available, nor will they be available in the foreseeable future, to provide any significant level of support for NASA testing requirements.

The availability, or lack thereof, of DoW facilities for NASA applications is emphasized here in the context of the HEAC study, because a frequent response to proposals for investments in NASA ground test infrastructure is that NASA should instead make use of DoW or other non-NASA facilities. That proposition would seem to be untenable in the current geopolitical climate. In fact, given the designation of NASA hypersonic testing capabilities as fulfilling a role in "*strategic national interests*" by a RAND corporation study jointly-funded by NASA and the Office of the Secretary of Defense (Refs. 6-7) – which was completed over decade prior to the current surge in DoW demand for hypersonic testing — it is far more likely that the DoW will require time in NASA facilities rather than being able to provide time in its own facilities for NASA use. This RAND assessment remained substantially unchanged in a 2009 update (Ref. 8), except to note that:

"*the lack of federal investments in new, more advanced facilities is forcing the retention of aging and sometimes inferior infrastructure for strategically important capabilities*"

As shown in the discussions above regarding investments, the DoW has acted to remedy this deficiency, while NASA has not.

[1] Formerly the Department of Defense (DoD), which terminology is applied herein with respect to references and discussions predating the 2025 redesignation.

Perspectives on Hypersonic Ground Testing Capabilities in Industry and Academia

In addition to US Government facilities that fall under the purview of NASA or the Department of War, there are also hypersonic test facilities operated by Industry and Academia.

Currently, the only significant hypersonic testing capability in the commercial sector is the suite of facilities operated by the Calspan University of Buffalo Research Center (CUBRC). The CUBRC facilities are strongly aligned with, and funded by, the Department of War – e.g. as per Ref. 9.

"*…CUBRC in Buffalo has received $16 million in FY2020 funding from the Department of Defense…"*.

As such, the same limitations on NASA testing that apply to DoW owned facilities can be expected to hold for those at CUBRC. In other words, NASA access to industry facilities will be very limited.

Significant advances in hypersonic testing capabilities are also being made in Academia, mainly under the auspices of Defense-related funding. For example, the DoW committed $100M (Ref. 10) to the University Consortium of Applied Hypersonics (UCAH) under the auspices of the Joint Hypersonics Transition Office (JHTO) in 2022. This federal funding, along with contributions from state governments and other institutional funding, has enabled the creation of new testing capabilities, e.g. the Ballistic, Aero-Optics, and Materials (BAM) Range at Texas A&M University ($68M investment, as per Ref. 11) and the Hypersonics and Applied Research Facility (HARF) at Purdue University ($41M investment, as per Ref. 12). Again, because of their alignment with, and funding from, the DoW use of facilities such as these cannot be considered as a practical option for NASA purposes.

Perspectives on Computational Fluid Dynamics

The discipline of Computational Fluid Dynamics (CFD) — which is sometimes referred to as "Modeling and Simulation" — is also considered herein because of its role as a "surrogate" for ground testing. The state-of-the-art of this discipline has made great strides since the first pioneering three-dimensional Navier-Stokes simulation of a complex vehicle at hypersonic speed (the experimental X-24C lifting body as per Ref. 13) in 1986. Computational Fluid Dynamics tools are now widespread and commonly employed for aerospace simulations across all speed ranges. Within NASA, the primary tools employed for hypersonic atmospheric flight and hypersonic entry, descent, and landing simulations include DPLR, FUN3D, Hypersolve, LAURA, LociChem, US3D and Vulcan.

The proposition has been advanced that at some future date, the development of numerical tools and methods will be sufficiently advanced that CFD will provide a better, faster, and cheaper alternative to ground testing (e.g. Ref. 15). For some classes of problems, that day may have already arrived. However, as noted in NASA's CFD 2030 Vision (Ref. 16):

"…CFD can largely replace wind-tunnel testing for easy cases, but wind tunnels will be necessary for making measurable advances in aeronautics unless the shortfalls in the CFD capability that are discussed above are overcome. The aerospace industry continues to use wind-tunnel testing extensively, and the expectation is that this trend will continue for the foreseeable future as a result of the inadequacy of the physical models in the current CFD codes."

Notably, this report identifies multiple gaps in computational modeling tools and outlines several "Grand Challenges" to be solved, one of which includes the aerothermodynamics modeling of a hypersonic vehicle. This report also calls out the need for increased investment in the development of numerical tools by using

data from new ground test facilities:

"Thus, there is a national imperative to reinvigorate the investment in physics-based engineering simulation tools in general, and in CFD in particular, and NASA is uniquely positioned to fill this role. In addition to enhancement of CFD technology, effective use of existing, and potentially new, ground-based testing facilities will be required to provide a complementary set of tools to best advance aerospace product development efforts and reduce technical risk in the future."

This report explicitly notes the continuing role of ground testing, both as a primary source of information in regimes where CFD tools are deficient and as a source of high-fidelity data sets to be used in the development and validation of new simulations capabilities:

"To help achieve the vision of CFD in 2030, an integrated approach involving well designed, ground-based (and perhaps flight) experiments to provide high quality datasets directly coupled with CFD technology and application code verification and validation is required."

In summary, CFD is not yet ready to fully replace ground testing for all aerospace problems of interest, nor will it achieve that goal without experimental datasets to be used in the development and validation of new modeling capabilities. And in addition to considerations of technical capability, there is also the issue of capacity. According to the latest list (Ref.17) of international high-performance computing (HPC) resources, NASA's fastest computing asset, the Athena cluster at NASA Ames, ranks as #116 as of November 2025. As with its physical capacity for ground testing, the capacity of NASA computational hardware is a limiting factor in the Agency's ability to perform hypersonic analyses.

Future State of NASA Hypersonic Ground Testing Capabilities

The historical draw-down of NASA's hypersonic ground testing facility roster and the ongoing productivity decline of the few remaining facilities has been demonstrated in the previous sections. And with Commercial and Defense test facilities becoming increasingly unavailable for any significant support for NASA, a projection of these trends suggests a potential outcome in the not-too-distant future when NASA no longer has access to *any* hypersonic ground testing capabilities.

A major contributor to the decline of NASA's hypersonic ground testing capabilities is, of course, the prioritization of the Agency's limited budgetary resources. As documented in the National Academies report (Ref. 2), NASA has focused on mission execution, rather than long-term institutional investments:

"In an opportunity-rich environment, such as NASA has confronted over the years, the choice has too frequently been to pursue near-term missions at the expense of investing in the ostensibly invisible foundational assets of the organization."

In short, the budget for conducting missions has grown, while the budget for maintaining the capabilities that will help enable those missions has shrunk. Again, from Ref. 2:

"Another overarching issue is that in recent years NASA's budget for missions has increased from 79 to 85 percent of the overall budget while the mission support budget has declined from 20 to 14 percent."

As result of this prioritization, all of NASA's infrastructure – not just hypersonic facilities – is at risk (Ref. 2).

"This plan documents that 83 percent of NASA's physical infrastructure is beyond its design life, and that the agency's Construction of Facilities (CoF) renewal rate is falling well below the 50-year target goal."

The deleterious effects of insufficient investments on National interests have been noted by the U.S. Congress as per the National Aeronautics and Space Administration Transition Act Authorization Act of 2017 (Ref. 3) with a call for a new direction:

"It is the sense of Congress that — (1) the Administration must address, mitigate, and reverse, where possible, the deterioration of its facilities and infrastructure, as their condition is hampering the effectiveness and efficiency of research performed by both the Administration and industry participants making use of Administration facilities, thus harming the competitiveness of the United States aerospace industry."

However, given the widespread deterioration of NASA's infrastructure, it is unlikely that sufficient funding could ever be appropriated to address *all* the deficiencies. Thus, the Agency will have to make difficult decisions on how to allocate its resources. To inform that decision-making process, the HEAC study provides a data-driven assessment on the importance of hypersonic ground testing capabilities to NASA and the Nation.

Overview of the HEAC Study

The Value-Based Justification Process

The starting point for the NASA HEAC study was the "Value-Based Justification Process" (Refs. 18-19) for infrastructure investments developed by the Institute for Defense Analyses (IDA) to assist the DoW in defining its infrastructure investment strategy. The key feature of this IDA process is that it provides a detailed and referenceable statistical analysis of stakeholder needs and the cost, schedule, and impacts on stakeholder missions if those needs are not meant. In the context of both IDA's analyses for the DoW and the current NASA study, this approach addresses the question of "what is the *value* to the National interest in hypersonic testing capabilities and what is the *risk* if those capabilities are insufficient to the demands?"

This approach stands in contrast to the so-called "business case" methodology (e.g. Ref. 20) that focuses on the financial *cost* of infrastructure investments and operations vs. the return on investment from selling test time to customers. That methodology relies on high-level managerial and fiscal inputs to guide the decision-making process instead of "bottom-up" assessments of risks and requirements from technical subject matter experts and program leaders.

The decision to apply a value-based or business-case approach to the question of investments is a philosophical issue rather than a technical one. Information herein will be presented to support using the IDA value-based methodology for investment decisions as that is the basis for the HEAC analyses. However, a few salient points are offered with respect to cost-based decision making.

It is unarguable that NASA should apply "best business practices" to activities such as accounting for its spending, issuing and monitoring contracts, following appropriate regulations for purchasing, etc. However, where a government agency such as NASA fundamentally differs from a commercial entity is that NASA does not accumulate yearly profits that can then be allocated to capital investments and stakeholder returns. Instead, NASA is appropriated an annual budget by Congress and is charged to conduct actions to benefit the public interest. Thus, while NASA must make difficult decisions on where and how to allocate its limited funding, such decisions should not be made solely on the question of whether or not a particular activity, e.g. operating a wind tunnel, is profitable on a yearly basis, but should rather be based on National interests and priorities.

Adapting the IDA Methodology to HEAC

To address the question of NASA hypersonic experimental capability investments, the IDA methodology was adapted to better fit the programmatic scope of this assessment and the resources available (i.e. limited personnel and very limited budget) to conduct the study. In the IDA assessment for the DoW, three conceptual hypersonic Defense acquisition programs were subjected to a detailed analysis of their mission cost, schedule, and requirements. Each of those "use-case" examples would have budgets well in excess of $1 billion allocated to develop, acquire, and expend multiple flight articles. The assessment of requirements for these programs encompassed all facets of the flight article, including aerothermodynamics, materials, propulsion, guidance and control, etc. And the DoW study had access to its own detailed historical and ongoing financial analyses from other such large acquisition programs.

In contrast, NASA's budget is much smaller than that of the DoW and would be spread over numerous smaller programs (170 *potential* activities were identified herein, as opposed to the three reference concepts in the DoW study) of which the majority would entail the purchase of a single, bespoke flight article (e.g. a hypersonic airbreathing propulsion technology demonstrator or a Mars science mission lander). Given

these differences, the detailed cost modeling and accounting aspect of the original IDA process were not well suited to the NASA analysis. Also, the HEAC study focused solely on the *external* aerothermodynamics requirements of these programs, not the overall system requirements (structures, propulsion, thermal response, avionics, etc.) as in the DoW study. Finally, with respect to the budgetary resources available to the HEAC study — there essentially were none. Other than a small procurement contract with IDA[2] for consultation and facilitation of the study, all work was conducted by NASA SMEs as a "white-space" activity. Since the HEAC SME team members were obligated first to their funded tasks, they were able to contribute to this work only on a time-available basis, which considerably extended the time required to complete this assessment.

HEAC Team Structure and Products

HEAC Team Organization and Tasks

The HEAC study was tasked with the goal of assessing the future role of NASA's hypersonic ground capabilities and its ability to support NASA's future programs, as well as those of its National partners in the Defense and Commercial sectors. The HEAC study team consisted of a large group of subject matter experts from multiple NASA centers, with facilitation by IDA and informal consultation and inputs from hypersonic stakeholders in the Defense and Academic communities. The HEAC workflow consisted of four teams, operating sequentially and each tasked to gather data and perform analyses on a specific topic and then provide the results as inputs to the next team. The end-product of this work was a set of recommendations that provide a NASA vision for 21st century technical excellence in the field of hypersonics.

The tasks of each HEAC team are outlined below and full details are provided in subsequent sections, along with tabulations of the data collected and generated by the HEAC study teams in the Appendices.

- **Team 1 – Vision and Goals:** Formulate a 21st Vision for world-class hypersonic aerothermodynamics ground testing capabilities and subject matter expertise at NASA and the Goals that must be achieved to realize that vision.

- **Team 2 –Programs, Objectives, and Requirements:** Consistent with the Vision and Goals defined by Team 1, forecast the potential Programs for the next 25+ years that could require hypersonic ground testing. Then, identify the potential Database Objectives needed to complete these programs and the Test Requirements for generating these data.

- **Team 3 – Capability and Capacity Gaps:** Assess the ability of NASA's hypersonic ground testing infrastructure to respond to the future demands projected by Team 2. Identify and prioritize any technical capability and logistical capacity Gaps.

- **Team 4 – Investment Recommendations:** Develop Investment Recommendations for NASA hypersonic ground testing capabilities to close the Gaps identified by Team 3.

HEAC Data Sources

The information presented in this report represents the informed speculation of the HEAC team members

[2] IDA facilitation of the structure and conduct of the HEAC study should not be taken as endorsement of the study results or recommendations.

on future hypersonic projects based on their own experience and involvement in NASA activities, technology surveys, and roadmaps, as well as policy statements, public news reports, press releases and websites, professional journals and conference publications, and various other sources. A partial list of sources consulted is given by Refs. 21-38. This list should not be considered as all-inclusive because the study focus was on collecting, collating, and analyzing data rather than formal reference documentation.

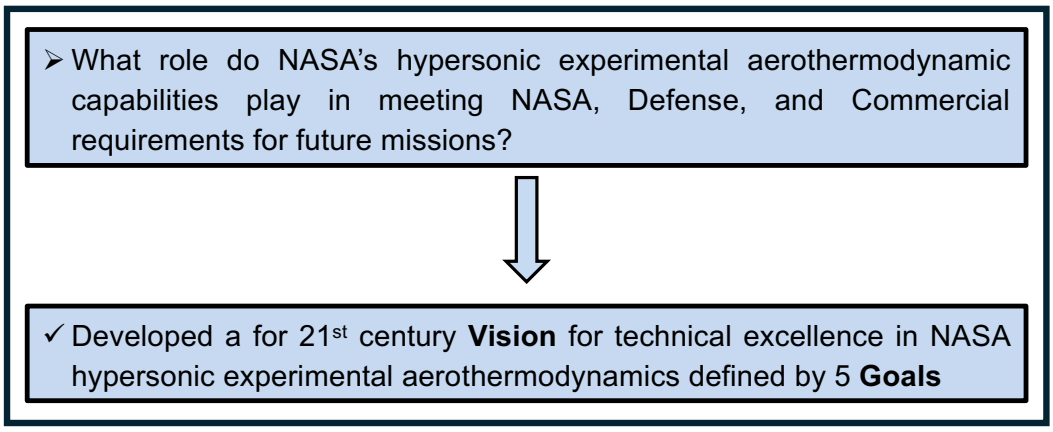
With respect to data sources for non-NASA programs — in all cases, information was drawn from publicly available information. In particular, no direct inputs were sought from any Defense or Commercial representatives or organizations in reference to any future work. Inclusion of a hypothetical activity in this database does not represent any formal endorsement of such activities or collaboration with NASA in their conduct.

The HEAC Database

The core product of the HEAC study is a database of potential NASA, Commercial, and Defense programs over the next 25+ years which could require hypersonic experimental data from NASA ground test facilities. The HEAC database contains information on the hypersonic database objectives for each program and the ground test requirements for each objective. The database also includes assessments of any NASA ground test facility capability and capacity gaps with respect to each objective and options for mitigating or closing those gaps. This study generated a large data set: 170 potential programs were identified, and multiple test objectives were defined for each program, for a total of 647 objectives. Each test objective was defined by 25 data entries containing details on the objective, test requirements, gaps, and mitigation options, all of which will be described in detail in subsequent sections. Taken together the database contains over 16,175 entries. The HEAC database is contained in a series of spreadsheets, which have been formatted for publication and reproduced in full in the Appendices to this report. Examples of the database contents will be show for each step of the HEAC work-flow.

The HEAC team employed these results to develop a documented, data-driven, SME-led assessment of future NASA hypersonic testing needs. This assessment led to a set of investment recommendations to close the capability and capacity gaps in NASA's hypersonic ground testing infrastructure, which are presented below. Each these recommendations calls for the repair, modification, or upgrade of an existing NASA hypersonic ground test facility or the construction of a new ground test facility to close these gaps.

HEAC Team 1: Vision and Goals



Contextualizing HEAC

In the 20th century, NASA's greatest challenge was to put humans on the moon. It met this challenge through the Mercury, Gemini and Apollo programs, but then National goals shrunk to just using the Space Transportation System (aka the "Shuttle") to maintain a human presence in Low Earth Orbit aboard the International Space Station. Exploration beyond LEO was performed only through robotic missions to Mars, Venus, and other destinations. In the commercial sector, the notion of developing economically viable systems for routine access-to-space was frequently promoted but never achieved. And proposed US supersonic and even hypersonic passenger transportation systems proved to be financially and/or technologically non-viable. And in the Defense sector, the 20th century ended with the US so effectively dominating the aerospace arena that development of high-speed systems had a low priority.

The 21st century brings new challenges, for which new tools and methods will be needed to develop new hypersonic system architectures. NASA's high-level vision calls for sustained human presence at LEO and on the moon and further human exploration to "Mars and beyond". The vehicles needed to transport humans to Mars (and back) must enable safe, precise landing of much higher masses than any of the architectures developed for robotic missions like the Mars Viking probe. And the now-viable commercialization of LEO and Lunar space will require families of new vehicles at multiple scales for many different classes of missions – none of which is likely to resemble the Shuttle Orbiter. And finally, there are growing demands for supersonic transportation in the commercial sector and both supersonic and hypersonic systems for Defense applications.

In summary, the 21st century will bring many requirements for the development of innovative new hypersonic systems for Civil, Commercial, and Defense applications. If NASA is to have a role in developing these systems – and according to the Agency's founding language, it does – then NASA will need world-class tool sets to meet these new challenges. One of those tool sets is hypersonic ground test capabilities and subject matter expertise, which is the focus of the HEAC study.

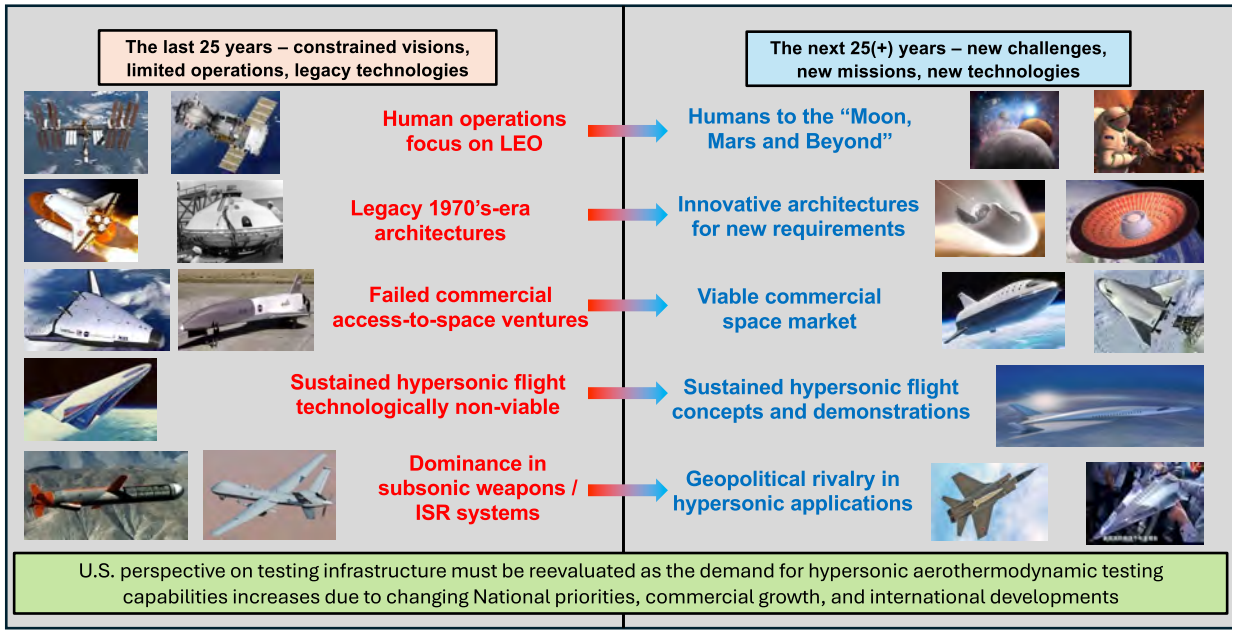


Figure 4. Hypersonics Challenges in the 21st Century.

Vision and Goals Team Analysis

The HEAC study rests on a foundational set of premises regarding the field of hypersonics. First, that hypersonics is a complex and challenging discipline; second, that hypersonic information is obtained through a project-dependent combination of ground-based testing, flight experiments, and numerical simulations; and third, that NASA's exploration goals will require the development and use of new hypersonic atmospheric flight and entry, descent, and landing systems.

In the context of these axioms, the Vision and Goals Team was tasked to formulate a "Vision for NASA 21st century excellence." This Vision, along with its supporting Goals, provides the framework for the HEAC assessment of the roles, requirements, gaps, and investment recommendations for NASA's hypersonic aerothermodynamics ground testing capabilities.

The fundamental tenet of this analysis, as noted above, is that the priorities and technological challenges that NASA (and the Nation) faced in the 20th century are not the same as those it will face in the 21st century. Based on that premise, the HEAC team conducted a survey of hypersonics subject matter experts and program leaders to obtain their opinions on the role of hypersonics at NASA. The responses to these questions were then evaluated by the team in the context of numerous public statements, exploration plans, and technology development roadmaps formulated by NASA in response to Administrative and Legislative Branch policy directives and budgetary allocations. The end-product was a Vision for NASA 21st century excellence in hypersonics and the Goals that must be accomplished to fulfill that Vision.

Vision and Goals Team Products

The HEAC Vision and Goals poll questions were:

Question 1: In 20 years, how would you like NASA's role in hypersonic research, development, test, and evaluation (RDT&E) to be viewed by the world?

Question 2: In 20 years, how would you like NASA's hypersonic RDT&E experimental aerothermodynamics capabilities to be viewed by the world?

Question 3: What are the technical-, financial-, and workforce development-related pros and cons of these four potential experimental aerothermodynamics capability futures?

- Sustain current hypersonic ground testing capabilities
- Improve / modernize current hypersonic ground capabilities
- Build new capabilities and divest old hypersonic ground capabilities
- Divest old capabilities and rely on external hypersonic ground capabilities

These survey questions elicited more than 150 responses, which are listed in Appendix B from 25 participants. Responses were provided by hypersonic subject matter experts from the NASA Ames, Johnson, Langley, and Marshall Centers, the Department of War – including the Air Force Research Laboratory, Air Force Office of Scientific Research (AFOSR), and Arnold Engineering Development Complex, and the Department of Energy (DOE), Sandia National Laboratories. Names were redacted to afford external respondents the freedom to provide frank answers without appearing to endorse any NASA policies.

From these survey responses, the Vision and Goals team formulated an overall Vision statement defined by 5 top-level Goals, each of which is supported by multiple sub-goals. These results defined the scope for the subsequent analyses performed by the HEAC Team 2 – Programs, Objectives, and Requirements.

HEAC Vision Statement:

Provide unique, world class, mission relevant aerothermodynamics capabilities that are cost effective, flexible and accessible to NASA, Defense, Commercial, and Academic partners that will enable NASA to fulfil the following Goals:

Goal 1: Enable NASA Missions and Programs:

Ensure NASA has the capabilities to generate the aerothermodynamics vehicle performance data required to fulfill NASA goals and timelines for LEO/Lunar access and return, solar-system exploration, hypersonic flight, and technology development programs.

Goal 1-1: Provide integrated aerothermodynamics testing and simulation capabilities needed to enhance system performance, reduce development cost, and minimize risk for NASA missions and programs.

Goal 1-2: Generate the aerothermodynamics data needed to fulfill mission-defined test objectives for concept design optimization and system development.

Goal 1-3: Rapidly respond to anomalies or incidents encountered during flight test or operational

missions by quickly providing experimental and computational analyses and assessments needed to ensure continued safe operations.

Goal 1-4: Produce high-fidelity experimental data to support the development and validation of aerothermodynamics computational tools.

Goal 1-5: Create strategic partnerships with other government agencies, industry, and academia to support the achievement of NASA's mission visions, goals, and timelines.

Goal 2: Lead the Nation in Hypersonic Aerothermodynamics Research:

Become the National leader in fundamental and applied research, and the steward of technical knowledge and experience, on the hypersonic aerothermodynamics of Entry-Descent-Landing (EDL) and sustained atmospheric flight for NASA, Commercial, and Defense partners.

Goal 2-1: Provide aerothermodynamics subject matter experts and test capabilities to advance NASA, commercial, and Defense-related system and technology development programs and to support operational missions.

Goal 2-2: Conduct experimental aerothermodynamics research on the salient physics of hypersonic flight to further expand the Nation's knowledge base.

Goal 2-3: Generate benchmark aerothermodynamics data to enable the development, verification, and validation of computational tools and the integration of experimental and computational capabilities.

Goal 2-4: Serve as a national repository for hypersonic aerothermodynamics knowledge.

Goal 3: Close Critical National Hypersonic Aerothermodynamics Testing Gaps:

Develop and sustain hypersonic test infrastructure that will close the capability gaps between small-scale academic facilities and large-scale Defense and Commercial facilities and that will provide the data required to advance flight systems from low Technology Readiness Level (TRL) concept definition to high-TRL ground/flight testing and acquisition. This infrastructure must also provide sufficient capacity to support NASA, Defense, and Commercial testing needs.

Goal 3-1: Develop mid-range aerothermodynamics facilities with mission-relevant capabilities that eliminate critical performance capability gaps and can be used by NASA and its partners throughout mission lifecycles from concept design and development to post-flight analysis.

Goal 3-2: Implement innovative test instrumentation, model fabrication methods, and diagnostic techniques that can rapidly generate the high-fidelity aerodynamic, aero-heating, and flow field databases needed to mature and validate hypersonic aerothermodynamics technologies.

Goal 3-3: Provide affordable, flexible facility access that can help to alleviate the capacity backlogs inhibiting NASA and its partners from meeting their programmatic schedules.

Goal 4: Grow the National Hypersonic Aerothermodynamics Workforce:

Inspire, attract, train, and sustain a globally preeminent hypersonic aerothermodynamics research,

development, test, and evaluation workforce, both for NASA and external partners/stakeholders.

Goal 4-1: Inspire the best and brightest young students to pursue careers in hypersonic aerothermodynamics by providing modern, world-class facilities in which to conduct innovative research.

Goal 4-2: Recruit a continuous supply of high-quality, degreed and non-degreed workforce candidates by partnering with Academia, Industry, and other Government organizations.

Goal 4-3: Develop early-career degreed and non-degreed workers by conducting frequent, collaborative government / industry / academia projects of National interest designed to advance their knowledge and understanding of hypersonic aerothermodynamics, test technologies and diagnostics techniques, and focused technology development programs.

Goal 4-4: Sustain the technical growth of the mid-career workforce by instituting a mentoring program to develop future subject matter experts and technical leaders.

Goal 5: Support National Defense Priorities:

Provide hypersonic aerothermodynamics testing and analysis capabilities to support the accelerated development of sustained hypersonic flight systems for National Defense purposes.

Goal 5-1: Provide high-quality hypersonic aerothermodynamics test data, independent analyses, and subject matter expertise in assessing, optimizing, validating, and developing systems.

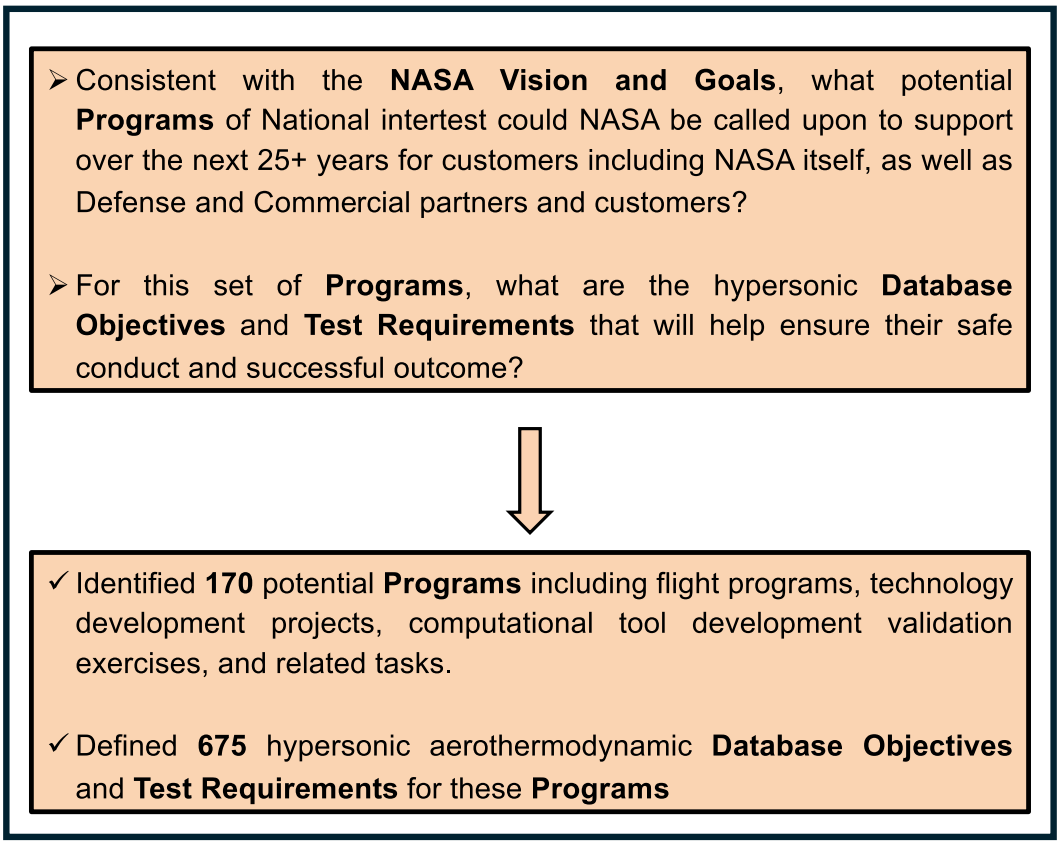
Goal 5-2: Reduce the national capacity backlog during the early phases of Department of War and Department of Energy system development by providing accessible, affordable, mission-relevant ground test facilities.

Goal 5-3: Rapidly replicate and analyze anomalies encountered in the salient physics during ground test, flight test, or mission execution in order to permit continued safe operations.

Goal 5-4: Partner with DoW / DoE and commercial facility operators in the development of test instrumentation and diagnostic techniques relevant to both government and commercial facilities.

Goal 5-5: Collaborate with DoW and DoE on the development and demonstration of innovative Defense-related hypersonic aerothermodynamics technologies of mutual benefit to NASA and its partners.

HEAC Team 2: Programs, Objectives, and Requirements



HEAC Team 2 Overview

In the context of the Vision and Goals defined by Team 1, the Programs, Objectives, and Requirements team was tasked to develop a list of potential **Programs** over the next 25+ years which could use NASA hypersonic ground testing capabilities, evaluate the hypersonic **Database Objectives** for those **Programs**, and define a set of **Test Requirements** to guide the conduct of a ground testing program to meet those **Database Objectives**. These bold-font terms have specific meanings in the context of the HEAC study and are defined below.

Program: A broad categorization of any formal activity undertaken to:

1) Use, build, or acquire a hypersonic flight system. For example, the Orion atmosphere reentry capsule to be used by NASA to return astronauts to Earth after a Lunar exploration mission under the Artemis Program.

2) Perform fundamental or applied research directed toward the understanding, development, or testing of a hypersonic technology. For example, the development and flight testing of a hypersonic, air-breathing propulsion system through the NASA X-43 Hyper-X Program.

3) Gather data to support the development and validation of both computational and experimental tools and methods for hypersonic analyses. For example, hypersonic wind tunnel testing to obtain

boundary-layer transition and turbulent heating data for computational code model development and validation under the NASA STMD Entry Systems Modeling Project.

Database Objective: A statement of the type and purpose of hypersonic information needed to complete a Program. For example: "define the hypersonic aerodynamic performance of a vehicle", "determine the effects of thermal protection system surface roughness on boundary-layer transition", or "evaluate the performance effectiveness of a maneuvering thruster subject to plume/shockwave interactions".

For the purposes of this step of the process, it assumed that the Database Objectives will be met through a hypersonic ground test, for which additional descriptive information is provided. However, alternatives to ground testing will also be considered later in the subsequent Gaps analyses.

Test Requirement: a list of what methods and measurements would be used to obtain the data needed to fulfill an Objective. Test Requirements include facility type, test parameters, instrumentation types, model fabrication capabilities, etc.

Team 2 Programs List

The **Programs List** represents the top-level of the HEAC database and the starting point for analyses. This list is a forward-looking projection of the potential hypersonic "programs" (as defined above) for which NASA's ground test capabilities could be called upon to produce hypersonic data. The Programs List has a National scope and encompasses potential activities in the Civil (NASA), Defense, and Commercial sectors over the next 25+ years.

In order to better categorize and analyze data for the Programs List, the overall domain space was partitioned into three top-level "**Themes"**, which were: Hypersonic Entry, Descent, and Landing; Hypersonic Atmospheric Flight and Access to Space; and Hypersonic Tools and Methods, each of which will be discussed below. Each Theme was then subdivided into "**Customer Types**" and "**Program Categories".** The Customer Types and Programs Categories are unique to each Theme and will be discussed in the relevant sections. Multiple potential **Programs** will be listed under each **Program Category**.

Hypersonic Entry, Descent, and Landing Theme

The Hypersonic Entry, Descent, and Landing (EDL) Theme encompasses hypersonic systems and technologies for the safe return of human crew, cargo, and/or scientific payloads from space. This theme includes return to Earth from Low-Earth-Orbit (LEO) missions (e.g. from the International Space Station), from Lunar missions (e.g. Artemis) and robotic sample return missions (e.g. Stardust or Genesis) and return of crew or cargo from Mars. This Theme also includes landing systems for other beyond-Earth destinations with atmospheres, such as Venus (e.g. the Pioneer mission), Mars (e.g. Mars Science Laboratory), Jupiter and other gas giants (e.g. Galileo mission) and proposed missions to large planetary satellites such as Titan (e.g. Dragonfly mission).

Hypersonic EDL systems are categorized as decelerators since their purpose is to slow the vehicle from ultra-high hypersonic speeds (usually well in excess of Mach 20) at atmospheric interface through the supersonic, transonic, and subsonic flight regimes to a safe, precision landing at their intended destination. Most EDL systems are large-diameter, blunt body geometries that create low lift and high drag, such as the Orion capsule. Lifting body or winged geometries (e.g. the Space Shuttle) can provide a mid-range lift-to-drag ratio for maneuverability. Propulsive descent systems (e.g. commercial reusable launch vehicles) are

also under consideration for EDL missions, although the propulsion systems would likely only be used after the hypersonic phase of the trajectory.

The EDL Theme Programs List is organized into three **Customer Types**: Human Exploration, Robotic Exploration, and EDL Technology Development, which are discussed below. Each **Customer Type** is followed by listings for **Program Categories** and multiple **Programs**. The top-level entries (**Customer Type** and **Program Category**) are shown in Table 2 and the full (and lengthier) **Program**-level list is presented in Appendix C through Appendix E

Human Exploration Customer Type and Program Categories

The Hypersonic EDL Theme **Customer Type** "Human Exploration" is defined as: "*Any NASA led, collaborative or reimbursable programs supporting development of atmospheric EDL systems that carry humans to, or return from, LEO, Moon, Mars, etc. Also uncrewed systems that provide support for human exploration missions.*"

Under this **Customer Type** are three **Program Categories**: NASA Human-Rated Earth Operations; NASA Human-Rated Mars Operations; and Commercial Systems. The NASA Earth and Mars Operations categories distinguish between the types of EDL systems required for Earth entry from LEO or Lunar destinations and those for both entry at Mars and return to Earth from Mars. NASA has issued multiple requirements, roadmaps, and plans for the development of vehicles for these **Program Categories**. The Commercial Systems category is more speculative and covers potential offerings from the Commercial sector for human-rated systems for Earth, Mars (or other) destinations.

One of the defining requirements for the development of any human-rated system is the extremely high safety rating necessary for a vehicle that carries a crew in comparison to those carrying only cargo or robotic systems. Certification of previous human-rated systems such as the Space Shuttle or Apollo capsule required thousands of hours of wind tunnel testing to define all aspects of vehicle performance across the entire entry trajectory speed range. Even newer human-rated vehicles such as the Orion capsule or commercially-developed equivalents are essentially the same class of entry system as Apollo and can trace a direct heritage to the extensive development program performed for that vehicle.

Robotic Exploration Customer Type and Program Categories

The Hypersonic EDL Theme **Customer Type** "Robotic Exploration" is defined as: "*Any NASA led or collaborative partnerships supporting development of entry systems for robotic exploration of the solar system including landers for planets & moons with atmospheres and capsules for return of samples to earth*".

Programs in the Robotic Exploration Customer Type are categorized into three **Program Categories** by their scope (i.e. objectives, cost, and size) as Flagship Missions, New Frontiers Missions, and Discovery Missions. These terms are common NASA parlance for mission types, where "Flagship Missions" are large, once-per-decade endeavors such as the Mars Science Lander, "New Frontiers Missions" are medium size, several-per-decade programs such as the Mars OSIRIS-Rex mission, and "Discovery Missions" are small, several-per-decade projects missions such as the Stardust comet sample return mission. More information on New Frontiers and Discovery class missions can be found at, respectively:

- https://science.nasa.gov/planetary-science/programs/new-frontiers/

- https://science.nasa.gov/planetary-science/programs/discovery/

Lacking a human crew, Robotic Exploration missions can be developed under a higher risk posture than Human Exploration missions. The allowable risk is, of course, still a question of cost and mission objectives; the resources applied to the development of such missions is generally the highest for a Flagship Mission and the lowest for a Discovery-class mission. For example, multiple hypersonic wind tunnel tests were performed during the development of the Flagship-class Mars Science Laboratory landing system to define its aeroheating environment, aerodynamics, and maneuvering thruster performance. In contrast, only a single hypersonic wind tunnel test was conducted for the Discovery-class Genesis mission.

EDL Technology Development Customer Type

The EDL Theme **Customer Type** "EDL Technology Development" is defined as "*NASA led, collaborative, or reimbursable activities supporting the development of new vehicle architectures for future exploration missions*."

The term "*New vehicle architectures*" is the key element for this Customer Type because the types of systems developed for previous NASA missions (e.g. the Space Shuttle, Orion, Mar Science Laboratory) have limited applications to the projected scope of future missions and customers for hypersonic EDL applications. Among these are both the ability to land large masses on Mars (e.g. 10 times that of the Mars Science Laboratory) and the ability to return small payloads (many of which and at rapid cadence) from LEO to support commercialization of space. NASA's "heritage" hypersonic vehicle architectures were not developed for such missions and will have limited future applicability.

Fulfilling the requirements for 21st century EDL programs will require the development, validation, and certification of many new hypersonic vehicle technologies. Each of these is defined by a **Program Category**: Hypersonic Inflatable Aerodynamic Decelerator (HIAD); Mid Lift-to-Drag Ratio Lifting Body; Deployable Aerodynamic Decelerator; Advanced Rigid Aeroshell Configuration; Super/Hyper-Sonic Retropropulsion; Aerocapture; and Magneto-Hydrodynamic Flow Field Control.

Table 2. EDL Theme: Customer Types and Program Categories.

Theme	ID	Customer / Category	Description	Notes	Sources	Time Frame
Hypersonic Entry, Descent and Landing	1	NASA and Partners Human-Rated Exploration	Any NASA led, collaborative or reimbursable programs supporting development of atmospheric EDL systems that carry humans to, or return from, LEO, Moon, Mars, etc. Also uncrewed systems that provide support for human exploration missions	Any human-rated system will have very low risk tolerance. Development programs will be on par with investments in prior human-rated systems like Shuttle Orbiter and Orion programs	NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)	
	1.1	NASA Human-Rated Earth Operations	LEO access and abort, LEO return	Orion / Artemis program	NASA policy	2021+
	1.2	NASA Human Mars Operations	EDL and ascent from Mars, EDL return to Earth	Initial evaluation of one or more configuration options. Then will need to develop detailed database for selected configuration with equal rigor and quantification scope as Orion development	Human Mars Entry, Descent, and Landing Architecture Study	2026-2040
	1.3	Commercial Systems	LEO, Lunar or Mars operations	Objectives TBD based on configuration, requirements, destination		2026-2040
Hypersonic Entry, Descent and Landing	2	NASA and Partners Robotic Exploration	NASA led or collaborative partnerships supporting development of entry systems for robotic exploration of the solar system including landers for planets & moons with atmospheres and capsules for return of samples to earth		NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)	
	2.1	Flagship Missions	High cost, low risk tolerance science/exploration missions	Likely only 1 or 2 per decade	NRC decadal survey	
	2.20	Common probe	Proposed standardized entry vehicle for small mission. Potential applicability to New Frontiers and Discovery class missions	Placeholder only. Common probe has been proposed but no formal plan of action on this		
	2.30	New Frontiers Missions	Moderate cost and risk tolerance science/exploration missions	Likely 2-4 per decade, order is speculative	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022", NASA directive.	0.00
	2.4	Discovery or other missions	Low-cost, high-risk tolerance science/exploration missions	Likely 2-4 per decade, order is speculative	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022", NASA directive.	0.00
Hypersonic Entry, Descent and Landing	3	NASA and Partners EDL Technology and Architecture Development	NASA led, collaborative, or reimbursable activities supporting the development of new vehicle architectures for future exploration missions		NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)	
	3.1	Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration	HIAD architecture is comprised of an inflatable aeroshell covered with a flexible TPS that protects a small rigid-body payload.	End state to allow high-mass payload to Mars; LEO and lunar return applications	HIAD project documents	

Theme	ID	Customer / Category	Description	Notes	Sources	Time Frame
	3.2	Mid L/D Lifting Body	Mid L/D lifting body flying at high-AoA to deliver high-mass cargo/crew payload to Mars	End state to allow high-mass payload to Mars; LEO and lunar return applications		
	3.3	Deployable Aerodynamic Decelerator Technology Development and Demonstration	small to large scale deployable decelerators	potential applications for LEO and lunar return		2022-2035
	3.4	Advanced Rigid Aeroshell Capsule configurations	New rigid aeroshell designs (asymmetric, C2 continuous shapes) and augmentations to reduce heating or provide lift for entry maneuvers.	Potential application to future Mars missions short of full High-Mass Human rated systems	AFE, ACV, Ellipsoidal, ALHAT Direct Force control studies	
	3.5	Super/Hypersonic Retropropulsion Technology Development and Demonstration	Use of engine thrust in place of aerodynamic drag for deceleration	Safe landing of high-mass payloads (cargo and crew) to Mars of 10x or more than previous robotic missions will likely require sub/super/hypersonic retropropulsion. RP may be employed in conjunction with ADEPT, HIAD or Mid L/D systems	Descent & Landing System Architecture Study. JSR Vol 51, No 3	
	3.6	Aerocapture	High-altitude atmospheric pass to circularize/capture vehicle into orbit	Development, demonstration and validation of aerocapture technology as a mission element for multiple destinations including Venus, Gas Giant systems and ice Giant systems	Various concept studies	
	3.7	MHD Control of Flow Field	Using electro-magnetic effects to control shock-shape / flow field and modulate aerodynamics and or heating environments		Moses, Cheatwood, Johnston et. Al, NIAC Phase 1 Report, "Advanced Aerocapture System for Enabling Faster-Larger Planetary Science & Human Exploration Missions" (19-NIAC20B-0128), expected February 2021	mid 2020s to 2030s

EDL Theme Program Category Example

Numerous potential Programs were identified through the HEAC Team 2 analyses for the Hypersonic EDL Theme. The full list is too long for the body of this text and is presented instead in Appendix C through Appendix E To illustrate the scope of the EDL Programs List, an example for a single Customer Type and Program Category is listed in Table 3. This sample case taxonomy is:

- **Theme**: Hypersonic Entry, Descent and Landing
    - **Customer**: 3. NASA and Partners
        - **Category**: 3.1 Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration.

Five potential **Programs** were identified under this Theme/Customer/Category. Each of these incorporates one or more wind tunnel test entries that would be conducted to aid the development of a HIAD technology to be demonstrated through a flight test. These Programs are:

3.11: LOFTID Demonstration Missions for TPS Performance. Wind tunnel testing and the successful flight demonstration for this Mission were underway during the HEAC activity and have been completed.

3.12: ISS Down-Mass: A proposed mission to demonstrate the use of HIAD technology to return a payload from the International Space Station

3.13 Launch Vehicle Booster Recovery: A proposed mission to demonstrate the use of a HIAD to return a launch vehicle stage or engine for recovery and reuse.

3.14 Asymmetric Aeroshell Morphing for Aerodynamic Control and Performance: A demonstration of "warping" the shape of an inflatable decelerator to provide additional lift-vector control for maneuvering purposes.

3.15 Skirt / Inflatable Tab Extension to Rigid Aeroshell: A demonstration of a HIAD "skirt" deployed from a conventional aeroshell (e.g. an Orion capsule) to provide additional aerodynamic drag, especially in a low-density environment such as Mars.

3.16 Human Mars Exploration Mission: A demonstration of the aerodynamic and aeroheating performance of a large (e.g. 20 m diameter) HIAD for landing high-mass payloads on Mars.

Table 3. EDL Programs – Focus on Program Category 3.1 HIAD Technology Development.

Theme	ID	Customer / Category / Program	Description	Notes	Sources	Time Frame
Hypersonic Entry, Descent and Landing	**3**	**NASA and Partners EDL Technology and Architecture Development**	**NASA led, collaborative, or reimbursable activities supporting the development of new vehicle architectures for future exploration missions**		**NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)**	
	3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**	**HIAD architecture is comprised of an inflatable aeroshell covered with a flexible TPS that protects a small rigid-body payload.**	**End state to allow high-mass payload to Mars; LEO and lunar return applications**	**HIAD project documents**	
	3.11	HIAD — LOFTID demonstration mission for TPS performance	Small-scale (6 m diam) vehicle for concept demonstration and Flexible TPS performance validation	based on prior THOR and IRVE test programs and planning for LOFTID	LOFTID Flight test program	2018-2022
	3.12	HIAD: ISS down mass	Medium scale (10 m diam) vehicle for small payload return from ISS	Assume similar development program to LOFTID, but for larger scale vehicle and bigger payload, higher-velocity entry	HIAD mission applications studies	2022-2024
	3.13	HIAD: launch vehicle booster recovery	Medium scale (10 m diam) vehicle for recovery of launch system engine/booster stage	Using proposed ULA recovery of Vulcan engine as prototype. Aftbody/payload MUCH larger than LOFTID, so requires more analysis/testing. Carbon copy ISS payload requirements until more detail available	builds from LOFTID and ESM wake flow testing requirements	2023-2026
	3.14	Asymmetric aeroshell morphing for aerodynamic control and performance	Apply tension forces to underlying toroids to create an asymmetric aeroshell for lift/drag modulation	Considered as a potential developmental option	Dwyer-Cianciolo, AIAA-2020-1266, "Low Lift-to-Drag Morphing Shape Design"	
	3.24	HIAD skirt / inflatable tab extension to rigid aeroshell nose cap	Skirt or tab provides additional aerodynamic control	Considered as a potential developmental option		
	3.15	HIAD: Human Mars Exploration mission	Large scale (~20 m diam) vehicle for high mass (cargo and crew) payload delivery to Mars. Full-scale flight test or operational mission. End-state of Inflatable development to enable high-mass Mars EDL. Database development for Human-rated system will be required much higher fidelity than architectural evaluation or uncrewed flight test	This sequence is continued on Sheet 1 — Human Operations under Section 1.21 due to change in requirements from development to human rating	Descent & Landing System Architecture Study	2024-2028

Hypersonic Atmospheric Flight and Access to Space Theme

The Hypersonic Atmospheric Flight and Access to Space Theme encompasses hypersonic systems and technologies for point-to-point travel within Earth's atmosphere, access to space, and return/reuse of launch vehicle components. In contrast to the Entry, Descent and Landing Theme which mostly deals with blunt body decelerators, systems under consideration here emphasize high-lift, low-drag configurations for maneuverability and high-speed, sustained flight between destinations, and various methods (deployable drag devices, retropropulsion, lifting configurations, etc.) to return and reuse launch vehicle components.

With respect to this Theme, "Sustained Flight" can be accomplished through gliding, air-breathing propulsion, or chemical rocket propulsion. And "Destinations" can include point-to-point ground locations (e.g. a super/hypersonic commercial transport), ground to LEO, or air-launched to LEO, as well as return-to-Earth of launch vehicle stages or components. Also note that for the purposes of this part of the HEAC analysis, the speed regime was expanded to include high-supersonic (Mach 3-5) flight.

The Hypersonic Atmospheric Flight and Access to Space Theme is subdivided into three Customer Types: NASA Hypersonic Atmospheric Flight Technology Development; Commercial Hypersonic Flight; and Defense Hypersonics, as discussed below. Each Customer Type is followed by listings for Program Categories and multiple Programs within each Category. The top-level entries (Customer Type and Program Category) are shown in Table 4 and the full (and lengthier) Program-level list is presented in Appendix F through Appendix H

<u>NASA Hypersonic Atmospheric Flight Technology Development Customer Type and Program Categories</u>

The **Customer Type** "Hypersonic Atmospheric Flight Technology Development" is defined as: "*NASA led development of hypersonic flight systems for civilian applications*". This Customer Type encompasses the development, testing, and use of hypersonic systems for sustained atmospheric flight. The development of the NASA X-43 Hyper-X Hypersonic Airbreathing Propulsion Demonstrator is the archetype for this Customer Type.

Program Categories for this Customer Type are Vehicle Architectures; System Components; and Fundamental Hypersonics Research. These definitions outline a hierarchy of hypersonic analysis: Vehicle Architecture means the testing of an actual vehicle; System Components represents testing a major vehicle subsystem; and Fundamental Hypersonics Research is targeted at the underlying flow field physics that define the performance of a subsystem.

<u>Commercial Hypersonic Flight Customer Type</u>

The **Customer Type** "Commercial Hypersonic Flight" is defined as: "*Collaborative work with commercial partners that benefits NASA or directed reimbursable work for customers in the development of hypersonic atmospheric flight systems for commercial purposes*". This Customer Type includes commercial development of both air-breathing propulsion and rocket propulsion systems for access to space or super/hypersonic point-to-point travel. For launch systems, this type also includes the hypersonic/supersonic flight regime during recovery and reuse of stages or components of a launch vehicle. And finally, testbeds for hypersonic technology flight demonstration are also included here.

Program Categories for this Customer Type are Commercial Airbreathing-Based Access to Space; Commercial Rocket-Based Access to Space; Commercial Point-to-Point Hypersonic Flight; and Commercial Research and Development Test Beds.

It is again noted that industry vendors were not consulted by the HEAC team for any information on potential applications, systems development, or customer forecasts. The HEAC team generated its database solely from publicly-available sources. Any mention of a potential future customer represents neither an endorsement of a commercial product, nor any commitment that a commercial entity would task NASA with supporting the development of its product. Because this activity was conducted without direct customer inputs, the data are sparser and more speculative than for sections based on NASA program inputs.

Defense Hypersonic Customer Type

The **Customer Type** "Defense Hypersonics" is defined as: "*NASA participation in flight testing, technology development, and specific missions*". This Customer Type covers any NASA work on hypersonic systems for Defense missions, either through direct engagement with the military service branches or with their vendors in the commercial sector.

This portion of the HEAC analysis was entirely based on "open-source" information to ensure that distribution of this report would remain unlimited. No inputs were sought from the DoW with respect to their programs, testing requirements, schedules, or budgets. Rather, data were gathered from publicly available sources including DoW press releases and websites (e.g. Air Force Material Command), trade publications (e.g. *Aviation Week & Space Technology*), websites (e.g. defensenews.com), unrestricted conference publications (e.g. AIAA papers), and Congressional testimony (www.congress.gov).

Inclusion of a potential Program on this list should not be construed as evidence that such a Program exists or that the DoW would require NASA support in its conduct. With respect to NASA support, the results of this part of the HEAC analyses should be taken as less of an indicator of future Defense work for NASA facilities than as a forecast of testing demands in DoW facilities that would make them even less available for NASA use. And as with the Commercial Hypersonic Flight analyses, the lack of any direct inputs from Defense customers means that these data are sparser and more speculative than for NASA program inputs.

The **Programs Categories** for the Defense Hypersonics Customer Type are: Fundamental / Applied Research and Development; Glide Systems; Airbreathing Vehicles; Intelligence Surveillance and Reconnaissance; Access-to-Space; and Flight Testbeds. Other than the public-facing Research and Development category, these categories are generic and speculative.

Table 4. Hypersonic Flight & Access-to-Space Theme: Customer Types and Program Categories.

Theme	ID	Customer / Category / Program	Description	Notes	Sources	Time Frame
Hypersonic Atmospheric Flight and Access-to-Space	4	NASA Hypersonic Atmospheric Flight Technology Development	NASA led development of hypersonic flight systems for civilian applications		NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)	
	4.1	Vehicle Architecture	vehicle concept trades, analysis, development	TBD based on future NASA goals		
	4.2	System Components	Focus on components of overall hypersonic airbreathing propulsions system	Targeted test objective to advance knowledge in specific areas		
	4.3	Fundamental Hypersonics Research	Experimentally investigate hypersonic flow phenomena (natural and forced boundary layer transition, shock/boundary layer interactions, shock/shock interactions, etc.).	Focus on unit problem investigation of hypersonic flow phenomena	NASA AAVP/HTP goals.	
Hypersonic Atmospheric Flight and Access-to-Space	5	Commercial Hypersonic Flight with NASA Support	Collaborative work with commercial partners that benefits NASA or directed reimbursable work for customers in the development of hypersonic atmospheric flight systems for commercial purposes		NASA collaborative programs, public statements by commercial entities	
	5.1	Commercial Airbreathing-Based Access-to-Space — some portion of trajectory includes sustained atmospheric flight (horizontal landing?)	This is not limited to SSTO, likely TSTO	Does not seem to be current market. Placeholder only		
	5.2	Commercial Rocket-Based Access-to-Space	Rocket launch of payload to space, ops plan may include recovery and reuse of stages or complete vehicle using SRP, HIAD, controlled lifting flight	Multiple commercial vendors developing or planning. Speculative but reasonable to extrapolate several programs over the next decade. Anticipated that this will become a market in the future.	Public statements by vendors	
	5.30	Commercial Point-to-Point — both sustained atmospheric and airbreathing	Development of proprietary commercial point-to-point vehicles. Payload and range to be set by external partners. Potential for supersonic to low hypersonic regime	Assume multiple entrants. NASA role will likely be limited to specific issues, not complete analysis	Public statements by vendors	

Theme	ID	Customer / Category / Program	Description	Notes	Sources	Time Frame
	5.40	Commercial R&D Testbed	Use of large, but conventional aircraft to launch small payloads to orbit or for hypersonic flight R&D	NASA analysis would focus on supersonic/hypersonic flight of carried payloads	Public statements by vendors	
Hypersonic Atmospheric Flight and Access-to-Space	6	Defense Hypersonics with NASA Support	Collaborative work with Defense partners on dual-use technologies or directed reimbursable work for DoD in the development of hypersonic flight systems for Defense applications		Open-source public information from the DoD and advisory/consulting groups	
	6.1	Defense Fundamental/Applied R&D Activities	NASA participation in flight testing, technology development, specific missions	NASA provides expertise in hypersonic analysis/testing	These are open-source projects	
	6.2	Defense Operational System Development: Glide Vehicles	Hypersonic vehicle with glide (unpowered) trajectory	Assume multiple development activities over next 25+ years	Open sources, e.g. DoD press releases, Aviation Week, etc.	2025-2050
	6.3	Defense Operational System Development: Airbreathing Vehicles	Hypersonic vehicle with air-breathing propulsion system	Assume multiple development activities over next 25+ years	Open sources, e.g. DoD press releases, Aviation Week, etc.	2025-2050
	6.4	Defense Operational System Develop: Intelligence, Surveillance and Reconnaissance (Point-to-point)	Hypersonic vehicle for ISR mission following development of airbreathing systems	Assume multiple development activities over next 25+ years	Open sources, e.g. DoD press releases, Aviation Week, etc.	2030-2050
	6.5	Defense Operational System Develop: Access-to-space	Hypersonic vehicle for space access mission following development of ISR system	Assuming reusable system for delivery/return of small to medium payloads. Similar to X-37	Open sources, e.g. DoD press releases, Aviation Week, etc.	2035-2050
	6.6	Defense Flight Testbeds	Hypersonic system used to carry or deploy new technologies for test and evaluation	Industry & DoD demand for increased flight test cadence as per Mach-TB program	Open sources, e.g. DoD press releases, Aviation Week, etc.	2020-

Hypersonic Atmospheric Flight and Access to Space Theme Program Example

A large, if somewhat speculative list of Programs under this theme was developed by HEAC Team 2. The full list at Program level is presented in Appendix F through Appendix H A snapshot of Programs for a single Customer-Type and Program Category is given in Table 5. This sample case taxonomy is:

- **Theme**: Hypersonic Atmospheric Flight and Access-to-Space
    - **Customer**: 6. Defense Hypersonics
        - **Category**: 6.1 Defense Fundamental / Applied Research.

This **Program** set is the least speculative for the Defense Customer Type, because it speaks to public-facing projects which the DoW has traditionally promoted and in which NASA has been an active participant. The potential Programs for this Customer Type / Program Category are:

3.11: BOLT-2: The Boundary Layer Transition (BOLT)-2 mission was the second successful flight in an U. S. Air Force sponsored program to obtain flight data on boundary-layer transition and turbulence. (See https://afresearchlab.com/bolt-ii-project-advances-hypersonics-research/) The BOLT program was ongoing during the HEAC study and several wind tunnel tests were performed at NASA.

3.12: BOLT-3: Is a proposed follow-on to the BOLT and BOLT-2 flight experiments.

3.13: HIFiRE X+1: The Hypersonic International Flight Research Experimentation (HIFiRE) program is a collaboration between the Australian Defense Science and Technology group and the U.S. Air Force (See https://www.dst.defence.gov.au/partnership/hifire-program) to obtain hypersonic flight data in which NASA has participated through analysis, simulations, and wind tunnel testing. At least 10 HIFiRE flight tests had been conducted or were planned during the HEAC study, and this entry represents an additional, hypothetical follow-on mission.

3.14: HIFiRE X+2: This is another hypothetical follow-on mission in the HIFiRE program.

3.15: HIFiRE X+3: This is another hypothetical follow-on mission in the HIFiRE program.

3.16: HIFLIER: The HIFLIER (acronym derivation unknown) program is a collaboration between the Air Force and the German Deutsches Zentrum für Luft- und Raumfahrt aerospace laboratory to fly additional missions similar to the HIFiRE series. (See https://www.dlr.de/en/bt/research-transfer/projects/ongoing-projects/hiflier).

3.17: SCIFiRE: The Southern Cross Integrated Flight Research Experiment (SCIFiRE) is a collaboration between the United States and Australia on hypersonics research. SCIFiRE is a follow-on to the hypersonic flight testing performed under the HIFiRE project (see https://www.airforce.gov.au/our-work/projects-and-programs/scifire-hypersonics).

Table 5. Hypersonic Atmospheric Flight & Access to Space Programs – Focus on Category 6.1 Defense Fundamental / Applied R&D.

Theme	ID	Customer / Category / Programs	Description	Notes	Sources	Time Frame
Hypersonic Atmospheric Flight and Access-to-Space	**6**	**Defense Hypersonics with NASA Support**	**Collaborative work with Defense partners on dual-use technologies or directed reimbursable work for DoD in the development of hypersonic flight systems for Defense applications**		**Open-source public information from the DoD and advisory/consulting groups**	
	6.1	**Defense Fundamental/Applied R&D Activities**	**NASA participation in flight testing, technology development, specific missions**	**NASA provides expertise in hypersonic analysis/testing**	**These are open-source projects**	
	6.11	BOLT-2	BOLT 1 follow on to include turbulent boundary layers	active program. Several more tests conducted since than listed in spreadsheet	AIAA publications	2020-2024
	6.12	BOLT-3	BOLT 2 follow on to include transitional and turbulent boundary layers as well as shock interactions	Assume brand new shape, cannot use legacy data	AIAA publications	2022-2026
	6.13	HIFiRE-X+1	additional HIFiRE (or similar program with new acronym) flights	Extrapolate from support for previous HIFIRE missions	Open source — assume continuation of current program	2020+
	6.14	HIFiRE-X+2	additional HIFiRE (or similar program with new acronym) flights	Extrapolate from support for previous HIFIRE missions	Open source — assume continuation of current program	2020+
	6.15	HIFiRE-X+3	additional HIFiRE (or similar program with new acronym) flights	Extrapolate from support for previous HIFIRE missions	Open source — assume continuation of current program	2020+
	6.16	HIFLiRE	follow on to the HIFiRE program	Extrapolate support from previous programs such as HIFIRE and BOLT	AIAA conferences	2025+
	6.17	Southern Cross Integrated Flight Research Experiment (SCIFiRe)	R&D with test flights to mature SCRAMJET systems. Multiple vendor contracts	Extrapolate support from previous programs such as HIFIRE and BOLT	Aviation Week	20225+

Hypersonics Tools and Methods Theme

The Hypersonics Tools and Methods Theme deals with the development of both computational and experimental techniques by which hypersonic data can be generated. The computational part of this Theme focusses on ground test programs conducted to obtain high-fidelity hypersonic data to be used in the development, testing, and validation of advanced numerical modeling and simulation tools (i.e. Computational Fluid Dynamics codes). The experimental part of this Theme deals with ground test programs conducted to develop and validate new wind tunnel measurement and diagnostics tools for acquiring hypersonic data. The Customer Type / Program Categories level listings for this Theme are presented in Table 6 and the complete Program-level list is given in Appendix I and Appendix J

Modeling and Simulation Code Development and Validation Customer Type

The Hypersonic Tools and Methods Theme **Customer Type** "Modeling and Simulation Code Development and Validation" is defined as: "*Ground test programs conducted to obtain high-fidelity data on phenomena for which CFD capabilities are nonexistent, impractical, or unvalidated for CFD tool development and validation*".

Ideally, data from EVERY hypersonic ground test program should be considered for its utility in code validation exercises. But for the purposes of this analysis, the focus is on programs performed with the express purpose of acquiring CFD validation data on hypersonic flow field phenomena. Such ground test programs should be conducted in the spirit of the CFD 2030 Vision (Ref. 16) and the "CFD as Surrogate" test campaigns (Refs. 39–46) in the LaRC Unitary Plan Wind Tunnel in which supersonic experimental datasets were generated for comparisons with CFD predictions.

There are nine Program Categories for the Customer Type: Wakes and Separated Flows; Shock-Shock and Shock-Boundary-Layer Interactions; Propulsion System Performance, Interactions and Vehicle Integration; Boundary-Layer Transition and Turbulence; Surface / Flow-Field Interactions; Thermophysical and Radiative Property Models; Multi-Phase Flows and Gas / Solid Interactions; Rarefied Flow; and "Miscellaneous." Each of these categories deals with a physical phenomenon that is especially challenging to model computationally, especially for hypersonic flows.

In this part of the HEAC analyses, the team composition was weighted in favor of NASA subject matter experts (and external consultants from Academia) experienced in the development and application of computational fluid dynamics codes for hypersonic problems. The Program Categories identified above resulted from their experiences with numerical modeling challenges and the impacts of those challenges on the design of actual flight systems.

Ground Test Technique Customer Type

The Hypersonic Tools and Methods Theme **Customer Type** "Ground Test Techniques" is defined as: "*Ground test programs conducted to develop and validate advanced new measurement capabilities*". This Customer Type deals with wind tunnel test programs conducted for the express purpose of developing, testing, and evaluating new test techniques and diagnostic methods for hypersonic flows. These tools are used for measurements of surface heating, pressure, temperature, and shear, boundary-layer transition, shock-wave imaging, chemical and radiative process rates, integrated forces and moments, surface deformation and response, flow field quantities, and other types of hypersonic data. These measurement types are organized into four **Program Categories**: Optical Surface Measurement Techniques; Flow Field Optical Techniques; Discrete Sensors; and Aerodynamic Forces and Measurements.

Table 6. Hypersonic Tools and Methods Theme: Customer Types and Program Categories.

Theme	ID	Customer / Category / Program	Description	Notes	Sources	Time Frame
Hypersonic Tools and Methods	7	Modeling and Simulation Code Development and Validation	Ground test programs conducted to obtain high-fidelity data on phenomena for which CFD capabilities are nonexistent, impractical or unvalidated for CFD tool development and validation		Surveys of NASA and external (DoD, Academia) subject matter experts in computational fluid dynamics	
	7.1	Wakes and separated flows	Validation data for Simulation of separated wake flows, including unsteady flow, shear-layer transition & turbulence, flow rarefication, shear-layer/aftbody interactions, parachute dynamics, etc.	Requires surface heating, surface pressure, flow field imagery		
	7.2	Shock-Shock and Shock-BL Interactions	Validation data for complex flow fields created by shock interactions — separation, transition, unsteadiness, etc.	Will required high-frequence flow field data, surface heating, surface pressure		
	7.3	Propulsion System Performance, Interactions and Integration	Includes RCS jets, Super/Hyper retropropulsion, airbreather inlets and flow paths, launch vehicle rocket nozzle flows, etc.	Requires surface heating, pressure, flow field visualization, etc.		
	7.4	Transition and Turbulence	The most challenging problems in physics — breakdown of smooth, laminar flow to chaotic turbulent flow	Highly dependent on surface roughness, free stream noise, Reynolds number, surface geometries		
	7.5	Surface / Flow field Interactions	Interactions between flow field and surface affecting, shape, pressure load and thermal response of vehicle	Requires, flow field visualization, surface geometry tracking, surface pressure, shear, heating, etc.		
	7.6	Thermophysical and Radiative Properties	Data on high-temperature/pressure response of gases to shock-wave	Generally requires shock-tube testing		
	7.7	Multi-phase Flows and gas/solid interactions	Includes blowing, transpiration, ablation, recession, gas-surface chemistry etc.			
	7.8	Rarefied flow	Non-CFD techniques (DSMC, Boltzmann, etc.) Applicable to high orbit mission, high atmospheric entry, micro-structure flow, porous BL,			

Theme	ID	Customer / Category / Program	Description	Notes	Sources	Time Frame
			property extractions for multi-scale stochastic CFD modeling			
	7.9	Miscellaneous	other topics with potential growth areas for testing, code development			
Hypersonic Tools and Methods	8	Ground Test Technique Development	Ground test programs conducted to develop and validate advanced new measurement capabilities	Facility time spent on calibration, diagnostics and instrumentation development counts against capacity for programmatic testing	Surveys of NASA facility operations staff, test engineers and experimental researchers	
	8.1	Global optical Surface Measurement Techniques	Global techniques for heating, temperature, pressure, shear			
	8.2	Flow Field Optical Diagnostics	Steady & fluctuating flow field measurements for temperature, velocity etc.			
	8.3	Discrete Sensor Development	Discrete sensors for temperature, pressure, shear, heating, etc.			
	8.4	Aerodynamic Force & Angle Measurement	Advanced techniques for aerodynamic force & moment measurements			

Hypersonics Tools and Methods Theme Program Example

The complete list of Hypersonic Tools and Methods Theme Programs is presented in Appendix I through Appendix J and an example of the Program set for a single Customer Type / Programs Category follows. The taxonomy for this case is:

- **Theme**: Hypersonic Tools and Methods
    - **Customer**: 7. Modeling and Simulation Code Development and Validation
        - **Category**: 7.6 Thermophysical and Radiative Property Models

As listed in Table 7, seven **Programs** were identified for this case by the HEAC Team:

7.61: Flow Field Radiation: High-energy radiative process models for both compressing (forebody) and expanding (wake) flows, for hypersonic flight through different atmospheric compositions, including Earth (air), Mars and Venus (CO2 and N2), Titan (N2 and CH4) and gas giants (H2 and He).

7.62: Flow Field Radiation / TPS interactions: Penetration of shock-wave radiation into porous/transmissive thermal protection system materials.

7.63: Kinetic Models for Planetary Atmospheres: Thermochemical models for hypersonic flight through different atmospheric compositions, including Earth (air), Mars and Venus (CO2 and N2), Titan (N2 and CH4) and gas giants (H2 and He).

7.64: Kinetic Models for Propulsion System Products: Thermochemical models for reactants and products of airbreathing and chemical rocket propulsion systems.

7.65: Kinetic Models for Ablation Products: Thermochemical and phase change models for the products of thermal protection systems ablation, recession, and out-gassing and their interactions with atmospheric constituents.

7.66: Shock-Layer Nonequilibrium Thermochemistry: High-temperature thermochemical models including non-equilibrium reactions and ionization for hypersonic flight through different atmospheric compositions, including Earth (air), Mars and Venus (CO2 and N2), Titan (N2 and CH4) and gas giants (H2 and He).

7.67: Surface Catalysis Effects: Effects of thermal protection system material catalytic efficiencies on recombination, phase-change and surface/flow-field energy exchange.

Table 7. Hypersonic Tools and Methods Programs – Focus on Program Category 7.6 Thermophysical and Radiative Properties.

Theme	ID	Customer / Category / Programs	Description	Notes	Sources	Time Frame
Hypersonic Tools and Methods	**7**	**Modeling and Simulation Code Development and Validation**	**Ground test programs conducted to obtain high-fidelity data on phenomena for which CFD capabilities are nonexistent, impractical or unvalidated for CFD tool development and validation**		**Surveys of NASA and external (DoD, Academia) subject matter experts in computational fluid dynamics**	
	7.6	**Thermophysical and Radiative Properties**	**Data on high-temperature/pressure response of gases to shock-wave**	**Generally requires shock-tube testing**		
	7.61	Flow field radiation	Radiation in compressive shock layer and in backshell expansion regions. Tests are needed for different planetary atmospheres (Air, CO2/N2, N2/CH4, H2/He)	Artemis, Mars 2020, Mars Sample Return (SRL & EEV), ESM portfolio	CFD SME team members	2020-
	7.62	Shock Radiation-TPS interactions	Shock-layer radiation penetration within porous ablator (surface vs volume effects)	ESM portfolio	CFD SME team members	2025-2040
	7.63	Kinetic models for planetary atmospheres			CFD SME team members	
	7.64	Kinetic models for propulsion system products		Noted, but not in HEAC domain	CFD SME team members	
	7.65	Kinetic models for ablation products			CFD SME team members	
	7.66	Shock layer non-equilibrium thermochemistry	Tests to validate new modeling practices, including non-Boltzmann behavior, pre-shock ionization, freestream-radiation interaction, ablation product impact and boundary layer reactivity	Artemis, Mars Sample Return EEV, ESM portfolio	CFD SME team members	2020-
	7.67	Surface catalysis effects	Surface or TPS properties that influence recombination rates and surface temperature / heating		CFD SME team members	

Team 2 Database Objectives and Test Requirements

After developing the list of 170 potential Programs that could require NASA hypersonic ground test capabilities over the next 25+ years, the next step of the HEAC analysis was to define the **Database Objectives** and **Test Requirements** for each of those Programs. There were multiple Objectives and Requirements entries for each Program, varying from a simple placeholder for a low-cost / high-risk-posture case like a robotic Discovery class mission (Programs 2.43 to 2.46) to ten or more for high-cost / low-risk-posture human-rated, high-mass systems for Mars exploration (Programs 1.21 to 1.24). In total, 647 Database Requirements and Test Objectives were identified for the potential list of future Programs. This list is far too large for the body of the text but is shown in complete detail in Appendix C through Appendix J The depth and fidelity of the information gathered for each entry varied depending on the complexity, performance requirements, the risk tolerance and safety posture of the mission, and the judgment and experience of the team members developing each entry.

Examples of Database Objective and Test Requirements follow below. These terms were defined previously but are repeated here for ease of reference. The guidelines followed by the HEAC team developing these datasets is also given.

Database Objective Definition: A statement of the type and purpose of hypersonic information to be generated to conduct a Program. For example: "define the hypersonic aerodynamic performance of a vehicle", "determine the effects of thermal protection system surface roughness on boundary-layer transition", or "evaluate the performance effectiveness of a maneuvering thruster subject to plume/shockwave interactions". The Database Objective categories for which data were gathered were:

- Test Category – The type of test, for example: "hypersonic aerodynamic performance".
- Test Approach – A description of how the test would be performed, for example: "Measure forces and moments with 2 and 3 axis balances. Use Schlieren photography for shock shapes. Measure surface pressure with fast-response pressure sensors".
- Test Parameters – A description of the variables to be considered, for example: "angle-of-attack, Reynolds number, Mach number".
- Measurement Types – The required instrumentation and diagnostics, for example: "Force and moment, surface pressure, flow-field visualization".
- Facility Types – The types of ground test facilities in which this objective could be fulfilled, for example: "high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range".
- Potential NASA Facilities – A list of NASA ground test facilities in which the test could be conducted, for example: "LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF".
- Potential non-NASA Facilities – A list of non-NASA ground test facilities in which the test could be conducted, for example: "AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS".

Database Objectives Guidance:

- Scope: The Database Objectives list should include all hypersonic performance database objectives pertaining only to the external aerothermodynamics environments of the system. This

scope *includes* phenomena such as surface convective heat-transfer, integrated aerodynamic performance forces and moments, thruster/flow-field interactions, boundary-layer transition location, etc. This scope *excludes* internal processes such as thermal response to external heating, propulsion system performance, structural response to aerodynamic loads, etc.

- Sources: The Database Objectives list should be source-agnostic. The database objectives could be met through flight-heritage, analytical methods, computational modeling and simulation, and/or ground testing. Whether or not these databases can be, or need to be, generated through ground testing will be considered later.

A sample set of **Database Objectives** is given in Table 8 for **Program** 3.13 Launch Vehicle Booster Recovery Using a HIAD, for which the taxonomy is:

- **Theme**: Hypersonic Entry, Descent and Landing
  - **Customer**: 3. NASA and Partners
    - **Category**: 3.1 Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology development and demonstration
      - **Program**: 3.13 Launch Vehicle Booster Recovery Using a HIAD
        - **Objectives**: 3.13xx

3.1301 — Develop hypersonic aerodynamic performance database.

3.1302 — Determine hypersonic aerodynamic influence of payload.

3.1303 — Develop supersonic aerodynamic performance database.

3.1304 — Define supersonic RCS performance and interactions.

3.1305 — Determine supersonic aerodynamic influence of payload.

3.1306 — Determine baseline, smooth-OML aeroshell convective heating.

3.1307 — Determine aeroshell heating augmentation due to flexible TPS deflections.

3.1308 — Determine aftbody and payload heating environments.

As an example of the information generated for each **Database Objective**, the following entries apply to Database Objective 3.1308 – *Determine aftbody and payload heating environments*:

Test Objective — Determine aftbody and payload heating environments.

Test Category — (4) convective aeroheating, (5) Flow Field Characterization, (16) CFD development and validation and (18) Test Technique Development.

Test Approach — Measure surface heating on aeroshell backface and payload at laminar and turbulent

conditions. Consider parametric tradeoffs on aeroshell geometry to ensure no impingement on payload.

Test Parameters — Reynolds number, angle-of-attack

Measurement Types — Global heat transfer, discrete heat transfer

Facility Types — Hypersonic wind tunnel

Potential NASA Facilities — LaRC 31-Inch Mach 10

Potential non-NASA Facilities — AEDC Tunnel 9, CUBRC LENS

Table 8. EDL Programs – Focus on Database Objectives for Program 3.13 HIAD: Launch Vehicle Booster Recovery.

ID	Customer / Category / Program / Objective	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3	**NASA and Partners EDL Technology and Architecture Development**							
3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**							
3.13	HIAD: launch vehicle booster recovery							
3.1301	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1302	Determine hypersonic aerodynamic influence of payload	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1303	Develop supersonic aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.1304	Define supersonic RCS performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Perform surface pressure, static aero force & moment and flow visualization with thrusters on/off	Mach, pitch, sideslip, Reynolds, AoA, RCS mass flow	Surface pressure, flow visualization, static force & moment, RCS plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.1305	Determine supersonic aerodynamic influence of payload	(2) Supersonic Aerodynamic	Measure forces and moments with 2/3 axis balances. Schlieren	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range

ID	Customer / Category / Program / Objective	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
		Performance (5) Flow Field Characterization	photography for shock shape. Measure surface pressure with fast-response pressure sensors					
3.1306	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating	Global and/or discrete surface heating measurements	Reynolds number, angle-of-attack	Global heat transfer and BL transition	Hypersonic wind tunnel or ballistic range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1307	Determine aeroshell heating augmentation due to flexible TPS deflections	(3) boundary-layer characterization, (4) convective aeroheating, (16) CFD development and validation	Measure surface temperature and heating distribution to determine TPS deflection effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, TPS scalloping heights	Global heat transfer and BL transition	Hypersonic wind tunnel, Hypersonic ballistic range	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1308	Determine aftbody and payload heating environments	(4) convective aeroheating, (5) Flow Field Characterization, (16) CFD development and validation (18) Test Technique Development	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions. Parametric tradeoffs on aeroshell geometry to ensure no impingement on payload	Reynolds number, angle-of-attack	Global heat transfer, discrete heat transfer	Hypersonic wind tunnel	LaRC 31-Inch Mach 10	AEDC Tunnel 9, CUBRC LENS

Test Requirement Definition: A list of what methods and measurements would be used to obtain the data needed to fulfill a Database Objective. Test Requirements include facility type, test parameters, instrumentation type and model fabrication capabilities.

The Test Requirements categories for which data were gathered were:

- Required Facility Capability – A high-level summary of the type of testing capabilities required, for example: "Hypersonic facilities capable of enthalpies relevant to the true thermochemical environment required to validate high temperature effects".

- Required Test Points – The range of test parameters required (both for testing in NASA or non-NASA facilities), for example: "Multiple combinations of Mach number, angle of attack, angle of sideslip, RCS jet location on model, and nozzle pressure ratios".

- Required Test Calendar Time – An estimate of how much calendar time would be required to complete the test program (both for testing in NASA and non-NASA facilities, for example: "2 to 4 weeks".

- Required Instrumentation Capability – A list of the measurement and diagnostics techniques required to obtain the data, for example: "Force-and-moment balances for aerodynamic measurements, static pressure sensors for surface pressure measurements, and laser-based instrumentation off-body flow diagnostics (e.g. velocity)".

- Required Test Article Fabrication Capability – A description of fabrication capabilities required to build a test article, for example: "Fabricate a metallic model with interchangeable control-surfaces compatible with a force-and-measurement balance".

Test Requirements Guidance:

- Scope: The Test Requirements list should define all aspects of a wind tunnel test that would be performed to meet a Database Objective. These Test Requirements should include the type of wind tunnel that would be used, the measurements and instruments needed, the required test conditions, estimates for the number of data points, expected number of hours, and any other pertinent information.

- Sources: NASA facilities in which the test could be performed are considered the default option given the expected lack of access to non-NASA sources. However, external facilities which would be technically appropriate as an alternative, regardless of actual availability, may also be listed.

A sample set of **Test Requirements** information for a Database Objective is given in Table 9 for **Program** 3.13 Launch Vehicle Booster Recovery Using a HIAD, for which the taxonomy is again:

- **Theme**: Hypersonic Entry, Descent and Landing
  - **Customer**: 3. NASA and Partners
    - **Category**: 3.1 Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology development and demonstration

- **Program**: 3.13 Launch Vehicle Booster Recovery Using a HIAD
    - **Objectives**: 3.13xx

3.1301 — Develop hypersonic aerodynamic performance database.

3.1302 — Determine hypersonic aerodynamic influence of payload.

3.1303 — Develop supersonic aerodynamic performance database.

3.1304 — Define supersonic RCS performance and interactions.

3.1305 — Determine supersonic aerodynamic influence of payload.

3.1306 — Determine baseline, smooth-OML aeroshell convective heating.

3.1307 — Determine aeroshell heating augmentation due to flexible TPS deflections.

3.1308 — Determine aftbody and payload heating environments.

As an example of the Test Requirements generated for each of these Database Objectives, the following entries apply to Database Objective 3.1308 – *Determine aftbody and payload heating environments*:

Required Facility Capability — Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. High stagnation temperature to produce sensible heating in wake.

Required Test Points in NASA Facilities — 5 AoA over range of 0-20-deg, 5 Reynolds numbers over laminar-to-turbulent range. Separate heating and flow visualization runs = 50 test points.

Required Calendar Time in NASA Facilities — 50 test points taking ~9 days in LaRC 31-Inch Mach 10 Air Tunnel.

Required Test Points in non-NASA Facilities — 5 AoA over range of 0-20-deg, 5 Reynolds numbers over laminar-to-turbulent range. Separate Heating and flow visualization runs = 50 test points.

Required Calendar Time in non-NASA Facilities — 50 test points. Assuming continuous sweep run in AEDC Tunnel 9 requires ~5 days for 10 runs. Assuming static AoA runs in CUBRC LENS requires ~30 days for 50 runs.

Required Instrumentation Capability — Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors. Laser seeding and schlieren flow visualization for wake.

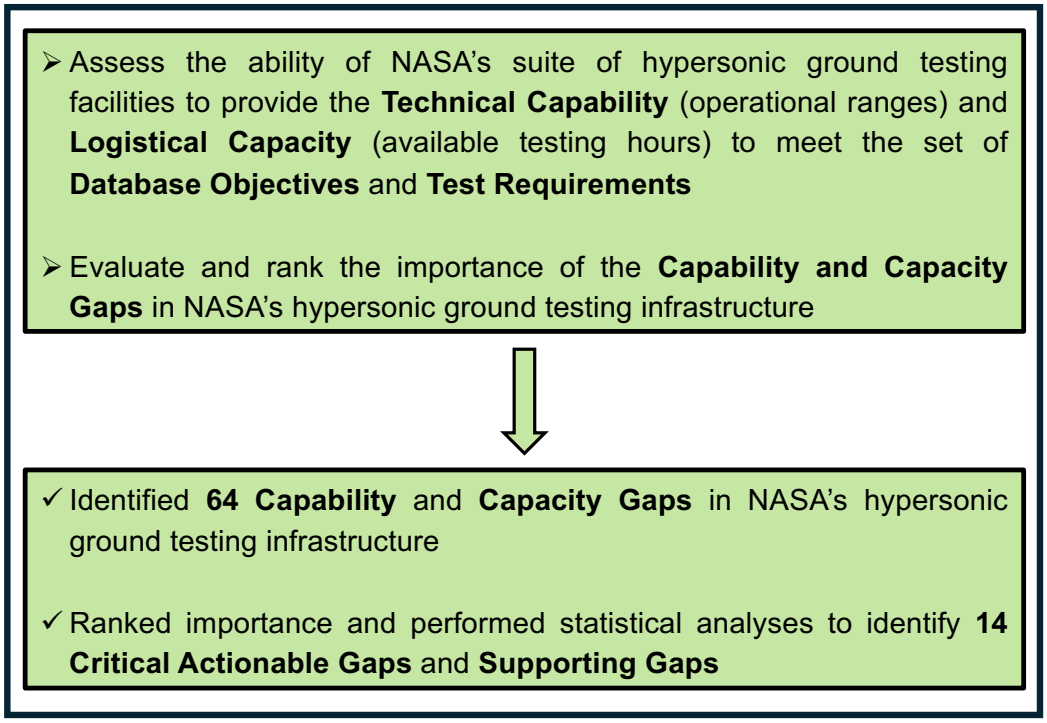
Required Test Article Fabrication Capability — cast ceramic or machined metallic models depending on test facility and test technique. Would require blade mount and offset sting for wake measurements.

Table 9. EDL Programs – Focus on Test Requirements for Program 3.13 HIAD: Launch Vehicle Booster Recovery.

ID	Customer / Category / Program / Test-Objective	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
3	**NASA and Partners EDL Technology and Architecture Development**							
3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**							
3.13	HIAD: launch vehicle booster recovery							
3.1301	Develop hypersonic aerodynamic performance database	High Mach / high-enthalpy capability	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.1302	Determine hypersonic aerodynamic influence of payload	High Mach / high-enthalpy capability	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances	Metallic force & moment model with blade mount & offset sting
3.1303	Develop supersonic aerodynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
3.1304	Define supersonic RCS performance and interactions	Flight-relevant Mach/Re range, mass flow for RCS firing	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	UPWT assume cont. AoA sweep, 45 runs = 2 weeks	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure — all with high-speed dynamic response	Metallic force & moment models with active blowing from RCS
3.1305	Determine supersonic aerodynamic influence of payload	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances using blade mount & offset sting	Metallic force & moment model fabrication

ID	Customer / Category / Program / Test-Objective	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
3.1306	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	15 test points ~ 1 week in any facility	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	12 test points ~ 1 week in any facility	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
3.1307	Determine aeroshell heating augmentation due to flexible TPS deflections	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Rapid turnaround time for multiple roughness parametric changes	3 AoA over range of 0-10-deg, 6 Reynolds numbers over laminar-to-turbulent ranges, 12 scallop heights. Total 216 test points	LaRC 20inM6 = 108 runs / 18 days.	3 AoA over range of 0-10-deg, 6 Reynolds numbers over laminar-to-turbulent ranges, 12 scallop heights. Total 216 test points	AEDC T9 (continuous pitch) = 72 runs / 36 days. CUBRC 216 runs = 108 days. AEDC VKF continuous ops not compatible with multiple parameter variations for heating tests	global optical techniques for measurement of heating distributions and BL transition onset	ability to accurately replicate scalloped OML in cast ceramic or machined metal
3.1308	Determine aftbody and payload heating environments	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. High stagnation temperature to produce sensible heating in wake	5 AoA over range of 0-20-deg, 5 Reynolds numbers over laminar-to-turbulent range. Heating + flow visualization runs = 50 test points	LaRC 31InM10 = 50 points, 9 days	5 AoA over range of 0-20-deg, 5 Reynolds numbers over laminar-to-turbulent range. Heating + flow visualization runs = 50 test points	AEDC T9 (continuous sweep) = 10 runs/ 5 days. CUBRC = 50 runs / 30 days	Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors. Laser seeding and schlieren flow visualization for wake	cast ceramic or machined metallic models with blade mount and offset sting

HEAC Team 3: Technical Capability and Logistical Capacity Gaps



HEAC Team 3 Overview

The HEAC Team 3 was tasked to evaluate whether the existing NASA portfolio of hypersonic ground test facilities could meet the HEAC Team 2 **Database Objectives** and **Test Requirements** and to identify any **Technical Capability** and **Logistical Capacity Gaps** in meeting those demands. The Gaps were then evaluated to determine their criticality and ranked according to priority. Currently available options to close and/or mitigate these Gaps in order fulfill the Database Objectives and Test Requirements were then proposed. Finally, these analyses were forwarded to the HEAC Team 4 to develop **Investment Options** to close the **Critical Gaps.**

Technical Capability and Logistical Capacity Gaps List

The following categories were considered in the Gaps assessment:

- Facility Capability: Identify any operational capability gaps – e.g. test core size, Mach number, Reynolds number, pitch / yaw range, enthalpy, dynamic pressure, or other flow field parameters.
- Facility Instrumentation: Identify any instrumentation gaps – e.g. data acquisition systems, measurement techniques and sensors and diagnostics.
- Test Article Fabrication: Identify any gaps in the ability of the host organization to either

fabricate the required test article or to accommodate a customer's test article.

- Facility Cost and Capacity: Identify any logistical gaps – e.g. facility cost, facility availability, facility productivity.

- Gap ID: a short-hand descriptor for a gap; to be discussed below.

These Gap categories were considered for each of the 647 Database Objectives and Test Requirements identified by Team 2. As with the Team 2 analyses, the depth and fidelity of database entries varied, depending on the complexity, performance requirements, the risk tolerance and safety posture of the mission, and the judgment and experience of the team members developing each entry. The full Gaps list is provided in Appendix C through Appendix J and a sample entry is provided below in Table 10. The taxonomy for this case is again:

- **Theme**: Hypersonic Entry, Descent and Landing
  - **Customer**: 3. NASA and Partners
    - **Category**: 3.1 Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology development and demonstration
      - **Program**: 3.13 Launch Vehicle Booster Recovery Using a HIAD
        - **Objectives**: 3.13xx

3.1301 — Develop hypersonic aerodynamic performance database.

3.1302 — Determine hypersonic aerodynamic influence of payload.

3.1303 — Develop supersonic aerodynamic performance database.

3.1304 — Define supersonic RCS performance and interactions.

3.1305 — Determine supersonic aerodynamic influence of payload.

3.1306 — Determine baseline, smooth-OML aeroshell convective heating.

3.1307 — Determine aeroshell heating augmentation due to flexible TPS deflections.

3.1308 — Determine aftbody and payload heating environments.

As an example of the Gaps for each Database Objective, the following entries apply to Database Objective 3.1308 – *Determine aftbody and payload heating environments*:

Facility Capability Gaps — CUBRC LENS may not provide sufficient test time for wake flow establishment. Lack of high-enthalpy capability in NASA & AEDC facilities.

Facility Instrumentation Gaps — Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring.

Test Article Fabrication Gaps — None expected.

Facility Cost and Capacity Gaps — Scheduling and cost in non-NASA facilities.

Gaps List — EDL-01, EDL-07, EDL-12.

Table 10. EDL Programs – Focus on Capability and Capacity Gaps for Program: 3.13 HIAD: Launch Vehicle Booster Recovery.

ID	Customer / Category / Program / Objective	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3	**NASA and Partners EDL Technology and Architecture Development**					
3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**					
3.13	HIAD: launch vehicle booster recovery					
3.1301	Develop hypersonic aerodynamic performance database	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-02, EDL-12, Inst-Aero-01
3.1302	Determine hypersonic aerodynamic influence of payload	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities. Potential for LaRC UPWT closure	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-02, EDL-07, EDL-12, Inst-Aero-01
3.1303	Develop supersonic aerodynamic performance database	Reynolds/Mach number ranges of NASA facilities and Aberdeen range	Scheduling and cost in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12
3.1304	Define supersonic RCS performance and interactions	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Scheduling and cost in non-NASA facilities	none	none	EDL-08, EDL-12
3.1305	Determine supersonic aerodynamic influence of payload	Reynolds/Mach number ranges of NASA facilities and Aberdeen range	Scheduling and cost in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12
3.1306	Determine baseline, smooth-OML aeroshell convective heating	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on smooth OML. Lack of NASA high-enthalpy capability may impact aeroheating	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.1307	Determine aeroshell heating augmentation due to flexible TPS deflections	NASA facilities may lack operational Reynolds number to generate turbulence at roughness scales. Ames HFFAF has limited AoA range	Scheduling and cost in non-NASA facilities	Optical access and validation of global aeroheating techniques at AEDC and CUBRC	1) Ability to 3D print/machine or cast detailed TPS roughness features for global techniques. 2)	EDL-01, EDL-09, EDL-12, Inst-Heat-02

ID	Customer / Category / Program / Objective	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
					Model design and fabrication with large number of discrete sensors	
3.1308	Determine aftbody and payload heating environments	CUBRC LENS may not provide sufficient test time for wake flow establishment. Lack of high-enthalpy capability in NASA & AEDC facilities	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-01, EDL-07, EDL-12

Technical Capability and Logistical Capacity Gaps Analysis

Having completed the Gaps list for each of the Test Requirements, the next step was to summarize and categorize the Gaps database and then rank the criticality of each Gap.

The Gaps list was divided into 4 categories based on the previously defined Themes for the hypersonic Programs set. The gap categories were: Hypersonic Entry, Descent and Landing (EDL); Hypersonic Flight and Access to Space (identified here as HTP, since most of this work falls under the aegis of NASA's Hypersonic Technology Project); Hypersonic Tools and Methods – Modeling and Simulation Code Development and Validation (identified here as CFD, for Computational Fluid Dynamics); and Hypersonic Tools and Methods – Ground Test Technique Development (identified here by the "INST" shorthand for Instrumentation).

The third theme of Hypersonic Tools and Methods was split into two categories and only the first, category – CFD – will be considered in detail in further analyses. It was felt that including the ranking and prioritization of Ground Test Technique Gaps was of secondary importance in comparison to the other categories that address facility operational capabilities since the need for a test technique is dependent on the need for a facility in which to perform the testing. And furthermore, since many instrumentation techniques are facility-independent and their development costs are *substantially* lower than that of new facilities, this category would be better considered in a different venue.

The Gaps List, sorted by category, is given in Table 11. For each identified Gap, the number of times that it is cited for each Theme / Customer Type / Database Objective is also given. A total of 64 gaps were identified, although that number drops to 40 when the Instrumentation category is excluded.

The entire HEAC team of subject matter experts was then polled to rank the criticality of each Gap in each category from 1 (lowest) to 3 (highest). The SMEs were asked to respond only to those Gaps for which they felt they had sufficient experience to provide an informed answer. The total number of responses for all categories was 90, with SMEs responding to single, multiple, or no categories. The poll responses are listed in Table 12, Table 13, and Table 14 for the EDL, HTP and CFD categories, respectively.

In addition to the SME rankings of Gap criticality, a simplified Pareto analysis was also performed to better represent both the *importance* and the *frequency* of each Gap. This Pareto value is defined as the number of times each Gap is cited multiplied by its critically. The averaged Pareto value, Gap Frequency, and Gap Criticality rankings were then normalized by their respective maxima and rescaled to range of 1 to 10. These results are listed for each Theme in Table 15 — Table 17. Also, the Scaled Criticality and Scaled Pareto Values were assigned a "Stoplight" color indicator where Green (range of 1 to 6) represents the lowest importance, Yellow (range of 6 to 8) represents moderate importance, and Red (range 8-10) represent the highest importance. Cells in these and following charts will be shaded by Yellow or Red when appropriate as a visual cue to the importance of results. These results are plotted for the EDL, HTP, and CFD Gaps in Figure 5, Figure 6, and Figure 7, respectively.

The above analyses refer to the **Technical Capability Gaps** in the operational range and instrumentation suites of ground test facilities. A separate concern is the **Logistical Capacity Gaps**, i.e. the number of future test hours that will be available in ground test facilities and how much they would cost. As has been discussed earlier, the productivity of NASA's roster of ground test facilities has been dropping dramatically and consistently over the last 30 years. Even the most pessimistic forecast for the number of potential test

programs that could actually take place would result in far more testing capacity demands than NASA's current facilities could accommodate.

In a similar vein, NASA's access to external (Defense and Commercial) ground test facilities is also expected to be extremely limited due to the rising demand for Defense-related hypersonic programs. Additionally, there is a cost issue to be considered: government agencies charge different hourly rates for internal and external customers; thus, NASA would be required to pay higher rates to test in DoW facilities than to test in its own facilities (and vice versa). Similarly, costs for using external Commercial facilities are subject to market demands, which means they will also be less affordable for the limited budgets of NASA programs.

In summary, there is projected to be a large Capacity Gap in the availability of NASA hypersonic ground test infrastructure to meet future testing demands. And while Defense and Commercial hypersonic ground testing facilities have some technical capabilities that NASA's facilities do not, they are not a viable option to close the Capacity Gap because of their higher costs and extremely limited availability to NASA. Since this Capacity Gap applies equally to any and all future test programs, this gap was rated by default as of the highest criticality.

Table 11. Gap ID, Description, and Frequency.

FACILITY GAP ID	FACILITY GAP DESCRIPTON	# Citations All categories	# Citations EDL Human	# Citations EDL NASA Robotic	# Citations EDL NASA Technology	# Citations Hypersonics-NASA	# Citations Hypersonics-Commercial	# Citations Hypersonics-Defense	# Citations Modeling and Simulation	# Citations Instrumentation
EDL-00	Productivity and availability of NASA facilities to meet demands	**ALL**	All	All	ALL	-	-	-	-	-
EDL-01	High Reynolds number test capability required to generate fully turbulent flow on blunt-body EDL configurations for convective aeroheating and aerodynamics testing	**89**	25	25	33	-	-	-	-	-
EDL-02	High enthalpy test capability required to generate shock-layer chemical kinetic effects on convective aeroheating and aerodynamics for simulation of flight in small planet and satellite (Earth, Mars, Venus, Titan) atmospheres	**91**	34	22	35	-	-	-	-	-
EDL-03	High enthalpy capability required to generate shock-layer chemical kinetic effects on convective aeroheating and aerodynamics for simulation of flight in gas giants (Jupiter, Saturn, Uranus, Neptune) atmospheres	**16**	0	4	12	-	-	-	-	-
EDL-04	Velocity, pressure, and test-gas composition required to generate shock-layer radiation transport physics for simulation of flight in small planet and satellite (Earth, Mars, Venus, Titan) atmospheres	**16**	6	6	4	-	-	-	-	-
EDL-05	Velocity, pressure, and test-gas composition to generate shock-layer radiation transport physics for simulation of flight in gas giant (Jupiter, Saturn, Uranus, Neptune) atmospheres	**1**	0	1	0	-	-	-	-	-
EDL-06	Non-reacting CO2 test gas capability for simulation of aerodynamic compressibility effects during flight in Mars atmosphere	**65**	33	7	25	-	-	-	-	-
EDL-07	Instrumentation and test capabilities for measurement of flow field structure and surface conditions in separated, blunt body wake flows	**33**	5	10	15	-	-	-	-	-
EDL-08	High-pressure injection mass-flow supply and test conditions for flight-relevant simulation of Reaction Control System and Retropropulsion flow fields and aerodynamic performance interactions	**29**	15	0	14	-	-	-	-	-
EDL-09	Sufficient core size to allow testing of larger models required to accurately replicate small surface features such as roughness, cavities, gaps, nozzles, etc.	**63**	25	15	14	-	-	-	-	-
EDL-10	Low density test capability required to simulate rarefied aerodynamic and aeroheating effects	**9**	0	4	5	-	-	-	-	-
EDL-11	Ballistics range with facility length and measurement stations sufficient for required number of aerodynamic oscillation cycles	**22**	5	6	11	-	-	-	-	-
EDL-12	Access to non-NASA facilities for exploration/research programs extremely unlikely in foreseeable future due to high demand on DoD, Commercial and Academic facilities from National Defense programs except highest-priority, human-rated missions	**All**	All	All	All	-	-	-	-	-
EDL-13	Ability to generate electro-magnetic and magneto-hydrodynamic effects	**2**	0	0	2	-	-	-	-	-
HTP-00	Productivity and availability of NASA facilities to meet demands and higher charge rates for non-NASA tests	**All**	-	-	-	All	All	All	0	0
HTP-01	Mach 4.6 — 6.0 test capability at flight relevant Reynolds numbers for HTP configuration aerodynamic measurements	**34**	-	-	-	12	21	1	0	0
HTP-02	Test section core of sufficient size to accommodate large vehicle models of integrated airframe/propulsion systems, multiple models for stage separation, resolve small surface OML features including gaps, steps, thruster nozzles, and/or provide sufficient internal volume for gas delivery systems	**122**	-	-	-	37	58	27	0	0

FACILITY GAP ID	FACILITY GAP DESCRIPTON	# Citations All categories	# Citations EDL Human	# Citations EDL NASA Robotic	# Citations EDL NASA Technology	# Citations Hypersonics-NASA	# Citations Hypersonics-Commercial	# Citations Hypersonics-Defense	# Citations Modeling and Simulation	# Citations Instrumentation
HTP-03	High Reynolds number test capability required to generate fully turbulent flow on slender HTP configurations for convective aeroheating testing	**132**	-	-	-	41	69	16	0	6
HTP-04	Quiet flow (low freestream noise) test capability at mid-range Reynolds number conditions for transition onset measurements	**9**	-	-	-	9	0	0	0	0
HTP-05	Mach / Reynolds / Enthalpy range to produce material/surface interactions including particulates and plasmas that affect boundary-layer instability growth and transition	**10**	-	-	-	10	0	0	0	0
HTP-06	High-enthalpy air test capability required to generate flight-like propulsion simulation effects and/or shock-layer chemical kinetic effects on convective aeroheating and aerodynamics for HTP configurations	**28**	-	-	-	6	5	17	0	0
HTP-07	High-pressure gas delivery/measurement system for propulsion simulation (flow-path simulation, RCS jets, thrusters and retropropulsion), with an ability to control pressure, temperature, mass-flow rate and injectant gas composition	**6**	-	-	-	3	0	0	0	3
HTP-08	Access to non-NASA facilities for NASA flight/research programs extremely unlikely in foreseeable future due to high demand on DoD, Commercial and Academic facilities from National Defense.	**All**	-	-	-	All	All	All	0	0
HTP-09	Long duration hypersonic test capability for moveable aerodynamic control system, vehicle dynamics and aeroheating active cooling/thermal management	**1**	-	-	-	0	0	1	0	0
CFD-00	Productivity and availability of NASA facilities to meet demands	**All**	-	-	-	-	-	-	All	-
CFD-01	High enthalpy aerothermodynamics test capability for gas kinetic effects on aerodynamics, aeroheating and flow field structure	**9**	-	-	-	-	-	-	9	-
CFD-02	High-enthalpy aerothermodynamics test capability for shock-layer radiation effects on aeroheating	**7**	-	-	-	-	-	-	7	-
CFD-03	High-pressure injection mass-flow systems for propulsion (RCS, thrusters, retropropulsion) simulation effects on aerodynamics and aeroheating	**6**	-	-	-	-	-	-	3	-
CFD-04	Continuous-flow supersonic (Mach 5-6) test capability for aerodynamic testing	**2**	-	-	-	-	-	-	2	-
CFD-05	Quiet tunnel test capability to mitigate free stream nose influence on boundary-layer transition	**14**	-	-	-	-	-	-	14	-
CFD-06	Measurement techniques for hot-surface discrete sensor measurements for ablation data	**3**	-	-	-	-	-	-	3	-
CFD-07	High-frequency sensors and force & moment balances for short-duration testing facilities and for dynamic measurements	**1**	-	-	-	-	-	-	0	-
CFD-08	Optical access for non-intrusive flow field diagnostics in hypersonic facilities	**35**	-	-	-	-	-	-	30	-
CFD-09	Low-density test conditions for simulation of rarefied aerodynamics	**4**	-	-	-	-	-	-	4	-
CFD-10	Forced-oscillation test capability in supersonic wind tunnels for measurement of unsteady vehicle dynamics	**4**	-	-	-	-	-	-	3	-
CFD-11	Ballistics ranges with sufficient measurements stations and/or range length to obtain validation quality vehicle dynamics data	**2**	-	-	-	-	-	-	2	-
CFD-12	Mach, Reynolds, and/or enthalpy ranges to duplicate flight relevant conditions and freestream disturbances (particulates, electrostatic discharge) for flow field / material surface interaction studies	**1**	-	-	-	-	-	-	1	-
CFD-13	Optical access for non-intrusive flow field diagnostics in supersonic facilities	**44**	-	-	-	-	-	-	44	-
CFD-14	Long-duration high-enthalpy TPS testing capability, including ablation and shape change and catalysis	**3**	-	-	-	-	-	-	3	-
CFD-15	Access to non-NASA facilities for EXTENSIVE test programs required for CFD validation extremely unlikely in foreseeable future due to high demand on DoD, Commercial and Academic facilities from National Defense	**56**	-	-	-	-	-	-	56	-

FACILITY GAP ID	FACILITY GAP DESCRIPTON	# Citations All categories	# Citations EDL Human	# Citations EDL NASA Robotic	# Citations EDL NASA Technology	# Citations Hypersonics-NASA	# Citations Hypersonics-Commercial	# Citations Hypersonics-Defense	# Citations Modeling and Simulation	# Citations Instrumentation
CFD-16	Non-reacting, supersonic CO2 test capability for Mars retropropulsion & aerodynamic testing	**2**	-	-	-	-	-	-	2	-
CFD-17	Expanded range of conditions (test time, pressure, velocity) in shock tubes for radiative and kinetic property measurements	**10**	-	-	-	-	-	-	10	-
CFD-18	Advanced sensors (fast response pressure, VUV radiation) for shock tube radiative and kinetic property measurements	**10**	-	-	-	-	-	-	10	-
Inst—00	Productivity and availability of NASA facilities to meet demands, charge rates are cost prohibitive for fundamental R&D to develop test techniques	**All**	-	-	-	-	-	-	-	All
Inst-01	Access to non-NASA facilities for NASA test technique development programs extremely unlikely in foreseeable future due to high demand on DoD, Commercial and Academic facilities from National Defense.	**ALL**	-	-	-	-	-	-	-	All
Inst-Aero-01	Fast-response aerodynamic force & moment balances suitable for short-duration impulse facility operation	**37**	2	8	4	3	5	12	1	2
Inst-Aero-02	Aerodynamic force & moment balances with high-frequency response for dynamic pitch-response measurement and separation of balance and strut effects	**49**	2	0	8	6	16	15	0	2
Inst-Aero-03	Aerodynamic force & moment balances with capability for accurate measurement of small changes in aerodynamic coefficients due to RCS and SRP firings	**20**	8	4	5	0	0	0	0	3
Inst-Aero-04	Flow-through aerodynamic force & moment balances for gas seeding that do not omit axial-force component	**5**	0	0	0	0	0	0	3	2
Inst-Aero-05	Higher signal-to-noise ratio and faster response-time pressure instrumentation	**3**	0	0	0	0	0	0	1	2
Inst-Aero-06	Ballistics range with sufficient measurement stations and length to acquire dynamic aero data and/or ability to fly at angle-of-attack	**14**	5	4	5	0	0	0	0	0
Inst-Flow-01	Application and validation of flow-field visualization techniques from supersonic flows to hypersonic flow conditions	**89**	0	0	5	20	20	0	37	7
Inst-Flow-02	Ability to perform near-surface measurements of boundary-layer properties	**58**	0	0	0	16	20	0	12	10
Inst-Flow-03	Flow field seeding techniques for RCS and SRP plumes to enable laser-based velocity measurements.	**4**	0	0	0	0	0	0	0	4
Inst-Flow-04	Inert gas other than air (e.g., heated ethane) for thruster / plume testing	**2**	0	0	0	0	0	0	1	1
Inst-Flow-05	Simultaneous, non-intrusive measurement of velocity and temperature for direct validation of Reynolds heat flux models	**4**	0	0	0	0	0	0	1	3
Inst-Flow-06	Optical tracking and characterization of particles in high-speed flow (gas seeding or “dusty” flows)	**5**	0	0	0	0	0	0	1	4
Inst-Flow-07	Ability to measure thermal state distributions and flow field temperatures along the stagnation streamline	**1**	0	0	0	0	0	0	1	0
Inst-Flow-08	Hardware and software for high frequency / high-resolution schlieren systems	**20**	0	0	0	0	0	0	18	2
Inst-Heat-01	Global optical aeroheating techniques for very low-temperature response conditions (e.g. wake flows)	**27**	2	0	1	8	12	0	0	4
Inst-Heat-02	Cost, fabrication time, and spatial resolution limitations on discrete sensors for small wind tunnel modes	**24**	10	2	6	0	0	0	0	6
Inst-Heat-03	Heat-flux sensors that separate convective and radiative components in high-enthalpy testing	**22**	1	6	9	0	0	0	6	0
Inst-Heat-04	Spectral range of shock-layer radiation sensors, especially VUV spectra	**11**	2	4	5	0	0	0	0	0
Inst-Heat-05	Limited high-speed data acquisition capabilities facilities	**3**	0	0	0	0	0	0	0	3
Inst-Heat-06	Higher frame-rate cameras for optical surface heating measurements	**5**	0	0	0	0	0	0	0	5

FACILITY GAP ID	FACILITY GAP DESCRIPTON	# Citations All categories	# Citations EDL Human	# Citations EDL NASA Robotic	# Citations EDL NASA Technology	# Citations Hypersonics-NASA	# Citations Hypersonics-Commercial	# Citations Hypersonics-Defense	# Citations Modeling and Simulation	# Citations Instrumentation
Inst-Heat-07	Techniques for mapping 2D optical aeroheating data to 3D CAD geometries	**6**	0	0	0	0	0	0	0	6
Inst-Heat-08	Higher frame-rate cameras for optical surface heating measurements	**32**	0	0	0	0	0	0	32	0
Inst-Heat-09	Hardware and software for IR thermography systems	**2**	0	0	0	0	0	0	0	2
Inst-Heat-10	Hardware and software for phosphor thermography systems, especially high-temperature	**2**	0	0	0	0	0	0	0	2

Table 12. SME Ranking of EDL Gap Criticality.

Respondent ID	EDL-01: High Reynolds number	EDL-02: High-Enthalpy for rocky planets	EDL-03: High-Enthalpy for Gas Giants	EDL-04: Shock-Layer radiation for rocky planets	EDL-05: Shock-layer radiation for gas giants	EDL-06: CO2 for Mars Aerodynamics	EDL-07: Wake Flow diagnostics	EDL-08: High-pressure air for propulsion simulation	EDL-09: Large test core	EDL-10: Rarefied Flow	EDL-11: Ballistic range dynamic aero	EDL-12: Access to non-NASA facilities	EDL-13: MHD effects
#1	3	3	1	2	1	2	2	2	3	1	2	3	1
#2	3	3	1	2	1	2	3	3	3	1	3	2	1
#3	3	2	2	1	1	2	3	2	3	1	2	2	1
#4	3	3	2	3	2	2	3	3	3	3	3	2	2
#5	3	3	n/r	n/r	n/r	3	2	2	2	2	n/r	n/r	n/r
#6	2	2	3	2	3	2	3	3	2	2	3	2	1
#7	2	2	3	2	2	1	3	2	3	1	2	3	2
#8	3	3	2	3	2	2	2	2	1	1	1	3	2
#9	3	2	2	2	2	3	3	3	2	3	3	1	2
#10	2	3	2	3	2	2	2	3	3	1	2	3	1
#11	3	3	3	2	2	1	2	2	2	1	1	1	1
#12	3	3	2	3	2	3	2	3	3	2	3	3	2
#13	3	3	3	3	3	2	3	2	3	2	3	2	1
#14	3	3	2	3	1	3	2	3	3	1	2	3	1
#15	3	3	2	3	2	2	3	3	2	2	3	2	2
#16	3	2	3	1	2	1	3	2	2	3	2	2	1
#17	3	3	2	3	2	1	3	2	3	1	3	3	3
#18	2	2	3	2	3	1	1	2	3	2	1	1	2
#19	3	2	2	2	2	2	3	3	2	1	1	2	1
#20	2	3	3	3	2	3	3	2	3	3	2	3	2
#21	3	2	3	2	3	1	3	3	2	2	2	2	1
#22	3	2	2	2	2	2	3	3	3	2	2	2	1
#23	1	3	3	3	3	3	3	3	1	1	2	1	1
#24	2	2	1	2	1	2	2	2	2	1	1	2	1
#25	3	3	3	3	3	3	3	2	3	2	2	3	2
#26	2	3	2	3	2	1	3	2	3	1	2	1	1
#27	3	2	2	2	2	3	3	3	2	2	3	3	1
#28	3	3	3	2	2	2	3	3	3	2	3	2	2
#29	3	3	3	2	3	2	3	3	3	2	3	3	2
#30	2	2	2	2	2	2	2	3	3	2	3	3	1
#31	1	2	2	1	2	1	2	2	2	1	1	2	1
#32	3	3	2	3	2	1	1	1	1	1	2	2	1
#33	n/r	1	1	n/r	n/r	1	1	1	n/r	1	n/r	n/r	1
#34	3	3	3	3	2	2	3	2	3	2	2	3	1
AVERAGE RANK	2.6	2.6	2.3	2.3	2.2	1.9	2.5	2.4	2.5	1.6	2.2	2.3	1.4
# RESPONSES	33	34	33	32	32	34	34	34	33	34	32	32	33

Table 13. SME Ranking of HTP Gap Criticality.

Respondent ID	HTP-01: Mach 4.6 to 6.0	HTP-03 High Reynolds number for Turbulence	HTP-02 Large Test Core	HTP-04 Quiet Flow	HTP-05 Mach / Reynolds / Enthalpy Range for Materials Surface Interactions	HTP-06 High-Enthalpy for Propulsion and shock-layer kinetics	HTP-07 High-Pressure gas supply for active propulsion	HTP-08 Access to non-NASA facilities	HTP-09 Long Duration Testing
#1	3	3	3	2	1	2	2	3	1
#2	3	2	3	2	1	2	2	3	1
#3	3	3	3	3	1	2	2	3	1
#4	2	3	2	2	1	2	2	2	1
#5	3	3	3	3	3	3	3	2	3
#6	3	3	n/r	n/r	N	n/r	2	n/r	n/r
#7	1	3	2	2	3	3	3	3	1
#8	3	2	2	3	3	2	2	3	2
#9	3	2	3	1	2	2	3	3	3
#10	3	3	3	2	2	3	3	3	3
#11	2	3	2	3	2	3	3	3	3
#12	3	2	2	3	1	2	2	3	3
#13	3	2	2	3	1	2	3	2	2
#14	3	3	3	3	3	3	3	3	3
#15	2	2	2	2	2	3	1	2	3
#16	3	2	3	2	1	2	2	2	3
#17	3	2	2	1	1	3	2	1	3
#18	3	3	3	2	2	3	2	1	2
#19	2	2	3	2	2	2	3	3	2
#20	3	1	2	2	2	2	3	3	2
#21	3	3	3	2	3	3	3	3	3
#22	2	3	3	2	2	3	3	3	1
#23	2	2	1	1	1	2	1	2	2
#24	n/r	n/r	n/r	1	1	1	n/r	n/r	
#25	3	3	3	3	2	2	2	3	2
AVERAGE RANK	2.7	2.5	2.5	2.2	1.8	2.4	2.4	2.6	2.2
# RESPONSES	24	24	23	24	24	24	24	23	23

Table 14. SME Ranking of CFD Gap Criticality.

Respondent ID	CFD-01: High Enthalpy for Gas Kinetics	CFD-02: High-Enthalpy for Shock Radiation	CFD-03: High-Pressure Air for Propulsion Systems	CFD-04: Continuous flow supersonic aerodynamics	CFD-05: Quiet Tunnel	CFD-06: Sensors for hot-surface ablation rates	CFD-07: High Frequency force & moment balances	CFD-08: Optical Access for Flow field Diagnostics	CFD-09: Rarefied Flow	CFD-10: Forced Oscillation for unsteady dynamics	CFD-11: Ballistics Range for Dynamic Aero	CFD-13: Free-stream particulate seeding	CFD-13: Optical Access for flow field diagnostics	CFD-14: Long duration flow for TPS response	CFD-15: Access to non-NASA facilities	CFD-16: CO2 capability for Mars Aerodynamics	CFD-17: Wider range of shock-tube conditions for kinetics/radiation	CFD-18: Advanced sensors for shock-tube measurements
#1	3	2	2	2	2	1	2	2	1	2	2	1	2	1	3	2	2	2
#2	1	1	2	3	3	2	1	3	1	1	1	1	3	2	3	1	1	1
#3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	3	3
#4	3	3	3	2	2	2	3	3	2	2	3	3	3	2	2	3	3	3
#5	3	3	3	1	2	3	3	3	2	2	2	3	3	1	3	2	3	3
#6	3	3	2	2	3	3	3	3	1	2	2	3	3	3	3	2	2	3
#7	2	2	3	2	3	3	3	3	1	1	3	2	3	3	3	2	2	2
#8	3	3	2	2	2	3	2	2	1	2	2	3	2	3	1	2	3	2
#9	3	2	3	2	1	3	3	2	1	2	3	2	2	3	3	2	2	2
#10	3	2	2	2	2	3	1	2	1	2	1	3	2	3	2	1	2	3
#11	3	3	3	2	2	3	2	3	2	2	3	2	3	3	3	3	3	3
#12	3	3	3	2	2	2	3	3	2	3	3	2	2	3	2	2	2	3
#13	1	3	3	2	2	2	2	3	1	2	1	1	3	2	3	3	2	2
#14	2	2	2	1	3	3	3	3	3	2	2	1	3	3	2	1	2	3
#15	3	3	2	2	3	1	3	3	1	2	3	3	3	2	1	2	3	3
#16	2	n/r	3	n/r	n/r	3	n/r	n/r	2	n/r	n/r	n/r	1	3	1	1	2	2
#17	3	2	2	1	2	2	2	2	2	2	2	3	2	2	3	2	2	2
#18	2	2	3	1	2	2	2	3	1	2	1	2	3	2	1	2	2	2
#19	3	3	3	3	3	3	3	3	3	2	2	3	3			3	3	2
#20	2	2	3	2	2	3	3	3	1	2	3	2	3	2	2	2	1	2
#21	2	2	3	2	2	2	3	2	2	2	3	2	2	2	3	2	2	3
#22	3	3	3	1	1	3	1	3	1	3	2	3	2	3	1	3	3	3
#23	3	3	3	2	2	3	2	3	2	2	2	3	3	3	3	3	2	3
#24	3	2	3	1	3	2	2	3	1	2	n/r	3	3	3	3	3	n/r	n/r
#25	3	3	2	1	1	2	3	3	1	3	2	2	2	3	1	1	3	2
#26	3	3	3	2	2	2	3	3	2	2	3	2	3	3	2	2	2	2
#27	3	3	3	3	2	3	3	3	2	3	3	3	2	3	3	2	3	3
#28	3	2	3	1	2	2	3	3	2	3	3	2	3	2	3	2	2	1
#29	3	3	2	1	1	2	1	3	1	2	1	1	2	2	2	1	2	2
#30	3	2	2	1	1	3	1	2	1	1	2	1	1	3	2	1	1	1
#31	1	2	n/r	n/r	1	1	n/r	1	1	n/r	n/r	1	1	1	n/r	1	n/r	n/r
AVERAGE RANK	2.6	2.5	2.6	1.8	2.1	2.4	2.4	2.7	1.5	2.1	2.3	2.2	2.5	2.5	2.3	2.0	2.2	2.3
# RESPONSES	31	30	30	29	30	31	29	30	31	29	28	30	31	30	29	31	29	29

Table 15. EDL Technical Gaps Frequency and Criticality.

Gap ID	Gap Title	Gap Description	Averaged Criticality	Scaled Criticality	Frequency	Scaled Frequency	Pareto Value	Scaled Pareto Value
EDL-00	NASA Test Capacity	Productivity and availability of NASA facilities to meet demands	N/A	10	N/A	N/A	N/A	10
EDL-01	High Reynolds Number Turbulent Flow	High Reynolds number test capability required to generate fully turbulent flow on blunt-body EDL configurations for convective aeroheating and aerodynamics testing	2.6	8.8	89	9.8	86	10.0
EDL-02	High Enthalpy Reacting Flow	High enthalpy test capability required to generate shock-layer chemical kinetic effects on convective aeroheating and aerodynamics for simulation of flight in small planet and satellite (Earthe, Venus, Mars, Titan)	2.6	8.5	91	10.0	85	9.9
EDL-03	High Enthalpy Reacting Flow (Gas Giants)	High enthalpy capability required to generate shock-layer chemical kinetic effects on convective aeroheating and aerodynamics for simulation of flight in gas giants (Jupiter, Saturn, Uranus, Neptune)	2.3	7.6	16	1.8	13	1.5
EDL-04	Shock Tube Radiation	Velocity, pressure, and test-gas composition required to generate shock-layer radiation transport physics for simulation of flight in small planet and satellite (Earth, Mars, Venus, Titan)	2.3	7.8	16	1.8	14	1.6
EDL-05	Shock Tube Radiation (Gas Giants)	Velocity, pressure, and test-gas composition to generate shock-layer radiation transport physics for simulation of flight in gas giant (Jupiter, Saturn, Uranus, Neptune) atmospheres	2.1	6.9	1	0.1	1	0.1
EDL-06	CO2 Test Gas	Non-reacting CO2 test gas capability for simulation of aerodynamic compressibility effects during flight in Mars atmosphere	1.9	6.5	65	7.1	46	5.4
EDL-07	Wake Flow Diagnostics	Instrumentation and test capabilities for measurement of flow field structure and surface conditions in separated, blunt body wake flows	2.5	8.4	33	3.6	31	3.6
EDL-08	Flow Field Mass Injection	High-pressure injection mass-flow supply and test conditions for flight-relevant simulation of Reaction Control System and Retropropulsion flow fields and aerodynamic performance interactions	2.4	8.0	29	3.2	26	3.0
EDL-09	Large Test Core	Sufficient core size to allow testing of larger models required to accurately replicate small surface features such as roughness, cavities, gaps, nozzles, etc.	2.5	8.3	63	6.9	57	6.7
EDL-10	Rarefied Flow	Low density test capability required to simulate rarefied aerodynamic and aeroheating effects	1.6	5.5	9	1.0	5	0.6
EDL-11	Ballistics Range	Ballistics range with facility length and measurement stations sufficient for required number of aerodynamic oscillation cycles	2.2	7.3	22	2.4	18	2.1
EDL-12	External Test Capacity	High cost and low productivity of external facilities	N/A	N/A	N/A	N/A	N/A	N/A
EDL-13	Magneto-Hydrodynamics	Ability to generate electro-magnetic and magneto-hydrodynamic effects	1.4	4.6	2	0.2	1	0.1

Table 16. HTP Technical Gaps Frequency and Criticality.

Gap ID	Gap Title	Gap Description	Averaged Criticality	Scaled Criticality	Frequency	Scaled Frequency	Pareto Value	Scaled Pareto Value
HTP-00	NASA Test Capacity	Productivity and availability of NASA facilities to meet demands	N/A	10	N/A	N/A	N/A	10
HTP-01	High Supersonic / Low Hypersonic Bridge Conditions	Mach 4.6 - 6.0 test capability at flight relevant Reynolds numbers for HTP configuration aerodynamic measurements	2.7	8.9	34	2.6	23	2.7
HTP-02	Large Test Core	Test section core of sufficient size to accommodate large vehicle models of integrated airframe/propulsion systems, multiple models for stage separation, resolve small surface OML features...	2.5	8.3	122	9.2	77	9.2
HTP-03	High Reynolds Number Turbulent Flow	High Reynolds number test capability required to generate fully turbulent flow on slender HTP configurations for convective aeroheating testing	2.5	8.4	132	10.0	84	10.0
HTP-04	Quiet Flow for Boundary-Layer Transition	Quiet flow (low free-stream noise) test capability at mid-range Reynolds number conditions for transition onset measurements	2.2	7.2	9	0.7	5	0.6
HTP-05	Flow Field / Surface Interactions	Mach / Reynolds / Enthalpy range to produce material/surface interactions including particulates and plasmas that affect boundary-layer instability growth and transition	1.8	6.0	10	0.8	5	0.5
HTP-06	High Enthalpy Kinetics for Propulsion and Shock-Layer Kinetics	High-enthalpy air test capability required to generate flight-like propulsion simulation effects and/or shock-layer chemical kinetic effects on convective aeroheating and aerodynamics for HTP configurations	2.4	7.9	28	2.1	17	2.0
HTP-07	Flow Field Mass Injection for Propulsion	High-pressure gas delivery/measurement system for propulsion simulation (flow-path simulation, RCS jets, thrusters and retropropulsion), with an ability to control pressure, temperature, mass flow, etc.	2.4	7.9	6	0.5	4	0.4
HTP-08	External Test Capacity	High cost and low productivity of external facilities	N/A	N/A	N/A	N/A	N/A	N/A
HTP-09	Long Run-Duration Thermal Effects	Long duration hypersonic test capability for moveable aerodynamic control system, vehicle dynamics and aeroheating active cooling/thermal management	2.2	7.2	1	0.1	1	0.1

Table 17. CFD Technical Gaps Frequency and Criticality.

Gap ID	Gap Title	Gap Description	Averaged Criticality	Scaled Criticality	Frequency	Scaled Frequency	Pareto Value	Scaled Pareto Value
CFD-00	NASA Test Capacity	Productivity and availability of NASA facilities to meet demands	N/A	10	All	All	N/A	10
CFD-01	High-Enthalpy Kinetics	High-enthalpy aerothermodynamics test capability for gas kinetic effects on aerodynamics, aeroheating and flow-field structure	2.6	8.7	9	6.4	56	8.1
CFD-02	High-Enthalpy Radiation	High-enthalpy aerothermodynamics test capability for shock-layer radiation effects on aeroheating	2.5	8.3	7	5.0	42	6.0
CFD-03	Flow Field Mass Injection for Propulsion	High-pressure injection mass-flow systems for propulsion (RCS, thrusters, retropropulsion) simulation effects on aerodynamics and aeroheating	2.6	8.8	6	4.3	38	5.5
CFD-04	High Supersonic / Low Hypersonic Bridge Conditions	Continuous-flow supersonic (Mach 5-6) test capability for aerodynamic testing	1.8	6.0	2	1.4	9	1.2
CFD-05	Quiet Flow for Boundary-Layer Transition	Quiet tunnel test capability to mitigate free stream nose influence on boundary-layer transition	2.1	6.9	14	10.0	69	10.0
CFD-06	High Temperature Surface Ablation Measurements	Measurement techniques for hot-surface discrete sensor measurements for ablation data	2.4	8.1	3	3.0	24	3.0
CFD-07	High-Frequency Force & Moment Measurements	High-frequency sensors and force & moment balances for short-duration testing facilities and for dynamic measurements	2.4	7.9	1	1.0	8	1.0
CFD-08	Optical Access for Flow Field Diagnostics	Optical access for non-intrusive flow field diagnostics in hypersonic facilities	2.7	9.0	35	8.0	72	8.8
CFD-09	Rarefied Flow	Low-density test conditions for simulation of rarefied aerodynamics	1.5	5.2	4	2.9	15	2.1
CFD-10	Forced Oscillation for Unsteady Aerodynamics	Forced-oscillation test capability in supersonic wind tunnels for measurement of unsteady vehicle dynamics	2.1	7.0	4	10.0	70	8.6
CFD-11	Ballistics Rnge	Ballistics range with sufficient measurements stations and/or range length to obtain validation quality vehicle dynamics data	2.3	7.5	2	1.4	11	1.6
CFD-12	Flow Field / Surface Interactions	Mach, Reynolds, and/or enthalpy ranges to duplicate flight relevant conditions and free-stream disturbances (particulates, electrostatic discharge) for flow field / material surface interactions	2.2	7.3	1	0.7	5	0.8
CFD-13	Optical Access for Surface Diagnostics	Optical access for non-intrusive flow field diagnostics in supersonic facilities	2.5	8.2	44	10.0	82	10.0
CFD-14	Lon Run-Duration for Ablation	Long-duration high-enthalpy TPS testing capability, including ablation, shape change and catalysis	2.5	8.2	3	2.1	18	2.6
CFD-15	External Test Capacity	High cost and low productivity of external facilities	N/A	N/A	All	All	N/A	N/A
CFD-16	CO2 Test Gas for Mars Aerodynamics	Non-reacting, supersonic CO2 test capability for Mars retropropulsion & aerodynamic testing	2.0	6.6	2	1.4	9	1.4
CFD-17	Shock Tube Radiation	Expanded range of conditions (test time, pressure, velocity) in shock tubes for radiative and kinetic property measurements	2.2	7.5	10	7.1	53	7.7
CFD-18	Advanced Shock Tube Sensors	Advanced sensors (fast response pressure, VUV radiation) for shock tube radiative and kinetic property measurements	2.3	7.8	10	10.0	78	9.6

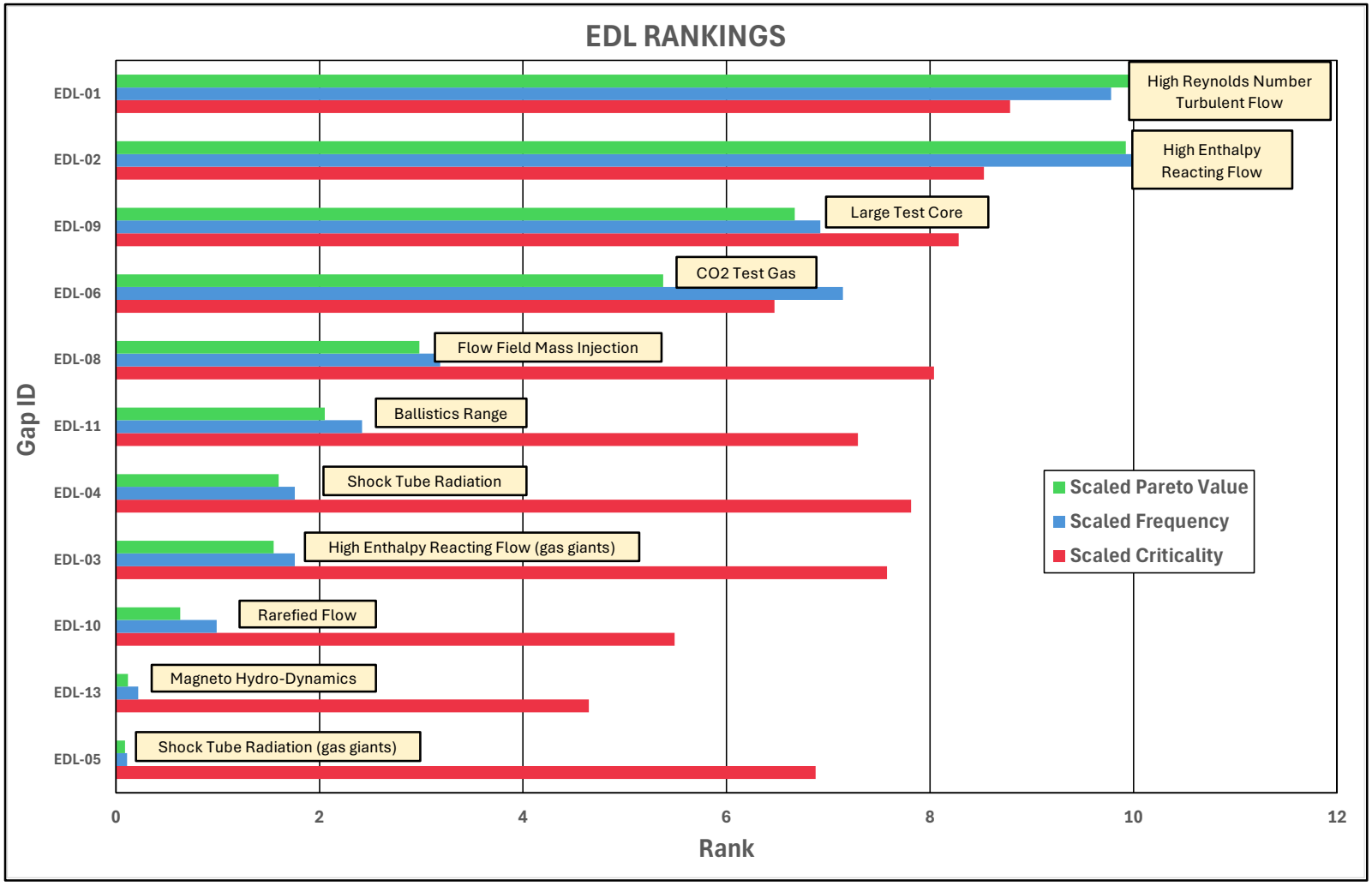


Figure 5. Pareto Analysis of EDL Technical Gaps.

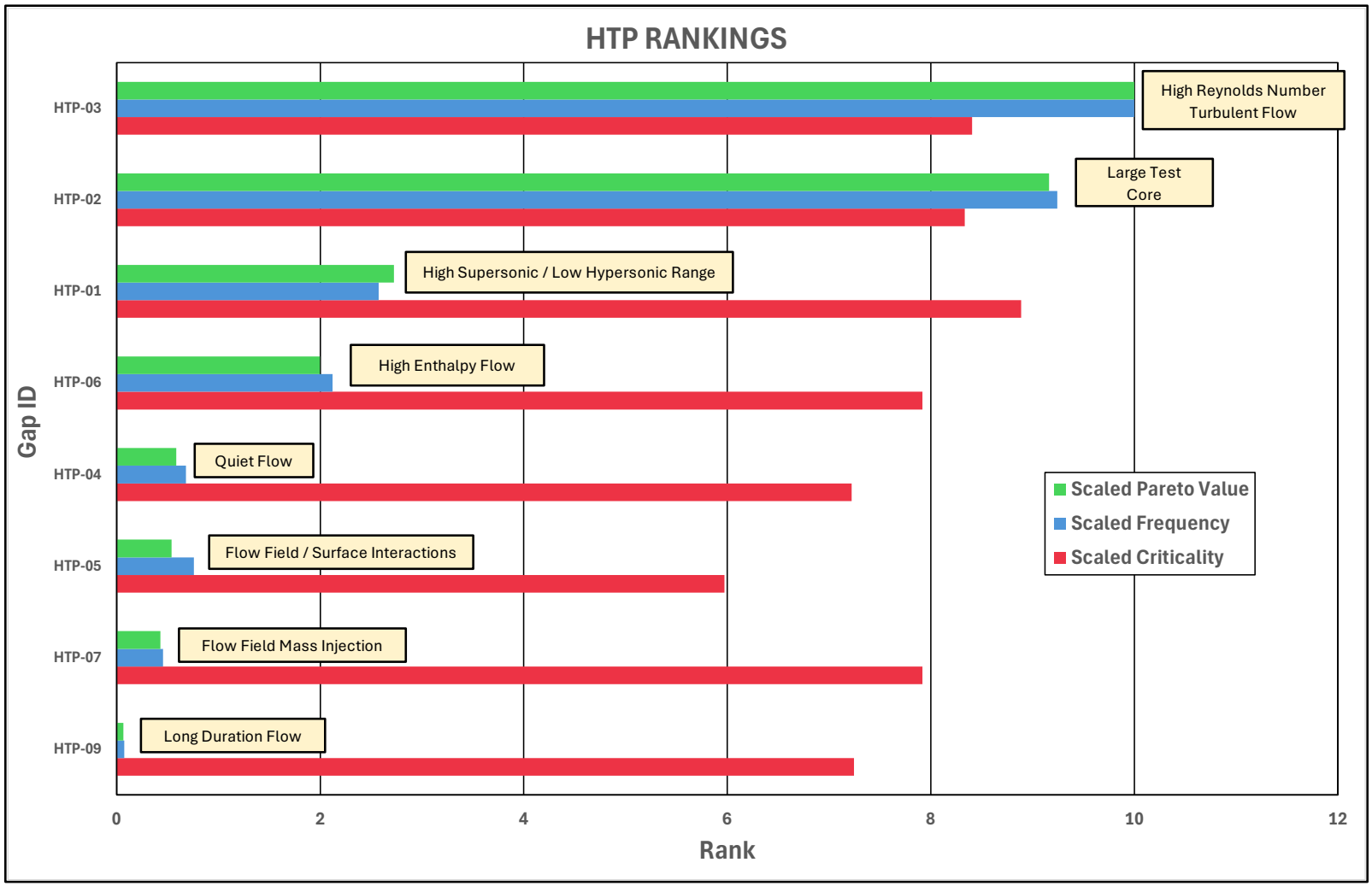


Figure 6. Pareto Analysis of HTP Technical Gaps.

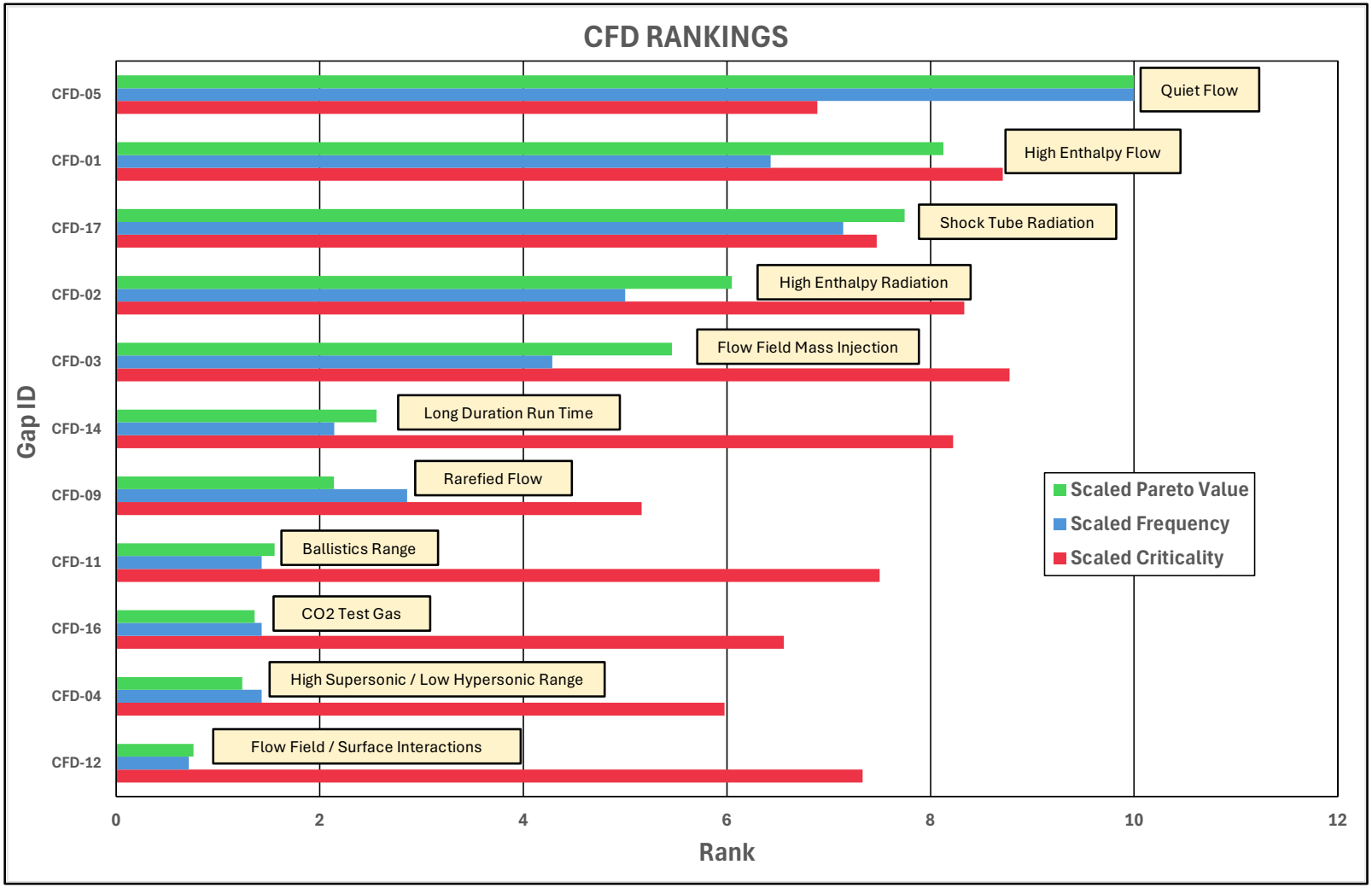


Figure 7. Pareto Analysis of CFD Technical Gaps.

Gap Closure and Mitigation Alternatives Analysis

The next task for HEAC Team 3 was to examine Gap Closure or Mitigation options for each of the 647 Database Objectives identified by HEAC Team 2. For each Database Objective, an evaluation was provided of:

- Gaps Summary – A summary of the technical capability gaps for this Objective.
- Program Criticality – The importance of the Gaps with respect to the individual Program – this is a simple, SME-supplied subjective estimate distinct from the Gap Criticality rankings.
- Gap Closure Alternatives – Recommendations for actions to mitigate or close the Gaps. Alternatives can include using simple analytical methods, using heritage data from similar prior programs, developing new, or modifying existing, ground test facilities, or using CFD.
- CFD Capability – An evaluation of the state-of-the-art of NASA CFD capability with respect to the cited gaps, specifically the accuracy and validity of numerical models for hypersonic flow processes, such as boundary-layer transition, shock-layer radiation, unsteady aerodynamics, etc.
- CFD Capacity – An evaluation of the logistical ability of computational hardware (e.g. processor speed, network connectivity, data storage) available to NASA to produce the required dataset with the cost and schedule expectations of a program.

The full Mitigation and Closure Analysis database is provided in Appendix C through Appendix J and a sample entry is provided below in Table 18. The taxonomy for this case is again:

- **Theme**: Hypersonic Entry, Descent and Landing
  - **Customer**: 3. NASA and Partners
    - **Category**: 3.1 Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology development and demonstration
      - **Program**: 3.13 Launch Vehicle Booster Recovery Using a HIAD
        - **Objectives**: 3.13xx

        3.1301 - Develop hypersonic aerodynamic performance database.

        3.1302 - Determine hypersonic aerodynamic influence of payload.

        3.1303 - Develop supersonic aerodynamic performance database.

        3.1304 - Define supersonic RCS performance and interactions.

        3.1305 - Determine supersonic aerodynamic influence of payload.

        3.1306 - Determine baseline, smooth-OML aeroshell convective heating.

3.1307 - Determine aeroshell heating augmentation due to flexible TPS deflections.

3.1308 - Determine aftbody and payload heating environments.

As an example of the Closure and Mitigation options for each Gap, the following entries apply to Database Objective 3.1308 – *Determine aftbody and payload heating environments*:

Gaps Summary - Instrumentation for very low temperature / heating environments not well developed. CFD is unvalidated for these flow fields and carries high uncertainty and design margins.

Gaps Program Criticality - High. Protection of payload is primary mission requirement. Use of CFD would include up to 100% uncertainty margins, which impacts mission performance.

Gaps Closure Alternatives - Test technique development program for low temperature / heating conditions required to support HIAD applications. Use of CFD.

CFD Capability - CFD capability to compute massively separated hypersonic wake flows is unvalidated with high uncertainty.

CFD Capacity - Extensive CPU/memory capacity required for unsteady wake flow simulations.

Table 18. EDL Programs – Focus on Gap Mitigation and Closure for Program 3.13 HIAD: Launch Vehicle Booster Recovery.

ID	Customer / Category / Program / Objective	# Gap List	Gaps Program Criticality	Gaps Closure Alternatives	CFD Capability	CFD Capacity
3	**NASA and Partners EDL Technology and Architecture Development**					
3.13	HIAD: launch vehicle booster recovery					
3.1301	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation	Sufficient
3.1302	Determine hypersonic aerodynamic influence of payload	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Moderate: CFD capability is lacking, but payload effects should be small at hypersonic conditions	Use CFD to estimate payload deltas on aerodynamics	CFD capability to compute massively separated hypersonic wake flows is unvalidated with high uncertainty	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.1303	Develop supersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for dynamic aero measurements. Potential for LaRC UPWT closure	Moderate: dynamic aero properties could have larger influence than for LOFTID because of larger payload with potential for shear layer impingement	Use CFD to obtain supersonic static aerodynamics and legacy data for dynamic properties	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.1304	Define supersonic RCS performance and interactions	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and potential for RCS / flow / surface interactions	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.1305	Determine supersonic aerodynamic influence of payload	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for dynamic aero measurements. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and potential for shear - layer / payload interaction	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	CFD capability to compute unsteady supersonic wake flows is unvalidated with high uncertainty	Dense grids and unsteady flow simulations require extensive CPU time
3.1306	Determine baseline, smooth-OML aeroshell convective heating	Scheduling and cost in non-NASA facilities	Low. CFD sufficient validated for smooth-OML blunt body heating	Use CFD to define baseline smooth-OML heating, Use non-NASA facilities. Develop high-Reynolds number NASA facility	CFD capability for baseline (smooth) OML is well developed	Sufficient
3.1307	Determine aeroshell heating augmentation due to flexible TPS deflections	non-NASA facilities likely not available for large NASA programs or cost-prohibitive	high - cannot complete all flight test goals without design information for TPS	Use CFD and historical data to design TPS with higher margins. Use non-NASA facilities. Develop high-Reynolds number NASA facility	Lacking validated/functional models for roughness transition and heating augmentation	
3.1308	Determine aftbody and payload heating environments	Instrumentation for very low temperature / heating environments not well developed. CFD is unvalidated for these flow fields and carries high margins	High. Protection of payload is primary mission. Use of CFD would include up to 100% margins, which impact mission performance	Test technique development program for low temperature / heating conditions required to support HIAD applications.	CFD capability to compute massively separated hypersonic wake flows is unvalidated with high uncertainty	Extensive CPU/memory capacity required for unsteady aerodynamic simulations

Gap Consolidation, Reevaluation, and Categorization

The HEAC Team 3 workflow employed sub-teams to perform the gaps analysis for each of the three top-level themes of Hypersonic Entry, Descent and Landing, Hypersonic Atmospheric Flight and Access to Space, and Hypersonic Tools and Methods. The results of their analyses have been presented above. The next step for Team 3 was to consolidate, reevaluate, and categorize the results for delivery to the HEAC Team 4 to develop Investment Recommendations.

Because the sub-teams operated independently, many identical or similar gaps were identified more than once, e.g. HTP-01 and CFD-04 Gaps both identify the need for a high-supersonic to low-hypersonic aerodynamic testing capability. All duplicative Gaps were grouped together to reevaluate their averaged criticality ranking, summed frequency ranking, and recomputed Pareto ranking. These "consolidated" gaps were then re-categorized into three types: Actionable, Supporting, and Diagnostics, which are defined as follows:

Actionable Gap: An identified deficiency in the operational range and capabilities of NASA's hypersonic facilities suite. For example, NASA has no testing capability in the Mach 4.6 to 6.0 range (HTP-01 and CFD-04 Gaps) which represents, respectively, the upper limit of the LaRC Unitary Plan Wind Tunnel and the lower limit of the LaRC 20-Inch Mach 6 Air Tunnel. Actionable Gaps could be closed through the construction of new facilities and/or modifications of existing facilities.

The Actionable Gaps list is presented in Table 19. This Actionable Gaps List also includes the "zeroth" EDL-00, HTP-00, CFD-00 Capacity Gaps that refer to the dramatic decline in NASA hypersonic wind tunnel productivity. Because the consolidated productivity Gap (ACT-00) applies to literally every single Mission / Requirement / Objective, it was omitted from the statistical analyses to avoid skewing the rankings of the other gaps. Instead, this gap was simply assigned the maximum values for Criticality, Frequency, and Pareto rankings.

Note that ACT-05 Gap "Ballistics Range" Gap Pareto rank was overwritten to zero, because this capability requirement refers to low-speed (subsonic to transonic) unsteady aerodynamic performance of EDL systems, which is not a hypersonic capability gap. Although database entries related to this topic were accepted during the study for informational purposes, it should be considered in a separate venue than this study. Also, this Gap has since been at least partially closed by the recent reactivation of the U.S. Army Aberdeen Ballistics Range and the completion of the NASA LaRC Flight Dynamics Research Facility.

Supporting Gap: An identified deficiency in testing capabilities that is not necessarily linked to any specific facility. For example, the ability to provide high-pressure mass injection for simulation of thruster or engine plumes was identified under Gaps EDL-08, HTP-07, and CFD-03 (consolidated Gap SUPP-04). This Gap could be closed by hardware modification to existing wind tunnels but also should be included in the design specification for any proposed new facilities. The Supporting Gaps list is presented in Table 20.

Diagnostics Gap: An identified deficiency in measurement, diagnostics, and/or data-acquisition capabilities that is not necessarily linked to any specific facility. For example, Gap INST-FLOW-05 calls out the need to develop laser-based diagnostics for simultaneous, non-intrusive measurement of flow field temperature and velocity. The Diagnostics Gaps list is presented in Table 21.

Table 19. Consolidated Rankings of Actionable Gaps.

Consolidated Gap ID	Theme Gap IDs	Consolidated Gap Title	Consolidated Average Criticality	Consolidated Scaled Criticality	Consolidated Frequency	Consolidated Scaled Frequency	Consolidated Pareto Value	Consolidated Scaled Pareto Value
ACT-00	EDL-00, HTP-00, CFD-00	NASA facility productivity	n/a	10.0	n/a	10.0	n/a	10.0
ACT-01	EDL-01, HTP-03	High Reynolds Number Turbulent Flow	2.6	10.0	221.0	10.0	100.0	10.0
ACT-02	EDL-03, EDL-02, HTP-06, CFD-01	High Enthalpy Reacting Gas	2.5	9.5	144.0	6.5	62.0	6.2
ACT-03	HTP-01, CFD-04	High Supersonic / Low Hypersonic Overlap	2.2	8.6	36.0	1.6	14.1	1.4
ACT-04	EDL-04, EDL-05, CFD-02, CFD-17	High Temperature, High Pressure Shockwave Radiation	2.3	8.9	34.0	1.5	13.6	1.4
ACT-05	EDL-11, CFD-11	Ballistics Range	2.2	8.6	24.0	1.1	9.3	0 (N/A)
ACT-06	HTP-04, CFD-05	Quiet Flow	2.1	8.2	23.0	1.0	8.5	0.9
ACT-07	EDL-10, CFD-09	Rarefied Flow	1.6	6.2	13.0	0.6	3.6	0.4

Table 20. Consolidated Rankings of Supporting Gaps.

Consolidated Gap ID	Theme Gap IDs	Consolidated Gap Title	Consolidated Average Criticality	Consolidated Scaled Criticality	Consolidated Frequency	Consolidated Scaled Frequency	Consolidated Pareto Value	Consolidated Scaled Pareto Value
SUPP-01	EDL-09, HTP-02	Large Test Core	2.5	9.7	185.0	10.0	96.8	10.0
SUPP-02	CFD-08, CFD-13	Optical Access for Visualization Techniques	2.6	10.0	79.0	4.3	42.7	4.4
SUPP-03	EDL-06, CFD-16	CO2 Test Gas	2.0	7.6	67.0	3.6	27.5	2.8
SUPP-04	EDL-08, HTP-07, CFD-03	Flow Field Mass Injection	2.5	9.6	41.0	2.2	21.3	2.2
SUPP-05	CFD-12, HTP-05	Flow Field / Surface Interactions	2.0	7.7	11.0	0.6	4.6	0.5
SUPP-06	HTP-09, CFD-14	Long Duration Run Time	2.3	9.0	4.0	0.2	1.9	0.2
SUPP-07	EDL-13	Magneto-Hydrodynamics	1.4	5.4	2.0	0.1	0.6	0.1

Table 21. Consolidated Rankings of Diagnostics Gaps.

Consolidated Gap ID	Theme Gap IDs	Consolidated Gap Title	Consolidated Gap Description
DIAG-01	EDL-07	Wake Flow Diagnostics	Instrumentation and test capabilities for measurement of flow field structure and surface conditions in separated, blunt body wake flows
DIAG-02	CFD-06	High Temperature Surface Ablation Measurements	Measurement techniques for hot-surface discrete sensor measurements for ablation data
DIAG-03	CFD-07	High-Frequency Force & Moment Measurements	High-frequency sensors and force & moment balances for short-duration testing facilities and for dynamic measurements
DIAG-04	CFD-18	Advanced Shock Tube Sensors	Advanced sensors (fast response pressure, VUV radiation) for shock tube radiative and kinetic property measurements
DIAG-05	CFD-10	Forced Oscillation for Unsteady Aerodynamics	Forced-oscillation test capability in supersonic wind tunnels for measurement of unsteady vehicle dynamics
DIAG-06	Inst-Flow-01	Flow Field Visualization	Application and validation of flow-field visualization techniques from supersonic flows to hypersonic flow conditions
DIAG-07	Inst-Flow-02	Near-Surface Measurements	Ability to perform near-surface measurements of boundary-layer properties
DIAG-08	Inst-Aero-02	High-Frequency Aerodynamics	Aerodynamic force & moment balances with high-frequency response for dynamic pitch-response measurement and separation of balance and strut effects
DIAG-09	Inst-Aero-01	Fast-Response Aerodynamics	Fast-response aerodynamic force & moment balances suitable for short-duration impulse facility operation
DIAG-10	Inst-Heat-08	High Resolution Optical Aeroheating	Higher resolution cameras for optical surface heating measurements
DIAG-11	Inst-Heat-01	Global Optical Aeroheating	Global optical aeroheating techniques for very low-temperature response conditions (e.g. wake flows)
DAIG-12	Inst-Heat-02	Improved Discrete Sensors	Cost, fabrication time, and spatial resolution limitations on discrete sensors for small wind tunnel modes
DIAG-13	Inst-Heat-03	Total Heat Flux Sensors	Heat-flux sensors that separate convective and radiative components in high-enthalpy testing
DIAG-14	Inst-Aero-03	High-Accuracy, Low Signal Aerodynamics	Aerodynamic force & moment balances with capability for accurate measurement of small changes in aerodynamic coefficients due to RCS and SRP firings
DAIG-15	Inst-Flow-08	High-Frequency & Resolution Schlieren	Hardware and software for high frequency / high-resolution schlieren systems
DIAG-16	Inst-Aero-06	Ballistics Range Measurements	Ballistics range with sufficient measurement stations and length to acquire dynamic aero data and/or ability to fly at angle-of-attack
DIAG-17	Inst-Heat-04	Extended Spectra Range Radiation Sensors	Spectral range of shock-layer radiation sensors, especially VUV spectra
DIAG-18	Inst-Heat-07	3D Mapping Techniques for Surface Data	Techniques for mapping 2D optical aeroheating data to 3D CAD geometries
DIAG-19	Inst-Aero-04	Aerodynamic Balances with Gas Seeding	Flow-through aerodynamic force & moment balances for gas seeding that do not omit axial-force component
DIAG-20	Inst-Flow-06	Flow Field Particle Tracking	Optical tracking and characterization of particles in high-speed flow (gas seeding or “dusty” flows)
DIAG-21	Inst-Heat-06	High Frequency Optical Aeroheating	Higher frame-rate cameras for optical surface heating measurements
DIAG-22	Inst-Flow-03	Flow-Seeding for Plume Visualization	Flow field seeding techniques for RCS and SRP plumes to enable laser-based velocity measurements.
DIAG-23	Inst-Flow-05	Laser-Based Flow Field Velocity and Temperature	Simultaneous, non-intrusive measurement of velocity and temperature for direct validation of Reynolds heat flux models
DIAG-24	Inst-Aero-05	Advanced Surface Pressure	Higher signal-to-noise ratio and faster response-time pressure instrumentation
DIAG-25	Inst-Heat-05	Higher Frequency Data Acquisition Systems	Limited high-speed data acquisition capabilities facilities
DIAG-26	Inst-Flow-04	Alternative Seeding Gas for Plume Visualization	Inert gas other than air (e.g., heated ethane) for thruster / plume testing
DIAG-27	Inst-Heat-09	IR Thermography Development	Hardware and software for IR thermography systems
DIAG-28	Inst-Heat-10	Phosphor Thermography Development	Hardware and software for phosphor thermography systems, especially high temperature
DIAG-29	Inst-Flow-07	Near-Surface Stagnation Region Flow Field Measurement	Ability to measure thermal state distributions and flow field temperatures along the stagnation streamline

Gap Prioritization for Investment Recommendations

The final step in the Gaps analysis was the prioritization of the need for Investment Recommendations to close the Actionable Gaps. Each of these gap closures would require the construction of a new facility or the modification and/or modernization of an existing facility. The prioritization was accomplished through consideration of the Criticality, Projected Cost range, and Pareto ranking, as discussed below. The final prioritization list is given in Table 22.

Table 22. Categorization and Prioritization of Actionable Gaps.

Gap ID	Theme Gap IDs	Gap Title	Cost Magnitude ($millions)	Consolidated Scaled Criticality	Consolidated Scaled Pareto Value	Prioritization
ACT-01	EDL-01, HTP-03	High Reynolds Number Turbulent Flow	Tier 1 $100M - $1000M	**10.0**	**10.0**	**High**
ACT-00	EDL-00, HTP-00, CFD-00	NASA facility productivity	Tier 2 $10M - $100M	**10.0**	**10.0**	**High**
ACT-02	EDL-03, EDL-02, HTP-06, CFD-01	High Enthalpy Reacting Gas	Tier2 $10M - $100M	**9.5**	**6.2**	**Medium**
ACT-03	HTP-01, CFD-04	High Supersonic / Low Hypersonic Overlap	Tier 2 $10M - $100M	**8.6**	**1.4**	**Medium**
ACT-07	EDL-10, CFD-09	Rarefied Flow	Tier 2 $10M - $100M	**6.2**	**0.4**	**Low (not recommended)**
ACT-04	EDL-04, EDL-05, CFD-02, CFD-17	High Temperature, High Pressure Shockwave Radiation	Tier 3 $1M - $10M	**8.9**	**1.4**	**High**
ACT-06	HTP-04, CFD-05	Quiet Flow	Tier 3 $1M - $10M	**8.2**	**0.9**	**Medium**
ACT-05	EDL-11, CFD-11	Ballistics Range	Tier 3 $1M - $10M	**8.6**	**1.1**	**Out of scope**

Criticality: Only the Actionable Gaps assigned a "red" stoplight (rank 8-10) for their Consolidated Scaled Criticality were considered for investment recommendations. Thus, the ACT-07 Gap "Rarified Flow", which was rated at 6.2 criticality, was eliminated.

Projected Cost: The Actionable Gaps were sorted into estimated "order-of-magnitude" cost ranges based on the expected complexity of the facility construction or modification/modernization needed to close the Gap. The cost ranges were Tier 3 = $1M to $10M; Tier 2 = $10M to $100M and Teir 1 = $100M to $1B. The rationale for this approach is that cost/benefit evaluations for investments across a four order-of-magnitude cost range should be considered separately rather than attempting to rank them uniformly.

Pareto Ranking: Within each Cost Range grouping, the Actionable Gaps were prioritized according to their Pareto ranking as High Priority, Medium Priority, or Low Priority. One note on the Pareto score for ACT-03 Gap "High Supersonic / Low Hypersonic Overlap" - because the HEAC survey was focused on *hypersonic* testing demands, there are expected to be many additional *supersonic* testing demands that were not captured by the HEAC team. Since this Gap spans both flight regimes, it has been elevated to Medium Priority despite its relatively lower Pareto rank for hypersonic requirements.

In summary, Team 3 identified and prioritized six Actionable Gaps in three different cost regimes for which Investment Recommendations were needed. Two other Actionable Gaps were deprecated due to low prioritization (ACT-07) or lack of applicability to hypersonics (ACT-05). Seven supporting Gaps were also identified that provide additional details for consideration of Investment Recommendations. The Investment Recommendations developed by HEAC Team 4 to close the Gaps are presented in the next section.

An additional facility modification proposal that was developed after the HEAC study was completed will also be considered in the next section. This low-cost proposal for conversion of an existing wind tunnel into a Ludwieg tube for hypersonic instrumentation and test technique development is identified as DIAG-XX and addresses many of the Diagnostics Gaps listed in Table 21. While not formally ranked through the HEAC process, it was assigned a high priority owing to its low cost and potential utility for multiple gap closures.

The High Priority Actionable Gaps which require Investment Recommendations are:

- Tier 1 (High Cost): ACT-01 High Reynolds Number Turbulent Flow
- Tier 2 (Moderate Cost): ACT-00 NASA Facility Productivity
- Tier 3 (Low Cost): ACT-04 High-Pressure, High-Temperature Shockwave Radiation

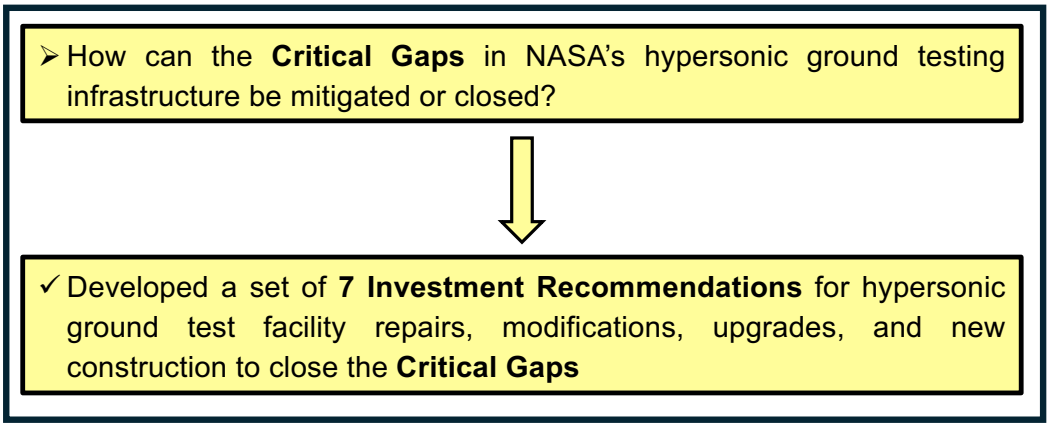
The Medium Priority Actionable Gaps which require Investment Recommendations are:

- Tier 1 (High Cost): none
- Tier 2 (Moderate Cost): ACT-02 High Enthalpy Reacting Gas Flow; ACT-03 High Supersonic / Low Hypersonic Overlap
- Tier 3 (Low Cost): ACT-06 Quiet Flow

The Low Priority Actionable Gaps which are not recommended for investments are:

- Tier 1 (High Cost): none
- Tier 2 (Moderate Cost): ACT-07 Rarefied Flow
- Tier 3 (Low Cost): none

HEAC Team 4: Investment Recommendations



The HEAC Team 4 was tasked to develop **Investment Recommendations** to close the **Actionable Gaps** (Table 22) identified by the Team 3 Capability and Capacity Gaps assessment. Closure of these gaps will require either the development of new ground test facilities or the modification and/or modernization of an existing ground test facility. Team 3 also identified **Supporting Gaps** (Table 20) to be considered in the formulation of these recommendations.

The Team 4 Investment Recommendations follow below, organized by order-of-magnitude investment costs and priority. A novel proposal for closing the **Diagnostics Gaps** (Table 21) that was developed after the HEAC study was completed is also included herein.

Tier 1 Large Investment Closure Recommendations

Tier 1 investments are those with projected costs in the hundreds-of-millions of dollar range; actual cost estimates would, of course, depend on the outcome of feasibility and design studies. There is only one Large Investment Recommendation, which deals with closure of Actionable Gap ACT-01 High Reynolds Number Turbulent Flow.

Construct a Hypersonic, High Reynolds Number Tunnel

The high-priority, large investment cost Actionable Gap ACT-01 High Reynolds Number Turbulent Flow can be closed through construction of a new, Hypersonic, High Reynolds Number Tunnel (HHNRT). This new hypersonic ground test facility would address the following Gaps:

Actionable Gap: HHRNT design and construction will close the Actionable Gap ACT-01 High Reynolds Number Turbulent Flow. This gap refers to the lack of a NASA capability to generate hypersonic, high Reynolds number test conditions that will produce fully turbulent flow over both blunt-body geometries for hypersonic Entry, Descent and Landing applications and slender-body geometries for sustained hypersonic atmospheric flight applications. These turbulent flow conditions will allow collection of high-fidelity convective aeroheating data that is critical to the design of thermal protection systems for hypersonic vehicles, as well for development and validation of physical models for computational fluid dynamics codes.

Supporting Gaps: Capabilities can be incorporated into the design specifications for the HHRNT to also concurrently address the following Supporting Gaps:

- SUPP-01 Large Test Core.
- SUPP-02 Optical Access for Visualization Techniques.
- SUPP-04 Flow Field Mass Injection.
- SUPP-05 Flow Field Surface Interactions could possibly be addressed, but more details on this requirement would be needed.
- SUPP-06 Long Duration Run Time could possibly be addressed, but more details on this requirement would be needed.

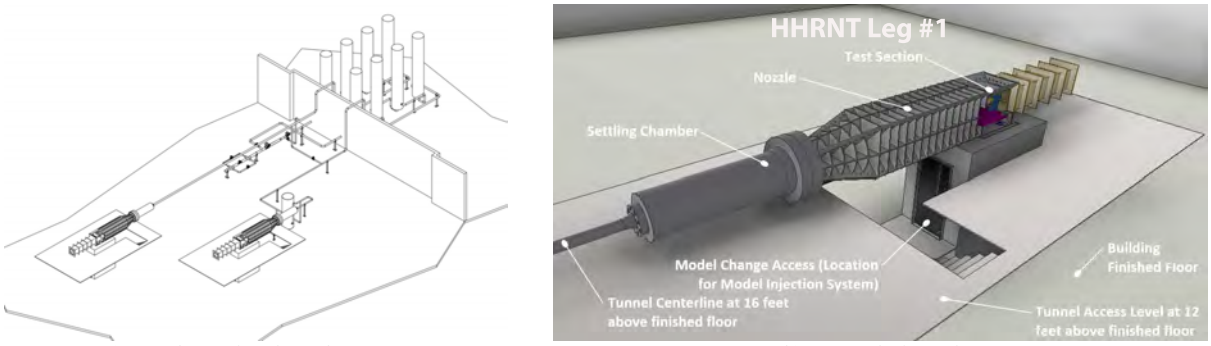
The proposed Hypersonic, High Reynolds Number Tunnel (Figure 8) is a conventional blow-down-to-atmosphere wind tunnel similar in concept to the existing LaRC 31-Inch Mach 10 and 20-Inch Mach 6 Air Tunnels. However, the HHRNT would supersede the operational capabilities of these legacy facilities by producing free stream test conditions with Reynolds numbers 2 to 4 times higher with a test core of equivalent or greater size.

The HHNRT concept incorporates two separate legs (i.e. nozzle, test section, diffuser) operating from a shared control room, data acquisition system, heater, high-pressure air delivery system and vacuum sphere. One leg would be designed for "low" hypersonic Mach number operations (Mach 6 to 9) and the other for "high" hypersonic Mach number operations (Mach 9 to 12). Multiple, interchangeable nozzles would be built for each leg, allowing for operations at different conditions as per user requirements. To address the Actionable and Supporting Gaps, the high-level design specification for HHRNT calls for:

- **ACT-01**: Low Mach Number Leg with Mach 6 and Mach 8 nozzles with Reynolds number ranges of 2×10^6/ft to 25×10^6/ft at Mach 6 and 4×10^6/ft to 20×10^6/ft at Mach 10. (For comparison, note that the existing 20-Inch Mach 6 Tunnel has a maximum Reynolds number of only

8×10^6/ft)

- **ACT-01:** High Mach Number Leg with Mach 10 and Mach 12 nozzles with Reynolds number ranges of 0.5×10^6/ft to 6×10^6/ft at Mach 10 and 1×10^6/ft to 3×10^6/ft at Mach 12. (For comparison, note that the existing 31-Inch Mach 10 Tunnel has a maximum Reynolds number of only 2×10^6/ft)
- **SUPP-01:** Test sections of sufficient size to permit high-quality flow test cores with minimum dimensions of 18" x 18" cross section and 48" length.
- **SUPP-02:** Large, optical-grade windows on the sides and top of the test section to permit use of optical measurement and diagnostic techniques for flow field and model surface data collection.
- **SUPP-04:** Internal (to the test section) hardware and control to permit the delivery of high-pressure, non-combustible gas for simulation of rocket, thruster and nozzle plumes.



a) Schematic of Dual-Leg Layout. b) Rendering of Leg 1.

Figure 8. Hypersonic High Reynolds Number Tunnel (HHRNT).

Tier 2 Moderate Investments Closure Recommendations

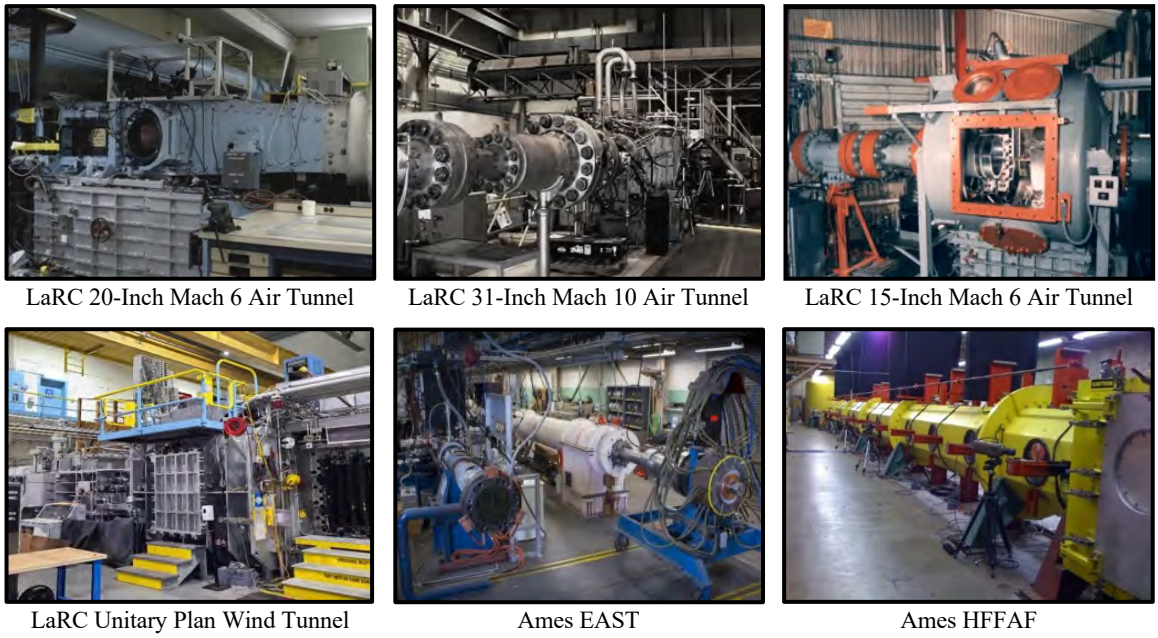
Tier 2 investments are those with projected costs in the tens-of-millions of dollar range. There are three recommendations in this category for closure of Actionable Gaps ACT-00 NASA Facility Productivity; ACT-02 High Enthalpy Reacting Gas Flow; and ACT-03 High Supersonic / Low Hypersonic Overlap.

Repair and Maintain Existing NASA Hypersonic Facilities

The high-priority, moderate investment Actionable Gap ACT-00 NASA Facility Productivity can be closed through an immediate infusion of funding to restore the operational capabilities of NASA's hypersonic ground test facilities (Figure 9), followed by sustained, annual funding for preventative maintenance. This action would help alleviate the backlog of delayed test programs and contribute to the development of hypersonics subject matter expertise.

Maintenance and repair issues are endemic not just to NASA's suite of hypersonic test facilities, but NASA facilities across the entire speed range. However, National priorities have been stated that emphasize human exploration of the solar system; commercialization of space; and defense of the country, all of which require hypersonic systems. Therefore, repairing and maintaining NASA's *hypersonic* ground test facilities should be an Agency priority.

A specific list of facility infrastructure deficiencies is too detailed (and too dynamic) for listing herein but include, for example: "replacement of cooling tower required for operations of the Langley Unitary Plan and 31-Inch Mach 10 Air Tunnels" (which share a building and some infrastructure). It suffices to say that the Facility Managers and operations staffs of NASA hypersonic facilities have generated (and regularly update) this information. A cursory survey of these lists is the basis for the categorization of maintenance and repair costs as falling within the Tier 2 "Tens-of-Millions of Dollars" level.



LaRC 20-Inch Mach 6 Air Tunnel | LaRC 31-Inch Mach 10 Air Tunnel | LaRC 15-Inch Mach 6 Air Tunnel

LaRC Unitary Plan Wind Tunnel | Ames EAST | Ames HFFAF

Figure 9. Current NASA Hypersonic Test Facilities.

Construct a High Enthalpy Flow Field Laboratory

The medium-priority, moderate investment cost Actionable Gap ACT-02 High Enthalpy Reacting Gas Flow can be closed by construction of a High Enthalpy Flow Field Laboratory (HEFFL). This new hypersonic ground test facility would address the following Gaps:

Actionable Gap: HEFFL will be designed and constructed to specifically address the Actionable Gap ACT-02 High Enthalpy Reacting Gas Flow. This Gap refers to the lack of any NASA test capability for testing at hyper-velocity, high Mach test conditions without the free stream dissociation produced in combustion-heated or arc-heated propulsion test facilities. HEFFL would be a NASA-unique "impulse" type hypersonic facility, which is a high-enthalpy, short-duration (micro- to milli-second) run time tunnel in which shockwave nonequilibrium gas kinetic and radiative processes are generated. HEFFL would feature a reconfigurable dual-mode capability to operate as either a reflected shock tunnel or shock-expansion tunnel. Reflected-shock mode produces hypersonic flow at Earth-atmosphere pressure / density conditions relevant to sustained atmospheric flight and shock-expansion mode produces hypersonic flow at conditions relevant to atmospheric entry. HEFFL would be able to employ Air, CO2, Nitrogen or other test gases appropriate for simulation of NASA exploration mission destinations such as Mars, Venus or Titan.

Supporting Gaps: Capabilities can be incorporated into the design specification for HEFFL to also concurrently address the following Supporting Gaps:

- SUPP-01 Large Test Core
- SUPP-02 Optical Access for Visualization Techniques
- SUPP-03 CO2 Test Gas
- SUPP-04 Flow Field Mass Injection.

High-enthalpy impulse tunnels such as the proposed HEFFL are classified as shock tunnels, which are relatively inexpensive facilities to construct and operate as compared to conventional wind tunnels. A shock tunnel is mechanically simple, consisting of one or more differentially pressurized cylindrical tubes separated by diaphragms, a nozzle, a test section, and a vacuum dump tank. High velocity flow is generated by the shock wave compression and expansion fan acceleration processes resulting from the sequential rupturing of the diaphragms. The flow is accelerated to hypersonic speeds in the nozzle and the resulting flow over the test article creates a high temperature shock-layer with gas kinetic and radiative processes at flight-like conditions.

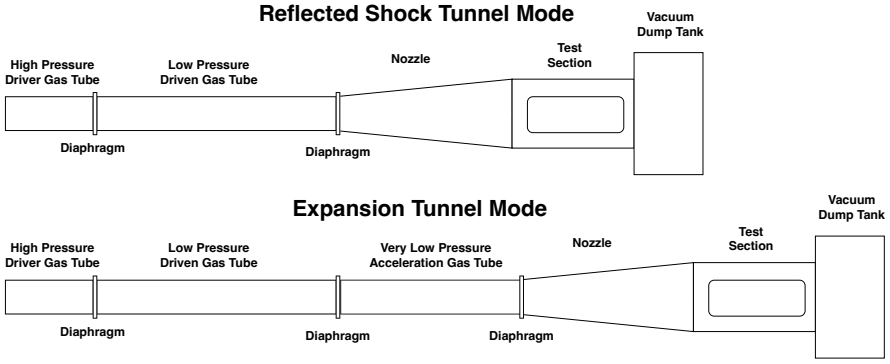


Figure 10. Schematic of HEFFL Shock Tunnel.

Upgrade the LaRC Unitary Plan Wind Tunnel to Mach 5+

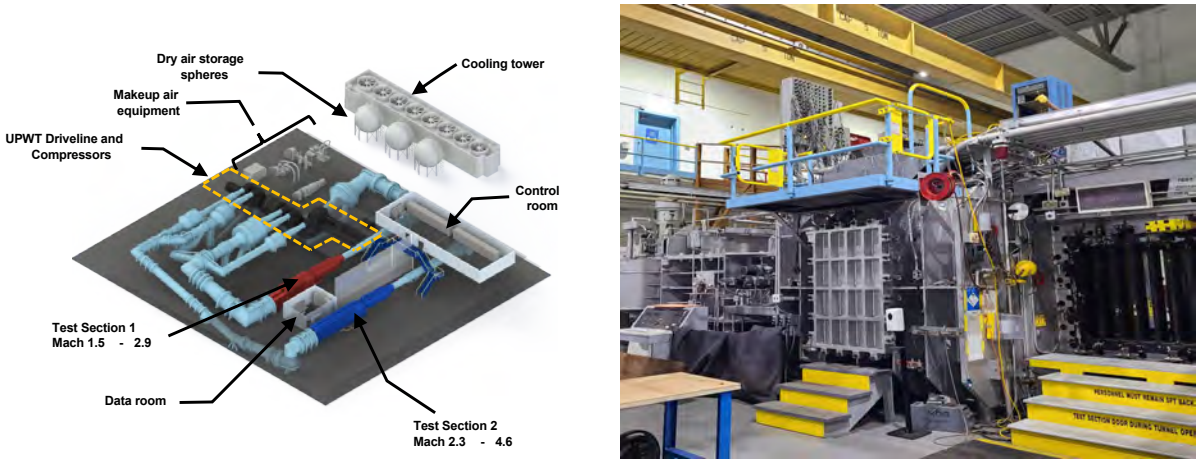
The medium-priority, moderate investment cost Actionable Gap ACT-03 High Supersonic / Low Hypersonic Overlap can be closed by upgrading the Langley Unitary Plan Wind Tunnel (henceforth UPWT+) to reach operating speeds of at least Mach 5. The facility upgrade would address the following Gaps:

Actionable Gap: The Langley Unitary Plan Wind Tunnel (Figure 11) can be upgraded to close the Actionable Gap ACT-03 High Supersonic / Low Hypersonic Overlap. This upgrade would provide NASA with a unique, continuous flow hypersonic testing capability. Testing in the Mach 4 – 6 regime that would be enabled by this upgrade is of particular interest for potential Defense and Commercial customers.

Supporting Gaps: Closure of the following Supporting Gaps is already addressed (for this facility) by its existing design features:

- SUPP-01 Large Test Core
- SUPP-02 Optical Access for Visualization Techniques
- SUPP-04 Flow Field Mass Injection.

The proposed UPWT+ upgrade would permit operations at up to at least Mach 5 (with potentially higher capability depending on detailed analyses) through the addition of another turbo-compressor to increase the tunnel's operational pressure limit, along with a new driver motor and cooling system for the turbo-compressor. And the current UWPT infrastructure already incorporates the Supplemental Gaps listed above.



a) Schematic of UWPT. b) UPWT Test Section 2.

Figure 11. Langley Unitary Plan Wind Tunnel.

Tier 3 Small Investment Closure Recommendations

Tier 3 investments are those with projected costs in the single-millions of dollar range. There are three recommendations in this category for closure of Actionable Gaps ACT-04 High Temperature, High Pressure Shockwave Radiation; ACT-06 Quiet Flow; and the DIAG-XX Diagnostic Gaps.

Modernize the Ames EAST Facility

The high-priority, low investment cost Actionable Gap ACT-04 High Temperature, High Pressure Shockwave Radiation can be closed by modernizing the Ames Electric Arc Shock Tube (henceforth EAST+) to improve throughput and reduce facility downtime. The facility currently relies on 60-year-old control and high voltage electrical systems that are no longer serviceable. These systems should be replaced with modern, reliable components. Ensuring the continued operation of the facility would address the following Gaps:

Actionable Gap: The Ames EAST+ upgrades would close the Actionable Gap ACT-04 High Temperature, High Pressure Shockwave Radiation. This facility is a NASA-unique resource for generating data on the gas kinetic and radiative processes of shockwaves produced by hypersonic vehicles. These data are used in the development and validation of physical models for computational fluid dynamics codes used for hypersonic flow simulations. Modernizing EAST will improve facility reliability and guard against future testing delays due to facility down-time that have in the pasted lasted for months or longer.

Supporting Gaps: Capabilities can be, or already are, incorporated into the design specification for EAST+ to address the following Supporting Gaps:

- SUPP-02 Optical Access for Visualization Techniques
- SUPP-04 CO2 Test Gas

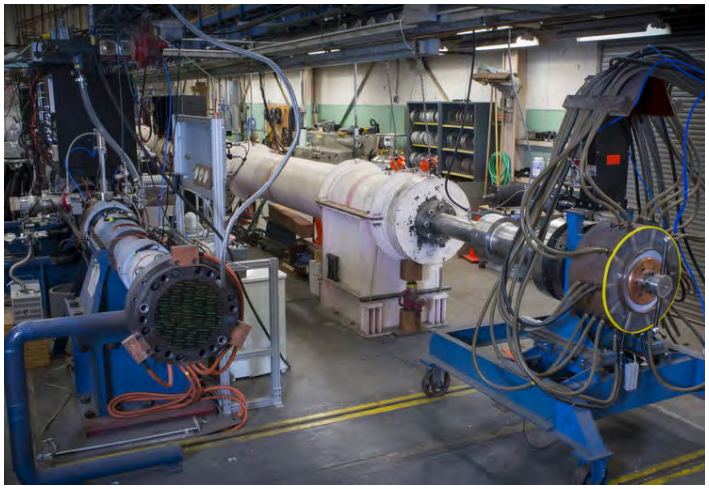


Figure 12. Ames Electric Arc Shock Tube (EAST).

Convert the LaRC Mach 6 Nozzle Test Chamber into a Hypersonic Quiet Tunnel

The medium priority, low investment cost Actionable Gap ACT-06 Quiet Flow can be closed by modifying the existing LaRC Mach 6 Nozzle Test Chamber to generate quiet flow conditions. The renamed Mach 6 Quiet Tunnel (M6QT) would address the following gaps:

Actionable Gap: The M6QT upgrade would close the Actionable Gap ACT-06 Quiet Flow. This gap refers to capabilities for performing boundary-layer transition testing and measurements in a noise-free environment. In a conventional wind tunnel, acoustic noise from the boundary layer on the tunnel wall radiates into the free stream and contaminates the boundary-layer transition processes on the actual test article. A "quiet" wind tunnel incorporates a specially designed nozzle in which the wall boundary layer is bled off before the test section, thus creating a noise-free test core. The resulting boundary-layer transition measurements are critical for the design of "slender-body" hypersonic systems such as inlets, missile, etc., as well as for development and validation of physical models of boundary-layer transition for computational fluid dynamics codes.

Supporting Gaps: Capabilities can be, or already are, incorporated into the design specifications for the M6QT to address the following Supporting Gaps:

- SUPP-02 Optical Access for Visualization Techniques
- SUPP-06 Long Duration Run Time

The conversion of the Mach 6 Nozzle Test Chamber to quiet-flow operations would retain most of the tunnel components but replace the existing nozzle with one specially designed to generate quiet flow. This nozzle would be highly polished to remove any surface imperfections that could create flow field disturbances and feature bleed slots to remove the tunnel wall boundary layer before the test section.



Figure 13. LaRC Mach 6 Nozzle Test Chamber.

Convert the LaRC 15-Inch Mach 6 Tunnel into a Hypersonic Ludwieg Tube

This recommendation is based on a proposal developed after the HEAC study was concluded, but it is nevertheless highly relevant here. Although not formally ranked through the HEAC analysis process, this closure action is assigned a high priority and low cost. Many of the Diagnostics Gaps (see Table 21) could be closed through conversion of the existing LaRC 15-Inch Mach 6 High Temperature Air Tunnel into a hypersonic Ludwieg Tube, which is a type of shock-tunnel.

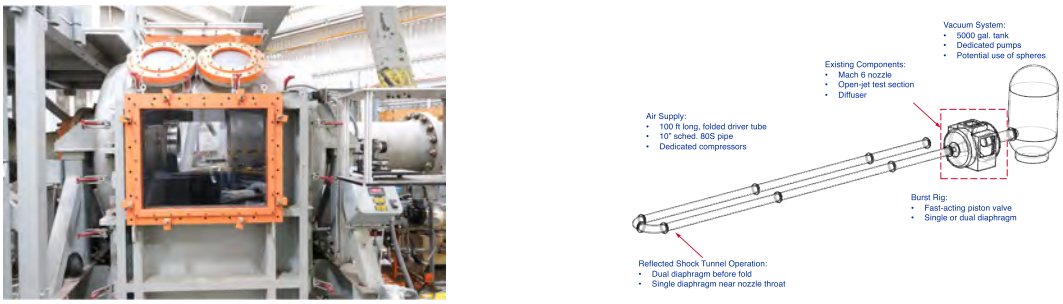
DIAG-XX Diagnostics Gaps: The redesigned Hypersonic Ludwieg Tube would provide a flexible, highly productive, low-cost capability for development of many of the hypersonic measurement techniques identified on the Diagnostics Gaps list.

Supporting Gaps: Capabilities already exist in the 15-Inch Mach 6 High Temperature Tunnel and/or can be incorporated into the Ludwieg tube conversion to address the following Supporting Gaps:

- SUPP-02 Optical Access for Visualization Techniques
- SUPP-03 CO2 Test Gas

The Hypersonic Ludwieg Tube capability would be developed through conversion of the existing LaRC 15-Inch Mach 6 High Temperature Air Tunnel. For administrative and logistical purposes, this asset is listed as a unique facility. However, since it shares the high-pressure air delivery system, heater, and vacuum sphere of the LaRC 31-Inch Mach 10 Air Tunnel it is, in fact, simply a leg of that tunnel. As such it cannot be used when the 31-Inch Mach 10 Tunnel is operating. Since that tunnel has historically been in high demand and since the LaRC 20-Inch Mach 6 Air Tunnel provides many of the same capabilities, the 15-Inch Mach 6 Air Tunnel has been idle for over a decade. This facility has been kept in "mothball" status since its maintenance requires minimal expenditures (as most costs are carried by the 31-Inch Mach 10 Air Tunnel) and because decommissioning it would entail extra costs for demolition, haulage, and environmental remediation. When the tunnel was last used extensively in the early 1990s - 2000s (e.g. Ref. 47), its primary purpose was for instrumentation and test technique development.

Conversion of this asset to a Ludwieg Tube would retain the 15-Inch Mach 6 Air Tunnel nozzle, test section, and diffuser, but remove the facility from the 31-Inch Mach 10 Air Tunnel "flow-path". These components would then be mated to an upstream compressor and shock tube segment and downstream vacuum pumps and gas dump tank. Operation as a Ludwieg tube would then greatly expand NASA capabilities for hypersonic test diagnostics development by a) Extending the operational capabilities of the facility to greater Mach, Reynolds Number, and enthalpy levels and b) Greatly enhancing its productivity since the conversion would provide an independent, self-contained system decoupled from 31-Inch Mach 10 Air Tunnel operations.



a) Test Section of 15-Inch Mach 6 Air Tunnel. b) Ludwieg Tube Conversion.

Figure 14. Ludwieg Tube Conversion of 15-Inch Mach 6 Air Tunnel.

Summary and Conclusions

A NASA-wide team of subject matter experts was formed to generate an assessment of NASA's ability to support National goals in hypersonics using its existing roster of hypersonic ground test facilities. This Hypersonic Experimental Aerothermodynamics Capabilities team compiled a detailed list of potential NASA and NASA partner flight missions, development projects, and research tasks spanning the next 25+ years that would require hypersonic aerothermodynamics information for the definition of flight mission environments, vehicle configuration evaluations, fundamental or applied research, and/or computational tool development and validation. This Programs List was organized into three top-level Themes of Hypersonic Entry, Descent and Landing; Hypersonic Atmospheric Flight and Access-to-Space; and Hypersonic Tools and Methods. Multiple Customer Types and Program Categories were defined for each Theme, and multiple Programs were identified under each Program Category for a total of 170 potential future Programs.

A set of 647 hypersonic Database Objectives and ground Test Requirements that support these Programs was compiled. The Technical Capability and Logistical Capacity of NASA's existing ground test infrastructure to meet these Database Objectives and Test Requirements was then evaluated. The result of this evaluation was a list of 64 Capability and Capacity Gaps. These Gaps were categorized by type, consolidated across the multiple Themes, and ranked by priority.

Investment Recommendations in NASA's hypersonic ground testing infrastructure were then developed to close the Critical Gaps. These recommendations provide a roadmap for NASA to realize this Vision for 21st century technical excellence in experimental hypersonics.

The HEAC team developed recommendations for seven Critical Gap closure Investments Recommendations, which were categorized by the scale of the investment cost and ranked by priority within each category. These Investment Recommendations call for the repair, modification, and/or conversion of existing ground test facilities and the construction of new ground test facilities. These gap closure recommendations are listed below in Table 23.

Table 23. HEAC Gap Closure Recommendations.

Cost Tier	Priority	Gap ID	Gap Title	Closure Action
High	High	ACT-01	High Reynolds Number Turbulent Flow	Construct a new Hypersonic High Reynolds Number Tunnel (HHRNT)
Medium	High	ACT-00	NASA Facility Productivity	Allocate funding to repair and maintain existing hypersonic facilities
Medium	Medium	ACT-02	High Enthalpy Reacting Gas Flow	Construct a new High Enthalpy Flow Field Laboratory (HEFFL)
Medium	Medium	ACT-03	High Supersonic / Low Hypersonic Overlap	Upgrade the LaRC Unitary Plan Wind Tunnel for Mach 5+ flow
Low	High	ACT-04	High Pressure, High Temperature Shock Radiation	Upgrade the Ames EAST facility
Low	High	DIAG-XX	Instrumentation and Test Technique Development	Convert the LaRC 15-Inch Mach 6 Air Tunnel into a Hypersonic Ludwieg Tube
Low	Medium	ACT-06	Quiet Flow	Convert the LaRC Nozzle Test Chamber into a Hypersonic Quiet Tunnel

Forward Action Items

The Critical Gap closure Investment Recommendations listed above are vital steps towards restoring NASA's existing hypersonic testing infrastructure to regular operational capacity and developing new technical capabilities required to meet the demands of 21st century hypersonic programs to be conducted by NASA itself, as well as by its Defense and Commercial partners. Implementation of these recommendations is an important action required to sustain and grow the Subject Matter Expertise of NASA's hypersonics workforce.

Prompt implementation of these recommendations will first require the authorization and funding of design and engineering studies to define repair, modification, and construction details, costs, and schedules. In tandem with these studies, socialization of the HEAC Vision and Goals to NASA's stakeholders and partners will be required to justify the necessary investment funding. Although the cost to implement these recommendations will be large in terms of NASA's annual budget allocation, these expenditures should be viewed in terms of a once-in-a-century, long-term investment in technical capabilities with a 100-year lifespan.

The model for just such an investment is the National Unitary Plan Act of 1949, which authorized construction of three large, transonic / supersonic "Unitary Plan" wind tunnels by the National Advisory Council for Aeronautics (NACA) at what would become the NASA Ames, Langley, and Glenn (originally Lewis) Research Centers.

This Congressional action, which was enacted into law by U.S.C. Title 50: War and National Defense / Chapter 20: Wind Tunnels / Subchapter II: Air Engineering Development Center Sec. 511. Joint development of unitary plan for construction of facilities (and as updated in 1958 to replace NACA with NASA and in 2000 to include "hypersonic") states that:

"The Administrator of the National Aeronautics and Space Administration (hereinafter referred to as the "Administrator") and the Secretary of Defense are authorized and directed jointly to develop a unitary plan for the construction of transsonic [sic], supersonic, and hypersonic wind-tunnel facilities for the solution of research, development, and evaluation problems in aeronautics, including the construction of facilities at educational institutions within the continental limits of the United States for training and research in aeronautics, and to revise the uncompleted portions of the unitary plan from time to time to accord with changes in national defense requirements and scientific and technical advances. The Administrator and the Secretaries of the Army, the Navy, and the Air Force are authorized to proceed with the construction and equipment of facilities in implementation of the unitary plan to the extent permitted by appropriations pursuant to existing authority and the authority contained in this chapter. Any further implementation of the unitary plan shall be subject to such additional authorizations as may be approved by Congress."

The supersonic facilities authorized by Congress in the 20th century are all still operational today, and likely still will be at their 100-year anniversaries. An update to the Unitary Plan Act for the 21st century will enable the development of a set of world-class hypersonic facilities that will serve the Nation well into the 22nd century.

Acknowledgments

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The HEAC study relied on the contributions of approximately 100 subject matter experts, project leaders, and technical authorities. These personnel were drawn from multiple NASA centers with expertise in external hypersonic aerothermodynamics, including the Ames Research Center, the Johnson Space Center, the Langley Research Center and the Marshall Space Flight Center. An attempt to acknowledge all these contributors follows below, with apologies to anyone inadvertently left off this list.

The HEAC team also interacted informally with many subject matter experts from the Defense and Academic communities. To protect external responders from any perception of endorsing the HEAC recommendations, they will not be listed by name, but their contributions are greatly appreciated.

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- External opinions were solicited from Air Force Arnold Engineering Development Complex, Air Force Research Laboratory, Office of Naval Research, Air Force Office of Scientific Research and Sandia National Laboratories

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- NASA JSC: Adam Amar, Joseph Garcia, Ray Gomez
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- NASA LaRC: Aaron Auslender, Steven Bauer, Karen Berger, Karen Bibb, Gregory Brauckmann, Gregory Buck, Neil Cheatwood, Amanda Chou, Alicia Dwyer Cianciolo, Vincent Cuda, Karl Edquist, John Evans, Shelly Ferlemann, Richard Gaffney, Francis Greene, Jeffrey Herath, Luther Jenkins, Christopher Johnston, Bill Kleb, Ashley Korzun, Victor Lessard, Alireza Mazaheri, Catherine McGinley, Ron Merski, Michelle Munk, Kelly Murphy, Gabriel Nastac, Ian Neel, Clark Pederson, Matthew Rhode, Mark Schoenenberger, Robert Scott, Kyle Thompson, Deborah Tomek, William Wood

Contributors to HEAC Team 4: Gap Closure Investments Recommendations

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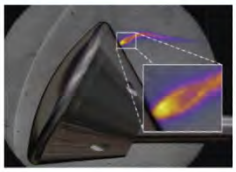
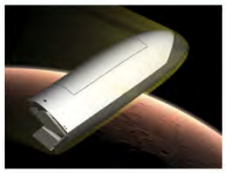
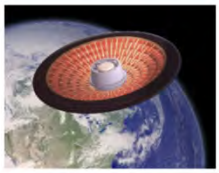
Appendix A Socialization and Advocacy

As of the release of this document, HEAC briefings have been given to the stakeholders listed below. Briefings given between 2019 to 2021 were progress reports on the HEAC study. Those from 2022 to the present were presentations of the HEAC findings and recommendations. A sample briefing package follows this list.

- May 2019: NASA Aeronautics Research Mission Directorate, Aerosciences Evaluation and Test Capabilities portfolio "Face to Face" annual meeting at NASA LaRC
- June 2019: AIAA Aerodynamics Technical Working Group at AIAA Aviation Conference
- October 2019: NASA Office of Strategic Investments (OSI) and NASA Aeronautics Research Mission Directorate, Aerosciences Evaluation and Test Capabilities portfolio at NASA HQ
- January 2020: AIAA Ground Testing Technical Committee at AIAA SciTech Conference
- January 2021: NASA Aerosciences Test Advisory Board (ATAB) at NASA LaRC
- July 2022: NASA Aeronautics Research Mission Directorate, Aerosciences Evaluation and Test Capabilities portfolio, virtual meeting
- November 2022: NASA / Air Force Research Laboratory Hypersonics Workshop, virtual meeting
- December 2022: NASA Aeronautics Mission Research Directorate, virtual meeting
- December 2022: NASA Space Technology Mission Directorate leadership at NASA HQ
- January 2023: NASA Aeronautics Research Mission Directorate Hypersonic Technology Project, virtual meeting
- January 2023: NASA LaRC Office of Director
- January 2023: NASA Ames, Glenn, Armstrong, and Langley Center leaders, virtual meeting
- February 2023: NASA Aeronautics Research Mission Directorate, Advanced Air Vehicles Program, virtual meeting
- March 2023: NASA Aeronautics Research Mission Directorate leadership at NASA HQ
- September 2023: IDGA Hypersonics Weapon Summit, Washington, DC
- April 2023: DoD Joint Hypersonics Transition Office (JHTO), virtual meeting
- June 2023: NASA USAF/AEDC Interactions Meeting, virtual meeting
- October 2023: NASA Aeronautics Research Mission Directorate leadership at NASA HQ
- November 2023: US Government National Hypersonics Stakeholders Meeting, virtual meeting
- November 2023: NASA Federated Board at NASA HQ
- March 2024: NASA Space Science Mission Directorate leadership at NASA HQ
- March 2025: NASA Engineering and Safety Center, Aerosciences Technical Discipline Team at LaRC
- April 2025: NASA/DoD National Partnership for Aeronautical Testing (NPAT), virtual meeting

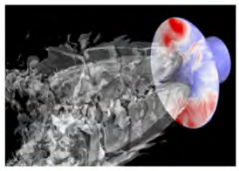
NASA Hypersonic Experimental Aerothermodynamics Capabilities (HEAC) Study

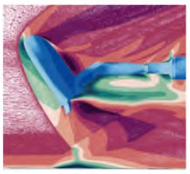



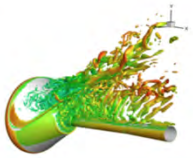




Enabling NASA and National Priorities





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HEAC Bottom Line Up Front

- **Risk**: because of critical gaps in our legacy hypersonic aerothermodynamic facilities, we risk losing the operational capacity, technical capability, and Subject Matter Expertise to:
  - Support the development of new architectures for human-rated Lunar / Mars systems
  - Provide high-fidelity data for validation of advanced Computational Fluid Dynamics Mod/Sim codes
  - Be the on-call 911 responder (e.g. Hyper-X failure, Columbia accident investigation, Artemis-I char loss)
  - Bring in new commercial and DoD customers
- **Recommendation**: investment in new construction and/or modification of four hypersonic aerothermodynamic facilities to close critical gaps identified by analysis of future mission requirements



- **Challenge**: cost of infrastructure investments exceeds NASA CoF and/or Mission Directorate funding.
- **Action**: engage with Executive and Legislative branches to fund a 21st century "Unitary Plan" centered around National (NASA / DoD / Industry) hypersonic testing requirements

- **Reward**: US preeminence in human space exploration
- **Reward**: nurture and support US industry in development of a sustainable space economy
- **Reward**: support DoD deterrence of adversary threats and advance US global interests



2

Our Past: NASA hypersonic facilities have enabled programs from multiple NASA mission directorates, DoD, Industry, and Academia

ESDMD Human Spaceflight
- Shuttle Columbia Accident and Return to Flight
- Orion EFT-1, Artemis I
- Artemis Char Loss



SMD Science and Exploration
- Genesis
- MSL / Mars 2020
- Mars Sample Return



STMD Technology Development
- IRVE
- LOFTID
- ESM



ARMD Hypersonic Airbreathing Flight
- Hyper-X
- BOLT
- HiFIRE
- Aether



- **Langley Aerothermodynamics Laboratory Tunnels**
- **Langley Unitary Plan Wind Tunnel**
- **ARC EAST Shock Tube and HFFAF Ballistics Range**













✓Aeroheating
✓Aerodynamics
✓Flow Visualization

✓Concept development
✓CFD validation data
✓Flight databases



National Defense
- USN - ONR
- USAF – AFOSR / AFRL
- DARPA
- Dod Industry partners



Commercial Development
- SpaceX
- Sierra Nevada
- Blue Origin
- United Launch Alliance
- Rocket Lab

Academic Research and Collaboration
- Purdue Univ.
- Texas A&M Univ.
- Univ. Tenn Space Inst.
- Univ. MD
- Ohio State Univ.
- N.C. State Univ
- Many more

Critical gaps in NASA hypersonic aerothermodynamic testing capabilities for future missions were identified by HEAC SMEs through data-driven, statistical analyses facilitated by the Institute for Defense Analyses

3

Our Future: The 21st Century is a challenging new era for Hypersonic Aerothermodynamics

The last 50 years – constrained visions, limited operations, legacy technologies		The next 50(+) years – new challenges, new missions, new technologies
 	Human operations focus on LEO	Humans to the "Moon, Mars and Beyond"  
 	Legacy 1970's-era architectures	Innovative architectures for new missions & requirements  
 	Failed commercial access-to-space ventures	Viable commercial space market  
	Sustained hypersonic flight technologically non-viable	Sustained super/hypersonic flight concepts and demonstrations 
 	Dominance in subsonic weapon / ISR systems	Geopolitical competition in hypersonic systems  

Ambitious NASA exploration goals, surging US Defense priorities, and vibrant Commercial Market growth are ***at risk*** due to critical gaps in hypersonic aerothermodynamic testing technical capabilities and operational capacity

4

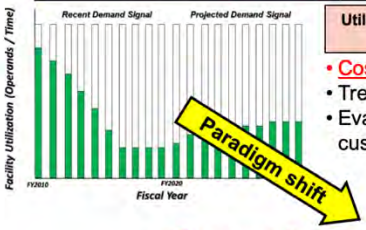
HEAC 411 Summary: study was conducted to respond to 21st century challenges

- **WHO**: HEAC team comprised of 100+ NASA Subject Matter Experts, programmatic leadership, and stakeholders from LaRC, ARC, JSC, GRC representing disciplines of: Entry, Descent and Landing; Hypersonic Flight; and Computational Fluid Dynamics. Consultation/collaboration with DoD/DoE partners through AFOSR, ONR, HVSI, AFRL, AEDC, SNL, JHTO, UCAH
- **WHAT**: Formulate a 21st century investment strategy in hypersonic aerothermodynamic testing infrastructure to meet national challenges in technical capabilities and operational capacity and assure NASA and National excellence
- **WHY**: National priorities are much different than before – new architectures for new missions, growing commercial sector and challenging geopolitical competition. Neither "heritage" databases nor Computational Fluid Dynamics can provide all enabling data to design and certify the new systems required to meet these demands, *especially for human-rating*
- **HOW**: Facilitation by the Institute for Defense Analyses (IDA) to identify future missions, develop testing requirements, identify capability/capacity gaps, and recommend investment strategy. Proven approach that has led to large DoD investments to revitalize AEDC capabilities
- **WHERE**: Investment in NASA ground testing infrastructure – academia and commercial not considered because HEAC premise is that US Gov must maintain subject matter expertise by owning and operating critical hypersonic testing capabilities; DoD assets are over-booked and not available to NASA
- **WHEN**: Now – immediate investments are needed to ensure that the capabilities and capacity are available to meet current and long-term test requirements to develop new NASA systems, assist DoD, and support commercial sector

Institute for Defense Analyses (IDA) Facilitation of HEAC Study

- IDA has facilitated prior gap studies for the DoD that supported extensive infrastructure investments
  - AEDC J-5 facility
  - Dragonfly arcjet
  - Augmentation to DoD FY23 budget request
- IDA is concurrently facilitating a comprehensive new Hypersonics S&T Facility Gaps analysis for DoD
  - Expected to result in additional infrastructure investments for DoD
  - Opportunity to incorporate HEAC results and elevate NASA requirements into National perspectives
- IDA has contacts in government, industry, DoD, and academia
  - Paul Piscopo is the IDA facilitator for HEAC
  - Extensive career experience in DoD and Executive Branch service

Because NASA is both the facility operator and the facility customer, IDA's paradigm emphasizes the customer's total project impact rather than the operator's full-cost accounting.

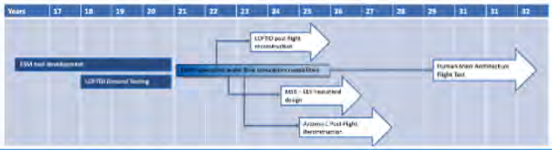


Utilization Based Assessment (Operator finances)

- Cost is the investment decision metric
- Treat facilities solely as a revenue center
- Evaluate operator cost vs. revenues from customers

Value Based Assessment (Customer Impact)

- Programmatic impact of gaps is the investment decision metric
- Determine capabilities and capacity needed to meet technical requirements
- Assess the programmatic impact of gaps on cost, risk, & schedule



HEAC Team Organization, Workflow, and Products

Team 1: Vision, Goals, and Objectives ✓
- What is NASA's role in hypersonic aerothermodynamics from a National (NASA / defense / commercial) perspective?
- How will NASA accomplish this role?

→ – Developed Vision for NASA Hypersonic Experimental Aerothermodynamics Capabilities with **5 Goals**

Team 2: Missions and Requirements ✓
- What programs and missions are projected for the next 25+ years?
- What hypersonic aerothermodynamic databases will be required to enable the successful accomplishment of these programs and missions?

→ – Identified **170 potential Programs** within scope of ***Goals*** including NASA and NASA-supported DoD / commercial flight tests, operational missions, development activities, and CFD validation exercises
– Developed a database of **800+ aerothermodynamic Test Objectives** for these potential ***Programs***

Team 3: Capability and Capacity Gaps Assessment ✓
- What type of tests, measurements, and analyses are required to generate these aerothermodynamic databases?
- What are the technical capability and operational capacity gaps in the facilities operated by, or available to, NASA

→ – Evaluated ***Test Objectives*** and identified **64 technical capability and operational capacity gaps** in the National testing infrastructure available to NASA
– Ranked importance and performed statistical analyses to identify **17 Critical Gaps**

Team 4: Investments, Advocacy and Socialization ✓
- What investments are required to close these gaps?
- How do NASA HEAC gap closure recommendation integrate into the larger national perspective on future National hypersonics requirements?

→ – HEAC recommends investments in **4 new construction or modified facilities** to close ***Critical Gaps***

7

HEAC Team #1: Vision, Goals, and Objectives Team Product

Vision, Goals and Objectives Team was tasked to formulate a 21st century vision and investment strategy for world-class experimental aerothermodynamic testing capabilities and Subject Matter Expertise at NASA

Goal 1: Enable NASA Missions and Programs

Ensure that NASA and its commercial partners have the capability to generate the experimental aerothermodynamic vehicle performance data required to fulfill NASA goals and timelines for LEO / Lunar / Mars access and return, solar-system exploration, hypersonic flight, and technology development programs

Goal 2: Lead the Nation in Experimental Aerothermodynamic Research and Expertise

Be the National leader in fundamental and applied research, and the steward of technical knowledge and experience, on the hypersonic aerothermodynamics of entry-descent-landing (EDL) and sustained atmospheric flight for NASA, Commercial, and Defense partners

Goal 3: Bridge Experimental Aerothermodynamic Capability and Capacity Gaps

Develop and sustain mid-range test infrastructure that will close the capability and capacity gaps between small-scale academic facilities and large-scale DoD/commercial facilities and that will provide the data required to advance flight systems from low Technology Readiness Level (TRL) concept definition to high-TRL ground/flight testing and acquisition

Goal 4: Grow the National Experimental Aerothermodynamics Workforce

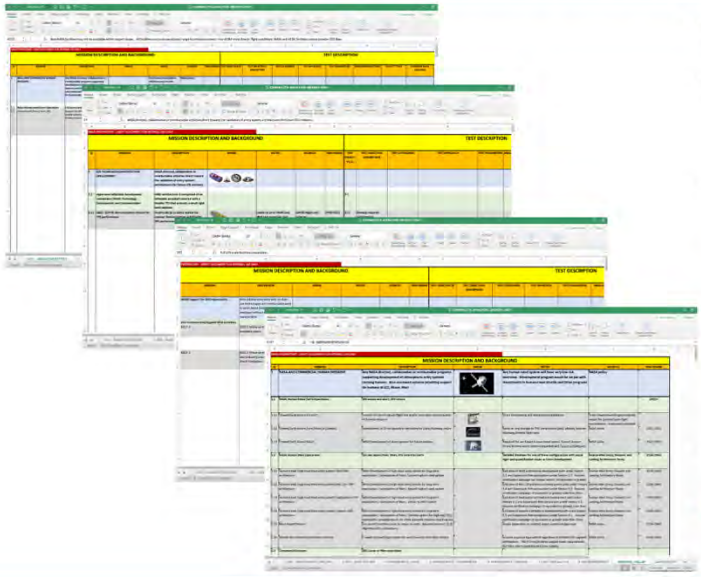
Inspire, recruit, develop, and sustain a nationally preeminent aerothermodynamic research, development, test, and evaluation workforce capable of supporting NASA and its external partners and stakeholders

Goal 5: Support National Defense Priorities and National Commercial Interests

Provide aerothermodynamic testing and data analysis capabilities to support accelerated deployment of sustained hypersonic flight systems for National defense purposes and the development of commercial space industry

8

HEAC Teams #2-3 Product: Missions, Objectives, and Gaps Database



- HEAC database is contained in a large Excel file (available upon request for NASA user)
- Database includes taxonomy of missions, description of test objectives, details of test requirements, evaluation of CFD capabilities, and assessment of testing gaps
- Multiple tabs contain data for each mission category
  - EDL: Human Operations, Robotic Exploration, Technology Development
  - Hypersonics: NASA HTP, commercial development, DoD requirements
  - CFD Research, development and validation
  - Instrumentation and test technique development
  - Rollup of all missions
  - Rollup of all gaps
- HEAC Excel database is the basis for evaluation and ranking of gap importance
- Details in subsequent slides

9

HEAC Team #2: Missions & Requirements Team Product: Develop NASA, Defense, and Commercial Mission Database

Commercial space applications have surged since these data were collected!

The *Missions and Requirements Team* surveyed project managers, organizational leaders, and subject matter experts to develop a database of 170 operational missions, technology development projects, and CFD development programs for the next 25+ years

Hypersonic Entry, Descent, and Landing

Category	Sub-categories	# of programs
NASA & Commercial Human-Rated Exploration	NASA Human-Rated LEO and Lunar Operations	3
	NASA Human-Rated Mars Exploration	6
	Commercial Systems	6
	Uncrewed Support Systems	2
NASA Robotic Exploration	Flagship Class Missions	8
	New Frontiers Class Missions	5
	Discovery Class Missions	6
NASA EDL Technology and Architecture Development	Hypersonic Inflatable Aerodynamic Decelerator	5
	Mid Lift-to-Drag Lifting Body	5
	Deployable Aerodynamic Decelerator	6
	Advanced Rigid Aeroshell Capsule	4
	Super/Hypersonic Retropropulsion	5
	Aerocapture	3
	MHD Flow Field Control	1

Hypersonic Atmospheric Flight

Category	Sub-categories	# of programs
NASA Hypersonic Programs	Vehicle Architecture Development	4
	System Component Development	2
	Fundamental Research	6
NASA Support for Commercial Hypersonics	Rocket-Based Access to Space	5
	Point-to-Point Airbreathing Flight	5
	Commercial Research & Development Testbed	2
NASA Support for DoD Hypersonics	Fundamental / Applied Research & Development Test Vehicles	7
	Glide Vehicle Operational System Development	3
	Airbreathing Vehicle Operational System Development	3
	Intelligence, Surveillance and Reconnaissance Vehicle Operational System Development	3
	Access-to-Space Operational System Development	3
	Research & Development Testbeds	2

Hypersonic Mod/Sim Validation

Category	Sub-categories	# of programs
NASA, DoD and Commercial CFD Model Development and Validation	Wakes and Separated Flows	3
	Shock-Shock and Shock-Boundary-Layer Interactions	3
	Propulsion System Performance, Interactions and Integration	3
	Boundary-Layer Transition and Turbulence	4
	Surface / Flow-Field Interactions	5
	Thermophysical and Radiative Properties	7
	Multi-Phase Flows and Gas/Solid Interactions	3
	Rarefied Flow	4
	Other	6

Hypersonic Test Technique Development: 23 programs (not shown)

10

HEAC Team #2: Missions & Requirements Product: Identify Test Objectives for Each Mission

SME's have identified 800 potential test objectives for the 170 missions.

- Objectives section of database details
  - Test category (aerodynamics, heating, BL transition, etc)
  - Test approach (measurement types, data required, test conditions, etc)
  - Facility type (Mach, Reynolds, enthalpy ranges, etc)

HEAC's complete Excel database including test description, approach, capability requirements and gaps, etc is available on request

Sample Test Objectives for a HIAD system

ID	MISSION	DESCRIPTION	IMAGE	NOTES	SOURCES	TIME-FRAME
3.13	HIAD: launch vehicle booster recovery	Medium scale (10 m diam) vehicle for recovery of launch system engine/booster stage		Using proposed ULA recovery of Vulcan engine as prototype. Aftbody/payload MUCH larger than LOFTID, so requires more analysis/testing. Carbon copy ISS payload requirements until more detail available	builds from LOFTID and ESM wake flow testing requirements	2023-2026

TEST OBJECTIVE ID	TEST OBJECTIVES DESCRIPTION	TEST CATEGORIES	TEST APPROACH	REQUIRED FACILITY OPERATIONAL CAPABILITY
3.131	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	High Mach / high-enthalpy capability
3.132	Determine hypersonic aerodynamic influence of payload	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	High Mach / high-enthalpy capability
3.133	Develop supersonic aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	Supersonic M2-M4 with wide range of Reynolds numbers
3.134	Define supersonic RCS performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Perform surface pressure, static aero force & moment and flow visualization with thrusters on/off	Flight-relevant Mach/Re range, mass flow for RCS firing
3.135	Determine supersonic aerodynamic influence of payload	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	Supersonic M2-M4 with wide range of Reynolds numbers
3.136	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating	Global and/or discrete surface heating measurements	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions
3.137	Determine aeroshell heating augmentation due to flexible TPS deflections	(3) boundary-layer characterization, (4) convective aeroheating, (16) CFD development and validation	Measure surface temperature and heating distribution to determine TPS deflection effects on hypersonic boundary-layer transition and turbulent heating augmentation	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Rapid turnaround time for multiple roughness parametric changes
3.138	Determine aftbody and payload heating environments	(4) convective aeroheating, (5) Flow Field Characterization, (16) CFD development and validation (18) Test Technique Development	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions. Parametric tradeoffs on aeroshell geometry to ensure no impingement on payload	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. High stagnation temperature to produce sensible heating in wake

11

HEAC Team #3: Capability and Capacity Gaps Assessment Product: Identify Ground Test Gaps for Each Test Objective

- SME's identified gaps for each objective in terms of
  - facility operational capability
  - facility availability / capacity
  - instrumentation and model fabrication capabilities

Sample Gaps Assessment for a HIAD system

ID	MISSION	DESCRIPTION	IMAGE	NOTES	SOURCES	TIME-FRAME
3.13	HIAD: launch vehicle booster recovery	Medium scale (10 m diam) vehicle for recovery of launch system engine/booster stage		Using proposed ULA recovery of Vulcan engine as prototype. Aftbody/payload MUCH larger than LOFTID, so requires more analysis/testing. Carbon copy ISS payload requirements until more detail available	builds from LOFTID and ESM wake flow testing requirements	2023-2026

TEST OBJECTIVE ID	TEST OBJECTIVES DESCRIPTION	FACILITY OPERATIONAL CAPABILITY GAPS	FACILITY COST / CAPACITY GAPS	FACILITY INSTRUMENTATION CAPABILITY GAPS	TEST ARTICLE FABRICATION CAPABILITY GAPS
3.131	Develop hypersonic aerodynamic performance database	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected
3.132	Determine hypersonic aerodynamic influence of payload	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities. Potential for LaRC UPWT closure	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected
3.133	Develop supersonic aerodynamic performance database	Reynolds/Mach number ranges of NASA facilities and Abardeen range	Scheduling and cost in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected
3.134	Define supersonic RCS performance and interactions	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Scheduling and cost in non-NASA facilities	none	none
3.135	Determine supersonic aerodynamic influence of payload	Reynolds/Mach number ranges of NASA facilities and Abardeen range	Scheduling and cost in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected
3.136	Determine baseline, smooth-OML aeroshell convective heating	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on smooth OML. Lack of NASA high-enthalpy capability may impact aeroheating	Scheduling and cost in non-NASA facilities	none expected	None expected
3.137	Determine aeroshell heating augmentation due to flexible TPS deflections	NASA facilities may lack operational Reynolds number to generate turbulence at roughness scales.	Scheduling and cost in non-NASA facilities	Optical access and validation of global aeroheating techniques at AEDC and CUBRC	Ability to 3D print/machine or cast detailed TPS roughness features for global techniques.
3.138	Determine aftbody and payload heating environments	CUBRC LENS may not provide sufficient test time for wake flow establishment. Lack of NASA high-enthalpy capability	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected

12

HEAC Team #3: Capability and Capacity Gaps Assessment Team Product:
Gap frequency totals and SME gap criticality ranking

- Evaluated every gap cited in the 800+ test objectives in the Missions database to define 64 consolidated gap statements
  - 13 EDL gaps
  - 9 Hypersonics gaps
  - 18 CFD gaps
  - 24 Instrumentation and Test Techniques gaps
- All SME's and program leaders participating in HEAC were asked to complete a TEAM's-based poll ranking the criticality of each gap in the areas of EDL, Hypersonics and CFD
  - ~80 SME's and program leaders overall in HEAC study. Not all participated in each of the mission categories
    - 33 respondents to EDL poll
    - 25 respondents to Hypersonics poll
    - 31 respondents to CFD poll
    - did not poll Instrumentation and Test Techniques gaps. These gaps are expected to be minor investments and dealt with through regular channels
- Participants ranked criticality on scale of 1-3. Re-scaled criticality to range of 1-10 based on averages for each gap
  - 1-5 = "low" criticality
  - 6-7 = moderate" criticality
  - 8-10 = "high" criticality

13

HEAC Team #3: Capability and Capacity Gaps Assessment Team Product:
CFD Development and Validation Testing Gaps Frequencies and SME Criticality Rankings

Gap ID	Gap Description	Gap Frequency	# of SME Poll Responses	SME Criticality Ranking
CFD-01	High-enthalpy aerothermodynamic test capability for gas kinetic effects on aerodynamics, aeroheating and flow field structure	9	31	8.7
CFD-02	High-enthalpy aerothermodynamic test capability for shock-layer radiation effects on aeroheating	7	30	8.3
CFD-03	High-pressure injection mass-flow systems for propulsion (RCS, thrusters, retropropulsion) simulation effects on aerodynamics and aeroheating	6	30	8.8
CFD-04	Continuous-flow supersonic (Mach 5-6) test capability for aerodynamic testing	2	29	6.0
CFD-05	Quiet tunnel test capability to mitigate free stream nose influence on boundary-layer transition	14	30	6.9
CFD-06	Measurement techniques for hot-surface discrete sensor measurements for ablation data	3	31	8.1
CFD-07	High-frequency sensors and force & moment balances for short-duration testing facilities and for dynamic measurements	1	29	7.9
CFD-08	Optical access for non-intrusive flow field diagnostics in hypersonic facilities	35	30	9.0
CFD-09	Low-density test conditions for simulation of rarefied aerodynamics	4	31	5.2
CFD-10	Forced-oscillation test capability in supersonic wind tunnels for measurement of unsteady vehicle dynamics	4	29	7.0
CFD-11	Ballistics ranges with sufficient measurements stations and/or range length to obtain validation quality vehicle dynamics data	2	28	7.5
CFD-12	Mach, Reynolds, and/or enthalpy ranges to duplicate flight relevant conditions and freestream disturbances (particulates, electrostatic discharge) for flow field / material surface interaction studies	1	30	7.3
CFD-13	Optical access for non-intrusive flow field diagnostics in supersonic facilities	44	31	8.2
CFD-14	Long-duration high-enthalpy TPS testing capability, including ablation and shape change and catalysis	3	30	8.2
CFD-15	Access to non-NASA facilities for EXTENSIVE test programs required for CFD validation extremely unlikely in foreseeable future due to high demand on DoD, Commercial and Academic facilities from National defense	56	29	7.6
CFD-16	Non-reacting, supersonic CO2 test capability for Mars retropropulsion & aerodynamic testing	2	31	6.6
CFD-17	Expanded range of conditions (test time, pressure, velocity) in shock tubes for radiative and kinetic property measurements	10	29	7.5
CFD-18	Advanced sensors (fast response pressure, VUV radiation) for shock tube radiative and kinetic property measurements	10	29	7.8

17

HEAC Team #3: Capability and Capacity Team Product: Facility Test Technique and Instrumentation Gaps

Gap ID	Gap Description	Gap Frequency
Inst-Aero-01	Fast-response aerodynamic force & moment balances suitable for short-duration impulse facility operation	37
Inst-Aero-02	Aerodynamic force & moment balances with high-frequency response for dynamic pitch-response measurement and separation of balance and strut effects	49
Inst-Aero-03	Aerodynamic force & moment balances with capability for accurate measurement of small changes in aerodynamic coefficients due to RCS and SRP firings	20
Inst-Aero-04	Flow-through aerodynamic force & moment balances for gas seeding that do not omit axial-force component	5
Inst-Aero-05	Higher signal-to-noise ratio and faster response-time pressure instrumentation	3
Inst-Aero-06	Ballistics range with sufficient measurement stations and length to aquire dynamic aero data and/or ability to fly at angle-of-attack	14
Inst-Flow-01	Application and validation of flow-field visualization techniques from supersonic flows to hypersonic flow conditions	89
Inst-Flow-02	Ability to perform near-surface measurements of boundary-layer properties	58
Inst-Flow-03	Flowfield seeding techniques for RCS and SRP plumes to enable laser-based velocity measurements.	4
Inst-Flow-04	Inert gas other than air (e.g., heated ethane) for thruster / plume testing	2
Inst-Flow-05	Simultaneous, non-intrusive measurement of velocity and temperature for direct validation of Reynolds heat flux models	4
Inst-Flow-06	Optical tracking and characterization of particles in high-speed flow (gas seeding or "dusty" flows)	5
Inst-Flow-07	Ability to measure thermal state distributions and flow field temperatures along the stagnation streamline	1
Inst-Flow-08	Hardware and software for high-frequency / high-resolution schlieren systems	20
Inst-Heat-01	Global optical aeroheating techniques for very low-temperature response conditions (e.g. wake flows)	27
Inst-Heat-02	Cost, fabrication time, and spatial resolution limitations on discrete sensors for small wind tunnel models	24
Inst-Heat-03	Heat-flux sensors that separate convective and radiative components in high-enthalpy testing	22
Inst-Heat-04	Spectral range of shock-layer radiation sensors, especially VUV spectra	11
Inst-Heat-05	Limited high-speed data acquisition capabilities facilities	3
Inst-Heat-06	Higher frame-rate cameras for optical surface heating measurements	5
Inst-Heat-07	Techniques for mapping 2D optical aeroheating data to 3D CAD geometries	6
Inst-Heat-08	Higher frame-rate cameras for optical surface heating measurements	32
Inst-Heat-09	Hardware and software for IR thermography systems	2
Inst-Heat-10	Hardware and software for phosphor thermography systems, especially high-temperature	2

Team was not asked to rank criticality of the category. Test technique and instrumentation projects add to the facility total capacity requirements

18

HEAC Team #4: Investment Recommendation – LaRC Unitary Plan Wind Tunnel Upgrades (UPWT+)

- LaRC UPWT+ is a high-supersonic / low hypersonic range, perfect-gas, hypersonic blowdown wind tunnel for external aerodynamic, aeroheating, and fluid dynamics testing that closes multiple critical gaps
  - (HTP-01): Mach 4-6 aerodynamics testing capability needed by NASA, DoD and Industry
  - (EDL-09 / HTP-02): Test sections will have wide cores to allow testing of large wind tunnel models with detailed geometric features
  - (CFD-08): Test sections will have multiple large windows to enable high-fidelity optical-based surface and flow field diagnostics
  - (EDL-08 / CFD-03): Integrated high-pressure mass flow supply to enable RCS and retropropulsion testing
- LaRC UPWT+ design is at a conceptual stage
  - Inputs from NASA SME's identified requirements for aerodynamics test capability in high supersonic to low hypersonic regimes (Mach 4 – 6)
  - Tentative Mach number requirements may be satisfied by conceptual design for LaRC UPWT upgrades – becomes **UPWT+**
  - Cost range TBD based on additional DoD/Industry inputs ($10's M to $100's M)

LaRC UPWT







23

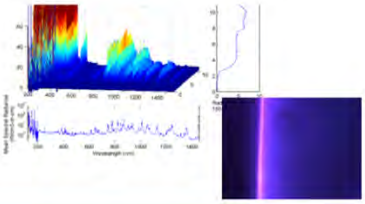
HEAC Team #4: Investment Recommendation – Ames Electric Arc Shock Tunnel Upgrades (EAST+)

- ARC EAST+ is a high-pressure / high-velocity shock tube designed for investigation of fundamental chemical-kinetic and radiative processes that fulfils multiple critical gaps
  - (CFD-02): for expanded shock-tube operational ranges
  - (CFD-08): Test sections will have multiple large windows to enable high-fidelity optical-based surface and flow field diagnostics
- ARC EAST+ requires modifications/upgrades to Ames Electric Arc Shock Tube (Aging infrastructure of EAST requires modernization
  - Significant opportunities exist to upgrade facility operational range
- Shock tubes like EAST are not a major (on the HEAC scale) investment
  - Probably in the millions $ investment
  - Existing infrastructure, instrumentation and diagnostics from EAST can be leveraged, as well as SME expertise

AMES EAST Complex



Shock-layer radiation data



24

HEAC Summary

HEAC gaps assessment had delivered a technical assessment that is:

- Comprehensive: includes both flight projects and technology development efforts that require experimental data in discipline areas of Entry, Descent, and Landing, Sustained Hypersonic Flight, and Computational Fluid Dynamics development and validation, with focus on NASA missions, but including DoD and commercial requirements
- Strategic: collected mission data set (170+ items) projecting 25+ years into future based on inputs from bottoms-up (SME's) and top-down (programmatic leaders) perspectives
- Technically sound: Diverse group of ~80 experimental and computational aerothermodynamics SMEs from multiple NASA centers defined test objectives (800+ identified) and assessed NASA ground test infrastructure ability to fulfill them
- Traceable: identified ground test gaps (64 across EDL, hypersonic flight, and CFD disciplines) and linked them to aerothermodynamic test objectives for missions
- Data-driven: identified critical gaps (15 critical out of 64 total) through statistical analysis of criticality and frequency
- Actionable: recommended facility investments (4 new/modified hypersonic facilities) to close critical technical gaps and enable future NASA, DoD, and commercial

HEAC team recommendations provide an investment roadmap to ensure NASA's technical excellence in the 21st century, contributing to National defense and supporting the growth of a commercial space economy

25

Updating the National Unitary Plan to Unlock Investments

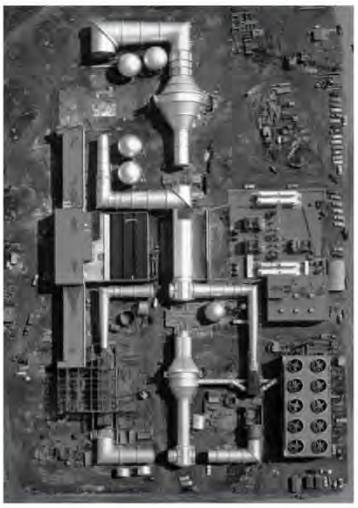
The 1949 "Unitary Plan" created the three NASA Unitary Plan Wind Tunnels at Ames, Lewis (Glenn) and Langley and was the precursor to the creation of the DoD Arnold Engineering and Development Center

U.S.C. Title 50: War and National Defense
Chapter 20: Wind Tunnels
Subchapter II : Air Engineering Development Center
Sec. 511. Joint development of unitary plan for construction of facilities

"The Administrator of the National Aeronautics and Space Administration and the Secretary of Defense are authorized and directed jointly to develop a unitary plan for the construction of transonic and supersonic wind-tunnel facilities for the solution of research, development, and evaluation problems in aeronautics … Any further implementation of the unitary plan shall be subject to such additional authorizations as may be approved by Congress"

- NASA and DoD need to synthesize investment needs to develop a multi-center, multi-agency National hypersonic aerothermodynamics infrastructure plan
- Both NASA HEAC and ongoing DoD studies were facilitated by the Institute for Defense Analysis (IDA) and follow similar methodology

Update the 20th century Unitary plan to fulfill NASA and DoD aerothermodynamic testing requirements for the 21st century and beyond



27

With the increased national emphasis on hypersonic flight and space exploration, NASA has a once-in-a-generation opportunity to invest in world class facility development to ensure US preeminence on Earth and in Space

28

Appendix B Responses to Vision and Goals Team Survey Questions

Response to each Vision and Goals survey question from hypersonic subject matter experts from NASA and other government agencies are listed below. Obvious spelling errors have been corrected, but otherwise the grammar and content have not been edited.

Question 1: In 20 years, how would you like NASA's role in hypersonic Research, Development, Testing and Engineering (RDT&E) to be viewed by the world?

1. Being instrumental in maintaining the technical integrity of the national RDT&E hypersonic infrastructure, contributing greatly to the skills development of expert practitioners, having a deep understanding of the salient physics, and making direct contributions that lead to (DoD) program successes through effective collaborations
2. Continuing to lead the world, having the EDL capabilities to land the masses we need to, where we need to, in order to meet exploration and science goals.
3. The nation's steward of all aeronautics, including hypersonics. NASA's role should span both Civil and Defense, as appropriate and required.
4. Leading the world in civilian hypersonic and space flight activities. NASA should also, as defined by its charter, provide technical expertise and support to the DoD as required and reimbursed by the DoD, so long as those activities do not interfere with NASA's primary mission.
5. In the Defense arena – being limited to existing areas of hypersonics where NASA holds a capability that does not otherwise exist (capability) or is not available (capacity) at DoD, or where there are overlapping requirements between the DoD and NASA Missions.
6. In the civil arena – participating in the sustainment, enhancement, and development of hypersonic technology and capabilities required for hypersonic applications. This will require a change to the present NASA Aeronautics focus and objectives, which do not include hypersonic flight systems.
7. In the Defense arena – being limited to providing SME inputs and critical testing capabilities in support of Defense-related RDT&E efforts.
8. In the civil arena – playing a leading role. However, it is not currently obvious that there is a civil hypersonics need outside of ascent and EDL for space access, but this is a critical area for which NASA is the only real provider.
9. Having sufficient partnerships that provide access and additional capabilities to support NASA and National needs – a Subject Matter Expert for hypersonic flight
10. Assuming "hypersonics" means air-breathing and slender-body glide vehicles, NASA will be viewed as an important partner in Defense-related RDT&E. From those efforts, technologies developed are helping enable air-breather applications to civil transportation.
11. NASA should be primary stewards of civil hypersonic RDT&E, and play a more minor supplementary role in Defense-related RDT&E. I think the coming decades will involve a paradigm shift in the civil hypersonics industry in that it will start to look like the civil aviation industry becoming increasingly filled with, and maybe potentially dominated by, commercial ventures. Like the aviation industry, NASA will play a critical role in advancing the discipline, improving safety and reliability, and providing technological breakthroughs.
12. The cheapest provider of globally preeminent hypersonic research information and data
13. Steward of the nation's (or world's) hypersonic research information and data [Boeing Seattle Commercial Airplane Example: Aircraft manufacturer vs aircraft integrator]
14. Having world-class test capabilities
15. Having access to world-class test capabilities
16. The go-to Agency for hypersonic research information and data
17. Honest broker for hypersonic test execution

Question 2: In 20 years, how would you like NASA's hypersonic RDT&E experimental aerothermodynamics capabilities to be viewed by the world?

1. Complimentary to the DoD's experimental aerothermodynamics capabilities – providing reach-back capacity, augmenting other capabilities, and discovering deep technical insights needed to ensure the U.S. lead in hypersonics is never relinquished
2. Leading the world and continuing to be a National asset so NASA can: (a) fly more and more systems at one time, (b) infuse new technologies more rapidly, and (c) support the rapid development and risk postures of the future.
3. Top-notch and relevant for the needs of the future – able to produce data that cannot be obtained by other means (i.e., via computational methods or from flight testing). Any flow phenomena that deal with boundary layer transition, in particular, will continue to be a difficult problem for the computational community to solve, even in the long term.
4. A world class repository of experience to be applied to fundamental research and support of flight test programs, as well as for validation of computational tools and methods
5. Fully supporting NASA's missions in human and robotic spaceflight and civil hypersonic applications, should they exist. If DoD works agreements with the Agency to retain and maintain these capabilities, then they should definitely be retained, maintained and potentially enhanced. If, however, DoD intends to use these unique capabilities to tie them over until they can obtain (or enhance) their own capabilities, then we should probably be out of those capabilities as they are developed and implemented by DoD.
6. Maintaining the infrastructure necessary to fulfill NASA's mission, The world of aerothermodynamics is slowly shifting to be more modeling focused, but since this shift is happening much more slowly than many thought, we continue to rely on experimental capability for tool and model validation and for fundamental testing and R&D purposes, as well as configuration analysis.
7. The National (really international) gold standard for hypersonics R&D, having solid collaborations with universities all of over the country and strong ties with DoD to partner on working their early system developments and unique physics problems
8. Engines for both National workforce training and cutting-edge computational tool validation
9. Having the ability and experts to conduct validations of concepts and technologies through experimentation that is well-integrated with measurement and computational capabilities
10. Being used less-and-less on basic vehicle assessments and being used primarily for highly advanced technology development and flow physics research
11. Providing an integrated testing and simulation technology base enabling the nation to be world leaders in space explorations and high-speed civilian transport
12. Should be thought of as the group to engage whenever a question arises about the aerodynamics/aerothermodynamics of atmospheric hypersonic flight (whether it is entry/reentry or sustained flight).
13. Should be an active and respected entity within both the Civil and Defense hypersonics industries. They should be leaders in computational and experimental aerothermodynamics research as well as providing in-line engineering support and application work for NASA, Commercial, and Defense flight programs. They should be an integral piece to a cooperative NASA Aerothermodynamics community that works in the national interest to collectively accomplish our goals.
14. The Agency has, and is the steward of, unique T&E capabilities.

Question 3: What are the technical-, financial-, and workforce development-related pros and cons of these four potential experimental aerothermodynamics capability futures?

Pros for Option 1 – Sustain Current Testing Capabilities

1. Provides known capabilities that offer important test environments for some salient physics in aerothermodynamics – no loss of capability during facility improvement / modernization
2. Sustainment ensures that NASA will retain some capabilities for a minimal investment over the next 10 years
3. NASA maintains some hypersonic testing capability
4. Lowest cost option for the near term
5. Economical in the short term (presumably), or at least puts off a major expenditure
6. Maintains the current workforce (I think)
7. These are the only operational hypersonic facilities in the Agency capable of executing NASA's programs and projects; they are relatively simple and inexpensive to operate; and testing in them is relatively efficient and flexible to model and configuration changes
8. The agency retains a barebones (low Re, low enthalpy, perfect gas) aerothermodynamics capability
9. Known costs / known capabilities
10. Less financial outlays, and so expertise is consequently not as threatened since it is not on the radar with decision-makers
11. SMEs and test capabilities co-located
12. Provides some level of validation capability for code predictions
13. Permits quick aerothermodynamics assessments of vehicle configurations / geometry features
14. Ideal for new technique development
15. Affords low-cost access for university research projects
16. On-demand response to national emergencies / priorities (design / flight test failures)

Cons for Option 1 - Sustain Current Testing Capabilities

1. Facilities are old, unreliable, and hard to maintain
2. Sustainment is a dead-end – within 10 years, maintenance costs of the 50+-year-old hardware will likely increase dramatically
3. Within 20 years, the current facilities will be technologically obsolete – at which point, NASA will no longer have a functional capability to support its own technical requirements and its core competency in hypersonic aerothermodynamics will have been lost
4. No high enthalpy capability for aero-sciences research
5. No capability for non-air testing
6. Reliance on CUBRC / LENS for both high enthalpy and non-air testing is incredibly expensive, and NASA is not a priority in those facilities
7. Current facilities are not ideal for the scope of future flight problems to be solved.
8. Expect repair costs to greatly increase over time
9. Doesn't advance NASA's capability in terms of facility understanding or uncertainty qualification
10. Puts the ability to support missions at risk, given that facility failure rates will likely increase
11. May be difficult to attract a new workforce to work in old facilities (not certain)
12. The current facilities are aging and increasingly difficult to maintain, and don't match up very well with today's hypersonic capability requirements and technical gaps
13. Putting resources into an aging infrastructure is a poor investment
14. Provides an insufficient capability to advance science for higher fidelity data / code validation

15. SME / workforce development suffers in the long term
16. Limited capabilities, limits solutions. Cost will increase over time. Loss or relevance. Unable to attract new workforce (obsolete capabilities)
17. Advanced research cannot be completed as readily, since no advancements in test capabilities are made. To a certain extent, this is what has been happening. Much of the technology in the facilities was developed in the nineties and there has been difficulty adapting the newer technologies in a user-friendly fashion.
18. Aging infrastructure reduces productivity
19. Does not reduce the Center footprint
20. 2022 UPWT demolition plan will shut down 31" / 15" facilities for some period of time

Question 3: What are the technical-, financial-, and workforce development-related pros and cons of these four potential experimental aerothermodynamics capability futures?

Pros for Option 2: Improve / modernize current capabilities

1. Improvements could bring technology up-to-date and increases reliability and maintainability
2. Investment could offer significant capability increases consistent with NASA vision and goals
3. In theory, improvement / modernization of existing facilities could provide the same benefits as the sustainment option, but over a longer time period of time (20 years?)
4. Likely better throughput and some additional capability over the current LAL (better, state-of-the-art instrumentation perhaps)
5. Current capabilities are aging and will require an infusion of funds to reduce the likelihood of infrastructure failure beyond repair
6. A balanced, cost-effective approach with a more modest expenditure than replacement
7. Option 2 retains needed hypersonic test capability to service Agency hypersonics problems, while alleviating some of the issues due to age and maintenance
8. Similar to Option 1 but modernization could certainly provide welcome improvements in efficiency and reliability
9. Provides short-term solution to meet immediate needs / relatively low cost
10. Modernizing the facilities could make some impact – advanced measurement methods (e.g. PLIF) have had difficulty being brought on-line.
11. Most realistic option that maintains and upgrades current hypersonic test capabilities and workforce sustainment/development
12. Besides maintaining the status quo, which doesn't appear to be an option, this is probably the quickest and cheapest way to get back online to having testing capabilities. IMO, the LAL currently occupies a nice, sweet spot for aerothermodynamics testing. It has a good balance of cost, speed, efficiency, scale, flow quality, measurement capability, and computation/simulation support that really is not found anywhere else. I think that this option has the most potential to not lose that sweet spot.
13. Enable the development of new diagnostic
14. Will attract new talent and provide a more energized work force
15. SMEs and test capabilities co-located
16. Provides some level of validation capability for code predictions
17. Permits quick aerothermodynamics assessments of vehicle configurations / geometry features
18. Ideal for new technique development
19. Affords low-cost access for university research projects
20. On-demand response to national emergencies / priorities (design / flight test failures)
21. State-of-the-art test capabilities will attract early-career and university faculty to come to LaRC
22. Better understanding of the current flow regimes these facilities provide
23. Improved productivity
24. Increased capability / access / better understanding of current flight regime capabilities

Cons for Option 2: Improve / modernize current capabilities

1. Limits the ability to create a capability that is ideally matched to emerging hypersonic missions, creates legacy challenges linking-in advances in instrumentation and diagnostics – loss of some capability during facility improvement / modernization
2. In practice, it's hard to define an "improvement / modernization" plan for 50+-year-old facilities that provides a positive cost / benefit rationale, since most NASA infrastructure (including its aerothermodynamics facilities) suffers from a backlog of deferred maintenance over many years.
3. The cost just to keep existing facilities running for 20 more years, let alone provide a meaningful expansion of those facilities' operational capabilities, would be substantial
4. Does not address any of the cons in Option 1 regarding both high enthalpy and non-air testing or NASA's reliance on CUBRC / LENS (which is incredibly expensive)
5. You can only squeeze so much blood from a stone – Option 2 does not posture NASA to be in a position to address the problems likely to arise in the future
6. Does not reduce the Center footprint
7. Option 2 may not provide the capability to make high-quality measurements (depending on the resources provided for facility improvement / modernization)
8. Not sure if modernization addresses many of the technical gaps we have today, such as high Reynolds number and high enthalpy flows.
9. Inconsistent with Center / Agency desire to minimize and consolidate Center footprint
10. Similar to Option 1, but modernization will not provide required capability advances for higher fidelity data / code validation.
11. Requires significant investment that is better directed to upgrading capabilities
12. SME / workforce development suffers in the long term
13. Limits NASA's abilities (does not provide the ability to advance understanding and technologies)
14. New flow field regimes would not be modeled that have criticality to NASA vehicle projects (i.e. higher Reynolds number flows)
15. Could take facility off-line for extended period(s) of time
16. 2022 UPWT demolition plan will shut down 31" / 15" facilities for some period of time

Question 3: What are the technical-, financial-, and workforce development-related pros and cons of these four potential experimental aerothermodynamics capability futures?

Pros for Option 3: Build new capabilities and divest old capabilities

1. Provides opportunity to design exactly what's needed and what would best compliment DoD
2. Construction of new facilities is the only viable means to develop world-class capabilities in experimental hypersonic aerothermodynamics. Current facilities were designed in the 50s-60s are no longer "cutting edge" in comparison to other National or international capabilities. If Aerothermodynamics is to remain a NASA core competency, then new facilities are a critical requirement. It should also be noted that any plan that includes demolition of current facilities must be structured to ensure that those facilities remain operational until new facilities are completed, validated, and become operational.
3. Addresses the current high enthalpy, non-air test gas capability gaps identified in Option 1
4. Enhances NASA's position as the leader in the aerothermodynamics arena
5. This is the only option that addresses the long-term needs of NASA and the Nation
6. Offers the potential to reduce Langley's footprint, as directed
7. Affords an opportunity to establish more efficient, sustainable facilities that can reduce near-term maintenance costs and reduce inoperable time periods
8. Affords an opportunity to enhance hypersonic capability and close technical gaps
9. Retains needed hypersonic test capability to service Agency hypersonics problems.
10. Provides the opportunity to address Agency / Center footprint objectives
11. Provides the infrastructure the Agency needs to achieve our proposed goals
12. New test capabilities will be obtained, some of which would be unique for the nation
13. This would require design efforts which would build a generation of engineers who have a deep understanding of how the facilities work
14. SMEs and test capabilities co-located
15. Provides some level of validation capability for code predictions
16. Permits quick aerothermodynamics assessments of vehicle configurations / geometry features
17. Ideal for new technique development
18. Affords low-cost access for university research projects
19. On-demand response to national emergencies / priorities (design / flight test failures
20. State-of-the-art capabilities will attract early-career and university faculty to come to LaRC
21. Increased capability / access / better understanding of new flight regime capabilities
22. Improved productivity
23. Promotes better workforce understanding of ground testing thru involvement in facility design
24. New opportunities for collaboration with academia
25. High fidelity, relevant data in new flight regimes for code development / validation
26. Facility can be used to acquire high-fidelity data for advanced CFD tool development/validation
27. Allows tailoring of new facilities to the sweet spot in the market. That is, low-cost parametric testing at higher Re and M than currently available.
28. I think that this question should be stated a little differently: Build all new LAL test capabilities then demolish those that no longer serve a purpose. I think that we should improve and modernize those facilities that it makes sense to do so. At the same time, we should design and build their replacements. These new facilities should have capabilities that will improve our understanding of aerodynamics/aerothermodynamics in the supersonic/hypersonic flow regimes. They should also provide insight into flight on other planets and their unique atmospheres. The agency does not invest in new ground facilities very often, so we need to make sure that we develop our story as to why we need these new facilities and what answers we will get from them that cannot be obtained anywhere else

Cons for Option 3: Build new capabilities and divest old capabilities

1. It's expensive and involves a long down-time – loss of capabilities while under construction
2. Might lose experienced folks waiting for capabilities to be built
3. Nothing is free and new facilities will require capital investments, so selling these investments will be challenging (the visibility of the aerothermodynamics discipline sometimes appears to be underrated at senior levels of NASA management)
4. Results in a potentially extended downtime when there is no capability available
5. There is a substantial risk that only the demolition phase will be executed, and construction will be postponed and eventually cancelled
6. Cannot be considered a near-term solution, as existing capability would need to remain in-place until the new facilities are ready in order to provide continuity of critical research – thus, it would be the most expensive option to consider
7. Unrealistic in current fiscal environment – may reduce funding for other LaRC / Agency priorities
8. Cost – and the ability to find a willing "funder"
9. Requires building new infrastructure that the Agency will have to pay for, staff, and maintain
10. This would take a lot of funding – in an agency with tight budgets, the costs could impact other important efforts. Great care would have to be taken to make sure the right balance is struck. The current white paper by on three proposed facilities strikes a good balance
11. Potentially significant downtime, which could preclude support in the event of an emergency, such as an accident with some flight program.

Question 3: What are the technical-, financial-, and workforce development-related pros and cons of these four potential experimental aerothermodynamics capability futures?

Pros for Option 4: Divest old capabilities and rely on external capabilities

1. Lowest cost option
2. Forces NASA PIs to interact with the rest of the national infrastructure, fosters collaboration with DoD, and creates best use of capabilities when utilization is low
3. Undoubtedly there would be Senior Executive Service bureaucrats who would receive bonuses for reduction of NASA infrastructure footprint and operational costs
4. Probably some potential short-term cost savings
5. NONE!
6. This would be the cheapest option in terms of institutional resources and longer-term sustainment costs
7. Provides the opportunity to address Agency/Center footprint objectives
8. If hypersonic experimental capabilities are lightly utilized, this option reduces the cost to the Center / Agency
9. Potentially improves relationships with external partners (or it could make relationships worse, depending on how things go)
10. Potentially accelerates computational development to compensate for reduction in test availability
11. Eliminates infrastructure the Center / Agency will no longer have to staff and maintain
12. Lowest cost in the short term
13. The agency is not required to maintain expensive infrastructure and can pay by the yard

Cons for Option 4: Divest old capabilities and rely on external capabilities

1. NASA is dependent on the facility schedule and availability of others – no testing accomplished for NASA when utilization by others is high
2. Research will be on a timescale consistent with other test facilities (cannot schedule discovery)
3. Research will be guided by capabilities that are available and not driven by Agency needs
4. "Pay me now or pay me later" – any short-term cost savings would be offset in the long-term due to NASA being unable to develop new hypersonic vehicles and technologies and / or the capital (and potential human) loss due to mission failures
5. Impacts to flagship class missions (e.g. Orion) may not be huge, but all smaller class missions will suffer
6. Experimental R&D will likely come to a near-complete halt as access to relevant non-NASA facilities is difficult, expensive and a scheduling nightmare
7. Not a viable solution for NASA, as there are not enough national assets to go around
8. NASA would not get the access required to conduct it's required research in a timely manner
9. If NASA does not own facilities, they will no longer be able to cultivate the next generation of subject matter experts in the various aerothermodynamics disciplines
10. Numerous studies show that DOD and other national facilities do not adequately span the range of flight conditions that NASA must design for, so there would be a gap in our ability to validate our predictions and design vehicles for certain flight regimes – this would result in increased mission risk, mass, and cost, moving us away from the general direction of understanding and reducing the cost of systems
11. For high demand situations, cost will be an issue as will getting test access (potential schedule impacts)
12. Potentially increases program risk due to higher reliance on computations
13. Differences in priority and/or risk posture could result in external partner divesting of facilities still needed by NASA
14. Difficult to conduct non-production (research) testing or perform facility modifications for NASA-specific

requirements

15. The limited availability and/or higher cost of utilizing outside facilities will atrophy Agency (and potentially national) aerothermodynamics SMEs – thus increasing future mission risk and cost, as well as reducing the likelihood that NASA mission requirements will be achieved
16. Presents a challenge for sustaining and attracting SMEs / NASA will lose its relevance
17. NASA is subject to the schedules of other organizations. This could impact the NASA mission in completing design of vehicles and even performing critical 911's on vehicle programs
18. Higher costs may be paid for a given test. This could impact a projects usage of important facility data
19. NASA's facilities are unique, and those capabilities would be lost, e.g. the number of runs per day of global heating data that can be obtained
20. This would require a lot of TDY – projects typically will not always be willing to pay for so much travel; so, experimental results may be incorporated less than should be, which could be to the detriment of the vehicle projects
21. Completing advanced research may be difficult if tunnels are not available locally
22. Building deep subject matter expertise in experimental work may be difficult, since that is built by spending a lot of time at a facility
23. At mercy of other organizations for testing. Lower priority among outside facility's customers. Loss of in-house experimental expertise.
24. Cost and schedule can be challenging especially with CUBRC and AEDC, which are two of the best for scale, flow regimes, and measurement capabilities. Defense-related work takes precedence, which often leaves NASA waiting. This has become more and more of a challenge as Defense-related funding in hypersonics has ramped up. NASA likely divests some expertise in experimental aerothermodynamics and instrumentation development. NASA executed fundamental research likely goes to zero. Instead, we'll fund and oversee fundamental testing, which will likely be few and far between.
25. From 2000 to 2004, I loudly voiced my opposition to closing and demolishing the 16-Foot Transonic Tunnel. I told our Center Director and Deputy Director that if we get rid of the facility, then PAI (propulsion airframe integration, which is led out of LaRC) would be forced to move to another center or agency. It has taken a long time, but the center of mass is slowly moving to the Ames UPWT 11-Foot Transonic Wind Tunnel. I also had similar discussions with the Center Director and Deputy Director (who became our Director) from 2003 to the present on closing and demolishing the LaRC UPWT. My argument was that if we don't have a supersonic facility for researchers (SMEs) to test in at the center then that capability will move to another center or agency. I have the same concerns about demolishing the LAL facilities. If we demolish them, then the center of research will move to locations that have or will have such capabilities and LaRC will slowly lose the expertise in those areas. This is a very bad idea and should not be pursued.
26. Reduced national engagement and impact

Appendix C Database for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human Rated Exploration

Table 24. Programs List for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration.

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
Hypersonic Entry, Descent and Landing	**1**	**NASA and Partners Human-Rated Exploration**	**Any NASA led, collaborative or reimbursable programs supporting development of atmospheric EDL systems that carry humans to, or return from, LEO, Moon, Mars, etc. Also uncrewed systems that provide support for human exploration missions**	**Any human-rated system will have very low risk tolerance. Development programs will be on par with investments in prior human-rated systems like Shuttle Orbiter and Orion programs**	**NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)**	
	1.1	**NASA Human-Rated Earth Operations**	**LEO access and abort, LEO return**	**Orion / Artemis program**	**NASA policy**	**2021+**
	1.11	Crewed Earth Return from LEO	Support for Orion capsule flight test and/or post-flight reconstruction of Artemis missions	Orion development largely complete, except for potential post-flight requirements. This assessment is provided for historical context. Note that extensive test campaign was conducted in 2022-2023 after Artemis-I char loss	Test records from Orion Aeroheating and Aerodynamic data books	2021-2030
	1.12	Crewed Earth Return from Moon or Gateway	Development of Orion capsule or derivative for Lunar/Gateway return	Focus on any changes to TPS, compression pads, aftbody features following Artemis flight tests	NASA policy	2025-2030
	1.13	Crewed Earth Ascent Abort	NASA Development of abort systems for future vehicles	Required for any future human-rated system. Cannot assume Orion/Artemis abort system compatible with future architectures	NASA policy	2025-2030
	1.2	**NASA Human Mars Operations**	**EDL and ascent from Mars, EDL return to Earth**	**Initial evaluation of one or more configuration options. Then will need to develop detailed database for selected configuration with equal rigor and quantification scope as Orion development**	**Human Mars Entry, Descent, and Landing Architecture Study**	**2026-2040**
	1.21	Human-rated, high mass Mars entry system: HIAD+SRP architecture	NASA Development of high-mass entry vehicle for long-term exploration / colonization of Mars. Current highest rated option	End state of HIAD architecture development path under Section 3.1 and Supersonic Retropropulsion under Section 3.3. Assume certification campaign for crewed vehicle of equivalent or greater scale than Orion capsule (much large than robotic missions)	Human Mars Entry, Descent, and Landing Architecture Study	2026-2040

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	1.22	Human-rated, high mass Mars entry system: Mid L/D + SRP architecture	NASA Development of high-mass entry vehicle for long-term exploration / colonization of Mars. Second highest rated option	End state of Mid L/D architecture development path under Section 3.4 and Supersonic Retropropulsion under Section 3.3. Assume certification campaign of equivalent or greater scale than Orion capsule	Human Mars Entry, Descent, and Landing Architecture Study	2026-2040
	1.23	Human-rated, high mass Mars entry system: Deployable + SRP architecture	NASA Development of high-mass entry vehicle for long-term exploration / colonization of Mars. Similar to HIAD option	End state of Deployable architecture development path under Section 3.2 and Supersonic Retropropulsion under Section 3.3. Assume certification campaign of equivalent or greater scale than Orion capsule	Human Mars Entry, Descent, and Landing Architecture Study	2026-2040
	1.24	Human-rated, high mass Mars entry system: Capsule + SRP architecture	NASA Development of high-mass entry vehicle for long-term exploration / colonization of Mars. Unlikely option for High mass EDL, retained for completeness or for other potential missions requiring less landed mass	End state of capsule architecture development path under Section 3.5 and Supersonic Retropropulsion under Section 3.3. Assume certification campaign of equivalent or greater scale than Orion capsule	Human Mars Entry, Descent, and Landing Architecture Study	2026-2040
	1.25	Mars Ascent Vehicle	For ascent from Mars prior to return to earth. Assumed common to all High-Mass EDL architectures	details dependent on selected ascent system configuration	NASA policy	2026-2040
	1.26	Human Mars Mission Earth Return Vehicle	Crewed capsule(?) type system for earth re-entry from Mars mission	Assume a capsule type of vehicle regardless of the Mars EDL segment architecture. TBD if Orion/Artemis capsule meets requirements for Mars return capability and crew capacity	NASA policy	2026-2040
	1.3	**Commercial Systems**	**LEO, Lunar or Mars operations**	**Objectives TBD based on configuration, requirements, destination**		**2026-2040**
	1.31	Commercial LEO system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)	Support development of commercial vehicles for return from LEO	Assume NASA carries support for two providers up to final selection. Assuming a capsule-type architecture	Reasonable to extrapolate additional programs from past work	2026-2040
	1.32	Commercial LEO system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)	Support development of commercial vehicles for return from LEO	Assume NASA carries support for two providers up to final selection. Assuming a capsule-type architecture	Reasonable to extrapolate additional programs from past work	2026-2040
	1.33	Commercial Lunar system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)	Support development of commercial vehicles for return from Moon, Gateway	Assume NASA carries support for two providers up to final selection. Assuming a capsule-type architecture	Reasonable to extrapolate additional programs from past work	2026-2040
	1.34	Commercial Lunar system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)	Support development of commercial vehicles for return from Moon, Gateway	Assume NASA carries support for two providers up to final selection. Assuming a capsule-type architecture	Reasonable to extrapolate additional programs from past work	2026-2040
	1.35	Commercial Mars system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)	Support development of commercial vehicle for human-rated Mars EDL and return to Earth	Assume NASA carries support for two providers up to final selection. Must assume new architecture since capsule have insufficient capacity	Reasonable to extrapolate additional programs from past work	2026-2040

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	1.36	Commercial Mars system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)	Support development of commercial vehicle for human-rated Mars EDL and return to Earth	Assume NASA carries support for two providers up to final selection. Must assume new architecture since capsule have insufficient capacity	Reasonable to extrapolate additional programs from past work	2026-2040
	1.40	Uncrewed Support Systems	Cargo up/down mass in support of human operations (e.g. Sierra Dreamchaser, SpaceX Cargo Dragon	Uncrewed systems that compliment human-rated operations	NASA policy	2020+
	1.41	Uncrewed support system #1	Support development of commercial ISS/Lunar cargo vehicle	Assume NASA carries support for two providers up to final selection. Assume growth in cargo return requirements beyond current ISS	Reasonable to extrapolate additional programs from past work	2020-2030
	1.42	Uncrewed support system #2	Support development of commercial ISS/Lunar cargo vehicle	Assume NASA carries support for two providers up to final selection. Assume growth in cargo return requirements beyond current ISS	Reasonable to extrapolate additional programs from past work	2020-2030

Table 25. Database Objectives for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration.

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1	**NASA and Commercial Human-Rated Exploration**							
1.1	**NASA Human-Rated Earth Operations**							
1.11	Crewed Earth Return from LEO							
1.1101	Post-flight assessment for comparison / evaluation of fight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	hypersonic tunnels, high-enthalpy shock/impulse facilities	TBD depending on flight data	TBD depending on flight data
1.1102	Develop hypersonic aerodynamic performance database	(1) Hypersonic aerodynamic performance (5) flow field characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	Mach number, Angle-of-attack, Reynolds number range	Force and moment, pressure, flow-field visualization	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS
1.1103	Develop supersonic aerodynamic performance	(2) Supersonic aerodynamic performance (5) flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, pressure, flow-field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, US Army Aberdeen range
1.1104	Determine aeroshell baseline acreage aeroheating environments	(3) Boundary-layer characterization, (4) Convective aeroheating environments, (10) High-Enthalpy kinetics	Measure convective heating distributions and BL transition onset locations on aeroshell	Reynolds number, AoA, Mach, enthalpy	Global heating and BL transition	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS
1.1105	Determine vehicle radiative aeroheating environments	(12) Radiative heating environments	Measure radiative heating on aeroshell and aftbody	Enthalpy / Mach range	Integrated and/or spectrally resolved radiative heating	High-enthalpy shock/impulse facility	none	CUBRC LENS
1.1106	Determine aftbody baseline acreage aeroheating environments	(4) convective aeroheating, (5) Flow-field characterization, (10) high-enthalpy kinetics	Measure convective heating distributions on aftbody	AoA, Mach, Reynolds number	Global heating and BL transition, flow field visualization	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS
1.1107	Determine RCS interaction effects on aftbody heating and aerodynamics	(4) convective aeroheating, (5) Flow-field characterization, (7) RCS performance and interactions (10) high-enthalpy kinetics	Measure localized heating augmentation due to RCS interactions, measure aero effects of RCS interactions	AoA, Mach, Reynolds number, RCS thrust levels, jet on/off pairings	Localized heating, flow field visualization, aerodynamic effects	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.1108	Determine TPS effects on aeroshell boundary-layer transition and turbulent aeroheating augmentation	(3) boundary-layer characterization, (4) Convective aeroheating environments	Measure surface temperature and heating distribution to determine TPS roughness / ablation effects on hypersonic boundary-layer transition and turbulent heating augmentation	AoA, Reynolds number, roughness scale height	Global heating and BL transition	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS
1.1109	Determine compression pad cavity effects on localized heating and boundary-layer transition	(3) boundary-layer characterization, (4) Convective aeroheating environments	Measure surface temperature and heating distribution to determine TPS roughness / ablation effects on hypersonic boundary-layer transition and turbulent heating augmentation	AoA, Reynolds number, cavity diameter/shape	Global heating and BL transition	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS
1.12	Crewed Earth Return from Moon or Gateway							
1.1201	Convective aerothermal (forebody)	(3) boundary-layer characterization, (4) Convective aeroheating environments	Measure BL transition and convective heating distributions on forebody	As-built/flown geometry, Mach, Reynolds, AoA, TPS roughness parameters	TSP, phosphor thermography, thin-film, optical	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS
1.1202	Convective aerothermal (aftbody)	(3) boundary-layer characterization, (4) Convective aeroheating environments	Measure BL transition and convective heating distributions aftbody	As-built/flown geometry, Mach, Reynolds, AoA	TSP, phosphor thermography, thin-film, optical	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS
1.1203	Convective aerothermal/RCS (aftbody)	(3) boundary-layer characterization, (4) Convective aeroheating environments (7) RCS Interactions	Measure RCS interaction heating on aftbody	As-built/flown geometry, Mach, Reynolds, AoA, thruster parameters	TSP, phosphor thermography, thin-film, optical	hypersonic tunnels, high-enthalpy shock/impulse facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B-C, CUBRC LENS
1.13	Crewed Earth Ascent Abort							
1.1301	Supersonic aerodynamic performance	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization. (7) RCS Performance and Interactions	Define supersonic performance including static and dynamic aero, RCS interactions, separation dynamics	Mach, Reynolds, alpha, beta, thruster parameters	Aerodynamic force & moment, surface pressures, flow visualization	Supersonic wind tunnels	LaRC UPWT, ARC UPWT	AEDC VKF Tunnel A
1.1302	Hypersonic aerodynamics performance	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization. (7) RCS Performance and Interactions	Define hypersonic aerodynamic performance	Mach, Reynolds, alpha	Aerodynamic force & moment, surface pressures, flow visualization	Hypersonic wind tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B-C
1.1303	Trans/sub sonic aerodynamics	(19) Transonic aerodynamics						

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2	**NASA Human Mars Operations**							
1.21	Human-rated, high mass Mars entry system: HIAD+SRP architecture							
1.2101	Define static supersonic aerodynamic performance database including payload effects	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF Tunnel A
1.2102	Define dynamic supersonic aerodynamic performance database including payload effects	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, wake flow visualization	Supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF Tunnel A, AF Aberdeen range
1.2103	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization. (7) RCS Performance and Interactions	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll, thruster parameters	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT,	AEDC VKF Tunnel A
1.2104	Define supersonic retro-propulsion (SRP) performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Perform surface pressure, static aero force & moment and flow visualization with SRP on/off	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Surface pressure, flow visualization, static force & moment, SRP plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF Tunnel A
1.2105	Develop hypersonic aerodynamic performance database including payload effects	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2106	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating, (10) High-enthalpy kinetics	Global and/or discrete surface heating measurements	Reynolds number, angle-of-attack	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2107	Determine aeroshell heating augmentation due to flexible TPS scalloping under pressure load	(3) boundary-layer characterization, (4) convective aeroheating	Measure surface temperature and heating distribution to determine TPS deflection effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, TPS scalloping heights	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2108	Determine aftbody and payload heating environments	(4) convective aeroheating, (5) flow-field characterization	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions. Parametric tradeoffs on aeroshell geometry to ensure no impingement on payload	Reynolds number, angle-of-attack. Payload geometry	Global heat transfer, discrete heat transfer	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6,	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2109	Define SRP nozzle-off aeroheating effects	(3) boundary-layer characterization, (4) convective aeroheating	Measure surface temperature and heating distribution SRP nozzle effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, nozzle geometry and location	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2110	Define SRP nozzle-on aeroheating effects	(4) convective aeroheating environments, (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Measure surface temperatures and heating in SRP interaction regions with thrusters on/off to determine augmentation levels	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Global heat transfer and BL transition, flow visualization	supersonic wind tunnel	LaRC UWPT, ARC UPWT	AEDC VKF Tunnel A
1.2111	Define RCS jet/surface interaction effects on heating	(4) convective aeroheating environments, (5) Flow Field Characterization, (7) RCS Performance and Interactions	Measure surface temperatures and heating in RCS interaction regions with thrusters on/off to determine augmentation levels	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Global heat transfer and BL transition, flow visualization	supersonic wind tunnel, hypersonic wind tunnel	LaRC UWPT, ARC UPWT, LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel A, AEDC VKF Tunnel B/C, AEDC Tunnel 9
1.2112	Determine radiative heating environments on aeroshell and payload	(12) Radiative heating environments	Measure radiative heating on aeroshell and aftbody at Mars relevant conditions	shock tube pressure, velocity, gas composition	Integrated and/or spectrally resolved radiative heating	High-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS
1.22	Human-rated, high mass Mars entry system: Mid L/D + SRP architecture							
1.2201	Develop supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA	Surface pressure, flow visualization, static force & moment	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2202	Develop supersonic dynamic aero response to pitch and sideslip	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform dynamic aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA	Surface pressure, flow visualization, dynamic force & moment	supersonic wind tunnel, ballistics ranges	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, CUBRC LENS, Aberdeen range
1.2203	Define supersonic control surface aerodynamic effectiveness	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA, Control deflections	Surface pressure, flow visualization around controls, static force & moment	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
1.2204	Define supersonic RCS performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Perform surface pressure, static aero force & moment and flow visualization with thrusters on/off	Mach, pitch, sideslip, Reynolds, AoA, RCS mass flow	Surface pressure, flow visualization, static force & moment, RCS plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
1.2205	Define supersonic retropropulsion performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Perform surface pressure, static aero force & moment and flow visualization with SRP on/off	Mach, pitch, sideslip, Reynolds, AoA, SRP mass flow	Surface pressure, flow visualization, static force & moment, SRP plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
1.2206	Develop hypersonic aerodynamic database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA	Surface pressure, flow visualization, static force & moment	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
1.2207	Define hypersonic control surface aerodynamic effectiveness	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform dynamic aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA, Control deflections	Surface pressure, flow visualization, static force & moment	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
1.2208	Develop hypersonic smooth-OML acreage convective heating	(3) Boundary-layer characterization (4) convective aeroheating environments, (10) High-enthalpy kinetics	Perform surface heating and BL transition measurements	Mach, Reynolds, enthalpy, AoA	global / discrete surface heating and BL onset	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
1.2209	Define TPS roughness effects on BL transition and aeroheating	(3) Boundary-layer characterization (4) convective aeroheating environments	Perform surface heating and BL transition measurements	Mach, Reynolds, enthalpy, AoA, roughness height/type	global / discrete surface heating and BL onset	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10, ARC HFFAF	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
1.2210	Define control surface convective heating environments	(3) Boundary-layer characterization (4) convective aeroheating environments, (10) High-enthalpy kinetics	Perform surface heating and BL transition measurements and flow field visualization	Mach, Reynolds, enthalpy, AoA, control deflections	global / discrete surface heating and BL onset, flow visualization around controls	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
1.2211	Define SRP nozzle-off aeroheating effects	(3) Boundary-layer characterization (4) convective aeroheating environments, (10) High-enthalpy kinetic	Perform surface heating and BL transition measurements	Mach, Reynolds, enthalpy, AoA	global / discrete surface heating and BL onset	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2212	Define RCS jet/surface interaction effects on heating	(4) convective aeroheating environments, (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions, (10) High-enthalpy kinetic	Perform surface heating in plume interaction areas and visualize plume shapes	Mach, Reynolds, AoA, RCS firing parameters	global / discrete surface heating, schlieren and PLIF flow visualization	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
1.2213	Develop acreage radiative heating database	(12) Radiative heating environments	perform surface radiative heating measurements and/or shock tube fundamental diagnostics	Velocity, pressure, composition, AoA	surface radiative heating, shock layer optical/spectral diagnostics	High-enthalpy shock/impulse facility, shock tube	ARC EAST	CUBRC LENS
1.2214	Determine effects of TPS material catalytic on heating	(4) convective aeroheating environments, (10) High-enthalpy kinetics			Discrete/global heat transfer	High-enthalpy tunnel, arc-jet, shock-tube		
1.23	Human-rated, high mass Mars entry system: Deployable + SRP architecture							
1.2301	Define static supersonic aerodynamic performance database including payload effects	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF Tunnel A
1.2302	Define dynamic supersonic aerodynamic performance database including payload effects	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, wake flow visualization	Supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF Tunnel A, AF Aberdeen range
1.2303	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization. (7) RCS Performance and Interactions	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll, thruster parameters	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT,	AEDC VKF Tunnel A

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2304	Define supersonic retro-propulsion (SRP) performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Perform surface pressure, static aero force & moment and flow visualization with SRP on/off	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Surface pressure, flow visualization, static force & moment, SRP plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF Tunnel A
1.2305	Develop hypersonic aerodynamic performance database including payload effects	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2306	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating, (10) High-enthalpy kinetics	Global and/or discrete surface heating measurements	Reynolds number, angle-of-attack	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2307	Determine aeroshell heating augmentation due to TPS roughness	(3) boundary-layer characterization, (4) convective aeroheating	Measure surface temperature and heating distribution to determine TPS deflection effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, TPS scalloping heights	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2308	Determine aftbody and payload heating environments	(4) convective aeroheating, (5) flow-field characterization	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions. Parametric tradeoffs on aeroshell geometry to ensure no impingement on payload	Reynolds number, angle-of-attack. Payload geometry	Global heat transfer, discrete heat transfer	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6,	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2309	Define SRP nozzle-off aeroheating effects	(3) boundary-layer characterization, (4) convective aeroheating	Measure surface temperature and heating distribution SRP nozzle effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, nozzle geometry and location	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2310	Define SRP nozzle-on aeroheating effects	(4) convective aeroheating environments, (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Measure surface temperatures and heating in SRP interaction regions with thrusters on/off to determine augmentation levels	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Global heat transfer and BL transition, flow visualization	supersonic wind tunnel	LaRC UWPT, ARC UPWT	AEDC VKF Tunnel A

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2311	Define RCS jet/surface interaction effects on heating	(4) convective aeroheating environments, (5) Flow Field Characterization, (7) RCS Performance and Interactions	Measure surface temperatures and heating in RCS interaction regions with thrusters on/off to determine augmentation levels	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Global heat transfer and BL transition, flow visualization	supersonic wind tunnel, hypersonic wind tunnel	LaRC UWPT, ARC UPWT, LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel A, AEDC VKF Tunnel B/C, AEDC Tunnel 9
1.2312	Determine radiative heating environments on aeroshell and payload	(12) Radiative heating environments	Measure radiative heating on aeroshell and aftbody at Mars relevant conditions	shock tube pressure, velocity, gas composition	Integrated and/or spectrally resolved radiative heating	High-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS
1.24	Human-rated, high mass Mars entry system: Capsule + SRP architecture							
1.2401	Define static supersonic aerodynamic performance database including aftbody effects	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF Tunnel A
1.2402	Define dynamic supersonic aerodynamic performance database including payload effects	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, wake flow visualization	Supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF Tunnel A, AF Aberdeen range
1.2403	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization. (7) RCS Performance and Interactions	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll, thruster parameters	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT,	AEDC VKF Tunnel A
1.2404	Define supersonic retro-propulsion (SRP) performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Perform surface pressure, static aero force & moment and flow visualization with SRP on/off	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Surface pressure, flow visualization, static force & moment, SRP plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF Tunnel A

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2405	Develop hypersonic aerodynamic performance database including aftbody effects	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, roll	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2406	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating, (10) High-enthalpy kinetics	Global and/or discrete surface heating measurements	Reynolds number, angle-of-attack	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2407	Determine aeroshell heating augmentation due to TPS roughness	(3) boundary-layer characterization, (4) convective aeroheating	Measure surface temperature and heating distribution to determine TPS deflection effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, TPS scalloping heights	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2408	Determine aftbody heating environments	(4) convective aeroheating, (5) flow-field characterization	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions. Parametric tradeoffs on aeroshell geometry to ensure no impingement on payload	Reynolds number, angle-of-attack. Payload geometry	Global heat transfer, discrete heat transfer	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6,	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2409	Define SRP nozzle-off aeroheating effects	(3) boundary-layer characterization, (4) convective aeroheating	Measure surface temperature and heating distribution SRP nozzle effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, nozzle geometry and location	Global heat transfer and BL transition	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
1.2410	Define SRP nozzle-on aeroheating effects	(4) convective aeroheating environments, (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Measure surface temperatures and heating in SRP interaction regions with thrusters on/off to determine augmentation levels	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Global heat transfer and BL transition, flow visualization	supersonic wind tunnel	LaRC UWPT, ARC UPWT	AEDC VKF Tunnel A
1.2411	Define RCS jet/surface interaction effects on heating	(4) convective aeroheating environments, (5) Flow Field Characterization, (7) RCS Performance and Interactions	Measure surface temperatures and heating in RCS interaction regions with thrusters on/off to determine augmentation levels	Mach, pitch, sideslip, Reynolds, AoA, SRP parameters	Global heat transfer and BL transition, flow visualization	supersonic wind tunnel, hypersonic wind tunnel	LaRC UWPT, ARC UPWT, LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel A, AEDC VKF Tunnel B/C, AEDC Tunnel 9

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2412	Determine radiative heating environments on aeroshell and payload	(12) Radiative heating environments	Measure radiative heating on aeroshell and aftbody at Mars relevant conditions	shock tube pressure, velocity, gas composition	Integrated and/or spectrally resolved radiative heating	High-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS
1.25	Mars Ascent Vehicle							
1.2501	Hypersonic aerodynamic performance	(1) Hypersonic aerodynamics, (5) flow-field characterizations (7) RCS performance	quantify hypersonic aerodynamic performance including RCS & propulsion interactions	Mach, Re, alpha, beta	Force and moment, pressure, visualization	High-enthalpy shock/impulse facility, hypersonic wind tunnels	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel A, AEDC VKF Tunnel B/C, AEDC Tunnel 9, CUBRC LENS
1.2502	Supersonic aerodynamic performance	(2) Supersonic aerodynamics, (5) flow-field characterizations (7) RCS performance	quantify supersonic aerodynamic performance including RCS & propulsion interactions	Mach, Re, alpha, beta	Force and moment, pressure, visualization	Supersonic wind tunnels	LaRC UWPT, ARC UPWT,	AEDC VKF Tunnel A
1.2503	Convective aerothermal	(3) boundary-layer characterization (4) convective aeroheating, (5) flow-field characterization	quantify aeroheating environments including BL transition and RCS/surface interactions	Mach, Re, alpha, beta	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility, hypersonic wind tunnels	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel A, AEDC VKF Tunnel B/C, AEDC Tunnel 9, CUBRC LENS
1.26	Human Mars Mission Earth Return Vehicle							
1.2601	Hypersonic aerodynamic performance	(1) Hypersonic aerodynamics, (5) flow-field characterizations	quantify hypersonic aerodynamic performance	Mach, Re, alpha, beta	Force and moment, pressure, visualization	High-enthalpy shock/impulse facility, hypersonic wind tunnels	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel B/C, AEDC Tunnel 9, CUBRC LENS
1.2602	Supersonic aerodynamic performance	(2) Supersonic aerodynamics, (5) flow-field characterizations	quantify supersonic aerodynamic performance	Mach, Re, alpha	Force and moment, pressure, visualization	Supersonic wind tunnels	LaRC UWPT, ARC UPWT,	AEDC VKF Tunnel A
1.2603	Convective aerothermal: aeroshell Baseline environments)	(3) boundary-layer characterization (4) convective aeroheating, (5) flow-field characterization	quantify aeroheating environments including BL transition and RCS/surface interactions	Mach, Re, alpha	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility, hypersonic wind tunnels	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel B/C, AEDC Tunnel 9, CUBRC LENS
1.2604	Convective aerothermal aeroshell TPS roughness, transition, features	(3) boundary-layer characterization (4) convective aeroheating, (5) flow-field characterization	quantify aeroheating environments including BL transition and RCS/surface interactions	Mach, Re, alpha, TPS roughness parameters	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility, hypersonic wind tunnels	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel B/C, AEDC Tunnel 9, CUBRC LENS
1.2605	Convective aerothermal: aftbody baseline environments	(3) boundary-layer characterization (4) convective aeroheating, (5) flow-field characterization	quantify aeroheating environments including BL transition and RCS/surface interactions	Mach, Re, alpha	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility, hypersonic wind tunnels	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel B/C, AEDC Tunnel 9, CUBRC LENS
1.2606	High-enthalpy aerothermal chemical-kinetic effects	4) convective aeroheating, (10) high-enthalpy kinetics	determine high-enthalpy kinetic effects on aeroheating	Reynolds, enthalpy	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility	none	CUBRC LENS
1.2607	Shock-layer radiative aerothermal effects	(12) shock-layer radiation	define shock-layer radiation environments	gas composition, velocity, pressure	Emission spectroscopy	High-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.2608	RCS interaction aerodynamics	(2) Supersonic aerodynamics, (5) flow-field characterizations (7) RCS performance	quantify supersonic RCS aero interactions	Mach, Re, alpha, beta, thruster parameters	Force and moment, pressure, visualization	Supersonic wind tunnels	LaRC UWPT, ARC UPWT,	AEDC VKF Tunnel A
1.2609	RCS interaction aeroheating	(4) convective aeroheating (7) RCS performance	quantify supersonic RCS heating interactions	Mach, Re, alpha, beta, thruster parameters	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility, hypersonic wind tunnels	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnel B/C, AEDC Tunnel 9, CUBRC LENS
1.3	**Commercial Systems**							
1.31	Commercial LEO system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3101	Supersonic / hypersonic aerodynamics	(1) Hypersonic Aerodynamics (2) Supersonic aerodynamics, (5) flow-field characterizations (7) RCS performance	define aerodynamic performance and environments	Mach, Reynolds, alpha, beta, RCS parameters	Force and moment, pressure, visualization	High-enthalpy shock/impulse facility, hypersonic wind tunnels, supersonic wind tunnels	LaRC UWPT, ARC UPWT, LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS
1.3102	Hypersonic aeroheating and BLT	(3) boundary-layer characterization (4) convective aeroheating, 10) high-enthalpy kinetics	define aeroheating performance and environments	Reynolds, enthalpy, alpha, TPS parameters	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility, hypersonic wind tunnels	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS
1.32	Commercial LEO system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3201	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1
1.3202	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1
1.33	Commercial Lunar system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3301	Supersonic / hypersonic aerodynamics	(1) Hypersonic Aerodynamics (2) Supersonic aerodynamics, (5) flow-field characterizations (7) RCS performance	define aerodynamic performance and environments	Mach, Reynolds, alpha, beta, RCS parameters	Force and moment, pressure, visualization	High-enthalpy shock/impulse facility, hypersonic wind tunnels, supersonic wind tunnels	LaRC UWPT, ARC UPWT, LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS
1.3302	Hypersonic aeroheating and BLT	(3) boundary-layer characterization (4) convective aeroheating, 10) high-enthalpy kinetics	define aeroheating performance and environments	Reynolds, enthalpy, alpha, TPS parameters	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility, hypersonic wind tunnels	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
1.34	Commercial Lunar system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3401	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1
1.3402	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1
1.35	Commercial Mars system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3501	Supersonic / hypersonic aerodynamics	(1) Hypersonic Aerodynamics (2) Supersonic aerodynamics, (5) flow-field characterizations (7) RCS performance	define aerodynamic performance and environments	Mach, Reynolds, alpha, beta, RCS parameters	Force and moment, pressure, visualization	High-enthalpy shock/impulse facility, hypersonic wind tunnels, supersonic wind tunnels	LaRC UWPT, ARC UPWT, LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS
1.3502	Hypersonic aeroheating and BLT	(3) boundary-layer characterization (4) convective aeroheating, 10) high-enthalpy kinetics	define aeroheating performance and environments	Reynolds, enthalpy, alpha, TPS parameters	TSP, phosphor thermography, thin-film, optical	High-enthalpy shock/impulse facility, hypersonic wind tunnels	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS	AEDC VKF Tunnels A/B/C, AEDC Tunnel 9, CUBRC LENS
1.36	Commercial Mars system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3601	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1
1.3602	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1
1.4	**Uncrewed Support Systems**							
1.41	Uncrewed support system #1							
1.4101	Supersonic / hypersonic aerodynamics	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1.4102	Hypersonic aeroheating and BLT	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1.42	Uncrewed support system #2							
1.4201	Supersonic / hypersonic aerodynamics	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1.4202	Hypersonic aeroheating and BLT	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Table 26. Test Requirements for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1	**NASA and Commercial Human-Rated Exploration**							
1.1	**NASA Human-Rated Earth Operations**							
1.11	Crewed Earth Return from LEO							
1.1101	Post-flight assessment for comparison / evaluation of fight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data
1.1102	Develop hypersonic aerodynamic performance database	Sufficient enthalpy to produce chemical kinetic effects, sufficient Reynolds number range to span laminar-turbulent conditions					measure static aerodynamics with force-and-moment balances	Metallic force & moment model
1.1103	Develop supersonic aerodynamic performance	Supersonic M2-M4 with wide range of Reynolds numbers					measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
1.1104	Determine aeroshell baseline acreage aeroheating environments	Facility with operational Reynolds number range to produce laminar-to-turbulent flow on smooth model					global and/or discrete heating measurements, global transition onset measurements	cast ceramic model for NASA testing, metallic model for non-NASA testing
1.1105	Determine vehicle radiative aeroheating environments	Facility with sufficient enthalpy to produce shock-layer radiation					Integrated and spectrally resolved radiative heat flux measurements	Metallic models with embedded radiative heat-flux sensors
1.1106	Determine aftbody baseline acreage aeroheating environments	Facility with operational Reynolds number range to produce laminar-to-turbulent flow on smooth model					Low temperature heating measurements for wake/aftbody, precision resolution of aftbody features	Cast ceramic models for NASA testing, metallic model for non-NASA testing
1.1107	Determine RCS interaction effects on aftbody heating and aerodynamics	Facility with operational range to generate relevant wake-flow conditions					Low temperature heating measurements for wake/aftbody, precision resolution of RCS interaction regions	Models with internal plumbing for high-pressure gas delivery to RCS nozzles
1.1108	Determine TPS effects on aeroshell boundary-layer transition and turbulent aeroheating augmentation	Facility with operational Reynolds number range to produce laminar-to-turbulent flow at roughness scales					Global and/or discrete heating and BL transition measurements	cast ceramic model for NASA testing, metallic model for non-NASA testing

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.1109	Determine compression pad cavity effects on localized heating and boundary-layer transition	Facility with operational Reynolds number range to produce laminar-to-turbulent flow at roughness scales					Global and/or discrete heating and BL transition measurements	cast ceramic model for NASA testing, metallic model for non-NASA testing
1.12	Crewed Earth Return from Moon or Gateway							
1.1201	Convective aerothermal (forebody)	Flight relevant Reynolds/enthalpy ranges		2-4 weeks		2-4 weeks	Global and/or discrete heating and BL transition measurements	cast ceramic model for NASA testing, metallic model for non-NASA testing
1.1202	Convective aerothermal (aftbody)	Flight relevant Reynolds/enthalpy ranges		2-4 weeks		2-4 weeks	Global and/or discrete heating and BL transition measurements	cast ceramic model for NASA testing, metallic model for non-NASA testing
1.1203	Convective aerothermal/RCS (aftbody)	Flight relevant Reynolds/enthalpy ranges		2-4 weeks		2-4 weeks	Global and/or discrete heating and BL transition measurements	cast ceramic model for NASA testing, metallic model for non-NASA testing
1.13	Crewed Earth Ascent Abort							
1.1301	Supersonic aerodynamic performance	Flight relevant Mach / Reynolds range		Assume ~ 2-4 months based on Orion project requirements		Assume ~ 2-4 months based on Orion project requirements	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
1.1302	Hypersonic aerodynamics performance	Flight relevant Reynolds number range, high-enthalpy air		Assume ~ 2-4 weeks based on Orion project requirements		Assume ~ 2-4 weeks based on Orion project requirements	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
1.1303	Trans/sub sonic aerodynamics			many months				
1.2	**NASA Human Mars Operations**							
1.21	Human-rated, high mass Mars entry system: HIAD+SRP architecture							
1.2101	Define static supersonic aerodynamic performance database including payload effects	Supersonic with wide range of Reynolds numbers, CO2 capability	Multiple AoA, Mach, Re points	4 weeks	Multiple AoA, Mach, Re points	4 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
1.2102	Define dynamic supersonic aerodynamic performance database including payload effects	Supersonic with wide range of Reynolds numbers, CO2 capability	Multiple AoA, Mach, Re points	4 weeks	Multiple AoA, Mach, Re points	4 weeks	measure dynamic aerodynamics with force-and-moment balances or free-flight range video	Metallic force & moment model fabrication

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.2103	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Supersonic with wide range of Reynolds numbers	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	8 weeks	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	8 weeks	Global and/or discrete surface pressure measurement. High-speed laser and schlieren systems for flow field diagnostics. High-pressure gas delivery to RCS jets	Metallic force & moment models with active blowing from RCS nozzles
1.2104	Define supersonic retro-propulsion (SRP) performance and interactions	CO2 for compressibility effects on aero, flight-relevant Mach/Re range, mass flow for SRP firing	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	12 weeks	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	12 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from SRP nozzles
1.2105	Develop hypersonic aerodynamic performance database including payload effects	Hypersonic conditions with high-enthalpy CO2	Multiple AoA, Mach, Reynolds, roll	3 weeks	Multiple AoA, Mach, Reynolds	3 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
1.2106	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions and high-enthalpy CO2 test capability	Reynolds number, AoA	2 weeks	Reynolds number, AoA	2 weeks	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
1.2107	Determine aeroshell heating augmentation due to flexible TPS scalloping under pressure load	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Test core sufficient to allow accurate simulation of TPS deflections heights	Reynolds number, AoA, TPS scalloping heights	6 weeks	Reynolds number, AoA, TPS scalloping heights	6 weeks	global optical techniques for measurement of heating distributions and BL transition onset	ability to replicate scalloped OML in cast ceramic or machined metal
1.2108	Determine aftbody and payload heating environments	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. Rapid turnaround time for multiple aeroshell/payload configuration changes	3 AoA over range of 0-10-deg, 4 Reynolds numbers over laminar-to-turbulent ranges. 3 aeroshell geometries	LaRC 31InM10 = 36 runs / 9 days.	3 AoA over range of 0-10-deg, 4 Reynolds numbers over laminar-to-turbulent ranges. 3 aeroshell geometries	AEDC T9 (continuous sweep) = 12 runs/ 6 days. CUBRC = 36 runs / 18 days	Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors	cast ceramic or machined metallic models
1.2109	Define SRP nozzle-off aeroheating effects	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Test core sufficient to allow accurate simulation of SRP nozzle geometry	Reynolds number, AoA, nozzle parameters	2 weeks	Reynolds number, AoA, nozzle parameters	2 weeks	global optical techniques for measurement of heating distributions and BL transition onset	ability to replicate nozzles in cast ceramic or machined metal

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.2110	Define SRP nozzle-on aeroheating effects	supersonic facility with CO2 for compressibility effects on aero, flight-relevant Mach/Re range, mass flow for SRP firing	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	6 weeks	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	6 weeks	global optical techniques for measurement of heating distributions and BL transition onset, PLIF and schlieren for flow visualization	Metallic force & moment models with active blowing from SRP nozzles
1.2111	Define RCS jet/surface interaction effects on heating	Supersonic and/or hypersonic tunnels with CO2 for compressibility effects on flow field, Mach/Re relevant range, mass flow rates for RCS firings	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	4 weeks	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	4 weeks	global optical techniques for measurement of heating distributions and BL transition onset, PLIF and schlieren for flow visualization	Metallic force & moment models with active blowing from RCS nozzles
1.2112	Determine radiative heating environments on aeroshell and payload	Facility with sufficient enthalpy to produce shock-layer radiation in CO2	multiple pressure, velocity, species points	3 weeks	multiple pressure, velocity, species points	3 weeks	spectral and flow field diagnostics	N/A
1.22	Human-rated, high mass Mars entry system: Mid L/D + SRP architecture							
1.2201	Develop supersonic static aerodynamic performance database	CO2 for compressibility effects on aero, flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points	Assume cont. AoA sweep, 27 runs = 1 weeks	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points	AEDC assumes cont. AoA sweep, 27 runs = 1 weeks. CUBRC 145 points = 15 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models
1.2202	Develop supersonic dynamic aero response to pitch and sideslip	CO2 for compressibility effects on aero, flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points in UPWT. 10 shots (AoA limited) in HFFAF	UPWT Assume cont. AoA sweep, 27 runs = 1 weeks. HFFAF = 2 weeks	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points in UPWT. 10 shots (AoA limited) in Aberdeen	AEDC assumes cont. AoA sweep, 27 runs = 1 weeks. CUBRC 145 points = 15 weeks. 10 shots (AoA limited) in Aberdeen	dynamic force & moment balances or range photography, discrete surface pressure	Metallic force & moment models
1.2203	Define supersonic control surface aerodynamic effectiveness	CO2 for compressibility effects on aero, flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 450 points	UPWT assume cont. AoA sweep, 90 runs = 4 weeks	3 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 450 points	AEDC assume cont. AoA sweep, 90 runs = 4 weeks. CUBRC 450 points = 45 weeks	static force & moment balances, schlieren, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with interchangeable or moveable control surfaces
1.2204	Define supersonic RCS performance and interactions	CO2 for compressibility effects on aero, flight-relevant Mach/Re range, mass flow for RCS firing	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	UPWT assume cont. AoA sweep, 45 runs = 2 weeks	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from RCS
1.2205	Define supersonic retropropulsion performance and interactions	CO2 for compressibility effects on aero, flight-relevant Mach/Re range, mass flow for SRP firing	3 x Mach x 3 Re x 5 AoA x 5 SRP firing parameters pairings = 175 points	UPWT assume cont. AoA sweep, 45 runs = 2 weeks	3 x Mach x 3 Re x 5 AoA x 5 SRP firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from SRP
1.2206	Develop hypersonic aerodynamic database	High-enthalpy for CO2 kinetic effects on heating, flight-relevant Mach/re range	2 x Mach x 5 AoA x 3 slip x 5 AoA = 150 points	Assume cont. AoA sweep, 30 runs = 1 weeks	2 x Mach/enthalpy x 5 AoA x 3 slip x 5 AoA = 150 points	AEDC Assume cont. AoA sweep, 30 runs = 1 weeks. CUBRC 30 shots = 4 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.2207	Define hypersonic control surface aerodynamic effectiveness	High-enthalpy for CO2 kinetic effects on heating, flight-relevant Mach/re range	2 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 300 points	Assume cont. AoA sweep 60 runs = 2 weeks	2 x Mach/enthalpy x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 300 points	AEDC assume cont. AoA sweep, 60 runs = 6 weeks. CUBRC 300 points = 30 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models with interchangeable or moveable control surfaces
1.2208	Develop hypersonic smooth-OML acreage convective heating	High-enthalpy for CO2 kinetic effects on heating, flight-relevant Mach/re range	5 x Re x 3 AoA x 2 slip = 30 points	30 runs = 1 weeks	5 Mach/enthalpy x 3 AoA x 2 slip = 30 points	AEDC assume continuous pitch, 10 runs = 1 weeks. CUBRC 30 runs = 3 weeks	global optical and/or discrete surface heating	instrumented metallic or cast ceramic heating models
1.2209	Define TPS roughness effects on BL transition and aeroheating	High-enthalpy for CO2 kinetic effects on heating, flight-relevant Mach/re range	5 x Re x 3 AoA x 5 roughness parameters = 45 points	45 runs = 2 weeks at LaRC or 3 weeks at ARC HFFAF	5 x Re x 3 AoA x 5 roughness parameters = 45 points	AEDC assume cont. pitch 15 points = 2 weeks. CUBRC 45 points = 4 weeks	global optical and/or discrete surface heating	instrumented metallic or cast ceramic heating models with precision, small-scale roughness elements
1.221	Define control surface convective heating environments	High-enthalpy for CO2 kinetic effects on heating, flight-relevant Mach/re range	5 x Re x 3 AoA x 5 control deflections = 45 points	45 runs = 2 weeks	5 x Re x 3 AoA x 5 control deflections = 45 points	AEDC assume cont. pitch 15 points = 2 weeks. CUBRC 45 points = 4 weeks	global optical and/or discrete surface heating. Small-scale discrete gages required between/under split flaps	instrumented metallic or cast ceramic heating models
1.2211	Define SRP nozzle-off aeroheating effects	High-enthalpy for CO2 kinetic effects on heating, flight-relevant Mach/re range	5 x Re x 3 AoA x 5 nozzle parameters = 45 points	45 runs = 2 weeks	5 x Re x 3 AoA x 5 nozzle parameters = 45 points	AEDC assume cont. pitch 15 points = 2 weeks. CUBRC 45 points = 4 weeks	global optical and/or discrete surface heating. Small-scale discrete gages in/around SRP nozzles	instrumented metallic or cast ceramic heating models
1.2212	Define RCS jet/surface interaction effects on heating	High-enthalpy for CO2 kinetic effects on heating, flight-relevant Mach/re range	3 x Mach x 3 Re x 5 AoA x 5 SRP firing parameters pairings = 175 points	175 runs = 6 weeks	3 x Mach/enthalpy x 3 Re x 5 AoA x 5 SRP firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	global optical and/or discrete surface heating	instrumented metallic or cast ceramic heating models with active blowing from RCS
1.2213	Develop acreage radiative heating database	CO2 test gas for radiative properties, flight-relevant velocity/pressure range	3 velocity x 3 pressure x 3 composition for unit testing = 27 points	27 points = 2 weeks	3 x Mach/enthalpy x 3 Re x 3 composition 27 points	27 points = 3 weeks	sensors with appropriate spectral range	instrumented metallic model
1.221	Determine effects of TPS material catalytic on heating							
1.23	Human-rated, high mass Mars entry system: Deployable + SRP architecture							
1.2301	Define static supersonic aerodynamic performance database including payload effects	Supersonic with wide range of Reynolds numbers, CO2 capability	Multiple AoA, Mach, Re points	4 weeks	Multiple AoA, Mach, Re points	4 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
1.2302	Define dynamic supersonic aerodynamic performance database including payload effects	Supersonic with wide range of Reynolds numbers, CO2 capability	Multiple AoA, Mach, Re points	4 weeks	Multiple AoA, Mach, Re points	4 weeks	measure dynamic aerodynamics with force-and-moment balances or free-flight range video	Metallic force & moment model fabrication

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.2303	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Supersonic with wide range of Reynolds numbers	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	8 weeks	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	8 weeks	Global and/or discrete surface pressure measurement. High-speed laser and schlieren systems for flow field diagnostics. High-pressure gas delivery to RCS jets	Metallic force & moment models with active blowing from RCS nozzles
1.2304	Define supersonic retro-propulsion (SRP) performance and interactions	CO2 for compressibility effects on aero, flight-relevant Mach/Re range, mass flow for SRP firing	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	12 weeks	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	12 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from SRP nozzles
1.2305	Develop hypersonic aerodynamic performance database including payload effects	Hypersonic conditions with high-enthalpy CO2	Multiple AoA, Mach, Reynolds, roll	3 weeks	Multiple AoA, Mach, Reynolds	3 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
1.2306	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions and high-enthalpy CO2 test capability	Reynolds number, AoA	2 weeks	Reynolds number, AoA	2 weeks	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
1.2307	Determine aeroshell heating augmentation due to TPS roughness	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Test core sufficient to allow accurate simulation of TPS roughness heights	Reynolds number, AoA, TPS scalloping heights	6 weeks	Reynolds number, AoA, TPS scalloping heights	6 weeks	global optical techniques for measurement of heating distributions and BL transition onset	ability to replicate scalloped OML in cast ceramic or machined metal
1.2308	Determine aftbody and payload heating environments	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. Rapid turnaround time for multiple aeroshell/payload configuration changes	3 AoA over range of 0-10-deg, 4 Reynolds numbers over laminar-to-turbulent ranges. 3 aeroshell geometries	LaRC 31InM10 = 36 runs / 9 days.	3 AoA over range of 0-10-deg, 4 Reynolds numbers over laminar-to-turbulent ranges. 3 aeroshell geometries	AEDC T9 (continuous sweep) = 12 runs/ 6 days. CUBRC = 36 runs / 18 days	Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors	cast ceramic or machined metallic models
1.2309	Define SRP nozzle-off aeroheating effects	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Test core sufficient to allow accurate simulation of SRP nozzle geometry	Reynolds number, AoA, nozzle parameters	2 weeks	Reynolds number, AoA, nozzle parameters	2 weeks	global optical techniques for measurement of heating distributions and BL transition onset	ability to replicate nozzles in cast ceramic or machined metal

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.2310	Define SRP nozzle-on aeroheating effects	supersonic facility with CO2 for compressibility effects on aero, flight-relevant Mach/Re range, mass flow for SRP firing	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	6 weeks	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	6 weeks	global optical techniques for measurement of heating distributions and BL transition onset, PLIF and schlieren for flow visualization	Metallic force & moment models with active blowing from SRP nozzles
1.2311	Define RCS jet/surface interaction effects on heating	Supersonic and/or hypersonic tunnels with CO2 for compressibility effects on flow field, Mach/Re relevant range, mass flow rates for RCS firings	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	4 weeks	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	4 weeks	global optical techniques for measurement of heating distributions and BL transition onset, PLIF and schlieren for flow visualization	Metallic force & moment models with active blowing from RCS nozzles
1.2312	Determine radiative heating environments on aeroshell and payload	Facility with sufficient enthalpy to produce shock-layer radiation in CO2	multiple pressure, velocity, species points	3 weeks	multiple pressure, velocity, species points	3 weeks	spectral and flow field diagnostics	N/A
1.24	Human-rated, high mass Mars entry system: Capsule + SRP architecture							
1.2401	Define static supersonic aerodynamic performance database including aftbody effects	Supersonic with wide range of Reynolds numbers, CO2 capability	Multiple AoA, Mach, Re points	4 weeks	Multiple AoA, Mach, Re points	4 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
1.2402	Define dynamic supersonic aerodynamic performance database including payload effects	Supersonic with wide range of Reynolds numbers, CO2 capability	Multiple AoA, Mach, Re points	4 weeks	Multiple AoA, Mach, Re points	4 weeks	measure dynamic aerodynamics with force-and-moment balances or free-flight range video	Metallic force & moment model fabrication
1.2403	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Supersonic with wide range of Reynolds numbers	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	8 weeks	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	8 weeks	Global and/or discrete surface pressure measurement. High-speed laser and schlieren systems for flow field diagnostics. High-pressure gas delivery to RCS jets	Metallic force & moment models with active blowing from RCS nozzles
1.2404	Define supersonic retro-propulsion (SRP) performance and interactions	CO2 for compressibility effects on aero, flight-relevant Mach/Re range, mass flow for SRP firing	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	12 weeks	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	12 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from SRP nozzles
1.2405	Develop hypersonic aerodynamic performance database including aftbody effects	Hypersonic conditions with high-enthalpy CO2	Multiple AoA, Mach, Reynolds, roll	3 weeks	Multiple AoA, Mach, Reynolds	3 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.2406	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions and high-enthalpy CO2 test capability	Reynolds number, AoA	2 weeks	Reynolds number, AoA	2 weeks	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
1.2407	Determine aeroshell heating augmentation due to TPS roughness	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Test core sufficient to allow accurate simulation of TPS roughness heights	Reynolds number, AoA, TPS scalloping heights	6 weeks	Reynolds number, AoA, TPS scalloping heights	6 weeks	global optical techniques for measurement of heating distributions and BL transition onset	ability to replicate scalloped OML in cast ceramic or machined metal
1.2408	Determine aftbody heating environments	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. Rapid turnaround time for multiple aeroshell/payload configuration changes	3 AoA over range of 0-10-deg, 4 Reynolds numbers over laminar-to-turbulent ranges. 3 aeroshell geometries	LaRC 31InM10 = 36 runs / 9 days.	3 AoA over range of 0-10-deg, 4 Reynolds numbers over laminar-to-turbulent ranges. 3 aeroshell geometries	AEDC T9 (continuous sweep) = 12 runs/ 6 days. CUBRC = 36 runs / 18 days	Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors	cast ceramic or machined metallic models
1.2409	Define SRP nozzle-off aeroheating effects	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Test core sufficient to allow accurate simulation of SRP nozzle geometry	Reynolds number, AoA, nozzle parameters	2 weeks	Reynolds number, AoA, nozzle parameters	2 weeks	global optical techniques for measurement of heating distributions and BL transition onset	ability to replicate nozzles in cast ceramic or machined metal
1.2410	Define SRP nozzle-on aeroheating effects	supersonic facility with CO2 for compressibility effects on aero, flight-relevant Mach/Re range, mass flow for SRP firing	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	6 weeks	Multiple AoA, Mach, Re points, SRP mass flow rates and thruster pairings	6 weeks	global optical techniques for measurement of heating distributions and BL transition onset, PLIF and schlieren for flow visualization	Metallic force & moment models with active blowing from SRP nozzles
1.2411	Define RCS jet/surface interaction effects on heating	Supersonic and/or hypersonic tunnels with CO2 for compressibility effects on flow field, Mach/Re relevant range, mass flow rates for RCS firings	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	4 weeks	Multiple AoA, Mach, Re points, RCS mass flow rates and thruster pairings	4 weeks	global optical techniques for measurement of heating distributions and BL transition onset, PLIF and schlieren for flow visualization	Metallic force & moment models with active blowing from RCS nozzles
1.2412	Determine radiative heating environments on aeroshell and payload	Facility with sufficient enthalpy to produce shock-layer radiation in CO2	multiple pressure, velocity, species points	3 weeks	multiple pressure, velocity, species points	3 weeks	spectral and flow field diagnostics	N/A

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.25	Mars Ascent Vehicle							
1.2501	Hypersonic aerodynamic performance	flight relevant Reynolds number and enthalpy	TBD	2-4 weeks	TBD	2-4 weeks	measure static aerodynamics with force-and-moment balances	machined metal models
1.2502	Supersonic aerodynamic performance	flight relevant Reynolds number and enthalpy	TBD	2-4 weeks	TBD	2-4 weeks	measure static aerodynamics with force-and-moment balances	machined metal models
1.2503	Convective aerothermal	flight relevant Reynolds number and enthalpy	TBD	2-4 weeks	TBD	2-4 weeks	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
1.26	Human Mars Mission Earth Return Vehicle							
1.2601	Hypersonic aerodynamic performance	flight relevant Reynolds number and Mach	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	1 month		1 month	force-and-moment balances, surface pressure, flow visualization	machined metallic models
1.2602	Supersonic aerodynamic performance	flight relevant Reynolds number and Mach	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	2 months		2 months	force-and-moment balances, surface pressure, flow visualization	machined metallic models
1.2603	Convective aerothermal: aeroshell Baseline environments)	flight relevant Reynolds number and enthalpy	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	2 months		2 months	Global optical surface and/or discrete heating measurements	cast ceramic or machined metallic models
1.2604	Convective aerothermal aeroshell TPS roughness, transition, features	flight relevant Reynolds number and enthalpy	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	2-4 months		2-4 months	Global optical surface and/or discrete heating measurements	cast ceramic or machined metallic models
1.2605	Convective aerothermal: aftbody baseline environments	flight relevant Reynolds number and enthalpy	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	2-4 months		2-4 months	Global optical surface and/or discrete heating measurements	cast ceramic or machined metallic models
1.2606	High-enthalpy aerothermal chemical-kinetic effects	flight relevant Reynolds number and enthalpy	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	1 month		1 month	Global optical surface and/or discrete heating measurements	cast ceramic or machined metallic models
1.2607	Shock-layer radiative aerothermal effects	flight relevant pressure and velocity	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	1 months		1 months	shock tube diagnostic instrumentation	none

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.2608	RCS interaction aerodynamics	flight relevant Reynolds number and Mach	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	2-4 months		2-4 months	force-and-moment balances, surface pressure, flow visualization	machined metallic models with sufficient fidelity for RCS nozzle operation
1.2609	RCS interaction aeroheating	flight relevant Reynolds number and Mach	TBD depending on configuration - extrapolating for Orion/Artemis program requirements	2-4 months		2-4 months	Global optical surface and/or discrete heating measurements	machined metallic models with sufficient fidelity for RCS nozzle operation
1.3	**Commercial Systems**							
1.31	Commercial LEO system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3101	Supersonic / hypersonic aerodynamics	flight relevant test conditions	TBD	1-2 months	TBD	1-2 months	force-and-moment balances, surface pressure, flow visualization	machined metallic models
1.3102	Hypersonic aeroheating and BLT	flight relevant test conditions	TBD	1-2 months	TBD	1-2 months	Global optical surface and/or discrete heating measurements	machined metallic models or cast ceramic models
1.32	Commercial LEO system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3201	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1
1.3202	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1
1.33	Commercial Lunar system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3301	Supersonic / hypersonic aerodynamics	flight relevant test conditions	TBD	1-2 months	TBD	2-4 months	force-and-moment balances, surface pressure, flow visualization	machined metallic models
1.3302	Hypersonic aeroheating and BLT	flight relevant test conditions	TBD	1-2 months	TBD	2-4 months	Global optical surface and/or discrete heating measurements	machined metallic models or cast ceramic models
1.34	Commercial Lunar system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3401	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
1.3402	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1
1.35	Commercial Mars system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3501	Supersonic / hypersonic aerodynamics	flight relevant test conditions	TBD	~ 6 months to 1 year. Note that NASA EDL requirements under 1.2 have extensive development planned prior to Mars EDL human rating, commercial systems do not	TBD	~ 6 months to 1 year. Note that NASA EDL requirements under 1.2 have extensive development planned prior to Mars EDL human rating, commercial systems do not	force-and-moment balances, surface pressure, flow visualization	machined metallic models
1.3502	Hypersonic aeroheating and BLT	flight relevant test conditions	TBD	~ 6 months to 1 year. Note that NASA EDL requirements under 1.2 have extensive development planned prior to Mars EDL human rating, commercial systems do not	TBD	~ 6 months to 1 year. Note that NASA EDL requirements under 1.2 have extensive development planned prior to Mars EDL human rating, commercial systems do not	Global optical surface and/or discrete heating measurements	machined metallic models or cast ceramic models
1.36	Commercial Mars system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)							
1.3601	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1
1.3602	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1
1.4	**Uncrewed Support Systems**							
1.41	Uncrewed support system #1							
1.4101	Supersonic / hypersonic aerodynamics	TBD	TBD	1 month	TBD	1 month	TBD	TBD
1.4102	Hypersonic aeroheating and BLT	TBD	TBD	1 month	TBD	1 month	TBD	TBD
1.42	Uncrewed support system #2							
1.4201	Supersonic / hypersonic aerodynamics	TBD	TBD	1 month	TBD	1 month	TBD	TBD
1.4202	Hypersonic aeroheating and BLT	TBD	TBD	1 month	TBD	1 month	TBD	TBD

Table 27. Gaps List for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration.

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
1	**NASA and Commercial Human-Rated Exploration**					
1.1	**NASA Human-Rated Earth Operations**					
1.11	Crewed Earth Return from LEO					
1.1101	Post-flight assessment for comparison / evaluation of fight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data
1.1102	Develop hypersonic aerodynamic performance database	LaRC facilities lacking enthalpy range to generate kinetics, Reynolds number range for smooth-wall turbulent flow	Scheduling and cost at non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-01, EDL-02 EDL-12, Inst-Aero-01
1.1103	Develop supersonic aerodynamic performance	Reynolds/Mach number ranges of NASA facilities limitations and Aberdeen range	Scheduling and cost at non-NASA facilities. Potential closure of LaRC UPWT	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-01, EDL-11, EDL-12, Inst-Aero-02, Inst-Aero-06
1.1104	Determine aeroshell baseline acreage aeroheating environments	NASA facilities lacking Reynolds number range to generate turbulent flow on smooth-OML, enthalpy range to generate kinetics	Scheduling and cost at non-NASA facilities	validation of global optical aeroheating techniques at non-NASA facilities	none expected	EDL-01, EDL-02 EDL-12
1.1105	Determine vehicle radiative aeroheating environments	NASA and AEDC facilities lacking operational range to produce shock-layer radiation, CUBRC capability minimal	Lack of operational range to generate shock-layer kinetics	validation of radiative flux instrumentation at test conditions	none expected	EDL-04, Inst-Heat-03, Inst-Heat-04
1.1106	Determine aftbody baseline acreage aeroheating environments	NASA facilities lack model size for precision measurement of aftbody features.	Scheduling and cost at non-NASA facilities	Ability to perform low temperature/heating measurements using NASA global techniques, ability to instrument small features with discrete sensors	none expected	EDL-07, EDL-09, EDL-12, Inst-Heat-01
1.1107	Determine RCS interaction effects on aftbody heating and aerodynamics	NASA facility operational range match to flight conditions, wake flow establishment times in non-NASA facilities	Scheduling and cost at non-NASA facilities	Ability to perform low temperature/heating measurements using NASA global techniques, ability to instrument small features with discrete sensors	High cost and complexity of manufacturing RCS models	EDL-08, EDL-12, Inst-Heat-01, Inst-Heat-02
1.1108	Determine TPS effects on aeroshell boundary-layer transition and turbulent aeroheating augmentation	NASA facilities lacking Reynolds number range / model-scale to produce full range of laminar-turbulent flows at roughness scales	Scheduling and cost at non-NASA facilities	none expected	none expected	EDL-01, EDL-12
1.1109	Determine compression pad cavity effects on localized heating and boundary-layer transition	NASA facilities lacking Reynolds number range / model-scale to produce full range of laminar-turbulent flows at cavity scales	Scheduling and cost at non-NASA facilities	inability to provide sufficient discrete gage resolution in/around cavities	none expected	EDL-01, EDL-12, Inst-Heat-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
1.12	Crewed Earth Return from Moon or Gateway					
1.1201	Convective aerothermal (forebody)	NASA facilities lack flight Reynolds number / flight enthalpy range	Scheduling and cost at non-NASA facilities	none expected	none expected	EDL-01, EDL-02, EDL-12
1.1202	Convective aerothermal (aftbody)	NASA facilities lack flight Reynolds number / flight enthalpy range	Scheduling and cost at non-NASA facilities	none expected	none expected	EDL-01, EDL-02, EDL-12
1.1203	Convective aerothermal/RCS (aftbody)	NASA facilities lack flight Reynolds number / flight enthalpy range	Scheduling and cost at non-NASA facilities	none expected	none expected	EDL-01, EDL-2, EDL-12
1.13	Crewed Earth Ascent Abort					
1.1301	Supersonic aerodynamic performance	TBD	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-12
1.1302	Hypersonic aerodynamics performance	lack of High-enthalpy air test capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-02
1.1303	Trans/sub sonic aerodynamics					
1.2	**NASA Human Mars Operations**					
1.21	Human-rated, high mass Mars entry system: HIAD+SRP architecture					
1.2101	Define static supersonic aerodynamic performance database including payload effects	Reynolds/Mach number ranges of NASA and AEDC may not be sufficient, all facilities lack CO2 test capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-06, EDL-12
1.2102	Define dynamic supersonic aerodynamic performance database including payload effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability. Ballistics ranges have limited AoA capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-06, EDL-11, EDL-12, Inst-Aero-02, Inst-Aero-06
1.2103	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability. Facilities may not have ability to simulate ratio of RCS mass flow to freestream	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure small deltas in aero coefficients due to RCS firings	Ability to design and fabricate of models with plumbing for active RCS jets	EDL-01, EDL-06, EDL-08, EDL-09, EDL-12, inst-Aero-03
1.2104	Define supersonic retro-propulsion (SRP) performance and interactions	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability. Facilities may not have ability to simulate ratio of SRP mass flow to freestream	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure SRP interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active SRP thrusters	EDL-01, EDL-06, EDL-08, EDL-09, EDL-12, inst-Aero-03
1.2105	Develop hypersonic aerodynamic performance database including payload effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack high-	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-01, EDL-02, EDL-12, Inst-Aero-01

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
		enthalpy / high-Reynolds number CO2 test capability.				
1.2106	Determine baseline, smooth-OML aeroshell convective heating	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on smooth OML. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
1.2107	Determine aeroshell heating augmentation due to flexible TPS scalloping under pressure load	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on scalloped OML. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	Ability to replicated small roughness features at test model scale	EDL-01, EDL-02, EDL-09, EDL-12
1.2108	Determine aftbody and payload heating environments	CUBRC LENS may not provide sufficient test time for wake flow establishment. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-01, EDL-02, EDL-07, EDL-12
1.2109	Define SRP nozzle-off aeroheating effects	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on scalloped OML. NASA and AEDC facilities lack CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	optical resolution or discrete sensor density in/around SRP nozzles	None expected	EDL-06, EDL-08, EDL-09, EDL-12, Inst-Heat-02
1.2110	Define SRP nozzle-on aeroheating effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure SRP interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active SRP thrusters	EDL-06, EDL-08, EDL-09, EDL-12, Inst-Heat-02
1.2111	Define RCS jet/surface interaction effects on heating	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure RCS interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active RCS thrusters	EDL-06 EDL-08 EDL-12, Inst-Heat-02, Inst-Aero-03
1.2112	Determine radiative heating environments on aeroshell and payload	TBD if required conditions could be obtained in LENS	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	spectral range of instrumentation?	N/A	EDL-04, Inst-Heat-04
1.22	Human-rated, high mass Mars entry system: Mid L/D + SRP architecture					
1.2201	Develop supersonic static aerodynamic performance database	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment"	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-06, EDL-12
1.2202	Develop supersonic dynamic aero response to pitch and sideslip	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment". NASA HFFAF has CO2 but would be AoA limited, as would Aberdeen range	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-06, EDL-11, EDL-12, Inst-Aero-06
1.2203	Define supersonic control surface aerodynamic effectiveness	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment" and define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-06, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
1.2204	Define supersonic RCS performance and interactions	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment" and define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-06, EDL-08, EDL-09, EDL-12, Inst-Heat-02, Inst-Aero-03
1.2205	Define supersonic retropropulsion performance and interactions	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment" and define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-06, EDL-09, EDL-12
1.2206	Develop hypersonic aerodynamic database	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment". Reynolds number range in NASA facilities to produce turbulent flow	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-02, EDL-12
1.2207	Define hypersonic control surface aerodynamic effectiveness	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment" and define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-02, EDL-12
1.2208	Develop hypersonic smooth-OML acreage convective heating	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment". Reynolds number range in NASA facilities may not be sufficient to produce turbulent flow	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-01, EDL-12
1.2209	Define TPS roughness effects on BL transition and aeroheating	NASA and AEDC facilities do not have CO2 or potentially required Reynolds number/roughness scale. Use data to extrapolate to flight. NASA HFFAF has CO2 but would be AoA limited	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	ability to fabricate small roughness heights at scale for NASA facilities	EDL-01, EDL-09, EDL-12
1.221	Define control surface convective heating environments	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment" and define heating-deltas to scale to flight. Reynolds number range in NASA facilities may not be sufficient to produce turbulent flow	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	lack of small, discrete sensor fab capability for instrumentation between/under gaps	EDL-01, EDL-12, Inst-Heat-02
1.2211	Define SRP nozzle-off aeroheating effects	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment" and define heating-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-06, EDL-09, EDL-12
1.2212	Define RCS jet/surface interaction effects on heating	NASA and AEDC facilities do not have CO2, using perfect-gas air for CFD "assessment" and define heating-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-06, EDL-09, EDL-12
1.2213	Develop acreage radiative heating database	Cannot perform full OML testing in EAST, only unit-problem shock-layer measurements. CUBRC may not have required vel/press. for radiation	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	potentially issues with spectral-range of radiative heating sensors	none	EDL-02, EDL-04, EDL-12
1.221	Determine effects of TPS material catalytic on heating					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
1.23	Human-rated, high mass Mars entry system: Deployable + SRP architecture					
1.2301	Define static supersonic aerodynamic performance database including payload effects	Reynolds/Mach number ranges of NASA and AEDC may not be sufficient, all facilities lack CO2 test capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-01, EDL-06, EDL-12
1.2302	Define dynamic supersonic aerodynamic performance database including payload effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability. Ballistics ranges have limited AoA capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-01, EDL-06, EDL-11, EDL-12, Inst-Aero-06
1.2303	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure small deltas in aero coefficients. due to RCS firings	Ability to design and fabrication of models with plumbing for active RCS jets	EDL-01, EDL-06, EDL-09, EDL-12, Inst-Aero-03
1.2304	Define supersonic retro-propulsion (SRP) performance and interactions	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure SRP interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active SRP thrusters	EDL-01, EDL-06, EDL-09, EDL-12, Inst-Aero-03
1.2305	Develop hypersonic aerodynamic performance database including payload effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack high-enthalpy / high-Reynolds number CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-01, EDL-02, EDL-12, Inst-Aero-03
1.2306	Determine baseline, smooth-OML aeroshell convective heating	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on smooth OML. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
1.2307	Determine aeroshell heating augmentation due to TPS roughness	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on models. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	Ability to replicate small roughness features at test model scale	EDL-01, EDL-02, EDL-09, EDL-12
1.2308	Determine aftbody and payload heating environments	CUBRC LENS may not provide sufficient test time for wake flow establishment. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-01, EDL-02, EDL-07, EDL-12
1.2309	Define SRP nozzle-off aeroheating effects	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on scalloped OML. NASA and AEDC facilities lack CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	optical resolution or discrete sensor density in/around SRP nozzles	None expected	EDL-06, EDL-08, EDL-09, EDL-12, Inst-Heat-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
1.2310	Define SRP nozzle-on aeroheating effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure SRP interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active SRP thrusters	EDL-06, EDL-08, EDL-09 EDL-12, Inst-Heat-02
1.2311	Define RCS jet/surface interaction effects on heating	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure RCS interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active RCS thrusters	EDL-06, EDL-08, EDL-09, EDL-12, inst-Heat-02
1.2312	Determine radiative heating environments on aeroshell and payload	TBD if required conditions could be obtained in LENS	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	spectral range of instrumentation?	N/A	EDL-02, EDL-04, EDL-12
1.24	Human-rated, high mass Mars entry system: Capsule + SRP architecture					
1.2401	Define static supersonic aerodynamic performance database including aftbody effects	Reynolds/Mach number ranges of NASA and AEDC may not be sufficient, all facilities lack CO2 test capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-01, EDL-06, EDL-12
1.2402	Define dynamic supersonic aerodynamic performance database including payload effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability. Ballistics ranges have limited AoA capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-01, EDL-06, EDL-11, EDL-12, Inst-Aero-06
1.2403	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure small deltas in aero coefficients due to RCS firings	Ability to design and fabrication of models with plumbing for active RCS jets	EDL-01 EDL-06 EDL-09 EDL-12, Inst-Aero-03
1.2404	Define supersonic retro-propulsion (SRP) performance and interactions	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure SRP interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active SRP thrusters	EDL-01, EDL-06, EDL-09 EDL-12, Inst-Aero-03
1.2405	Develop hypersonic aerodynamic performance database including aftbody effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack high-enthalpy / high-Reynolds number CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-01, EDL-02, EDL-12, Inst-Aero-03
1.2406	Determine baseline, smooth-OML aeroshell convective heating	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on smooth OML. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
1.2407	Determine aeroshell heating augmentation due to TPS roughness	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on models. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	Ability to replicate small roughness features at test model scale	EDL-01, EDL-02, EDL-09, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
1.2408	Determine aftbody heating environments	CUBRC LENS may not provide sufficient test time for wake flow establishment. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-01, EDL-02, EDL-07, EDL-12
1.2409	Define SRP nozzle-off aeroheating effects	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on scalloped OML. NASA and AEDC facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	optical resolution or discrete sensor density in/around SRP nozzles	None expected	EDL-06, EDL-08, EDL-09, EDL-12, Inst-Aero-Heat-02
1.2410	Define SRP nozzle-on aeroheating effects	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure SRP interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active SRP thrusters	EDL-06, EDL-08, EDL-09, EDL-12, Inst-Aero-Heat-02
1.2411	Define RCS jet/surface interaction effects on heating	Reynolds/Mach number ranges of NASA and AEDC facilities range may not be sufficient and lack CO2 test capability.	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	Ability to accurately measure RCS interactions effects on flow field and surface	Ability to design and fabrication of models with plumbing for active RCS thrusters	EDL-06, EDL-08, EDL-09, EDL-12, inst-Aero-Heat-02
1.2412	Determine radiative heating environments on aeroshell and payload	TBD if required conditions could be obtained in LENS	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	spectral range of instrumentation?	N/A	EDL-02, EDL-04, EDL-12
1.25	Mars Ascent Vehicle					
1.2501	Hypersonic aerodynamic performance	NASA facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
1.2502	Supersonic aerodynamic performance	NASA facilities lack CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-06, EDL-12
1.2503	Convective aerothermal	NASA facilities lack high-enthalpy CO2 capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
1.26	Human Mars Mission Earth Return Vehicle					
1.2601	Hypersonic aerodynamic performance	Lack of NASA high-enthalpy air capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
1.2602	Supersonic aerodynamic performance	none expected	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
1.2603	Convective aerothermal: aeroshell Baseline environments)	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-01, EDL-12
1.2604	Convective aerothermal aeroshell TPS roughness, transition, features	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	Ability to replicate small roughness features at test model scale	EDL-01, EDL-02, EDL-09, EDL-12
1.2605	Convective aerothermal: aftbody baseline environments	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-01, EDL-02, EDL-07, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
1.2606	High-enthalpy aerothermal chemical-kinetic effects	Lack of NASA high-enthalpy air capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
1.2607	Shock-layer radiative aerothermal effects	none expected	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-02, EDL-04, EDL-12
1.2608	RCS interaction aerodynamics	none expected	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	none expected	EDL-08, EDL-12
1.2609	RCS interaction aeroheating	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none expected	Ability to design and fabrication of models with plumbing for active RCS thrusters	EDL-08, EDL-09, EDL-12, Inst-Heat-02
1.3	**Commercial Systems**					
1.31	Commercial LEO system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3101	Supersonic / hypersonic aerodynamics	Lack of NASA high-Reynolds number air capability	Schedule and cost in non-NASA facilities	none expected	none expected	EDL-01, EDL-12
1.3102	Hypersonic aeroheating and BLT	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Schedule and cost in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
1.32	Commercial LEO system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3201	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	EDL-01, EDL-12
1.3202	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	EDL-02, EDL-12
1.33	Commercial Lunar system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3301	Supersonic / hypersonic aerodynamics	Lack of NASA high-Reynolds number air capability	Schedule and cost in non-NASA facilities	none expected	none expected	EDL-01, EDL-12
1.3302	Hypersonic aeroheating and BLT	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Schedule and cost in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
1.34	Commercial Lunar system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3401	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	EDL-01, EDL-12
1.3402	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	EDL-02, EDL-12
1.35	Commercial Mars system #1 (e.g. Blue Origin,					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
	SpaceX, Sierra Nevada, Boeing, other)					
1.3501	Supersonic / hypersonic aerodynamics	Lack of NASA high-Reynolds number air capability	Schedule and cost in non-NASA facilities	none expected	none expected	EDL-01, EDL-06, EDL-12
1.3502	Hypersonic aeroheating and BLT	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Schedule and cost in non-NASA facilities	none expected	none expected	EDL-01, EDL-06, EDL-12
1.36	Commercial Mars system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3601	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	EDL-01, EDL-06, EDL-12
1.3602	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	EDL-01, EDL-06, EDL-12
1.4	**Uncrewed Support Systems**					
1.41	Uncrewed support system #1					
1.4101	Supersonic / hypersonic aerodynamics	TBD	TBD	TBD	TBD	
1.4102	Hypersonic aeroheating and BLT	TBD	TBD	TBD	TBD	
1.42	Uncrewed support system #2					
1.4201	Supersonic / hypersonic aerodynamics	TBD	TBD	TBD	TBD	
1.4202	Hypersonic aeroheating and BLT	TBD	TBD	TBD	TBD	

Table 28. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Human-Rated Exploration.

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1	**NASA and Commercial Human-Rated Exploration**					
1.1	**NASA Human-Rated Earth Operations**					
1.11	Crewed Earth Return from LEO					
1.1101	Post-flight assessment for comparison / evaluation of fight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	TBD depending on flight data	
1.1102	Develop hypersonic aerodynamic performance database	Operational conditions of NASA facilities, schedule and cost of non-NASA facilities	Minimal. CFD accepted for baseline hypersonic aerodynamics of blunt bodies	Use CFD to develop databases	Sufficient for Orion, but lacking validation for direct mission-relevant validation	
1.1103	Develop supersonic aerodynamic performance	Reynolds/Mach number of NASA facilities, schedule and cost of non-NASA facilities. Measurement of dynamic aero quantities	Moderate. CFD accepted for supersonic aerodynamics except for dynamic aero properties.	Use CFD to develop databases and/or rely on legacy data from other vehicles	Extensive CPU/memory capacity required for unsteady aerodynamic simulations	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
1.1104	Determine aeroshell baseline acreage aeroheating environments	Reynolds number and enthalpy range of NASA facilities, schedule and cost of non-NASA facilities	Moderate. CFD generally accepted for smooth blunt-body heating, but lacking validation of turbulence modeling in high-enthalpy flow	Use CFD to develop baseline smooth OML heating environments	Sufficient for Orion, but lacking validation for direct mission-relevant validation for BL transition issues	
1.1105	Determine vehicle radiative aeroheating environments	Operation range of all facilities, validation of radiative flux sensors	Minimal. CFD tools accepted for Earth entry radiation, but lacking direct validation at relevant conditions	Use CFD to develop radiative heating environments	Expected to be sufficient, but additional validation for flight-relevant conditions useful	
1.1106	Determine aftbody baseline acreage aeroheating environments	Model size limitations in NASA facilities, higher uncertainties in NASA measurements of low temp regions, sensor spatial resolution on non-NASA models	Moderate. CFD tools carry high-uncertainties for separated wake flows. Wake flow heating measurements carry high uncertainties in low heating regions	Use CFD to predict environments with higher uncertainties. Development program for low-temperature / dynamic wake flow heating measurements	High uncertainty margins for separated unsteady flow	Extensive CPU requirements
1.1107	Determine RCS interaction effects on aftbody heating and aerodynamics	Model size limitations in NASA facilities, higher uncertainties in NASA measurements of low temp regions, sensor spatial resolution on non-NASA models	Moderate. CFD tools carry high-uncertainties for separated wake flows. Wake flow heating measurements carry high uncertainties in low heating regions	Use CFD to predict environments with higher uncertainties. Development program for low-temperature / dynamic wake flow heating measurements	High uncertainty margins for RCS interactions	Extensive CPU requirements
1.1108	Determine TPS effects on aeroshell boundary-layer transition and turbulent aeroheating augmentation	Reynolds number range in NASA facilities, cost/availability of non-NASA faculties	High. CFD tools and legacy data contribute to higher design uncertainty/margins	Use CFD to predict heating / BL transition with high uncertainties, use legacy roughness data from other programs	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.1109	Determine compression pad cavity effects on localized heating and boundary-layer transition	Reynolds number range in NASA facilities, cost/availability of non-NASA facilities, resolution of discrete sensors	High. CFD tools and legacy data contribute to higher design uncertainty/margins	Use CFD to predict heating / BL transition with high uncertainties, use legacy cavity data from other programs	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	
1.12	Crewed Earth Return from Moon or Gateway					
1.1201	Convective aerothermal (forebody)	Lack of Reynolds / enthalpy range in NASA facilities	TBD depending on flight data	Rely on CFD with high margins. Develop NASA high Reynolds / high-enthalpy capabilities	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	
1.1202	Convective aerothermal (aftbody)	Lack of Reynolds / enthalpy range in NASA facilities	TBD depending on flight data	Rely on CFD with high margins. Develop NASA high Reynolds / high-enthalpy capabilities	High uncertainty margins for separated unsteady flow	
1.1203	Convective aerothermal/RCS (aftbody)		TBD depending on flight data		High uncertainty margins for RCS interactions	Extensive CPU requirements
1.13	Crewed Earth Ascent Abort					
1.1301	Supersonic aerodynamic performance		Moderate - additional validation desired for human rating	Use CFD with higher uncertainties. Develop NASA high-enthalpy CO2 capability	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.1302	Hypersonic aerodynamics performance	Lack of high-enthalpy air in NASA and AEDC facilities	Moderate - additional validation desired for human rating	Use CFD with higher uncertainties.	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.1303	Trans/sub sonic aerodynamics					
1.2	**NASA Human Mars Operations**					
1.21	Human-rated, high mass Mars entry system: HIAD+SRP architecture					
1.2101	Define static supersonic aerodynamic performance database including payload effects	Non-NASA facility may not be available within project scope. Lack of CO2 test capability at NASA and AEDC	Moderate due to large uncertainties in payload/wake-flow interactions. Human rating requires low risk posture	Use CFD to obtain supersonic static aerodynamics. Develop NASA CO2 test capability. Sub-scale / uncrewed flight test	Expect to be sufficient for aeroshell but lacking configuration/trajectory specific validation. Unsteady wake flow computations for payload lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations
1.2102	Define dynamic supersonic aerodynamic performance database including payload effects	Non-NASA facility may not be available within project scope. Instrumentation may not be adequate for dynamic aero measurements. AoA in ballistics ranges. Lack of CO2 test capability	Moderate: large payload likely to have significant effects on dynamic aero properties due to shear layer impingement. Human rating requires low risk posture	Use CFD and legacy to define dynamic aero characteristics. Develop NASA CO2 test capability. Develop new national range capability. Sub-scale / uncrewed flight test	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.2103	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of RCS mass flow to flight conditions. NASA and AEDC facilities cannot provide CO2 flow	Moderate - lack of data could lead to increase aero performance margins. Human rating requires low risk posture	Use unvalidated hypersonic wake flow CFD simulations to define RCS/surface interaction effects. Develop NASA CO2 test capability. Sub-scale / uncrewed flight test	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for RCS simulations
1.2104	Define supersonic retro-propulsion (SRP) performance and interactions	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of SRP mass flow to flight conditions. NASA and AEDC facilities cannot provide CO2 flow	Major: SRP may be mission-enabling requirement but lacks data and simulation validation. Human rating requires low risk posture	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic SRP jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2105	Develop hypersonic aerodynamic performance database including payload effects	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Moderate due to large uncertainties in payload/wake-flow interactions. Human rating requires low risk posture	Use CFD to obtain supersonic static aerodynamics. Develop NASA high-Reynolds / high-enthalpy CO2 test capability. Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Expect to be sufficient for aeroshell but lacking configuration/trajectory specific validation. Unsteady wake flow computations for payload lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations
1.2106	Determine baseline, smooth-OML aeroshell convective heating	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Minimal: CFD sufficient validated for smooth-OML blunt body heating	Use CFD to define baseline smooth-OML heating. Develop NASA high-Reynolds / high-enthalpy CO2 test capability. Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Expect to be sufficient for aeroshell but lacking configuration specific validation data	Large CPU memory/time requirements for wake flow simulations
1.2107	Determine aeroshell heating augmentation due to flexible TPS scalloping under pressure load	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Moderate: cannot design TPS without validated heating information	Use unvalidated CFD to simulate scalloped TPS, rely on legacy data, develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Lacking validated/functional models for TPS scalloping effects on BL transition and heating augmentation	sufficient
1.2108	Determine aftbody and payload heating environments	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC. Instrumentation for very low temperature / heating environments not well developed	High. Protection of payload is a primary requirement. Use of CFD would include up to 100% margins, which impact mission performance due to lack of TPS on HIAD back-face	Use unvalidated CFD to simulate wake flow. Develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data. Invest in Test technique development program for low temperature / heating conditions required to support HIAD applications.	Unsteady wake flow computations for payload lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations
1.2109	Define SRP nozzle-off aeroheating effects	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Moderate: cannot design TPS without validated heating information	Use unvalidated CFD to simulate SRP cavity flows, develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Lacking validation data for SRP-nozzle cavity type flows	sufficient

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.2110	Define SRP nozzle-on aeroheating effects	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of SRP mass flow to flight condition. NASA and AEDC facilities cannot provide CO2 flow	Moderate to major: SRP may be mission-enabling requirement but lacks data and simulation validation. Human rating requires low risk posture. Magnitude of SRP interaction heating at supersonic conditions is TBD	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic SRP jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2111	Define RCS jet/surface interaction effects on heating	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of RCS mass flow to flight conditions. NASA and AEDC facilities cannot provide CO2 flow	Minor to moderate: magnitude of RCS interactions and relevant Mach range for firing are TBD, but heating impact should not be large	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2112	Determine radiative heating environments on aeroshell and payload	Non-NASA facilities may not be available within project scope. Facilities may not have operational range (pressure, enthalpy) to simulate conditions, radiation sensors may not have spectral range to be useful	Minimal: radiation transport simulations should be sufficient for conditions of interest	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient
1.22	Human-rated, high mass Mars entry system: Mid L/D + SRP architecture					
1.2201	Develop supersonic static aerodynamic performance database	No CO2 compressibility effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to moderate due to lack of CFD validation for specific vehicle	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	CFD as primary source, but would require validation data for human rating	Sufficient
1.2202	Develop supersonic dynamic aero response to pitch and sideslip	No CO2 compressibility effects on NASA or AEDC facilities, schedule for non-NASA facilities. Ability to capture dynamics in all tunnels / sufficient AoA in ranges	Human rating increases criticality to major due to lack of CFD validation and importance of dynamic aero	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic/separated flow would require extensive validation data. RANS likely insufficient so LES/DES required	Dense grids and unsteady flow simulations require extensive CPU time
1.2203	Define supersonic control surface aerodynamic effectiveness	No CO2 compressibility effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to major due to lack of CFD validation for specific vehicle / control configuration	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in unsteady shock/control interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
1.2204	Define supersonic RCS performance and interactions	No CO2 compressibility effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to moderate due to lack of CFD validation for specific vehicle / RCS configuration	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.2205	Define supersonic retropropulsion performance and interactions	No CO2 compressibility effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to major due to lack of CFD validation for specific vehicle / SRP configuration	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic SRP jet/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
1.2206	Develop hypersonic aerodynamic database	No CO2 compressibility effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to moderate due to lack of CFD validation for specific vehicle	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	CFD as primary source, but would require validation data for human rating	Sufficient
1.2207	Define hypersonic control surface aerodynamic effectiveness	No CO2 kinetics effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to major due to lack of CFD validation for specific vehicle / control configuration	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in unsteady shock/control interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
1.2208	Develop hypersonic smooth-OML acreage convective heating	No CO2 kinetics effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to moderate due to lack of CFD validation for specific vehicle configuration	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 and high Reynolds capability. Invest in CFD development / validation using flight & WT data	CFD as primary source, but would require validation data on kinetic/catalytic effects for human rating	Sufficient
1.2209	Define TPS roughness effects on BL transition and aeroheating	No CO2 kinetics effects on NASA or AEDC facilities, schedule for non-NASA facilities Ability to maintain roughness fidelity for small size of NASA/AEDC models	Human rating increases criticality to major due to lack of predictive capability for roughness BLT and impact to TPS	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 and high-Reynolds capability. Invest in CFD development / validation using flight & WT data	Lacking validated/functional models for roughness transition and heating augmentation	N/A
1.221	Define control surface convective heating environments	No CO2 kinetics effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to moderate due to lack of CFD validation for specific vehicle / control configuration	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 and high-Reynolds capability. Invest in CFD development / validation using flight & WT data	CFD as primary source but would require validation data. Disparate scales of external flow and flow between/under flaps may require DSMC	Dense grids and unsteady flow simulations required extensive CPU time
1.2211	Define SRP nozzle-off aeroheating effects	No CO2 kinetics effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to moderate due to lack of CFD validation for specific vehicle / SRP configuration	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	CFD as primary source, but would require validation data for human rating	Sufficient
1.2212	Define RCS jet/surface interaction effects on heating	No CO2 kinetics effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to moderate due to lack of CFD validation for specific vehicle / RCS configuration	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.2213	Develop acreage radiative heating database	No CO2 kinetics effects on NASA or AEDC facilities, schedule for non-NASA facilities	Human rating increases criticality to moderate due to lack of validation data for specific configuration	Invest in CFD development / validation using flight & WT data using shock tube data	CFD as primary source, but would require validation data for human rating	sufficient
1.221	Determine effects of TPS material catalytic on heating					
1.23	Human-rated, high mass Mars entry system: Deployable + SRP architecture					
1.2301	Define static supersonic aerodynamic performance database including payload effects	Non-NASA facility may not be available within project scope. Lack of CO2 test capability at NASA and AEDC	Moderate due to large uncertainties in payload/wake-flow interactions. Human rating requires low risk posture	Use CFD to obtain supersonic static aerodynamics. Develop NASA CO2 test capability. Sub-scale / uncrewed flight test	Expect to be sufficient for aeroshell but lacking configuration/trajectory specific validation. Unsteady wake flow computations for payload lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations
1.2302	Define dynamic supersonic aerodynamic performance database including payload effects	Non-NASA facility may not be available within project scope. Instrumentation may not be adequate for dynamic aero measurements	Moderate: large payload likely to have significant effects on dynamic aero properties due to shear layer impingement. Human rating requires low risk posture	Use CFD and legacy to define dynamic aero characteristics. Develop NASA CO2 test capability. Develop new national range capability. Sub-scale / uncrewed flight test	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
1.2303	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of RCS mass flow to flight conditions, measurements of low. NASA and AEDC facilities cannot provide CO2 flow	Moderate - lack of data could lead to increase aero performance margins. Human rating requires low risk posture	Use unvalidated hypersonic wake flow CFD simulations to define RCS/surface interaction effects. Develop NASA CO2 test capability. Sub-scale / uncrewed flight test	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for RCS simulations
1.2304	Define supersonic retro-propulsion (SRP) performance and interactions	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of SRP mass flow to flight conditions, measurements of low. NASA and AEDC facilities cannot provide CO2 flow	Major: SRP may be mission-enabling requirement but lacks data and simulation validation. Human rating requires low risk posture	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic SRP jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2305	Develop hypersonic aerodynamic performance database including payload effects	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Moderate due to large uncertainties in payload/wake-flow interactions. Human rating requires low risk posture	Use CFD to obtain hypersonic aerodynamics. Develop NASA high-Reynolds / high-enthalpy CO2 test capability. Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Expect to be sufficient for aeroshell but lacking configuration/trajectory specific validation. Unsteady wake flow computations for payload lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.2306	Determine baseline, smooth-OML aeroshell convective heating	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Minimal: CFD sufficient validated for smooth-OML blunt body heating	Use CFD to define baseline smooth-OML heating. Develop NASA high-Reynolds / high-enthalpy CO2 test capability. Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Expect to be sufficient for aeroshell but lacking configuration specific validation data	Large CPU memory/time requirements for wake flow simulations
1.2307	Determine aeroshell heating augmentation due to TPS roughness	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Moderate: cannot design TPS without validated heating information	Use unvalidated CFD to simulate rough TPS, rely on legacy data, develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Lacking validated/functional models for TPS scalloping effects on BL transition and heating augmentation	sufficient
1.2308	Determine aftbody and payload heating environments	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC. Instrumentation for very low temperature / heating environments not well developed	High. Protection of payload is a primary requirement. Use of CFD would include up to 100% margins, which impact mission performance due to lack of TPS on HIAD back-face	Use unvalidated CFD to simulate wake flow. Develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data. Invest in Test technique development program for low temperature / heating conditions required to support deployable applications.	Unsteady wake flow computations for payload lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations
1.2309	Define SRP nozzle-off aeroheating effects	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Moderate: cannot design TPS without validated heating information	Use unvalidated CFD to simulate SRP cavity flows, develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Lacking validation data for SRP-nozzle cavity type flows	sufficient
1.2310	Define SRP nozzle-on aeroheating effects	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of SRP mass flow to flight conditions, measurements of low. NASA and AEDC facilities cannot provide CO2 flow	Moderate to major: SRP may be mission-enabling requirement but lacks data and simulation validation. Human rating requires low risk posture. Magnitude of SRP interaction heating at supersonic conditions is TBD	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic SRP jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2311	Define RCS jet/surface interaction effects on heating	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of RCS mass flow to flight conditions, measurements of low. NASA and AEDC facilities cannot provide CO2 flow	Minor to moderate: magnitude of RCS interactions and relevant Mach range for firing are TBD, but heating impact should not be large	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.2312	Determine radiative heating environments on aeroshell and payload	Non-NASA facilities may not be available within project scope. Facilities may not have operational range (pressure, enthalpy) to simulate conditions, radiation sensors may not have spectral range to be useful	Minimal: radiation transport simulations should be sufficient for conditions of interest	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient
1.24	Human-rated, high mass Mars entry system: Capsule + SRP architecture					
1.2401	Define static supersonic aerodynamic performance database including aftbody effects	Non-NASA facility may not be available within project scope. Lack of CO2 test capability at NASA and AEDC	Minimal to Moderate due to large uncertainties in unsteady/separated wake behavior. Human rating requires low risk posture	Use CFD to obtain supersonic static aerodynamics. Develop NASA CO2 test capability. Sub-scale / uncrewed flight test	Expect to be sufficient for aeroshell but lacking configuration/trajectory specific validation. Unsteady wake flow computations for payload lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations
1.2402	Define dynamic supersonic aerodynamic performance database including payload effects	Non-NASA facility may not be available within project scope. Instrumentation may not be adequate for dynamic aero measurements	Minimal to Moderate: dynamic aero effects may not be large in supersonic regime. Human rating requires low risk posture	Use CFD and legacy to define dynamic aero characteristics. Develop NASA CO2 test capability. Develop new national range capability. Sub-scale / uncrewed flight test	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
1.2403	Define supersonic Reaction control systems (RCS) aerodynamic performance and interactions	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of RCS mass flow to flight conditions, measurements of low. NASA and AEDC facilities cannot provide CO2 flow	Minimal to Moderate - lack of data could lead to increase aero performance margins. Human rating requires low risk posture	Use unvalidated hypersonic wake flow CFD simulations to define RCS/surface interaction effects. Develop NASA CO2 test capability. Sub-scale / uncrewed flight test	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for RCS simulations
1.2404	Define supersonic retro-propulsion (SRP) performance and interactions	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of SRP mass flow to flight conditions, measurements of low. NASA and AEDC facilities cannot provide CO2 flow	Major: SRP may be mission-enabling requirement but lacks data and simulation validation. Human rating requires low risk posture	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic SRP jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2405	Develop hypersonic aerodynamic performance database including aftbody effects	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Minimal to Moderate due to large uncertainties in unsteady/separated wake behavior. Human rating requires low risk posture	Use CFD to obtain hypersonic aerodynamics. Develop NASA high-Reynolds / high-enthalpy CO2 test capability. Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Expect to be sufficient for aeroshell but lacking configuration/trajectory specific validation. Unsteady wake flow computations for aftbody lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.2406	Determine baseline, smooth-OML aeroshell convective heating	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Minimal: CFD sufficient validated for smooth-OML blunt body heating	Use CFD to define baseline smooth-OML heating. Develop NASA high-Reynolds / high-enthalpy CO2 test capability. Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Expect to be sufficient for aeroshell but lacking configuration specific validation data	Large CPU memory/time requirements for wake flow simulations
1.2407	Determine aeroshell heating augmentation due to TPS roughness	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Moderate: cannot design TPS without validated heating information	Use unvalidated CFD to simulate rough TPS, rely on legacy data, develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Lacking validated/functional models for TPS scalloping effects on BL transition and heating augmentation	sufficient
1.2408	Determine aftbody heating environments	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC. Instrumentation for very low temperature / heating environments not well developed	Moderate. Protection of payload is a primary requirement. Use of CFD would include high uncertainty margins	Use unvalidated CFD to simulate wake flow. Develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data.	Unsteady wake flow computations for payload lack validation and carry high margins	Extensive CPU/memory capacity required for unsteady wake flow simulations
1.2409	Define SRP nozzle-off aeroheating effects	Non-NASA facility may not be available within project scope. Lack of high-Reynolds number / high-enthalpy CO2 test capability at NASA and AEDC	Moderate: cannot design TPS without validated heating information	Use unvalidated CFD to simulate SRP cavity flows, develop high-Reynolds / high-enthalpy CO2 test capability, Sub-scale / uncrewed flight test. Extrapolate perfect-gas air data	Lacking validation data for SRP-nozzle cavity type flows	sufficient
1.2410	Define SRP nozzle-on aeroheating effects	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of SRP mass flow to flight conditions, measurements of low. NASA and AEDC facilities cannot provide CO2 flow	Moderate to major: SRP may be mission-enabling requirement but lacks data and simulation validation. Human rating requires low risk posture. Magnitude of SRP interaction heating at supersonic conditions is TBD	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic SRP jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2411	Define RCS jet/surface interaction effects on heating	Non-NASA facilities may not be available within project scope. All facilities may lack operational range to simulate correct ratio of RCS mass flow to flight conditions, measurements of low. NASA and AEDC facilities cannot provide CO2 flow	Minor to moderate: magnitude of RCS interactions and relevant Mach range for firing are TBD, but heating impact should not be large	Higher margins on unvalidated CFD. Pre-Mars flight testing. Develop NASA CO2 capability. Invest in CFD development / validation using flight & WT data. Sub-scale / uncrewed flight test, Extrapolate perfect-gas air data	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2412	Determine radiative heating environments on aeroshell and payload	Non-NASA facilities may not be available within project scope. Facilities may not have operational range (pressure, enthalpy) to simulate conditions, radiation sensors may not have spectral range to be useful	Minimal: radiation transport simulations should be sufficient for conditions of interest	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.25	Mars Ascent Vehicle					
1.2501	Hypersonic aerodynamic performance	Lack of high-enthalpy CO2 in NASA and AEDC facilities	Moderate - additional validation desired for human rating	Use CFD with higher uncertainties. Develop NASA high-enthalpy CO2 capability	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.2502	Supersonic aerodynamic performance	Lack of compressible CO2 in NASA and AEDC facilities	Moderate - additional validation desired for human rating	Use CFD with higher uncertainties. Develop NASA compressible CO2 capability	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.2503	Convective aerothermal	Lack of high-enthalpy CO2 in NASA and AEDC facilities	Moderate - additional validation desired for human rating	Use CFD with higher uncertainties. Develop NASA high-enthalpy CO2 capability	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.26	Human Mars Mission Earth Return Vehicle					
1.2601	Hypersonic aerodynamic performance	Lack of high-enthalpy air in NASA and AEDC facilities	Moderate - additional validation desired for human rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.2602	Supersonic aerodynamic performance	none expected	Moderate - no "gap" but additional validation data desired for human rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.2603	Convective aerothermal: aeroshell Baseline environments)	Lack of high-enthalpy air in NASA and AEDC facilities. Lack of high-Reynolds air in NASA facilities	Moderate - additional validation desired for human rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.2604	Convective aerothermal aeroshell TPS roughness, transition, features	Lack of high-enthalpy air in NASA and AEDC facilities. Lack of high-Reynolds air in NASA facilities	High - CFD cannot predict TPS roughness transition and heating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	Lacking validated/functional models for TPS roughness effects on BL transition and heating augmentation	sufficient
1.2605	Convective aerothermal: aftbody baseline environments	Lack of high-enthalpy air in NASA and AEDC facilities. Lack of high-Reynolds air in NASA facilities	Moderate - additional validation desired for human rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.2606	High-enthalpy aerothermal chemical-kinetic effects	Lack of high-enthalpy air in NASA and AEDC facilities. Lack of high-Reynolds air in NASA facilities	Moderate - additional validation desired for human rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.2607	Shock-layer radiative aerothermal effects	none expected	Minimal - additional validation desired for human rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	Expected to be sufficient, but additional validation for flight-relevant conditions desired for human-rating	expected to be sufficient
1.2608	RCS interaction aerodynamics	none expected	Moderate - no "gap" but additional validation data desired for human rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.2609	RCS interaction aeroheating	Lack of high-enthalpy air in NASA and AEDC facilities. Lack of high-Reynolds air in NASA facilities	Moderate - no "gap" but additional validation data desired for human rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions will require extensive validation data. RANS may be insufficient so LES/DES may be required	Large CPU memory/time requirements for SRP simulations
1.3	**Commercial Systems**					
1.31	Commercial LEO system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3101	Supersonic / hypersonic aerodynamics	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Minimal - CFD sufficient but additional validation required for human-rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities		should be sufficient
1.3102	Hypersonic aeroheating and BLT	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Minimal - CFD sufficient but additional validation required for human-rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities		should be sufficient
1.32	Commercial LEO system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3201	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1
1.3202	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1	As per Commercial LEO system #1
1.33	Commercial Lunar system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.3301	Supersonic / hypersonic aerodynamics	Lack of NASA high-Reynolds number air capability	Moderate - CFD sufficient but additional validation required for human-rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities		should be sufficient
1.3302	Hypersonic aeroheating and BLT	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Moderate- CFD sufficient but additional validation required for human-rating	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities		should be sufficient
1.34	Commercial Lunar system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3401	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1
1.3402	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1	As per Commercial Lunar system #1
1.35	Commercial Mars system #1 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3501	Supersonic / hypersonic aerodynamics	Lack of NASA high-Reynolds number air capability	Moderate to major: new architectures and human rating would require extensive testing and CFD validations	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities		TBD
1.3502	Hypersonic aeroheating and BLT	Lack of NASA high-enthalpy air and high-Reynolds number air capability	Moderate to major: new architectures and human rating would require extensive testing and CFD validations	Rely on CFD with higher margins, invest in CFD development, flight testing, invest in NASA high-enthalpy and/or high Reynolds number capabilities		TBD
1.36	Commercial Mars system #2 (e.g. Blue Origin, SpaceX, Sierra Nevada, Boeing, other)					
1.3601	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1
1.3602	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1	As per Commercial Mars system #1
1.4	**Uncrewed Support Systems**					
1.41	Uncrewed support system #1					
1.4101	Supersonic / hypersonic aerodynamics	TBD	TBD	TBD	TBD	TBD

ID	Customer / Categories / Programs / Database Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
1.4102	Hypersonic aeroheating and BLT	TBD	TBD	TBD	TBD	TBD
1.42	Uncrewed support system #2					
1.4201	Supersonic / hypersonic aerodynamics	TBD	TBD	TBD	TBD	TBD
1.4202	Hypersonic aeroheating and BLT	TBD	TBD	TBD	TBD	TBD

Appendix D Database for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration

Table 29. Programs List for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration.

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
Hypersonic Entry, Descent and Landing	**2**	**NASA and Partners Robotic Exploration**	**NASA led or collaborative partnerships supporting development of entry systems for robotic exploration of the solar system including landers for planets & moons with atmospheres and capsules for return of samples to earth**		**NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)**	
	2.1	**Flagship Missions**	**High cost, low risk tolerance science/exploration missions**	**Likely only 1 or 2 per decade**	**NRC decadal survey**	
	2.11	Mars 2020	Post-flight reconstruction of successful Mars 2020 mission	Based on formulation plans for post-flight reconstruction	post-flight reconstruction program	2021-2024
	2.12	Mars Sample Retrieval Flagship Mission: Sample Return Lander (SRL)	SRL is the Mars EDL system that carries the Mars Ascent Vehicle (MAV) and the fetch rover	NASA Flagship mission: SRL, MAV and EEV components, SRL architecture is still TBD and requirements may change	NASA mission of record	2026-2030
	2.13	Mars Sample Retrieval Flagship Mission: Mars Ascent Vehicle (MAV)	MAV is the ascent vehicle to put sample return EEV into Mars orbit	NASA Flagship mission: SRL, MAV and EEV components	NASA mission of record	2026-2030
	2.14	Mars Sample Retrieval Flagship Mission: Earth Entry Vehicle (EEV)	EEV will return the sample to Earth. Sample return will entail stringent planetary protection requirements and thus high-fidelity design databases	NASA Flagship mission: SRL, MAV and EEV components, EEV architecture is still TBD and requirements may change	NASA mission of record	2026-2030
	2.15	Titan-Saturn Flagship Mission	Would require aerocapture to brake into Saturn system and a Titan atmospheric probe/lander	Technical requirements will be mostly generic until mission architecture and operations are defined	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022"	2030-2040
	2.16	Venus Climate Flagship Mission	Includes an atmospheric entry probe to study structure of Venus.	Technical requirements will be mostly generic until mission architecture and operations are defined	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022"	2030-2040
	2.17	Ice Giant (Uranus or Neptune) Orbiter/Probe Flagship Mission	Includes an atmospheric entry probe to study structure of Ice Giant. Mission may utilize high-velocity aerocapture to brake into Uranus orbit	Technical requirements will be mostly generic until mission architecture and operations are defined	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022"	2030-2040

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	2.18	Enceladus orbiter and lander Flagship Mission	Options for orbiters and/or landers with potential sample return of plume sample. May require aerogravity assist at Titan first	Technical requirements will be mostly generic until mission architecture and operations are defined	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022"	2030-2040
	2.20	**Common probe**	**Proposed standardized entry vehicle for small mission. Potential applicability to New Frontiers and Discovery class missions**	**Placeholder only. Common probe has been proposed but no formal plan of action on this**		
	2.21	Placeholder				
	2.30	**New Frontiers Missions**	**Moderate cost and risk tolerance science/exploration missions**	**Likely 2-4 per decade, order is speculative**	**NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022", NASA directive.**	**0.00**
	2.31	Titan DragonFly - New Frontiers Mission	Deliver a quadcopter to Titan's surface.	Expect minimal requirements. New Frontiers missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022", NASA directive.	2020-2025
	2.32	Lunar South-Pole Aitkens Basin Sample Return New Frontiers Mission	Capsule(s) to return Lunar samples	Expect minimal requirements. New Frontiers missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022"	2025-2040
	2.33	Comet Sample Return - New Frontiers Mission	Acquisition and return of cometary body sample materials. Sample return will entail stringent planetary protection requirements and thus high-fidelity design databases	Expect minimal requirements. New Frontiers missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022"	Placeholder
	2.34	Venus in Situ Explorer New Frontiers Mission		Expect minimal requirements. New Frontiers missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022"	2025-2040
	2.35	Saturn Probe New Frontiers Mission		Expect minimal requirements. New Frontiers missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022"	2025-2040

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	2.4	**Discovery or other missions**	**Low-cost, high-risk tolerance science/exploration missions**	**Likely 2-4 per decade, order is speculative**	**NRC Decadal Survey "Vision and Voyages for Planetary Science in the Decade 2013-2022", NASA directive.**	**0.00**
	2.41	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging Plus (DAVINCI+)	need description	Placeholder only. Discovery-class missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NASA 2019 Discovery mission selection	2025-2030
	2.42	VERITAS	Venus aerobraking	Placeholder only. Discovery-class missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NASA 2019 Discovery mission selection	2025-2030
	2.43	Discovery mission #3	TBD	Placeholder only. Discovery-class missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey	2030-2035
	2.44	Discovery mission #4	TBD	Placeholder only. Discovery-class missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey	2030-2035
	2.45	Discovery mission #5	TBD	Placeholder only. Discovery-class missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey	2035-2040
	2.46	Discovery mission #6	TBD	Placeholder only. Discovery-class missions are cost-capped and generally are expected to rely on off-the-shelf technology developed for other programs.	NRC Decadal Survey	2035-2040

Table 30. Database Objectives for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration.

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2	**NASA and Partners Robotic Exploration**							
2.1	**Flagship Missions**							
2.11	Mars 2020							
2.1101	Evaluate aeroshell aeroheating with simulated TPS test data vs MEDLI2 flight data	(3) Boundary-layer characterization, (4) Convective heating environments	Measure convective heating and BL transition on models with simulated TPS features	Reynolds number, roughness pattern, AoA	surface heating / temperature distributions and BL onset locations	hypersonic wind tunnel	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	N/A
2.1102	Evaluate aftbody convective heating test data vs MEDLI2 flight data	(4) Convective heating environments	Measure convective heating on aftbody	Reynolds number, Mach number, AoA	surface heating / temperature distributions and BL onset locations	hypersonic wind tunnel	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	N/A
2.1103	Radiation data for MEDLI-2 specific conditions	(12) Radiative aeroheating environments	Obtain validation data for MEDLI-2 conditions	shock tube pressure, velocity, gas compositions	spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	ARC EAST	N/A
2.12	Mars Sample Retrieval Flagship Mission: Sample Return Lander (SRL)							
2.1201	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	NASA LaRC 31-Inch Mach 10, NASA 20-Inch Mach 6	CUBRC LENS, AEDC VKF-B/C, AEDC Tunnel 9
2.1202	Develop supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
2.1203	Determine dynamic stability parameters for vehicle at supersonic conditions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, US Army Aberdeen range

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1204	Define supersonic RCS aerodynamic performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization. (7) RCS Performance and Interactions	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT,	AEDC VKF-A
2.1205	Determine baseline, smooth-OML convective aerothermal environments of aeroshell	(4) Convective heating environments, (10) High-enthalpy thermochemical kinetics	Measure convective heat-transfer distributions on aeroshell at high-enthalpy conditions	Total Enthalpy, Mach number, angle-of-attack, Reynolds number	surface heating	high-enthalpy shock/impulse facility, hypersonic wind tunnel	ARC HFFAF, NASA LaRC 31-Inch Mach 10, 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1206	Determine convective aerothermal effects of aeroshell TPS response to step / gaps between TPS blocks	(3) Boundary-layer characterization, (4) Convective heating environments	Measure surface temperature and heating distributions to determine gap filler effects on hypersonic boundary-layer transition and turbulent heating augmentation	Step / gap size and location. Angle-of-attack, Reynolds number	surface heating / temperature distributions and BL onset locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1207	Determine convective aerothermal effects of aeroshell TPS response to distributed surface ablation roughness	(3) Boundary-layer characterization, (4) Convective heating environments	Measure surface temperature and heating distributions to determine TPS roughness effects on hypersonic boundary-layer transition and turbulent heating augmentation	roughness height & distribution-density, angle-of-attack, Reynolds number	surface heating / temperature distributions and BL onset locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1208	Define convective aerothermal environments of aftbody/payload	(4) Convective heating environments	Measure convective heating distributions on backface/payload of vehicle	Angle of attack, Reynolds number, Mach number	surface heating distributions	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1209	Determine RCS jet/surface interaction effects on aftbody heating	(4) Convective heating environments, (5) Flow-field characterization, (7) RCS performance and interactions	Measure RCS jet impingement effect on aftbody heating	Angle of attack, Reynolds number, Mach number, Jet firing	surface temperature and heating and interaction locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1210	Define radiative aerothermal environments of vehicle	(12) Radiative aeroheating environments	Measure radiative heat-transfer distributions on vehicle and/or obtain fundamental radiative property data to develop/validate computational models	shock velocity, pressure, gas composition, vehicle AoA	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS
2.1211	Post-flight assessment / reconstruction based on aeroshell flight data	(4) Convective heating environments	Measure heating and BL transition on flight-relevant configuration	Angle-of-attack, Reynolds number, roughness	surface heating and BL transition	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1212	Post-flight assessment / reconstruction based on aftbody flight data	(4) Convective heating environments, (5) Flow-field characterization	Measure heating and BL transition on flight-relevant configuration	Angle of attack, Reynolds number, Mach number	surface heating and flow field structure	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.13	Mars Sample Retrieval Flagship Mission: Mars Ascent Vehicle (MAV)							
2.1301	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10	CUBRC LENS, AEDC VKF-B/C, AEDC Tunnel 9
2.1302	Develop supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
2.1303	Determine dynamic stability parameters for vehicle at supersonic conditions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, US Army Aberdeen range
2.1304	Develop hypersonic aeroheating database	(3) Boundary-layer characterization, (4) Convective heating environments	Measure convective heat-transfer distributions on ascent vehicle at high-enthalpy conditions	Total Enthalpy, Mach number, angle-of-attack, Reynolds number	surface heating	high-enthalpy shock/impulse facility, hypersonic wind tunnel	NASA LaRC 31-Inch Mach 10, 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.14	Mars Sample Retrieval Flagship Mission: Earth Entry Vehicle (EEV)							
2.1401	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	NASA LaRC 31-Inch Mach 10	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1402	Develop supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
2.1403	Determine dynamic stability parameters for vehicle at supersonic conditions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, US Army Aberdeen range
2.1404	Determine baseline, smooth-OML convective aerothermal environments of aeroshell	(4) Convective heating environments, (10) High-enthalpy thermochemical kinetics	Measure convective heat-transfer distributions on aeroshell at high-enthalpy conditions	Total Enthalpy, Mach number, angle-of-attack, Reynolds number	surface heating	high-enthalpy shock/impulse facility	ARC HFFAF, NASA LaRC 31-Inch Mach 10, 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1405	Determine convective aerothermal effects of aeroshell TPS response to discrete micro-meteoroid & orbital debris (MMOD) impact cavities	(3) Boundary-layer characterization, (4) Convective heating environments	Measure surface temperature and heating distributions to determine MMOD impact crater effects on hypersonic boundary-layer transition and turbulent heating augmentation	Cavity size and location. Angle-of-attack, Reynolds number	surface heating / temperature distributions	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1406	Determine convective aerothermal effects of aeroshell TPS response to distributed surface ablation roughness	(3) Boundary-layer characterization, (4) Convective heating environments	Measure surface temperature and heating distributions to determine TPS roughness effects on hypersonic boundary-layer transition and turbulent heating augmentation	roughness height & distribution-density, angle-of-attack, Reynolds number	surface heating / temperature distributions	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1407	Define convective aerothermal environments of aftbody/payload	(4) Convective heating environments, (5) Flow-field characterization	Measure convective heating distributions on backface/payload of vehicle	Angle of attack, Reynolds number, Mach number	surface heating distributions, wake flow field diagnostics through schlieren or PLIF	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1408	Define radiative aerothermal environments of vehicle	(12) Radiative aeroheating environments	Measure radiative heat-transfer distributions on vehicle and/or obtain fundamental radiative property data to develop/validate computational models	shock velocity, pressure, gas composition, vehicle AoA	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS
2.1409	Post-flight assessment / reconstruction based on aeroshell flight data	(4) Convective heating environments	Measure heating and BL transition on flight-relevant configuration	Angle-of-attack, Reynolds number, roughness	surface heating and BL transition	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1410	Post-flight assessment / reconstruction based on aftbody flight data	(4) Convective heating environments, (5) Flow-field characterization	Measure heating and BL transition on flight-relevant configuration	Angle of attack, Reynolds number, Mach number	surface heating and flow field structure	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.15	Titan-Saturn Flagship Mission							
2.1501	Define Titan-specific vehicle radiative aeroheating environments	(10) High-enthalpy thermochemical kinetics, (12) Radiative aeroheating environments	Measure radiative heat-transfer distributions on vehicle and/or obtain fundamental radiative property data to develop/validate computational models at Titan-specific high-enthalpy conditions	pressure, shock speed, gas composition, vehicle AoA	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS
2.1502	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	(4) Convective heating environments, (10) High-enthalpy thermochemical kinetics	Measure convective heat-transfer distributions on aeroshell at Titan-specific high-enthalpy conditions	Mach, Reynolds, AOA	surface heating	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	ARC HFFAF, NASA LaRC 31-Inch Mach 10, 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1503	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	(3) Boundary-layer characterization, (4) Convective heating environments	Obtain data on mission-specific TPS roughness effects on BL transition and turbulent heating augmentation	Reynolds, AoA, roughness parameters	surface heating / temperature distributions and BL onset locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10 ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1504	Define RCS/surface interaction effects on aftbody convective heating	(4) Convective heating environments, (5) Flow-field characterization, (7) RCS performance and interactions	Measure RCS jet impingement effect on aftbody heating and perform flow visualization of RCS thruster plumes	Angle of attack, Reynolds number, Mach number, Jet firing	surface temperature and heating and interaction locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1505	Define rarefied aerocapture phase aerodynamic performance database	(20) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	low-density wind tunnel	LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9
2.1506	Define hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	NASA LaRC 31-Inch Mach 10, LARC 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1507	Define supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
2.1508	Determine dynamic stability parameters for vehicle at supersonic conditions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, US Army Aberdeen range

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1509	Define supersonic RCS performance	(2) Supersonic Aerodynamic Performance, (5) Flow Field Characterization, (7) RCS performance and interactions	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT,	AEDC VKF-A
2.16	Venus Climate Flagship Mission							
2.1601	Define vehicle radiative aeroheating environments	(12) Radiative aeroheating environments	Measure radiative heat-transfer distributions on vehicle and/or obtain fundamental radiative property data to develop/validate computational models at Venus-specific high-enthalpy conditions	pressure, shock speed, gas composition, vehicle AoA	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS
2.1602	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	(4) Convective heating environments, (10) High-enthalpy thermochemical kinetics	Measure convective heat-transfer distributions on aeroshell at Venus-specific high-enthalpy conditions	Mach, Reynolds, AOA	surface heating	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	ARC HFFAF, NASA LaRC 31-Inch Mach 10, 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1603	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	(3) Boundary-layer characterization, (4) Convective heating environments	Obtain data on mission-specific TPS roughness effects on BL transition and turbulent heating augmentation	Reynolds, AoA, roughness parameters	surface heating / temperature distributions and BL onset locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10 ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1604	Define RCS/surface interaction effects on aftbody convective heating	(4) Convective heating environments, (5) Flow-field characterization, (7) RCS performance and interactions	Measure RCS jet impingement effect on aftbody heating and perform flow visualization of RCS thruster plumes	Angle of attack, Reynolds number, Mach number, Jet firing	surface temperature and heating and interaction locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1605	Define rarefied aerocapture phase aerodynamic performance database	(20) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	low-density wind tunnel	LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1606	Define hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	NASA LaRC 31-Inch Mach 10, LARC 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1607	Define supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
2.1608	Determine dynamic stability parameters for vehicle at supersonic conditions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, US Army Aberdeen range
2.1609	Define supersonic RCS performance	(2) Supersonic Aerodynamic Performance, (5) Flow Field Characterization, (7) RCS performance and interactions	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT,	AEDC VKF-A
2.17	Ice Giant (Uranus or Neptune) Orbiter/Probe Flagship Mission							
2.1701	Define vehicle radiative aeroheating environments at Ice Giant specific conditions	(12) Radiative aeroheating environments	Measure radiative heat-transfer distributions on vehicle and/or obtain fundamental radiative property data to develop/validate computational models at Uranus-specific high-enthalpy conditions	pressure, shock speed, gas composition, vehicle AoA	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1702	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	(4) Convective heating environments, (10) High-enthalpy thermochemical kinetics	Measure convective heat-transfer distributions on aeroshell at Uranus-specific high-enthalpy conditions	Mach, Reynolds, AOA	surface heating	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	ARC HFFAF, NASA LaRC 31-Inch Mach 10, 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1703	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	(3) Boundary-layer characterization, (4) Convective heating environments	Obtain data on mission-specific TPS roughness effects on BL transition and turbulent heating augmentation	Reynolds, AoA, roughness parameters	surface heating / temperature distributions and BL onset locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10 ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1704	Define RCS/surface interaction effects on aftbody convective heating	(4) Convective heating environments, (5) Flow-field characterization, (7) RCS performance and interactions	Measure RCS jet impingement effect on aftbody heating and perform flow visualization of RCS thruster plumes	Angle of attack, Reynolds number, Mach number, Jet firing	surface temperature and heating and interaction locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1705	Define rarefied aerocapture phase aerodynamic performance database	(20) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	low-density wind tunnel	LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9
2.1706	Define hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	NASA LaRC 31-Inch Mach 10, LARC 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1707	Define supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1708	Determine dynamic stability parameters for vehicle at supersonic conditions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, US Army Aberdeen range
2.1709	Define supersonic RCS performance	(2) Supersonic Aerodynamic Performance, (5) Flow Field Characterization, (7) RCS performance and interactions	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistics range	LaRC UPWT, ARC UPWT,	AEDC VKF-A
2.18	Enceladus orbiter and lander Flagship Mission							
2.1801	Define radiative aerothermal environments of vehicle during Titan aerocapture phase	(12) Radiative aeroheating environments	Measure radiative heat-transfer distributions on vehicle and/or obtain fundamental radiative property data to develop/validate computational models	shock velocity, pressure, gas composition, vehicle AoA	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	ARC EAST	CUBRC LENS
2.1802	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	(4) Convective heating environments, (10) High-enthalpy thermochemical kinetics	Measure convective heat-transfer distributions on aeroshell at Titan-specific high-enthalpy conditions	Mach, Reynolds, AOA	surface heating	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	ARC HFFAF, NASA LaRC 31-Inch Mach 10, 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1803	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	(3) Boundary-layer characterization, (4) Convective heating environments	Obtain data on mission-specific TPS roughness effects on BL transition and turbulent heating augmentation	Reynolds, AoA, roughness parameters	surface heating / temperature distributions and BL onset locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10 ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
2.1804	Define RCS/surface interaction effects on aftbody convective heating	(4) Convective heating environments, (5) Flow-field characterization, (7) RCS performance and interactions	Measure RCS jet impingement effect on aftbody heating and perform flow visualization of RCS thruster plumes	Angle of attack, Reynolds number, Mach number, Jet firing	surface temperature and heating and interaction locations	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.1805	Define rarefied aerocapture phase aerodynamic performance database	(20) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	low-density wind tunnel	LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9
2.1806	Define hypersonic aerodynamic performance database during Titan aerocapture	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	NASA LaRC 31-Inch Mach 10, LARC 20-Inch Mach 6	CUBRC LENS, AEDC VKF B/C, AEDC Tunnel 9
2.1807	Define supersonic static aerodynamic performance database	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.1808	Determine dynamic stability parameters for vehicle at supersonic conditions	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.1809	Define supersonic RCS performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.2	**Common probe**							
2.21	Placeholder							
2.3	**New Frontiers Missions**							
2.31	Titan DragonFly - New Frontiers Mission							
2.3101	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3102	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3103	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.32	Lunar South-Pole Aitkens Basin Sample Return New Frontiers Mission							
2.3201	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3202	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3203	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.33	Comet Sample Return - New Frontiers Mission							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
2.3301	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3302	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3303	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.34	Venus in Situ Explorer New Frontiers Mission							
2.3401	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3402	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3403	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.35	Saturn Probe New Frontiers Mission							
2.3501	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3502	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3503	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.4	**Discovery or other missions**							
2.41	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging Plus (DAVINCI+)							
2.4101	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.42	VERITAS							
2.4201	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.43	Discovery mission #3							
2.4301	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.44	Discovery mission #4							
2.4401	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.45	Discovery mission #5							
2.4501	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.46	Discovery mission #6							
2.4601	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 31. Test Requirements for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2	**NASA and Partners Robotic Exploration**							
2.1	**Flagship Missions**							
2.11	Mars 2020							
2.1101	Evaluate aeroshell aeroheating with simulated TPS test data vs MEDLI2 flight data	Hypersonic facility with sufficient Reynolds numbers to produce transitional / turbulent blunt-body flow	3 AoA over range of 0-10 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 5 roughness patterns. Total 65 test points.	LaRC 20M6 = 65 runs/ 2 weeks	N/A	N/A	Global aeroheating measurement and/or high-density discrete measurement to determine turbulent heating augmentation	fabrication of small roughness elements at model scale
2.1102	Evaluate aftbody convective heating test data vs MEDLI2 flight data	High stagnation temperature to produce measurable aftbody heating	Minimum 3 AoA over range of 10 to 20 deg. 3 roll angles for visualization of back-face. 5 Mach/Reynolds test points = 45 runs	LaRC 31M10 = 45 runs / 1.5 weeks.	N/A	N/A	Global and/or discrete surface heating measurement.	ceramic and/or metallic model for heating measurements. Possibly instrumented sting. Offset or blade sting to minimize wake flow disturbance
2.1103	Radiation data for MEDLI-2 specific conditions	Hypersonic facility operating at sufficient enthalpy to produce shock-layer radiation	range of shock tunnel pressure, velocity, composition points	3 weeks	N/A	N/A	flow field spectral diagnostics	N/A
2.12	Mars Sample Retrieval Flagship Mission: Sample Return Lander (SRL)							
2.1201	Develop hypersonic aerodynamic performance database	Hypersonic facility with high-enthalpy CO2 capability	4 x AoA x 2 Mach x 5 Reynolds = 40 points	40 points = 1 week	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 3 weeks assuming 2 shots/day at CUBRC, ~ 1 week at AEDC	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1202	Develop supersonic static aerodynamic performance database	Supersonic Mach 2-5 with wide range of Reynolds numbers and CO2 compressibility effects	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
2.1203	Determine dynamic stability parameters for vehicle at supersonic conditions	Supersonic Mach 2-5 with wide range of Reynolds numbers and CO2 compressibility effects	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	Dynamic oscillation rig for wind tunnel force & moment. High speed imaging for ballistics range test	Metallic force & moment model fabrication

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.1204	Define supersonic RCS aerodynamic performance and interactions	Supersonic Mach 2-5 with wide range of Reynolds numbers and CO2 compressibility effects	3 AoA, 5 Reynolds, 3 Mach, 5 thruster firings = 225 runs	8 weeks	3 AoA, 5 Reynolds, 3 Mach, 5 thruster firings = 225 runs	8 weeks	Global and/or discrete surface pressure measurement. High-speed laser and schlieren systems for flow field diagnostics. High-pressure gas delivery to RCS jets	Ability to fabricate gas delivery systems and RCS nozzles
2.1205	Determine baseline, smooth-OML convective aerothermal environments of aeroshell	Hypersonic facility with high-enthalpy CO2 capability	3 AoA over range of 0 to 10 deg. At least 5 enthalpy conditions and 3 Reynolds numbers. Total 45 test points	assume 2 shots/day ~ 5 weeks	3 AoA over range of 0 to 10 deg. At least 5 enthalpy conditions and 3 Reynolds numbers. Total 45 test points	assume 2 shots/day ~ 5 weeks	Discrete convective heat-transfer sensors at CUBRC, optical aeroheating at HFFAF	metallic model with convective heat-flux sensors
2.1206	Determine convective aerothermal effects of aeroshell TPS response to step / gaps between TPS blocks	Hypersonic facility with sufficient Reynolds numbers to produce transitional / turbulent blunt-body flow	LaRC 20-Inch Mach 6: 3 AoA over range of 10-20 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 6 step/gap parameters. Total 135 test points. ARC HFFAF: 5 Mach/pressure points numbers x 6 step/gap parameter = 30 shots	LaRC 20M6 = 135 runs / 4 weeks. HFFAF = 30 shots / 3 weeks	3 AoA over range of 10-20 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 6 step/gap parameters. Total 135 test points.	AEDC T9 (continuous pitch sweeps) = 40 runs / 4 weeks. CUBRC LENS 135 runs / 13 weeks	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models for phosphor thermography at LaRC M6; 2) Metallic models for IR thermography at HFFAF; or 3) highly-instrumented discrete sensors on metallic models at non-NASA
2.1207	Determine convective aerothermal effects of aeroshell TPS response to distributed surface ablation roughness	Hypersonic facility with sufficient Reynolds numbers to produce transitional / turbulent blunt-body flow	3 AoA over range of 0-10 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 5 roughness patterns. Total 65 test points. ARC HFFAF: 5 Mach/pressure points numbers x 5 roughness patterns = 25 shots	LaRC 20M6 = 65 runs / 1.5 weeks. HFFAF = 25 shots / 3 weeks	3 AoA over range of 0-10 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 5 roughness patterns. Total 65 test points	AEDC T9 (continuous pitch sweeps) = 20 runs / 2 weeks. CUBRC LENS 65 runs / 6.5 weeks	Global aeroheating measurement and/or high-density discrete measurement to determine turbulent heating augmentation	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
2.1208	Define convective aerothermal environments of aftbody/payload	High stagnation temperature to produce measurable aftbody heating	Minimum 3 AoA over range of 10 to 20 deg. 3 roll angles for visualization of back-face. 5 Mach/Reynolds test points = 45 runs	LaRC 31M10 = 45 runs / 1.5 weeks.	Minimum 3 AoA over range of 10 to 20 deg. 3 roll angles for visualization of back-face. 5 Mach/Reynolds test points = 45 runs	AEDC (cont. pitch sweeps) 15 runs / 1 weeks. CUBRC LENS 45 runs / 5 weeks	Global and/or discrete surface heating measurement.	ceramic and/or metallic model for heating measurements. Possibly instrumented sting. Offset or blade sting to minimize wake flow disturbance

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.1209	Determine RCS jet/surface interaction effects on aftbody heating	Sufficient Mach/Re range to simulate flight conditions and RCS mass flow relative to freestream and CO2 compressibility	3 AoA x 3 Mach/Re x 5 Jet firing pressure/pairing = 45 runs	LaRC 31M10 = 45 runs / 1.5 weeks.	3 AoA x 3 Mach/Re x 5 Jet firing pressure/pairing = 45 runs	AEDC facilities w/continuous sweep = 15 runs / 2 weeks, CUBRC 45 runs = 5 weeks	Global and/or discrete surface heating measurement. High-speed laser and schlieren systems for flow field diagnostics. High-pressure gas delivery to RCS jets	Ability to fabricate gas delivery systems and RCS nozzles
2.121	Define radiative aerothermal environments of vehicle	Hypersonic facility operating at sufficient enthalpy to produce CO2 shock-layer radiation	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	Discrete surface heat-flux and radiation gages	metallic model with radiation sensors
2.1211	Post-flight assessment / reconstruction based on aeroshell flight data	Hypersonic facility with sufficient Reynolds numbers to produce transitional / turbulent blunt-body flow	5 Reynolds x 2 AoA x 5 roughness = 50 points	50 points / 6 days / 1 week	5 Reynolds x 2 AoA x 5 roughness = 50 points	50 points / 6 days / 1 week at AEDC. 50 points 50 days / 8 weeks at CUBRC	Global and/or discrete surface heating measurement.	ceramic and/or metallic model for heating measurements.
2.1212	Post-flight assessment / reconstruction based on aftbody flight data	High stagnation temperature to produce measurable aftbody heating	5 Reynolds x 2 AoA x 5 roughness = 50 points	50 points / 6 days / 1 week	5 Reynolds x 2 AoA x 5 roughness = 50 points	50 points / 6 days / 1 week	Global and/or discrete surface heating measurement. High-speed laser and schlieren systems for flow field diagnostics.	ceramic and/or metallic model for heating measurements. Possibly instrumented sting. Offset or blade sting to minimize wake flow disturbance
2.13	Mars Sample Retrieval Flagship Mission: Mars Ascent Vehicle (MAV)							
2.1301	Develop hypersonic aerodynamic performance database	Hypersonic conditions at enthalpies sufficient to produce chemical kinetics	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week at AEDC, 3 weeks CUBRC	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1302	Develop supersonic static aerodynamic performance database	Supersonic Mach 2-5 with wide range of Reynolds numbers	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
2.1303	Determine dynamic stability parameters for vehicle at supersonic conditions	Supersonic Mach 2-5 with wide range of Reynolds numbers	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	Dynamic oscillation rig for wind tunnel force & moment. High speed imaging for ballistics range test	Metallic force & moment model fabrication
2.1304	Develop hypersonic aeroheating database	Hypersonic facility operating at sufficient enthalpy to produce shock-layer chemical kinetic response	3 AoA over range of 0 to 10 deg. At least 5 enthalpy conditions and 3 Reynolds numbers. Total 45 test points	1 week LaRC Tunnels	3 AoA over range of 0 to 10 deg. At least 5 enthalpy conditions and 3 Reynolds numbers. Total 45 test points	1 week AEDC Tunnel, 3 weeks CUBRC	Global and/or discrete surface heating measurement.	ceramic and/or metallic model for heating measurements.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.14	Mars Sample Retrieval Flagship Mission: Earth Entry Vehicle (EEV)							
2.1401	Develop hypersonic aerodynamic performance database	Hypersonic conditions at enthalpies sufficient to produce chemical kinetics	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	30 runs / 1 week	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 3 weeks assuming 2 shots/day	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1402	Develop supersonic static aerodynamic performance database	Supersonic Mach 2-5 with wide range of Reynolds numbers	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
2.1403	Determine dynamic stability parameters for vehicle at supersonic conditions	Supersonic Mach 2-5 with wide range of Reynolds numbers	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	5 AoA, 5 Reynolds numbers, 3 Mach numbers = 75 points	2 weeks, depending on conditions and use of continuous pitch sweep	Dynamic oscillation rig for wind tunnel force & moment. High speed imaging for ballistics range test	Metallic force & moment model fabrication
2.1404	Determine baseline, smooth-OML convective aerothermal environments of aeroshell	Hypersonic facility operating at sufficient enthalpy to produce shock-layer chemical kinetic response	3 AoA over range of 0 to 10 deg. At least 5 enthalpy conditions and 3 Reynolds numbers. Total 45 test points	assume 2 shots/day ~ 5 weeks	3 AoA over range of 0 to 10 deg. At least 5 enthalpy conditions and 3 Reynolds numbers. Total 45 test points	assume 2 shots/day ~ 5 weeks	Discrete convective heat-transfer sensors at CUBRC, optical aeroheating at HFFAF	metallic model with convective heat-flux sensors
2.1405	Determine convective aerothermal effects of aeroshell TPS response to discrete micro-meteoroid & orbital debris (MMOD) impact cavities	Hypersonic facility with sufficient Reynolds numbers to produce transitional / turbulent blunt-body flow	LaRC 20-Inch Mach 6: 3 AoA over range of 0-10 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 3 Cavity sizes at 3 locations. Total 135 test points. ARC HFFAF: 5 Mach/pressure points numbers x 3 cavity sizes x 3 cavity locations = 45 shots	LaRC 20M6 = 135 runs / 4 weeks. HFFAF = 45 shots / 5 weeks	3 AoA over range of 0-10 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 3 Cavity sizes at 3 locations. Total 135 test points.	AEDC T9 (continuous pitch sweeps) = 40 runs / 4 weeks. AEDC VKF continuous flow operations not beneficial to heat transfer testing / multiple parametrics. CUBRC LENS 135 runs / 13 weeks	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models for phosphor thermography at LaRC M6; 2) Metallic models for IR thermography at HFFAF; or 3) highly-instrumented discrete sensors on metallic models at non-NASA
2.1406	Determine convective aerothermal effects of aeroshell TPS response to distributed surface ablation roughness	Hypersonic facility with sufficient Reynolds numbers to produce transitional / turbulent blunt-body flow	3 AoA over range of 0-10 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 5 roughness patterns. Total 65 test points. ARC HFFAF: 5 Mach/pressure points numbers x 5 roughness patterns = 25 shots	LaRC 20M6 = 65 runs / 1.5 weeks. HFFAF = 25 shots / 3 weeks	3 AoA over range of 0-10 deg. 5 Reynolds numbers over required range of laminar to turbulent flow. 5 roughness patterns. Total 65 test points	AEDC T9 (continuous pitch sweeps) = 20 runs / 2 weeks. CUBRC LENS 65 runs / 6.5 weeks	Global aeroheating measurement and/or high-density discrete measurement to determine turbulent heating augmentation	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.1407	Define convective aerothermal environments of aftbody/payload	Hypersonic facility with extensive optical access for flow visualization techniques	Minimum 3 AoA over range of -10 to +10 deg. 3 roll angles for visualization of back-face. Multiple repeat conditions for different flow-field diagnostic techniques. Est. 100+ test points	LaRC 20M6 = 100 runs / 2.5 weeks. LaRC 31M10 = 100 runs / 5 weeks.	Minimum 3 AoA over range of -10 to +10 deg. 3 roll angles for visualization of back-face. Multiple repeat conditions for different flow-field diagnostic techniques. Est. 100+ test points	AEDC T9 (cont. pitch sweeps) 30 runs / 3 weeks. AEDC VKF (continuous operations) TBD. CUBRC LENS 100 runs / 10 weeks	Global and/or discrete surface heating measurement. High-speed laser and schlieren systems for flow field diagnostics	ceramic and/or metallic model for heating measurements. Possibly instrumented sting. Offset or blade sting to minimize wake flow disturbance
2.1408	Define radiative aerothermal environments of vehicle	Hypersonic facility operating at sufficient enthalpy to produce shock-layer radiation	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	Discrete surface heat-flux and radiation gages	metallic model with radiation sensors
2.1409	Post-flight assessment / reconstruction based on aeroshell flight data	Hypersonic facility with sufficient Reynolds numbers to produce transitional / turbulent blunt-body flow	5 Reynolds x 2 AoA x 5 roughness = 50 points	50 points / 6 days / 1 week	5 Reynolds x 2 AoA x 5 roughness = 50 points	50 points / 6 days / 1 week at AEDC. 50 points 50 days / 8 weeks at CUBRC	Global and/or discrete surface heating measurement.	ceramic and/or metallic model for heating measurements.
2.141	Post-flight assessment / reconstruction based on aftbody flight data	High stagnation temperature to produce measurable aftbody heating	5 Reynolds x 2 AoA x 5 roughness = 50 points	50 points / 6 days / 1 week	5 Reynolds x 2 AoA x 5 roughness = 50 points	50 points / 6 days / 1 week	Global and/or discrete surface heating measurement. High-speed laser and schlieren systems for flow field diagnostics.	ceramic and/or metallic model for heating measurements. Possibly instrumented sting. Offset or blade sting to minimize wake flow disturbance
2.15	Titan-Saturn Flagship Mission							
2.1501	Define Titan-specific vehicle radiative aeroheating environments	High-enthalpy facility operating at sufficient enthalpy to produce shock-layer radiation at Titan-specific conditions	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	Discrete surface heat-flux and radiation gages. Flow field and spectrographic sensor	metallic model with radiation sensors
2.1502	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	High enthalpy, reacting gas N2 and sufficient Reynolds number range to produce turbulent flow	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	4 weeks at ARC HFFAF, 2 weeks at LaRC Tunnels	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	4 weeks at CUBRC LENS, 2 weeks at AEDC Tunnels	Global optical and / or discrete surface heat transfer instrumentation	Ceramic models for global optical, metallic for discrete surface
2.1503	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	Sufficient Reynolds number range / model scale to produce transitional and turbulent flow for TPS roughness	TBD AoA / Reynolds number / roughness parameters	3 weeks	TBD AoA / Reynolds number / roughness parameters	3 weeks	Global optical and / or discrete surface heat transfer instrumentation	Ceramic models for global optical, metallic for discrete surface

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.1504	Define RCS/surface interaction effects on aftbody convective heating	Sufficient Mach/Re range to simulate flight conditions and RCS mass flow relative to freestream in N2	TBD Mach / AoA / Reynolds number / thruster parameters	3 weeks	TBD Mach / AoA / Reynolds number / thruster parameters	3 weeks	Global and/or discrete surface heating and pressure measurements. High-speed laser and schlieren systems for flow field diagnostics	Metallic models with internal plumbing for RCS jet mass flow
2.1505	Define rarefied aerocapture phase aerodynamic performance database	Reynolds / Mach range relevant to high-altitude Titan aerocapture	TBD AoA / Mach / Reynolds number points	1 week	TBD AoA / Mach / Reynolds number points	1 week	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1506	Define hypersonic aerodynamic performance database	Hypersonic conditions at enthalpies sufficient to produce N2 chemical kinetics at Titan specific conditions	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	1 week	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	1 week	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1507	Define supersonic static aerodynamic performance database	Supersonic Mach 2-5 with wide range of Reynolds numbers and Titan-specific N2 real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	2 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	2 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
2.1508	Determine dynamic stability parameters for vehicle at supersonic conditions	Supersonic Mach 2-5 with wide range of Reynolds numbers and Titan-specific N2 real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	Dynamic oscillation rig for wind tunnel force & moment. High speed imaging for ballistics range test	Metallic force & moment model fabrication
2.1509	Define supersonic RCS performance	Supersonic Mach 2-5 with wide range of Reynolds numbers and Titan-specific N2 real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	Global and/or discrete surface pressure measurement. High-speed laser and schlieren systems for flow field diagnostics. High-pressure gas delivery to RCS jets	Ability to fabricate gas delivery systems and RCS nozzles
2.16	Venus Climate Flagship Mission							
2.1601	Define vehicle radiative aeroheating environments	High-enthalpy facility operating at sufficient enthalpy to produce shock-layer radiation at Venus-specific CO2 conditions	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	Discrete surface heat-flux and radiation gages. Flow field and spectrographic sensor	metallic model with radiation sensors
2.1602	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	High enthalpy, reacting gas CO2 and sufficient Reynolds number range to produce turbulent flow	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	4 weeks at ARC HFFAF, 2 weeks at LaRC Tunnels	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	4 weeks at CUBRC LENS, 2 weeks at AEDC Tunnels	Global optical and / or discrete surface heat transfer instrumentation	Ceramic models for global optical, metallic for discrete surface

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.1603	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	Sufficient Reynolds number range / model scale to produce transitional and turbulent flow for TPS roughness	TBD AoA / Reynolds number / roughness parameters	3 weeks	TBD AoA / Reynolds number / roughness parameters	3 weeks	Global optical and / or discrete surface heat transfer instrumentation	Ceramic models for global optical, metallic for discrete surface
2.1604	Define RCS/surface interaction effects on aftbody convective heating	Sufficient Mach/Re range to simulate flight conditions and RCS mass flow relative to freestream in CO2	TBD Mach / AoA / Reynolds number / thruster parameters	3 weeks	TBD Mach / AoA / Reynolds number / thruster parameters	3 weeks	Global and/or discrete surface heating and pressure measurements. High-speed laser and schlieren systems for flow field diagnostics	Metallic models with internal plumbing for RCS jet mass flow
2.1605	Define rarefied aerocapture phase aerodynamic performance database	Reynolds / Mach range relevant to high-altitude Venus aerocapture	TBD AoA / Mach / Reynolds number points	1 week	TBD AoA / Mach / Reynolds number points	1 week	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1606	Define hypersonic aerodynamic performance database	Hypersonic conditions at enthalpies sufficient to produce CO2 chemical kinetics at Venus specific conditions	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	1 week	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	1 week	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1607	Define supersonic static aerodynamic performance database	Supersonic Mach 2-5 with wide range of Reynolds numbers and Venus-specific CO2 real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	2 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	2 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
2.1608	Determine dynamic stability parameters for vehicle at supersonic conditions	Supersonic Mach 2-5 with wide range of Reynolds numbers and Venus-specific CO2 real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	Dynamic oscillation rig for wind tunnel force & moment. High speed imaging for ballistics range test	Metallic force & moment model fabrication
2.1609	Define supersonic RCS performance	Supersonic Mach 2-5 with wide range of Reynolds numbers and Venus-specific CO2 real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	Global and/or discrete surface pressure measurement. High-speed laser and schlieren systems for flow field diagnostics. High-pressure gas delivery to RCS jets	Ability to fabricate gas delivery systems and RCS nozzles
2.17	Ice Giant (Uranus or Neptune) Orbiter/Probe Flagship Mission							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.1701	Define vehicle radiative aeroheating environments at Ice Giant specific conditions	High-enthalpy facility operating at sufficient enthalpy to produce shock-layer radiation at Ice Giant-specific H2/He conditions	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	Discrete surface heat-flux and radiation gages. Flow field and spectrographic sensor	metallic model with radiation sensors
2.1702	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	High enthalpy, reacting gas H2/He and sufficient Reynolds number range to produce turbulent flow	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	4 weeks at ARC HFFAF, 2 weeks at LaRC Tunnels	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	4 weeks at CUBRC LENS, 2 weeks at AEDC Tunnels	Global optical and / or discrete surface heat transfer instrumentation	Ceramic models for global optical, metallic for discrete surface
2.1703	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	Sufficient Reynolds number range / model scale to produce transitional and turbulent flow for TPS roughness	TBD AoA / Reynolds number / roughness parameters	3 weeks	TBD AoA / Reynolds number / roughness parameters	3 weeks	Global optical and / or discrete surface heat transfer instrumentation	Ceramic models for global optical, metallic for discrete surface
2.1704	Define RCS/surface interaction effects on aftbody convective heating	Sufficient Mach/Re range to simulate flight conditions and RCS mass flow relative to freestream in H2/He	TBD Mach / AoA / Reynolds number / thruster parameters	3 weeks	TBD Mach / AoA / Reynolds number / thruster parameters	3 weeks	Global and/or discrete surface heating and pressure measurements. High-speed laser and schlieren systems for flow field diagnostics	Metallic models with internal plumbing for RCS jet mass flow
2.1705	Define rarefied aerocapture phase aerodynamic performance database	Reynolds / Mach range relevant to high-altitude Ice Giant aerocapture	TBD AoA / Mach / Reynolds number points	1 week	TBD AoA / Mach / Reynolds number points	1 week	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1706	Define hypersonic aerodynamic performance database	Hypersonic conditions at enthalpies sufficient to produce H2/He chemical kinetics at Ice Giant specific conditions	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	1 week	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	1 week	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1707	Define supersonic static aerodynamic performance database	Supersonic Mach 2-5 with wide range of Reynolds numbers and Ice Giant-specific H2/He real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	2 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	2 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
2.1708	Determine dynamic stability parameters for vehicle at supersonic conditions	Supersonic Mach 2-5 with wide range of Reynolds numbers and Ice Giant-specific H2/He real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	Dynamic oscillation rig for wind tunnel force & moment. High speed imaging for ballistics range test	Metallic force & moment model fabrication

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.1709	Define supersonic RCS performance	Supersonic Mach 2-5 with wide range of Reynolds numbers and Ice Giant-specific H2/He real gas compressibility effects	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	TBD Mach / Reynolds / AoA range sufficient to ensure flagship mission success	4 weeks	Global and/or discrete surface pressure measurement. High-speed laser and schlieren systems for flow field diagnostics. High-pressure gas delivery to RCS jets	Ability to fabricate gas delivery systems and RCS nozzles
2.18	Enceladus orbiter and lander Flagship Mission							
2.1801	Define radiative aerothermal environments of vehicle during Titan aerocapture phase	High-enthalpy facility operating at sufficient enthalpy to produce shock-layer radiation at Titan-specific N2 conditions	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	TBD AoA/pressure/velocity-composition points to define radiative heating at mission specific conditions	3 weeks	Discrete surface heat-flux and radiation gages. Flow field and spectrographic sensor	metallic model with radiation sensors
2.1802	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	High enthalpy, reacting gas N2 and sufficient Reynolds number range to produce turbulent flow	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	4 weeks at ARC HFFAF, 2 weeks at LaRC Tunnels	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	4 weeks at CUBRC LENS, 2 weeks at AEDC Tunnels	Global optical and / or discrete surface heat transfer instrumentation	Ceramic models for global optical, metallic for discrete surface
2.1803	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	Sufficient Reynolds number range / model scale to produce transitional and turbulent flow for TPS roughness	TBD AoA / Reynolds number / roughness parameters	3 weeks	TBD AoA / Reynolds number / roughness parameters	3 weeks	Global optical and / or discrete surface heat transfer instrumentation	Ceramic models for global optical, metallic for discrete surface
2.1804	Define RCS/surface interaction effects on aftbody convective heating	Sufficient Mach/Re range to simulate flight conditions and RCS mass flow relative to freestream in Titan-specific N2	TBD Mach / AoA / Reynolds number / thruster parameters	3 weeks	TBD Mach / AoA / Reynolds number / thruster parameters	3 weeks	Global and/or discrete surface heating and pressure measurements. High-speed laser and schlieren systems for flow field diagnostics	Metallic models with internal plumbing for RCS jet mass flow
2.1805	Define rarefied aerocapture phase aerodynamic performance database	Reynolds / Mach range relevant to high-altitude Titan aerocapture	TBD AoA / Mach / Reynolds number points	1 week	TBD AoA / Mach / Reynolds number points	1 week	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1806	Define hypersonic aerodynamic performance database during Titan aerocapture	Hypersonic conditions at enthalpies sufficient to produce N2 chemical kinetics at Titan specific conditions	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	1 week	TBD Mach / AoA / Reynolds numbers sufficient to ensure flagship mission success	1 week	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
2.1807	Define supersonic static aerodynamic performance database	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.1808	Determine dynamic stability parameters for vehicle at supersonic conditions	N/A	N/A	N/A	N/A	N/A	N/A	N/A

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.1809	Define supersonic RCS performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.2	**Common probe**							
2.21	Placeholder							
2.3	**New Frontiers Missions**							
2.31	Titan DragonFly - New Frontiers Mission							
2.3101	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3102	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3103	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.32	Lunar South-Pole Aitkens Basin Sample Return New Frontiers Mission							
2.3201	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3202	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3203	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.33	Comet Sample Return - New Frontiers Mission							
2.3301	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3302	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3303	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.34	Venus in Situ Explorer New Frontiers Mission							
2.3401	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3402	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3403	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.35	Saturn Probe New Frontiers Mission							
2.3501	Define radiative heating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3502	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3503	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
2.4	**Discovery or other missions**							
2.41	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging Plus (DAVINCI+)							
2.4101	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.42	VERITAS							
2.4201	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.43	Discovery mission #3							
2.4301	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.44	Discovery mission #4							
2.4401	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.45	Discovery mission #5							
2.4501	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.46	Discovery mission #6							
2.4601	Placeholder	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 32. Gaps List for Theme: Hypersonic Entry, Descent, and Landing, Customer: NASA and Partners Robotic Exploration.

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
2	**NASA and Partners Robotic Exploration**					
2.1	**Flagship Missions**					
2.11	Mars 2020					
2.1101	Evaluate aeroshell aeroheating with simulated TPS test data vs MEDLI2 flight data	Potentially insufficient Reynolds number range in NASA facilities.	None	N/A	Ability to 3D print/machine or cast detailed surface features for global techniques.	EDL-01, EDL-09, EDL-12
2.1102	Evaluate aftbody convective heating test data vs MEDLI2 flight data	No high-enthalpy CO2 effects in NASA wind tunnels.	N/A	Ability to install discrete sensors due to internal volume constraints, Lack of global techniques for very low-temperature response conditions.	none expected	EDL-02, EDL-07, EDL-09, EDL-12
2.1103	Radiation data for MEDLI-2 specific conditions	Potential gap in facility operating conditions w/respect to flight	N/A	none expected	none expected	EDL-04, EDL-12
2.12	Mars Sample Retrieval Flagship Mission: Sample Return Lander (SRL)					
2.1201	Develop hypersonic aerodynamic performance database	Cannot reproduce high-enthalpy CO2 effects in NASA LaRC and AEDC facilities	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation at CUBRC	none expected	EDL-02, EDL-12, Inst-Aero-01
2.1202	Develop supersonic static aerodynamic performance database	Reynolds/Mach number ranges limitations. Lack of CO2 real-gas compressibility effects capability in AEDC and NASA facilities	Cost and scheduling at AEDC. Potential LaRC UPWT closure	none expected	none expected	EDL-01, EDL-06, EDL-12
2.1203	Determine dynamic stability parameters for vehicle at supersonic conditions	Reynolds/Mach number ranges of wind tunnels. Lack of CO2 real-gas compressibility effects capability in AEDC and NASA facilities. Ames HFFAF AoA limitations for ballistics ranges	Cost and scheduling at AEDC. Potential LaRC UPWT closure	Aerodynamic force and moment balances with high-frequency response for dynamic pitch-response measurement nay not be available. Inability to separate strut/balance effects from dynamic response	none expected	EDL-06, EDL-11, EDL-12, Inst-Aero-06
2.1204	Define supersonic RCS aerodynamic performance and interactions	Lack of CO2 real-gas compressibility effects capability in AEDC and NASA facilities.	Cost and scheduling at AEDC facilities.	Ability to accurately measure small deltas in aero coefficients due to thruster	Ability to design and fabrication of models with plumping for active RCS jets	EDL-06, EDL-09, EDL-12, Inst-Aero-03
2.1205	Determine baseline, smooth-OML convective aerothermal environments of aeroshell	Inability to produce sufficient enthalpy for to produce nonequilibrium chemical kinetics at relevant Mach/Re in CO2 for NASA and AEDC facilities. Model scale, AoA range at HFFAF	Cost and scheduling at CUBRC	none expected	none expected	EDL-01, EDL-02, EDL-12
2.1206	Determine convective aerothermal effects of aeroshell TPS response to step / gaps between TPS blocks	Potentially insufficient Reynolds number range in NASA facilities. AoA range in ARC HFFAF	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validation of global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
2.1207	Determine convective aerothermal effects of aeroshell TPS response to distributed surface ablation roughness	Potentially insufficient Reynolds number range in NASA facilities. AoA range in ARC HFFAF	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12
2.1208	Define convective aerothermal environments of aftbody/payload	No high-enthalpy CO2 kinetic effects in NASA or AEDC. Sufficient run time for wake flow establishment at CUBRC	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	Ability to install discrete sensors due to internal volume constraints, Lack of global techniques for very low-temperature response conditions.	non expected	EDL-02, EDL-07, EDL-12
2.1209	Determine RCS jet/surface interaction effects on aftbody heating	No high-enthalpy CO2 real-gas effects in NASA or AEDC tunnels. Sufficient run time for wake / RCS flow establishment at CUBRC	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	Ability to accurately measure low temp / low heating aftbody / RCS interaction in all facilities	Ability to design and fabrication of models with plumping for active RCS jets	EDL-02, EDL-07, EDL-09, EDL-12
2.121	Define radiative aerothermal environments of vehicle	NASA EAST can only provide fundamental physics data, not vehicle configuration testing. CUBRC may not have operational range to produce mission relevant radiation processes	Cost and scheduling at CUBRC	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, EDL-12, Inst-Heat-03, Inst-Heat-04
2.1211	Post-flight assessment / reconstruction based on aeroshell flight data	lack of high-enthalpy CO2 in NASA and AEDC Tunnels, lack of high-Reynolds capability in NASA faculties	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	none expected	none expected	EDL-01, EDL-02, EDL-12
2.1212	Post-flight assessment / reconstruction based on aftbody flight data	lack of high-enthalpy CO2 in NASA and AEDC Tunnels, lack of high-Reynolds capability in NASA faculties	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	none expected	none expected	EDL-01, EDL-02, EDL-07, EDL-12
2.13	Mars Sample Retrieval Flagship Mission: Mars Ascent Vehicle (MAV)					
2.1301	Develop hypersonic aerodynamic performance database	Cannot reproduce high-enthalpy CO2 effects in NASA or AEDC facilities	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-02, EDL-12, Inst-Aero-01
2.1302	Develop supersonic static aerodynamic performance database	Cannot reproduce CO2 compressibility effects in NASA or AEDC facilities	Cost and scheduling at AEDC. Potential LaRC UPWT closure	none expected	none expected	EDL-01, EDL-06, EDL-12
2.1303	Determine dynamic stability parameters for vehicle at supersonic conditions	Reynolds/Mach number ranges of wind tunnels. Cannot reproduce CO2 compressibility effects in NASA or AEDC facilities. Ames HFFAF AoA limitations for ballistics ranges	Cost and scheduling at AEDC. Potential LaRC UPWT closure	Aerodynamic force and moment balances with high-frequency response for dynamic pitch-response measurement nay not be available. Inability to separate strut/balance effects from dynamic response	none expected	EDL-06, EDL-11, EDL-12, Inst-Aero-06
2.1304	Develop hypersonic aeroheating database	Cannot reproduce high-enthalpy CO2 effects in NASA or AEDC wind tunnels	Cost and scheduling at CUBRC and AEDC	none expected	none expected	EDL-02, EDL-12, Inst-Aero-01

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
2.14	Mars Sample Retrieval Flagship Mission: Earth Entry Vehicle (EEV)					
2.1401	Develop hypersonic aerodynamic performance database	Cannot reproduce high-enthalpy air kinetic effects in NASA and AEDC facilities	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation at CUBRC	none expected	EDL-02, EDL-12, Inst-Aero-01
2.1402	Develop supersonic static aerodynamic performance database	Reynolds/Mach number ranges of NASA facilities limitations.	Cost and scheduling at AEDC. Potential LaRC UPWT closure	none expected	none expected	EDL-01, EDL-06, EDL-12
2.1403	Determine dynamic stability parameters for vehicle at supersonic conditions	Reynolds/Mach number ranges of wind tunnels. AoA limitations for HFFAF ballistics ranges	Cost and scheduling at AEDC. Potential LaRC UPWT closure	Aerodynamic force and moment balances with high-frequency response for dynamic pitch-response measurement nay not be available. Inability to separate strut/balance effects from dynamic response	none expected	EDL-06, EDL-11, EDL-12, Inst-Aero-06
2.1404	Determine baseline, smooth-OML convective aerothermal environments of aeroshell	LaRC and AEDC cannot produce sufficient enthalpy for to produce nonequilibrium chemical kinetics at relevant Mach/Re in Air. Model scale, AoA range at HFFAF	Cost and scheduling at CUBRC	none expected	none expected	EDL-01, EDL-02, EDL-12
2.1405	Determine convective aerothermal effects of aeroshell TPS response to discrete micro-meteoroid & orbital debris (MMOD) impact cavities	Potentially insufficient Reynolds number range in NASA facilities. AoA range in ARC HFFAF	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validation of global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12
2.1406	Determine convective aerothermal effects of aeroshell TPS response to distributed surface ablation roughness	Potentially insufficient Reynolds number range in NASA facilities. AoA range in ARC HFFAF	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12
2.1407	Define convective aerothermal environments of aftbody/payload	No high-enthalpy air kinetic effects in AEDC and NASA wind tunnels	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	Ability to install discrete sensors due to internal volume constraints, Lack of global techniques for very low-temperature response conditions. Flow-field visualization techniques for hypersonic flows are in developmental stage	Design of models with internal plumbing and nozzles for flow-field seeding for flow-visualization, as well as discrete sensors	EDL-02, EDL-07, EDL-12
2.1408	Define radiative aerothermal environments of vehicle	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Cost and scheduling at CUBRC	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, EDL-12, Inst-Heat-03, Inst-Heat-04

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
2.1409	Post-flight assessment / reconstruction based on aeroshell flight data	lack of high-enthalpy Air capability in NASA and AEDC Tunnels, lack of high-Reynolds capability in NASA faculties	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	none expected	none expected	EDL-01, EDL-02, EDL-12
2.141	Post-flight assessment / reconstruction based on aftbody flight data	lack of high-enthalpy Air capability in NASA and AEDC Tunnels, lack of high-Reynolds capability in NASA faculties	Cost and scheduling at AEDC facilities. Cost, scheduling and run productivity at CUBRC	none expected	none expected	EDL-01, EDL-02, EDL-07, EDL-12
2.15	Titan-Saturn Flagship Mission					
2.1501	Define Titan-specific vehicle radiative aeroheating environments	NASA EAST can only provide fundamental physics data, not vehicle configuration testing. CUBRC may not have operational range to produce mission relevant radiation processes	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, EDL-12, Inst-Heat-03, Inst-Heat-04
2.1502	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	NASA and AEDC wind tunnels lack high-enthalpy N2 capability. NASA facilities may lack Reynolds number range. ARC HFFAF is AoA limited	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-01, EDL-02, EDL-12
2.1503	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	LaRC wind tunnels may lack Reynolds range to produce turbulence, ARC HFFAF is AoA limited.	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	Spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validated global aeroheating techniques at AEDC and CUBRC	1) Ability to 3D print/machine or cast detailed TPS roughness features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12
2.1504	Define RCS/surface interaction effects on aftbody convective heating	NASA and AEDC facilities lack high-enthalpy N2 capability.	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-02, EDL-07, EDL-12
2.1505	Define rarefied aerocapture phase aerodynamic performance database	No US facilities can provide rarefied aerodynamic test conditions	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-10
2.1506	Define hypersonic aerodynamic performance database	NASA and AEDC wind tunnels cannot produce high-enthalpy N2 kinetic effects	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-02, EDL-12, Inst-Aero-01
2.1507	Define supersonic static aerodynamic performance database	There are no NASA or AEDC facilities for supersonic N2 flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	none expected	none expected	EDL-01, EDL-12
2.1508	Determine dynamic stability parameters for vehicle at supersonic conditions	There are no NASA or AEDC facilities for supersonic N2 flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	Aerodynamic force and moment balances with high-frequency response for dynamic pitch-response measurement nay not be available. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12, Inst-Aero-06

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
2.1509	Define supersonic RCS performance	There are no NASA or AEDC facilities for supersonic N2 flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	Ability to accurately measure small deltas in aero coefficients due to thruster	Ability to design and fabrication of models with plumping for active RCS jets	EDL-09, EDL-12, Inst-Aero-03
2.16	Venus Climate Flagship Mission					
2.1601	Define vehicle radiative aeroheating environments	NASA EAST can only provide fundamental physics data, not vehicle configuration testing. CUBRC may not have operational range to produce mission relevant radiation processes	Cost and scheduling at CUBRC	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, EDL-12, Inst-Heat-03, Inst-Heat-04
2.1602	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	NASA and AEDC wind tunnels lack high-enthalpy CO2 capability. NASA facilities may lack Reynolds number range. ARC HFFAF is AoA limited	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-01, EDL-02, EDL-12
2.1603	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	LaRC wind tunnels may lack Reynolds range to produce turbulence, ARC HFFAF is AoA limited.	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	Spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validated global aeroheating techniques at AEDC and CUBRC	1) Ability to 3D print/machine or cast detailed TPS roughness features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12
2.1604	Define RCS/surface interaction effects on aftbody convective heating	NASA and AEDC facilities lack high-enthalpy CO2 capability.	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-02, EDL-07, EDL-12
2.1605	Define rarefied aerocapture phase aerodynamic performance database	No US facilities can provide rarefied aerodynamic test conditions	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-10
2.1606	Define hypersonic aerodynamic performance database	NASA and AEDC wind tunnels cannot produce high-enthalpy CO2 kinetic effects	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-02, EDL-12, Inst-Aero-01
2.1607	Define supersonic static aerodynamic performance database	There are no NASA or AEDC facilities for supersonic CO2 flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	none expected	none expected	EDL-01, EDL-12
2.1608	Determine dynamic stability parameters for vehicle at supersonic conditions	There are no NASA or AEDC facilities for supersonic CO2 flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	Aerodynamic force and moment balances with high-frequency response for dynamic pitch-response measurement nay not be available. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12
2.1609	Define supersonic RCS performance	There are no NASA or AEDC facilities for supersonic CO2 flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	Ability to accurately measure small deltas in aero coefficients due to thruster	Ability to design and fabrication of models with plumping for active RCS jets	EDL-09, EDL-12, Inst-Aero-03
2.17	Ice Giant (Uranus or Neptune) Orbiter/Probe Flagship Mission					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
2.1701	Define vehicle radiative aeroheating environments at Ice Giant specific conditions	NASA EAST can only provide fundamental physics data, not vehicle configuration testing. CUBRC may not have operational range to produce mission relevant radiation processes	Cost and scheduling at CUBRC	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-05, Inst-Heat-02, Inst-Heat-03
2.1702	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	NASA and AEDC wind tunnels lack high-enthalpy H2/He capability. NASA facilities may lack Reynolds number range. ARC HFFAF is AoA limited	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-01, EDL-03, EDL-12
2.1703	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	LaRC wind tunnels may lack Reynolds range to produce turbulence, ARC HFFAF is AoA limited.	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	Spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validated global aeroheating techniques at AEDC and CUBRC	1) Ability to 3D print/machine or cast detailed TPS roughness features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12
2.1704	Define RCS/surface interaction effects on aftbody convective heating	NASA and AEDC facilities lack high-enthalpy H2/He capability.	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-03, EDL-07, EDL-12
2.1705	Define rarefied aerocapture phase aerodynamic performance database	No US facilities can provide rarefied aerodynamic test conditions	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-10
2.1706	Define hypersonic aerodynamic performance database	NASA and AEDC wind tunnels cannot produce high-enthalpy H2/He kinetic effects	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-03, EDL-12, Inst-Aero-01
2.1707	Define supersonic static aerodynamic performance database	There are no NASA or AEDC facilities for supersonic H2/He flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	none expected	none expected	EDL-01, EDL-12
2.1708	Determine dynamic stability parameters for vehicle at supersonic conditions	There are no NASA or AEDC facilities for supersonic H2/He flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	Aerodynamic force and moment balances with high-frequency response for dynamic pitch-response measurement nay not be available. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12
2.1709	Define supersonic RCS performance	There are no NASA or AEDC facilities for supersonic H2/He flow, would be extrapolating from perfect-gas facility data	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship. Potential LaRC UPWT closure	Ability to accurately measure small deltas in aero coefficients due to thruster	Ability to design and fabrication of models with plumping for active RCS jets	EDL-09, EDL-12, Inst-Aero-03
2.18	Enceladus orbiter and lander Flagship Mission					
2.1801	Define radiative aerothermal environments of vehicle during Titan aerocapture phase	NASA EAST can only provide fundamental physics data, not vehicle configuration testing. CUBRC may not have operational range to produce mission relevant radiation processes	Cost and scheduling at CUBRC	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, Inst-Heat-02, Inst-Heat-03

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
2.1802	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	NASA and AEDC wind tunnels lack high-enthalpy N2 capability. NASA facilities may lack Reynolds number range. ARC HFFAF is AoA limited	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-01, EDL-02, EDL-12
2.1803	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	LaRC wind tunnels may lack Reynolds range to produce turbulence, ARC HFFAF is AoA limited.	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	Spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validated global aeroheating techniques at AEDC and CUBRC	1) Ability to 3D print/machine or cast detailed TPS roughness features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12
2.1804	Define RCS/surface interaction effects on aftbody convective heating	NASA and AEDC facilities lack high-enthalpy N2 capability.	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-03, EDL-07, EDL-12
2.1805	Define rarefied aerocapture phase aerodynamic performance database	No US facilities can provide rarefied aerodynamic test conditions	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-10
2.1806	Define hypersonic aerodynamic performance database during Titan aerocapture	NASA and AEDC wind tunnels cannot produce high-enthalpy N2 kinetic effects	Schedule capacity at non-NASA facilities- but assume cost not a factor for flagship	none expected	none expected	EDL-02, EDL-12, Inst-Aero-01
2.1807	Define supersonic static aerodynamic performance database	N/A	N/A	N/A	N/A	
2.1808	Determine dynamic stability parameters for vehicle at supersonic conditions	N/A	N/A	N/A	N/A	
2.1809	Define supersonic RCS performance	N/A	N/A	N/A	N/A	
2.2	**Common probe**					
2.21	Placeholder					
2.3	**New Frontiers Missions**					
2.31	Titan DragonFly - New Frontiers Mission					
2.3101	Define radiative heating environments	N/A	N/A	N/A	N/A	
2.3102	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	
2.3103	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	
2.32	Lunar South-Pole Aitkens Basin Sample Return New Frontiers Mission					
2.3201	Define radiative heating environments	N/A	N/A	N/A	N/A	
2.3202	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	
2.3203	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
2.33	Comet Sample Return - New Frontiers Mission					
2.3301	Define radiative heating environments	N/A	N/A	N/A	N/A	
2.3302	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	
2.3303	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	
2.34	Venus in Situ Explorer New Frontiers Mission					
2.3401	Define radiative heating environments	N/A	N/A	N/A	N/A	
2.3402	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	
2.3403	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	
2.35	Saturn Probe New Frontiers Mission					
2.3501	Define radiative heating environments	N/A	N/A	N/A	N/A	
2.3502	Define hypersonic convective aeroheating environments	N/A	N/A	N/A	N/A	
2.3503	Define hypersonic / supersonic aerodynamic performance	N/A	N/A	N/A	N/A	
2.4	**Discovery or other missions**					
2.41	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging Plus (DAVINCI+)					
2.4101	Placeholder	N/A	N/A	N/A	N/A	
2.42	VERITAS					
2.4201	Placeholder	N/A	N/A	N/A	N/A	
2.43	Discovery mission #3					
2.4301	Placeholder	N/A	N/A	N/A	N/A	
2.44	Discovery mission #4					
2.4401	Placeholder	N/A	N/A	N/A	N/A	
2.45	Discovery mission #5					
2.4501	Placeholder	N/A	N/A	N/A	N/A	
2.46	Discovery mission #6					
2.4601	Placeholder	N/A	N/A	N/A	N/A	

Table 33. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Robotic Exploration.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2	**NASA and Partners Robotic Exploration**					
2.1	**Flagship Missions**					
2.11	Mars 2020					
2.1101	Evaluate aeroshell aeroheating with simulated TPS test data vs MEDLI2 flight data	NASA facilities may not have high enough Reynolds number. Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Develop NASA high-Reynolds number capability. Use these data to develop/validate CFD models	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	expected to be sufficient
2.1102	Evaluate aftbody convective heating test data vs MEDLI2 flight data	NASA cannot simulate high-enthalpy CO2	Moderate - lack of data could lead to increased margins	Use unvalidated hypersonic wake flow CFD simulations to define aftbody/payload heating environments. Develop NASA high-enthalpy CO2 capability. Use these data to develop/validate CFD models	Limited data to validate simulations of unsteady, transitional/turbulent vortices in wake flow fields	Large CPU memory/time requirements
2.1103	Radiation data for MEDLI-2 specific conditions	EAST may not have operational range (pressure, enthalpy) to simulate all conditions, radiation sensors may not have spectral range to be useful	Minimal: radiation transport simulations should be sufficient for conditions of interest	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions. Use these data to develop/validate CFD models	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient
2.12	Mars Sample Retrieval Flagship Mission: Sample Return Lander (SRL)					
2.1201	Develop hypersonic aerodynamic performance database	Non-NASA facilities may not be available/affordable within project scope and Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA and AEDC wind tunnels cannot provide high-enthalpy CO2 flow	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aerodynamics. ** risk category assumes SRL configuration does not change	Use CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy CO2 test capability	Expected to be sufficient, but lacking direct mission/configuration specific validation	expected to be sufficient
2.1202	Develop supersonic static aerodynamic performance database	Non-NASA facilities may not be available/affordable within project scope. LaRC UPWT at risk of closure. NASA and AEDC wind tunnels cannot provide CO2 compressibility effects	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body supersonic aerodynamics ** risk category assumes SRL configuration does not change	Use CFD to obtain supersonic static aerodynamics. Develop NASA CO2 test capability	Expected to be sufficient, but lacking direct mission/configuration specific validation	expected to be sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.1203	Determine dynamic stability parameters for vehicle at supersonic conditions	Non-NASA facilities may not be available/affordable within project scope. LaRC UPWT at risk of closure. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. NASA and AEDC wind tunnels cannot provide CO2 compressibility effects	Moderate: dynamic aero properties may not have large influence due to small payload and lack of impingement. However, high degree of confidence required due to planetary protection requirements ** risk category assumes SRL configuration does not change	Use developmental CFD tools (unvalidated) and/or legacy data for dynamic properties. Develop NASA CO2 test capability	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
2.1204	Define supersonic RCS aerodynamic performance and interactions	Non-NASA facilities may not be available / affordable within project scope. All facilities may lack operational range to simulate correct ratio of RCS mass flow to flight conditions, measurements of low. NASA and AEDC wind tunnels cannot provide CO2 compressibility effects	Moderate - lack of data could lead to aero performance margins ** risk category assumes SRL configuration does not change	Trajectory modification, if possible, use unvalidated hypersonic wake flow CFD simulations to define RCS/surface interaction effects. Develop NASA CO2 test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows. CFD will carry large uncertainties	Large CPU memory/time requirements
2.1205	Determine baseline, smooth-OML convective aerothermal environments of aeroshell	Non-NASA facilities may not be available / affordable within project scope. Facilities may not have operational range (pressure, enthalpy) to simulate kinetics. NASA facilities lack CO2, high-enthalpy capability	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aeroheating on smooth OML. ** risk category assumes SRL configuration does not change	Reliance on CFD simulations. Develop NASA CO2 high-enthalpy capability	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient
2.1206	Determine convective aerothermal effects of aeroshell TPS response to step / gaps between TPS blocks	Non-NASA facilities may not be available / affordable within project scope. NASA facilities lack high-Reynolds capability.	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of block TPS steps/gaps on aeroheating ** risk category assumes SRL configuration does not change	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine block TPS step/gap effects on aeroheating. Develop NASA high-Reynolds capability. Rely on low-Reynolds number testing and extrapolate	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	expected to be sufficient
2.1207	Determine convective aerothermal effects of aeroshell TPS response to distributed surface ablation roughness	NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available / affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness. ** risk category assumes SRL configuration does not change	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating. Develop NASA high Reynolds capability. Rely on low-Reynolds number testing and extrapolate	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	expected to be sufficient
2.1208	Define convective aerothermal environments of aftbody/payload	NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available / affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate - lack of data could lead to increased margins ** risk category assumes SRL configuration does not change	Trajectory modification, if possible, use unvalidated hypersonic wake flow CFD simulations to define aftbody/payload heating environments. Develop NASA high-Reynolds capability	Limited data to validate simulations of unsteady, transitional/turbulent vortices in wake flow fields	Large CPU memory/time requirements

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.1209	Determine RCS jet/surface interaction effects on aftbody heating	Non-NASA facilities may not be available / affordable within project scope. All facilities may lack operational range to simulate correct ratio of RCS mass flow to flight conditions, measurements of low. NASA facilities lack high-enthalpy CO2 capability	Moderate - lack of data could lead to increased margins and/or TPS redesign ** risk category assumes SRL configuration does not change	Trajectory modification, if possible, use unvalidated hypersonic wake flow CFD simulations to define RCS/surface interaction effects. Develop NASA CO2 test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows	Large CPU memory/time requirements
2.121	Define radiative aerothermal environments of vehicle	Operating conditions of CUBRC and cost/availability, Insufficient scale to test OML at NASA EAST	Minimal: radiation transport simulations should be sufficient for conditions of interest	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions. Rely on CFD	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient
2.1211	Post-flight assessment / reconstruction based on aeroshell flight data	Non-NASA facilities may not be available / affordable within project scope. NASA facilities lack high-Reynolds and high-enthalpy CO2 capability.	Minimal - this is a CFD validation task not supporting the flight	Develop/validate better CFD models using data. Develop NASA high Reynolds, CO2 capabilities	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	expected to be sufficient
2.1212	Post-flight assessment / reconstruction based on aftbody flight data	Non-NASA facilities may not be available / affordable within project scope. NASA facilities lack high-Reynolds and high-enthalpy CO2 capability.	Minimal - this is a CFD validation task not supporting the flight	Develop/validate better CFD models using data. Develop NASA high Reynolds, CO2 capabilities	Limited data to validate simulations of unsteady, transitional/turbulent vortices in wake flow fields	Large CPU memory/time requirements
2.13	Mars Sample Retrieval Flagship Mission: Mars Ascent Vehicle (MAV)					
2.1301	Develop hypersonic aerodynamic performance database	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for ascent vehicle	Expected to be sufficient, but lacking direct mission/configuration specific validation	Sufficient
2.1302	Develop supersonic static aerodynamic performance database	Non-NASA facilities may not be available/affordable within project scope. LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide CO2 flow	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for ascent vehicle supersonic aerodynamic	Use CFD to obtain supersonic static aerodynamics. Develop NASA CO2 test capability	Expected to be sufficient, but lacking direct mission/configuration specific validation	expected to be sufficient
2.1303	Determine dynamic stability parameters for vehicle at supersonic conditions	Non-NASA facilities may not be available/affordable within project scope. LaRC UPWT at risk of closure. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. NASA and AEDC facilities cannot provide CO2 flow	Minimal: dynamic aero properties may not have large influence due to small payload and lack of impingement. However, high degree of confidence required due to planetary protection requirements ** risk category assumes SRL configuration does not change	Use developmental CFD tools (unvalidated) and/or legacy data for dynamic properties. Develop NASA CO2 test capability	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.1304	Develop hypersonic aeroheating database	Non-NASA facilities may not be available / affordable within project scope. Facilities may not have operational range (pressure, enthalpy) to simulate kinetics. NASA and AEDC wind tunnels lack CO2 high-enthalpy capability	Minimal: CFD lacks direct validation for specific vehicle / trajectory heating is not expected to be large	Reliance on CFD simulations. Develop NASA CO2 high-enthalpy capability	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient
2.14	Mars Sample Retrieval Flagship Mission: Earth Entry Vehicle (EEV)					
2.1401	Develop hypersonic aerodynamic performance database	Non-NASA facilities may not be available/affordable within project scope and Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA and AEDC facilities cannot provide high-enthalpy air kinetics	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy capability	Expected to be sufficient, but lacking direct mission/configuration specific validation	expected to be sufficient
2.1402	Develop supersonic static aerodynamic performance database	Non-NASA facilities may not be available/affordable within project scope. LaRC UPWT at risk of closure.	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics	Expected to be sufficient, but lacking direct mission/configuration specific validation	expected to be sufficient
2.1403	Determine dynamic stability parameters for vehicle at supersonic conditions	Non-NASA facilities may not be available/affordable within project scope. LaRC UPWT at risk of closure. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field	Moderate: dynamic aero properties may not have large influence due to small payload and lack of impingement. However, high degree of confidence required due to planetary protection requirements	Use developmental CFD tools (unvalidated) and/or legacy data for dynamic properties	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
2.1404	Determine baseline, smooth-OML convective aerothermal environments of aeroshell	NASA and AEDC wind tunnels lack high-enthalpy air kinetics. Cost and Schedule in non-NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aeroheating	Reliance on CFD simulations. Develop NASA high-Reynolds / high-enthalpy capabilities	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient
2.1405	Determine convective aerothermal effects of aeroshell TPS response to discrete micro-meteoroid & orbital debris (MMOD) impact cavities	NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of MMOD on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine MMOD effects on aeroheating. Develop NASA high-Reynolds / high-enthalpy capabilities.	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	expected to be sufficient
2.1406	Determine convective aerothermal effects of aeroshell TPS response to distributed surface ablation roughness	NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating. Develop NASA high-Reynolds / high-enthalpy capabilities. Rely on lower-Re wind tunnel testing and legacy data	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	expected to be sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.1407	Define convective aerothermal environments of aftbody/payload	Non-NASA facilities may not be available/affordable within project scope. Test techniques for hypersonic flow visualization and low-heating aftbody measurements are developmental/unvalidated	High - lack of data will lead to increased margins and planetary protection requirements on Payload TPS are critical	Trajectory modification, if possible, use unvalidated hypersonic wake flow CFD simulations to define aftbody/payload heating environments. Rely on CFD with high margins	No data to validate simulations of unsteady, transitional/turbulent vortices in wake flow fields.	Large CPU memory/time requirements
2.1408	Define radiative aerothermal environments of vehicle	Non-NASA facilities may not be available/affordable within project scope. Facilities likely do not have operational range (pressure, enthalpy) to simulate conditions, radiation sensors may not have spectral range to be useful	Minimal: radiation transport simulations should be sufficient for conditions of interest	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions	Expected to be sufficient, but additional validation for flight-relevant conditions useful	expected to be sufficient
2.1409	Post-flight assessment / reconstruction based on aeroshell flight data	Non-NASA facilities may not be available / affordable within project scope. NASA facilities lack high-Reynolds and high-enthalpy Air capability.	Minimal - this is a CFD validation task not supporting the flight	Develop/validate better CFD models using data. Develop NASA high Reynolds, CO2 capabilities	Inability to predict roughness bypass transition onset. Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	expected to be sufficient
2.141	Post-flight assessment / reconstruction based on aftbody flight data	Non-NASA facilities may not be available / affordable within project scope. NASA facilities lack high-Reynolds and high-enthalpy Air capability.	Minimal - this is a CFD validation task not supporting the flight	Develop/validate better CFD models using data. Develop NASA high Reynolds, CO2 capabilities	Limited data to validate simulations of unsteady, transitional/turbulent vortices in wake flow fields	Large CPU memory/time requirements
2.15	Titan-Saturn Flagship Mission					
2.1501	Define Titan-specific vehicle radiative aeroheating environments	Operating conditions of CUBRC and cost/availability, Insufficient scale to test OML at NASA EAST	Minimal to moderate: radiation transport simulations may be sufficient for conditions of interest, but reduced uncertainty required for flagship missions	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions, expand operating range of EAST	May be sufficient, but additional validation for flight-relevant conditions required	expected to be sufficient
2.1502	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	Lack of high-enthalpy N2 kinetics in NASA and AEDC wind tunnels. Availability of non-NASA facilities	Minimal to moderate: depending on mission-specific. CFD will be employed but uncertainty reduction through testing may be desired	Primary reliance on CFD with higher margins. Develop NASA high-enthalpy and hN2 test capability	CFD generally accepted for blunt body, smooth OML aeroheating, but additional validation will be required for a flagship mission	expected to be sufficient
2.1503	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	Lack of Reynolds number range in NASA wind tunnels. Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating. Develop NASA high-Reynolds / high-enthalpy capabilities	CFD cannot predict roughness bypass transition but relies on empirical, TPS-specific models	expected to be sufficient
2.1504	Define RCS/surface interaction effects on aftbody convective heating	Lack of high-enthalpy N2 kinetics in NASA and AEDC wind tunnels, lack of Reynolds number in NASA wind tunnels, AoA range in ARC HFFAF. Availability of non-NASA facilities	Minimal to moderate: depending on mission-specific RCS usage. CFD will be employed by uncertainty reduction through testing in required	Primary reliance on CFD with higher margins. Develop NASA high-enthalpy N2 test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows. CFD will carry large uncertainties	Large CPU memory/time requirements

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.1505	Define rarefied aerocapture phase aerodynamic performance database	Lack of rarefied flow test capabilities. Availability of non-NASA facilities	Minimal to moderate: CFD lacks direct validation for specific vehicle/trajectory but should be sufficient unless configuration is departure from previous experience	Primary reliance on CFD to obtain rarefied static aerodynamics for blunt bodies. Develop NASA rarefied flow test capability	CFD generally accepted for blunt body rarefied aerodynamics, but additional validation desirable	expected to be sufficient
2.1506	Define hypersonic aerodynamic performance database	Lack of high-enthalpy N2 kinetics in NASA and AEDC wind tunnels. Availability of non-NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aerodynamics	Primary reliance on CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy N2 capability	CFD generally accepted for blunt body hypersonic aerodynamics, but additional validation desirable	expected to be sufficient
2.1507	Define supersonic static aerodynamic performance database	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide N2 real-gas compressibility effects. Availability of non-NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body static supersonic aerodynamics	Primary reliance on CFD to obtain supersonic static aerodynamics for blunt bodies. Develop NASA real-gas N2 aero testing capability	CFD generally accepted for blunt body static supersonic aerodynamics, but additional validation desirable	expected to be sufficient
2.1508	Determine dynamic stability parameters for vehicle at supersonic conditions	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide N2 real-gas compressibility effects. Availability of non-NASA facilities. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field.	Minimal to moderate: TBD if supersonic dynamics are important to specific architecture / flight conditions	Use developmental CFD tools (unvalidated) and/or legacy data for dynamic properties. Develop NASA N2 test capability	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
2.1509	Define supersonic RCS performance	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide N2 real-gas compressibility effects. Availability of non-NASA facilities. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field.	Minimal to moderate: TBD if supersonic RCS interactions are important to specific architecture / flight conditions	Use unvalidated wake flow CFD simulations to define RCS/surface interaction effects. Develop NASA N2 test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows. CFD will carry large uncertainties	Large CPU memory/time requirements
2.16	Venus Climate Flagship Mission					
2.1601	Define vehicle radiative aeroheating environments	Operating conditions of CUBRC and cost/availability, Insufficient scale to test OML at NASA EAST	Minimal to moderate: radiation transport simulations may be sufficient for conditions of interest, but reduced uncertainty required for flagship missions	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions, expand operating range of EAST	May be sufficient, but additional validation for flight-relevant conditions required	expected to be sufficient
2.1602	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	Lack of high-enthalpy CO2 in NASA and AEDC wind tunnels, lack of Reynolds number in NASA wind tunnels, AoA range in ARC HFFAF. Availability of non-NASA facilities	Minimal to moderate: depending on mission-specific. CFD will be employed but uncertainty reduction through testing may be desired	Primary reliance on CFD with higher margins. Develop NASA high-enthalpy and hN2 test capability	CFD generally accepted for blunt body, smooth OML aeroheating, but additional validation will be required for a flagship mission	expected to be sufficient
2.1603	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	Lack of Reynolds number range in NASA wind tunnels. Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating. Develop NASA high-Reynolds / high-enthalpy capabilities	CFD cannot predict roughness bypass transition but relies on empirical, TPS-specific models	expected to be sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.1604	Define RCS/surface interaction effects on aftbody convective heating	Lack of high-enthalpy CO2 kinetics in NASA and AEDC wind tunnels, lack of Reynolds number in NASA wind tunnels, AoA range in ARC HFFAF. Availability of non-NASA facilities	Minimal to moderate: depending on mission-specific RCS usage. CFD will be employed by uncertainty reduction through testing in required	Primary reliance on CFD with higher margins. Develop NASA high-enthalpy CO2 test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows. CFD will carry large uncertainties	Large CPU memory/time requirements
2.1605	Define rarefied aerocapture phase aerodynamic performance database	Lack of rarefied flow test capabilities. Availability of non-NASA facilities	Minimal to moderate: CFD lacks direct validation for specific vehicle/trajectory but should be sufficient unless configuration is departure from previous experience	Primary reliance on CFD to obtain rarefied static aerodynamics for blunt bodies. Develop NASA rarefied flow test capability	CFD generally accepted for blunt body rarefied aerodynamics, but additional validation desirable	expected to be sufficient
2.1606	Define hypersonic aerodynamic performance database	Lack of high-enthalpy CO2 kinetics in NASA and AEDC wind tunnels. Availability of non-NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aerodynamics	Primary reliance on CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy CO2 capability	CFD generally accepted for blunt body hypersonic aerodynamics, but additional validation desirable	expected to be sufficient
2.1607	Define supersonic static aerodynamic performance database	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide CO2 real-gas compressibility effects. Availability of non-NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body static supersonic aerodynamics	Primary reliance on CFD to obtain supersonic static aerodynamics for blunt bodies. Develop NASA real-gas CO2 aero testing capability	CFD generally accepted for blunt body static supersonic aerodynamics, but additional validation desirable	expected to be sufficient
2.1608	Determine dynamic stability parameters for vehicle at supersonic conditions	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide CO2 real-gas compressibility effects. Availability of non-NASA facilities. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field.	Minimal to moderate: TBD if supersonic dynamics are important to specific architecture / flight conditions	Use developmental CFD tools (unvalidated) and/or legacy data for dynamic properties. Develop NASA CO2 test capability	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
2.1609	Define supersonic RCS performance	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide CO2 real-gas compressibility effects. Availability of non-NASA facilities. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field.	Minimal to moderate: TBD if supersonic RCS interactions are important to specific architecture / flight conditions	Use unvalidated wake flow CFD simulations to define RCS/surface interaction effects. Develop NASA CO2 test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows. CFD will carry large uncertainties	Large CPU memory/time requirements
2.17	Ice Giant (Uranus or Neptune) Orbiter/Probe Flagship Mission					
2.1701	Define vehicle radiative aeroheating environments at Ice Giant specific conditions	Operating conditions of CUBRC and cost/availability, Insufficient scale to test OML at NASA EAST	Minimal to moderate: radiation transport simulations may be sufficient for conditions of interest, but reduced uncertainty required for flagship missions	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions, expand operating range of EAST	May be sufficient, but additional validation for flight-relevant conditions required	expected to be sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.1702	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	Lack of high-enthalpy H2/He in NASA and AEDC wind tunnels, lack of Reynolds number in NASA wind tunnels, AoA range in ARC HFFAF. Availability of non-NASA facilities	Minimal to moderate: depending on mission-specific. CFD will be employed but uncertainty reduction through testing may be desired	Primary reliance on CFD with higher margins. Develop NASA high-enthalpy and hN2 test capability	CFD generally accepted for blunt body, smooth OML aeroheating, but additional validation will be required for a flagship mission	expected to be sufficient
2.1703	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	Lack of Reynolds number range in NASA wind tunnels. Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating. Develop NASA high-Reynolds / high-enthalpy capabilities	CFD cannot predict roughness bypass transition but relies on empirical, TPS-specific models	expected to be sufficient
2.1704	Define RCS/surface interaction effects on aftbody convective heating	Lack of high-enthalpy H2/He kinetics in NASA and AEDC wind tunnels, lack of Reynolds number in NASA wind tunnels, AoA range in ARC HFFAF. Availability of non-NASA facilities	Minimal to moderate: depending on mission-specific RCS usage. CFD will be employed by uncertainty reduction through testing in required	Primary reliance on CFD with higher margins. Develop NASA high-enthalpy H2/He test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows. CFD will carry large uncertainties	Large CPU memory/time requirements
2.1705	Define rarefied aerocapture phase aerodynamic performance database	Lack of rarefied flow test capabilities. Availability of non-NASA facilities	Minimal to moderate: CFD lacks direct validation for specific vehicle/trajectory but should be sufficient unless configuration is departure from previous experience	Primary reliance on CFD to obtain rarefied static aerodynamics for blunt bodies. Develop NASA rarefied flow test capability	CFD generally accepted for blunt body rarefied aerodynamics, but additional validation desirable	expected to be sufficient
2.1706	Define hypersonic aerodynamic performance database	Lack of high-enthalpy H2/He kinetics in NASA and AEDC wind tunnels. Availability of non-NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aerodynamics	Primary reliance on CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy H2/He capability	CFD generally accepted for blunt body hypersonic aerodynamics, but additional validation desirable	expected to be sufficient
2.1707	Define supersonic static aerodynamic performance database	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide H2/He real-gas compressibility effects. Availability of non-NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body static supersonic aerodynamics	Primary reliance on CFD to obtain supersonic static aerodynamics for blunt bodies. Develop NASA real-gas H2/He aero testing capability	CFD generally accepted for blunt body static supersonic aerodynamics, but additional validation desirable	expected to be sufficient
2.1708	Determine dynamic stability parameters for vehicle at supersonic conditions	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide H2/He real-gas compressibility effects. Availability of non-NASA facilities. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field.	Minimal to moderate: TBD if supersonic dynamics are important to specific architecture / flight conditions	Use developmental CFD tools (unvalidated) and/or legacy data for dynamic properties. Develop NASA H2/He test capability	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
2.1709	Define supersonic RCS performance	LaRC UPWT at risk of closure. NASA and AEDC facilities cannot provide H2/He real-gas compressibility effects. Availability of non-NASA facilities. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field.	Minimal to moderate: TBD if supersonic RCS interactions are important to specific architecture / flight conditions	Use unvalidated wake flow CFD simulations to define RCS/surface interaction effects. Develop NASA H2/He test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows. CFD will carry large uncertainties	Large CPU memory/time requirements

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.18	Enceladus orbiter and lander Flagship Mission					
2.1801	Define radiative aerothermal environments of vehicle during Titan aerocapture phase	Operating conditions of CUBRC and cost/availability, Insufficient scale to test OML at NASA EAST	Minimal to moderate: radiation transport simulations may be sufficient for conditions of interest, but reduced uncertainty required for flagship missions	Primary reliance on radiation transport simulations, extrapolation of any experimental data to flight conditions, expand operating range of EAST	May be sufficient, but additional validation for flight-relevant conditions required	expected to be sufficient
2.1802	Define aeroshell baseline smooth-OML convective aeroheating environments at laminar, transitional and turbulent conditions	Lack of high-enthalpy N2 in NASA and AEDC wind tunnels, lack of Reynolds number in NASA wind tunnels, AoA range in ARC HFFAF. Availability of non-NASA facilities	Minimal to moderate: depending on mission-specific. CFD will be employed but uncertainty reduction through testing may be desired	Primary reliance on CFD with higher margins. Develop NASA high-enthalpy and hN2 test capability	CFD generally accepted for blunt body, smooth OML aeroheating, but additional validation will be required for a flagship mission	expected to be sufficient
2.1803	Define TPS-specific roughness effects on aeroshell BL transition and turbulent heating augmentation	Lack of Reynolds number range in NASA wind tunnels. Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating. Develop NASA high-Reynolds / high-enthalpy capabilities	CFD cannot predict roughness bypass transition but relies on empirical, TPS-specific models	expected to be sufficient
2.1804	Define RCS/surface interaction effects on aftbody convective heating	Lack of high-enthalpy N2 kinetics in NASA and AEDC wind tunnels, lack of Reynolds number in NASA wind tunnels, AoA range in ARC HFFAF. Availability of non-NASA facilities	Minimal to moderate: depending on mission-specific RCS usage. CFD will be employed by uncertainty reduction through testing in required	Primary reliance on CFD with higher margins. Develop NASA high-enthalpy N2 test capability	Limited data to validate simulations of RCS/surface interactions in unsteady wake flows. CFD will carry large uncertainties	Large CPU memory/time requirements
2.1805	Define rarefied aerocapture phase aerodynamic performance database	Lack of rarefied flow test capabilities. Availability of non-NASA facilities	Minimal to moderate: CFD lacks direct validation for specific vehicle/trajectory but should be sufficient unless configuration is departure from previous experience	Primary reliance on CFD to obtain rarefied static aerodynamics for blunt bodies. Develop NASA rarefied flow test capability	CFD generally accepted for blunt body rarefied aerodynamics, but additional validation desirable	expected to be sufficient
2.1806	Define hypersonic aerodynamic performance database during Titan aerocapture	Lack of high-enthalpy N2 kinetics in NASA and AEDC wind tunnels. Availability of non-NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / trajectory but is generally accepted for blunt body hypersonic aerodynamics	Primary reliance on CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy N2 capability	CFD generally accepted for blunt body hypersonic aerodynamics, but additional validation desirable	expected to be sufficient
2.1807	Define supersonic static aerodynamic performance database	N/A	N/A	N/A	N/A	N/A
2.1808	Determine dynamic stability parameters for vehicle at supersonic conditions	N/A	N/A	N/A	N/A	N/A
2.1809	Define supersonic RCS performance	N/A	N/A	N/A	N/A	N/A
2.2	**Common probe**					
2.21	Placeholder					
2.3	**New Frontiers Missions**					
2.31	Titan DragonFly - New Frontiers Mission					
2.3101	Define radiative heating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	None expected	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.3102	Define hypersonic convective aeroheating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.3103	Define hypersonic / supersonic aerodynamic performance	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.32	Lunar South-Pole Aitkens Basin Sample Return New Frontiers Mission					
2.3201	Define radiative heating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	None expected	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.3202	Define hypersonic convective aeroheating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.3203	Define hypersonic / supersonic aerodynamic performance	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.33	Comet Sample Return - New Frontiers Mission					
2.3301	Define radiative heating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	None expected	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.3302	Define hypersonic convective aeroheating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.3303	Define hypersonic / supersonic aerodynamic performance	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.34	Venus in Situ Explorer New Frontiers Mission					
2.3401	Define radiative heating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	None expected	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.3402	Define hypersonic convective aeroheating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.3403	Define hypersonic / supersonic aerodynamic performance	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.35	Saturn Probe New Frontiers Mission					
2.3501	Define radiative heating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	None expected	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.3502	Define hypersonic convective aeroheating environments	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
2.3503	Define hypersonic / supersonic aerodynamic performance	Expected to be sufficient unless departure from prior EDL architecture and experience	N/A	N/A	Expected to be sufficient unless departure from prior EDL architecture and experience	Expected to be sufficient
2.4	**Discovery or other missions**					
2.41	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging Plus (DAVINCI+)					
2.4101	Placeholder	N/A	N/A	N/A	N/A	N/A
2.42	VERITAS					
2.4201	Placeholder	N/A	N/A	N/A	N/A	N/A
2.43	Discovery mission #3					
2.4301	Placeholder	N/A	N/A	N/A	N/A	N/A
2.44	Discovery mission #4					
2.4401	Placeholder	N/A	N/A	N/A	N/A	N/A
2.45	Discovery mission #5					
2.4501	Placeholder	N/A	N/A	N/A	N/A	N/A
2.46	Discovery mission #6					
2.4601	Placeholder	N/A	N/A	N/A	N/A	N/A

Appendix E Database for Theme: Hypersonic Entry, Descent and Landing, Customer: NASA and Partners Technology and Architecture Development

Table 34. Programs List for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development.

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
Hypersonic Entry, Descent and Landing	**3**	**NASA and Partners EDL Technology and Architecture Development**	**NASA led, collaborative, or reimbursable activities supporting the development of new vehicle architectures for future exploration missions**		**NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)**	
	3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**	**HIAD architecture is comprised of an inflatable aeroshell covered with a flexible TPS that protects a small rigid-body payload.**	**End state to allow high-mass payload to Mars; LEO and lunar return applications**	**HIAD project documents**	
	3.11	HIAD - LOFTID demonstration mission for TPS performance	Small-scale (6 m diam) vehicle for concept demonstration and Flexible TPS performance validation	based on prior THOR and IRVE test programs and planning for LOFTID	LOFTID Flight test program	2018-2022
	3.12	HIAD: ISS down mass	Medium scale (10 m diam) vehicle for small payload return from ISS	Assume similar development program to LOFTID, but for larger scale vehicle and bigger payload, higher-velocity entry	HIAD mission applications studies	2022-2024
	3.13	HIAD: launch vehicle booster recovery	Medium scale (10 m diam) vehicle for recovery of launch system engine/booster stage	Using proposed ULA recovery of Vulcan engine as prototype. Aftbody/payload MUCH larger than LOFTID, so requires more analysis/testing. Carbon copy ISS payload requirements until more detail available	builds from LOFTID and ESM wake flow testing requirements	2023-2026
	3.14	Asymmetric aeroshell morphing for aerodynamic control and performance	Apply tension forces to underlying toroids to create an asymmetric aeroshell for lift/drag modulation	Considered as a potential developmental option	Dwyer-Cianciolo, AIAA-2020-1266, "Low Lift-to-Drag Morphing Shape Design"	
	3.24	HIAD skirt / inflatable tab extension to rigid aeroshell nose cap	Skirt or tab provides additional aerodynamic control	Considered as a potential developmental option		

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	3.15	HIAD: Human Mars Exploration mission	Large scale (~20 m diam) vehicle for high mass (cargo and crew) payload delivery to Mars. Full-scale flight test or operational mission. End-state of Inflatable development to enable high-mass Mars EDL. Database development for Human-rated system will require much higher fidelity than architectural evaluation or uncrewed flight test	This sequence is continued on Sheet 1 - Human Operations under Section 1.21 due to change in requirements from development to human rating	Descent & Landing System Architecture Study	2024-2028
	3.2	**Mid L/D Lifting Body**	**Mid L/D lifting body flying at high-AoA to deliver high-mass cargo/crew payload to Mars**	**End state to allow high-mass payload to Mars; LEO and lunar return applications**		
	3.21	Mid L/D Lifting-Body Architecture Configuration Evaluation for Mars Application	Evaluation of configuration options and performance for Mid L/D system	parametric studies to evaluate configuration options	Descent & Landing System Architecture Study. JSC proposal to STMD	
	3.22	Evaluation of CFD capability for Mid L/D Aero/Aeroheating prediction for Mars entry	Ground testing to obtain data to evaluate / validate / develop CFD simulation capabilities		AETC UPWT study and STMD/GCD	2020-2022
	3.23	Mid L/D Lifting Body - sub-scale flight test for aerodynamics and aeroheating	Precursor to sub-scale SRP flight test		Descent & Landing System Architecture Study	
	3.24	Mid L/D Lifting Body - sub-scale flight test for SRP performance	Precursor to operational Mars mission		Human Mars Entry, Descent, and Landing Architecture Study	
	3.25	Mid L/D Lifting Body - full-scale Mars flight test and/or missions	Flight test (or operational system) mission to Mars. End-state of Mid L/D development to enable high-mass Mars EDL. Database development for Human-rated system will require much higher fidelity than architectural evaluation or uncrewed flight test	This sequence is continued on Sheet 1 - Human Operations under Section 1.22 due to change in requirements from development to human rating	Descent & Landing System Architecture Study	
	3.3	**Deployable Aerodynamic Decelerator Technology Development and Demonstration**	**small to large scale deployable decelerators**	**potential applications for LEO and lunar return**		**2022-2035**
	3.31	SNC Deployable	Small system for payload return for ISS/LEO	Ongoing concept development and testing for Sierra Nevada		2020-2022
	3.32	Pterodactyl Control Systems for DEVs Sample Return	2.5m scale (Hypersonic to Subsonic, 11 km/s entry)	Less stringent risk/margin posture for development activity		2022-2024

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	3.33	ADEPT Drag Modulated Aerocapture Demonstration (Earth GTO). ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts	1.5-3m SmallSat scale (High altitude aerocapture, Air, 10.5 km/s entry)	Less stringent risk/margin posture for demo mission		2020-2024
	3.34	ADEPT Drag Modulated Aerocapture SmallSat Venus/Mars Orbiter. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts	1.5-3m SmallSat scale (High Altitude aerocapture, CO2)	Mission risk/margin posture becomes more stringent for flight mission		2022-2026
	3.35	ADEPT Drag Modulated Aerocapture Flagship Ice Giant Orbiter/Probe Mission. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts	12m scale (High altitude, H2-He atmosphere, 26+ km/s entry)	Mission risk/margin posture becomes more stringent for flight mission		2024-2028
	3.36	Large scale deployable aeroshell for Human rated Mars missions	Large scale (~20 m diam) vehicle for high mass (cargo and crew) payload delivery to Mars. Full-scale flight test or operational mission. End-state of deployable development to enable high-mass Mars EDL. Database development for Human-rated system will require much higher fidelity than architectural evaluation or uncrewed flight test	This sequence is continued on Sheet 1 - Human Operations under Section 1.23 due to change in requirements from development to human rating	Descent & Landing System Architecture Study	2035+
	3.4	**Advanced Rigid Aeroshell Capsule configurations**	**New rigid aeroshell designs (asymmetric, C2 continuous shapes) and augmentations to reduce heating or provide lift for entry maneuvers.**	**Potential application to future Mars missions short of full High-Mass Human rated systems**	**AFE, ACV, Ellipsoidal, ALHAT Direct Force control studies**	
	3.41	Geometric scaling of standard MSL / Orion type aeroshells	Enable higher mass	Mission/configuration trade study level of fidelity or TRL advancement. Flight mission requirements much greater		
	3.42	Asymmetric rigid Aeroshell - AFE, ACV optimized shapes, elliptical/hyperboloid cross-section, etc.	Generate lifting flight with asymmetric aeroshell OML	Mission/configuration trade study level of fidelity or TRL advancement. Flight mission requirements much greater	Multiple concept studies	

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	3.43	Aerodynamic Trim Tabs	One or more actuated trim tabs used to modulate L/D about one or two axes for improve entry performance (more payload to surface)	Mission/configuration trade study level of fidelity or TRL advancement	Korzun, AIAA-2013-2809, "Supersonic Aerodynamic Characteristics of Blunt Body Trim Tab Configurations:	
	3.44	Large scale rigid-TPS aeroshell for Human rated Mars missions utilizing any/all advance options listed under advanced rigid-aeroshell capsule development path	Large scale (~20 m diam) vehicle for high mass (cargo and crew) payload delivery to Mars. Full-scale flight test or operational mission. End-state of rigid-TPS aeroshell development to enable high-mass Mars EDL. Database development for Human-rated system will require much higher fidelity than architectural evaluation or uncrewed flight test. Unlikely option for High mass EDL, retained for completeness or for other potential missions requiring less landed mass	This sequence is continued on Sheet 1 - Human Operations under Section 1.24 due to change in requirements from development to human rating	Descent & Landing System Architecture Study	2035+
	3.5	**Super/Hypersonic Retropropulsion Technology Development and Demonstration**	**Use of engine thrust in place of aerodynamic drag for deceleration**	**Safe landing of high-mass payloads (cargo and crew) to Mars of 10x or greater than previous robotic missions will likely require sub/super/hypersonic retropropulsion. RP may be employed in conjunction with ADEPT, HIAD or Mid L/D systems**	**Descent & Landing System Architecture Study. JSR Vol 51, No 3**	
	3.51	Evaluation of CFD capability for SRP	RP testing in UPWT sponsored by AETC to evaluate capabilities of perfect gas CFD in supersonic regime		AETC UPWT study and STMD/GCD	2020-2022
	3.52	RP System ground testing capability development and unit-problem testing	Development of new capabilities for ground testing of retropropulsion systems including hot inert gas, sub-scale rocket engines, flow through balances, CO2 test environment		Edquist, JSR V51, No3	
	3.53	SRP Architecture Configuration Evaluation for Mars Application	Retropropulsion system demonstration at Earth as precursor to Mars flight demo		Edquist, JSR V51, No3	
	3.54	Earth reentry flight tests and system demonstration	Retropropulsion system demonstration at Earth as precursor to Mars flight demo			

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	3.55	Mars reentry flight tests and system demonstration	Full-scale flight test or operational mission. End-state of SRP development to enable high-mass Mars EDL. Database development for Human-rated system will require much higher fidelity than architectural evaluation or uncrewed flight test	There is no specific SRP mission to Mars entry here. The sequences for architecture + SRP options are listed on Sheet 1 - Human Operations under Sections 1.21 to 1.24 on Table 1	Descent & Landing System Architecture Study	2030s+
	3.6	**Aerocapture**	**High-altitude atmospheric pass to circularize/capture vehicle into orbit**	**Development, demonstration and validation of aerocapture technology as a mission element for multiple destinations including Venus, Gas Giant systems and ice Giant systems**	**Various concept studies**	
	3.61	Trade studies on aerocapture options for EDL exploration missions	Analyses to support concept/trade studies			
	3.62	Sub-scale Earth flight test for TRL advancement to mission application of aerocapture	Sub-scale flight test of aerocapture for a selected architecture (HIAD, Deployable, Mid L/D or rigid). Architecture would depend on NASA exploration priorities/mission-destination	Radiative heating not relevant for sub-scale earth demonstrator. Does not include post-aerocapture EDL sequence (if any)		**2025-2030**
	3.63	Small planet or satellite Mission (Venus, Titan, Mars, etc.) or Ice Giant (Uranus, Neptune)	Mission application using aerocapture pass at destination prior to EDL sequence			**2030-2035**
	3.7	**MHD Control of Flow Field**	**Using electro-magnetic effects to control shock-shape / flow field and modulate aerodynamics and or heating environments**		**Moses, Cheatwood, Johnston et. al, NIAC Phase 1 Report, "Advanced Aerocapture System for Enabling Faster-Larger Planetary Science & Human Exploration Missions" (19-NIAC20B-0128), expected February 2021**	**mid 2020s to 2030s**
	3.71	Fundamental Research on aerodynamic aeroheating and BL transition effects	Pilot studies to obtain data for comparison with predictions			

Table 35. Database Objectives for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development.

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3	**NASA and Partners EDL Technology and Architecture Development**							
3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**							
3.11	HIAD - LOFTID demonstration mission for TPS performance							
3.1101	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1102	Develop supersonic aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.1103	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating	Global and/or discrete surface heating measurements	Reynolds number, angle-of-attack	Global heat transfer and BL transition	Hypersonic wind tunnel or ballistic range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1104	Determine aeroshell heating augmentation due to flexible TPS scalloping over supporting toroids	(3) boundary-layer characterization, (4) convective aeroheating, (16) CFD development and validation	Measure surface temperature and heating distribution to determine TPS deflection effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, TPS scalloping heights	Global heat transfer and BL transition	Hypersonic wind tunnel, Hypersonic ballistic range	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10, ARC HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.1105	Determine aftbody and payload heating environments	(4) convective aeroheating, (16) CFD development and validation (18) Test Technique Development	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions	Reynolds number, angle-of-attack	Global heat transfer, discrete heat transfer	Hypersonic wind tunnel	LaRC 31-Inch Mach 10	AEDC Tunnel 9, CUBRC LENS
3.1106	Determine wake flow-field structure	(5) flow field characterization, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine extent of separated flow, state of wake shear-layer, and temporal variations	Reynolds number, angle-of-attack	Wake flow visualization	Hypersonic wind tunnel, Hypersonic ballistic range	LaRC 31-Inch Mach 10	AEDC Tunnel 9
3.12	HIAD: ISS down mass							
3.1201	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1202	Determine hypersonic aerodynamic influence of payload	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1203	Develop supersonic aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.1204	Define supersonic RCS performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Perform surface pressure, static aero force & moment and flow visualization with thrusters on/off	Mach, pitch, sideslip, Reynolds, AoA, RCS mass flow	Surface pressure, flow visualization, static force & moment, RCS plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.1205	Determine supersonic aerodynamic influence of payload	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.1206	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating	Global and/or discrete surface heating measurements	Reynolds number, angle-of-attack	Global heat transfer and BL transition	Hypersonic wind tunnel or ballistic range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1207	Determine aeroshell heating augmentation due to flexible TPS deflections	(3) boundary-layer characterization, (4) convective aeroheating, (16) CFD development and validation	Measure surface temperature and heating distribution to determine TPS deflection effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, TPS scalloping heights	Global heat transfer and BL transition	Hypersonic wind tunnel, Hypersonic ballistic range	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1208	Determine aftbody and payload heating environments	(4) convective aeroheating, (5) Flow Field Characterization, (16) CFD development and validation (18) Test Technique Development	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions. Parametric tradeoffs on aeroshell geometry to ensure no impingement on payload	Reynolds number, angle-of-attack	Global heat transfer, discrete heat transfer	Hypersonic wind tunnel	LaRC 31-Inch Mach 10	AEDC Tunnel 9, CUBRC LENS
3.13	HIAD: launch vehicle booster recovery							
3.1301	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1302	Determine hypersonic aerodynamic influence of payload	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	high-enthalpy shock/impulse facility, hypersonic wind tunnel, ballistics range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.1303	Develop supersonic aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.1304	Define supersonic RCS performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Perform surface pressure, static aero force & moment and flow visualization with thrusters on/off	Mach, pitch, sideslip, Reynolds, AoA, RCS mass flow	Surface pressure, flow visualization, static force & moment, RCS plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.1305	Determine supersonic aerodynamic influence of payload	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.1306	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating	Global and/or discrete surface heating measurements	Reynolds number, angle-of-attack	Global heat transfer and BL transition	Hypersonic wind tunnel or ballistic range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1307	Determine aeroshell heating augmentation due to flexible TPS deflections	(3) boundary-layer characterization, (4) convective aeroheating, (16) CFD development and validation	Measure surface temperature and heating distribution to determine TPS deflection effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, TPS scalloping heights	Global heat transfer and BL transition	Hypersonic wind tunnel, Hypersonic ballistic range	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.1308	Determine aftbody and payload heating environments	(4) convective aeroheating, (5) Flow Field Characterization, (16) CFD development and validation (18) Test Technique Development	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions. Parametric tradeoffs on aeroshell geometry to ensure no impingement on payload	Reynolds number, angle-of-attack	Global heat transfer, discrete heat transfer	Hypersonic wind tunnel	LaRC 31-Inch Mach 10	AEDC Tunnel 9, CUBRC LENS
3.14	Asymmetric aeroshell morphing for aerodynamic control and performance							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.1401	Evaluate supersonic aerodynamic static performance and validate CFD predictions	(2) Supersonic Aerodynamic Performance, (16) CFD development and validation	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, morphed shapes	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.1402	Evaluate hypersonic aerodynamic static performance and validate CFD predictions	(1) Supersonic Aerodynamic Performance, (16) CFD development and validation	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, morphed shapes	Force and moment, surface pressure, flow field visualization	hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C
3.1403	Configuration specific evaluation of morphed aeroshell heating and BL transition	(3) boundary-layer characterization, (4) convective aeroheating, (16) CFD development and validation	Measure surface temperature and heating distribution to determine morph shape change effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, morphed shapes	Global heat transfer and BL transition	Hypersonic wind tunnel, Hypersonic ballistic range	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C
3.24	HIAD skirt / inflatable tab extension to rigid aeroshell nose cap							
3.2401	Evaluate supersonic aerodynamic static performance and validate CFD predictions	(2) Supersonic Aerodynamic Performance, (16) CFD development and validation	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, skirt/tab shapes	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.2402	Evaluate hypersonic aerodynamic static performance and validate CFD predictions	(1) Supersonic Aerodynamic Performance, (16) CFD development and validation	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number, skirt/tab shapes	Force and moment, surface pressure, flow field visualization	hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.2403	Configuration specific evaluation of skirt/tab aeroshell heating and BL transition	(3) boundary-layer characterization, (4) convective aeroheating, (16) CFD development and validation	Measure surface temperature and heating distribution to determine morph shape change effects on hypersonic boundary-layer transition and turbulent heating augmentation	angle-of-attack, Reynolds number, skirt/tab shapes	Global heat transfer and BL transition	Hypersonic wind tunnel, Hypersonic ballistic range	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C
3.15	HIAD: Human Mars Exploration mission							
3.2	**Mid L/D Lifting Body**							
3.21	Mid L/D Lifting-Body Architecture Configuration Evaluation for Mars Application	2020+						
3.2101	Parametric evaluation of configuration acreage convective aeroheating and BL transition	(3) Boundary-layer characterization, (4) convective heating	perform global optical surface temperature heating measurements on multiple parametric configurations	Vehicle configuration, AoA, Reynolds number	Global heating and BL transition	blow down hypersonic tunnel, shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9
3.2102	Parametric evaluation of configuration acreage radiative heating	(12) Radiative heating environments	Measure radiative heat-transfer distributions on aeroshell and payload at high-enthalpy conditions	Total enthalpy, angle-of-attack, vehicle configuration	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	NASA EAST	CUBRC LENS
3.2103	Hypersonic control surface aerodynamic effectiveness	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Perform testing at multiple AoA & control deflections to obtain aerodynamic force-and-moment data, shock-shape imagery	Control deflections, pitch-roll-yaw deflections, Reynolds number	Surface pressure, flow visualization, force & moments	blow down hypersonic tunnel, shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9, AEDC VKF-B/C
3.2104	Hypersonic control surface aeroheating environments	(4) convective heating (5) Flow Field Characterization	Perform testing at multiple AoA & control deflections to obtain shock-shape imagery and heating data on control surfaces	Control deflections, pitch-roll-yaw deflections, Reynolds number	Flow visualization, control surface heating	blow down hypersonic tunnel, shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9, AEDC VKF-B/C
3.2105	Supersonic Control surface effectiveness evaluation	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Perform testing at multiple AoA & control deflections to obtain aerodynamic force-and-moment data, shock-shape imagery	Control deflections, pitch-roll-yaw deflections, Reynolds number, Mach number	Surface pressure, flow visualization, force & moments, control surface heating	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.2106	Supersonic Retro-Propulsion performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Perform testing with multiple SRP parameters to evaluate aero performance	SRP mass flow, engine pairings, AoA, Mach	Surface pressure, flow visualization, force & moments	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.22	Evaluation of CFD capability for Mid L/D Aero/Aeroheating prediction for Mars entry	2025+						
3.2201	Obtain surface pressure, flow visualization and aerodynamic data on COBRA w/ body flaps for CFD evaluation	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization, (16) CFD Development and Validation	Perform testing at multiple AoA & control deflections to obtain aerodynamic force-and-moment data, shock-shape imagery	Mach, AoA, control deflection, Reynolds	Force & moment, global surface pressure, global surface heating, flow visualization	Supersonic wind tunnel	LaRC UPWT	N/A
3.2202	Obtain acreage laminar and turbulent convective heating data for CFD evaluation	(3) Boundary-layer characterization, (4) Convective heating, (10) High-enthalpy kinetics, (16) CFD Development and Validation	Perform surface heating measurements on acreage	AoA, Re, enthalpy	Surface heating and BL transition	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10 and 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF-B/C. CUBRC LENS
3.2203	Obtain heating data on / around / between / behind control flaps for CFD evaluation	(4) Convective heating, (5) Flow Field Characterization, (16) CFD Development and Validation	Perform surface heating measurements in / around flaps, obtain flow imagery to define shock interactions	AoA, Re, enthalpy, control deflections	Surface heating and pressure, flow field schlieren	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10 and 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF-B/C. CUBRC LENS
3.2204	Obtain "thrust-off" heating and flow field data on / around SRP installations for CFD evaluation	(4) Convective heating, (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions, (16) CFD Development and Validation	Perform surface heating measurements in / around SRP nozzles	AoA, Re, Mach	Surface heating and BL transition	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10 and 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF-B/C. CUBRC LENS
3.2205	Obtain data on integrated SRP / vehicle performance for CFD evaluation	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions (16) CFD Development and Validation	Perform surface pressure, flow visualization and aero force & moment measurements	AoA, thruster parameters, Mach	Aerodynamic force & moment, flow field schlieren	Supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.2206	Obtain data on dynamic aero pitch / sideslip for CFD evaluation	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization, (16) CFD Development and Validation	Perform dynamic aero force & moment measurements	AoA, Mach, Re	Dynamic aero pitch/sideslip F & M	Supersonic wind tunnel	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A. Aberdeen Range
3.23	Mid L/D Lifting Body - sub-scale flight test for aerodynamics and aeroheating	2030+						
3.2301	Develop supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA	Surface pressure, flow visualization, static force & moment	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.2302	Develop supersonic dynamic aero response to pitch and sideslip	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform dynamic aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA	Surface pressure, flow visualization, dynamic force & moment	supersonic wind tunnel, ballistics ranges	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, CUBRC LENS, Aberdeen range
3.2303	Define supersonic control surface aerodynamic effectiveness	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA, Control deflections	Surface pressure, flow visualization around controls, static force & moment	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.2304	Define supersonic RCS performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Perform surface pressure, static aero force & moment and flow visualization with thrusters on/off	Mach, pitch, sideslip, Reynolds, AoA, RCS mass flow	Surface pressure, flow visualization, static force & moment, RCS plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.2305	Develop hypersonic aerodynamic database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA	Surface pressure, flow visualization, static force & moment	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
3.2306	Define hypersonic control surface aerodynamic effectiveness	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform dynamic aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA, Control deflections	Surface pressure, flow visualization, static force & moment	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
3.2307	Develop hypersonic smooth-OML acreage convective heating	(3) Boundary-layer characterization (4) convective aeroheating environments	Perform surface heating and BL transition measurements	Mach, Reynolds, enthalpy, AoA	global / discrete surface heating and BL onset	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
3.2308	Define control surface convective heating environments	(3) Boundary-layer characterization (4) convective aeroheating environments,	Perform surface heating and BL transition measurements and flow field visualization	Mach, Reynolds, enthalpy, AoA, control deflections	global / discrete surface heating and BL onset, flow visualization around controls	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.2309	Define RCS jet/surface interaction effects on heating	(4) convective aeroheating environments, (5) Flow Field Characterization, (8) Retropropulsion Performance and Interactions	Perform surface heating in plume interaction areas and visualize plume shapes	Mach, Reynolds, AoA, RCS firing parameters	global / discrete surface heating, schlieren and PLIF flow visualization	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
3.24	Mid L/D Lifting Body - sub-scale flight test for SRP performance	2035+						
3.2401	Develop supersonic static aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA	Surface pressure, flow visualization, static force & moment	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.2402	Develop supersonic dynamic aero response to pitch and sideslip	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform dynamic aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA	Surface pressure, flow visualization, dynamic force & moment	supersonic wind tunnel, ballistics ranges	LaRC UPWT, ARC UPWT, ARC HFFAF	AEDC VKF-A, CUBRC LENS, Aberdeen range
3.2403	Define supersonic control surface aerodynamic effectiveness	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA, Control deflections	Surface pressure, flow visualization around controls, static force & moment	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.2404	Define supersonic RCS performance and interactions	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Perform surface pressure, static aero force & moment and flow visualization with thrusters on/off	Mach, pitch, sideslip, Reynolds, AoA, RCS mass flow	Surface pressure, flow visualization, static force & moment, RCS plume shape visualization with schlieren and PLIF	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.25	Mid L/D Lifting Body - full-scale Mars flight test and/or missions	2035+						
3.3	**Deployable Aerodynamic Decelerator Technology Development and Demonstration**							
3.31	SNC Deployable							
3.3101	Preliminary evaluation of hypersonic aerodynamic performance	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	hypersonic wind tunnel	LaRC 31-Inch Mach 10	N/A (scheduled test at LaRC)
3.3102	Preliminary evaluation of aeroheating effects on aeroshell	(3) Boundary-layer characterization, (4) convective heating	Measure global surface heating and BL transition	angle-of-attack, Reynolds number	phosphor thermography	hypersonic wind tunnel	LaRC 20-Inch Mach 10	N/A (scheduled test at LaRC)

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.3103	Detailed supersonic aerodynamic performance for flight mission	(2) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, control deflection, roll, Mach	Force and moment, surface pressure, flow-field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC Tunnel A
3.3104	Detailed hypersonic aerodynamic performance for flight mission	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, control deflection, roll	Force and moment, surface pressure, flow-field visualization	hypersonic wind tunnel	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC VKF B/C, AEDC Tunnel 9
3.3105	Detailed aeroshell aeroheating for flight mission	(3) Boundary-layer characterization, (4) convective heating	Measure global surface heating and BL transition	angle-of-attack, Reynolds number, control deflection, roll	global and/or discrete surface heating	hypersonic wind tunnel	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC VKF B/C, AEDC Tunnel 9
3.32	Pterodactyl Control Systems for DEVs Sample Return							
3.3201	Develop supersonic aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.3202	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	angle-of-attack, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3203	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating	Global and/or discrete surface heating measurements	Reynolds number, angle-of-attack	Global heat transfer and BL transition	Hypersonic wind tunnel or ballistic range	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.3204	Determine aftbody and payload heating environments	(4) convective aeroheating, (16) CFD development and validation (18) Test Technique Development	Measure surface heating on aeroshell backface and payload at laminar and turbulent conditions. Parametric tradeoffs on aeroshell geometry to ensure no impingement on payload	Reynolds number, angle-of-attack	Global heat transfer, discrete heat transfer	Hypersonic wind tunnel	LaRC 31-Inch Mach 10	AEDC Tunnel 9, CUBRC LENS
3.33	ADEPT Drag Modulated Aerocapture Demonstration (Earth GTO). ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts							
3.3301	Develop supersonic aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.3302	Develop supersonic dynamic aero database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Measure unsteady aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization, free-flight observations (range)	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.3303	Develop supersonic RCS performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure RCS effects on aero forces and moments, visualize plume and shock shapes	angle-of-attack, roll, Reynolds number, Mach number, RCS mass flow / thruster pairings	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.3304	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3305	Determine baseline, smooth-OML aeroshell convective heating	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3306	Define TPS roughness effect on convective heating and BL transition	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack, roughness parameters	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.3307	Determine RCS interaction effects on payload heating	(4) convective heating, (5) Flow Field Characterization (7) RCS performance and interactions	Measure payload & aeroshell backface heating and RCS interaction footprint, visualize plumes and wake flow structure	angle-of-attack, roll, Reynolds number, Mach number, RCS mass flow / thruster pairings	Global optical or discrete sensor heat transfer, flow-field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3308	Determine aftbody and payload heating environments	(4) convective aeroheating, (5) Flow Field Characterization	Measure payload & aeroshell backface heating, visualize wake flow structure	Reynolds number, angle-of-attack	Global optical or discrete sensor heating, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.34	ADEPT Drag Modulated Aerocapture SmallSat Venus/Mars Orbiter. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts							
3.3401	Develop supersonic aerodynamic performance database in CO2 atmosphere	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.3402	Develop supersonic dynamic aero database in CO2 atmosphere	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Measure unsteady aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization, free-flight observations (range)	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.3403	Develop supersonic RCS performance database in CO2 atmosphere	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure RCS effects on aero forces and moments, visualize plume and shock shapes	angle-of-attack, roll, Reynolds number, Mach number, RCS mass flow / thruster pairings	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.3404	Develop hypersonic aerodynamic performance database in CO2 atmosphere	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3405	Determine baseline, smooth-OML aeroshell convective heating in CO2 atmosphere	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3406	Define TPS roughness effect on convective heating and BL transition	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack, roughness parameters	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.3407	Determine RCS interaction effects on payload heating in CO2 atmosphere	(4) convective heating, (5) Flow Field Characterization (7) RCS performance and interactions	Measure payload & aeroshell backface heating and RCS interaction footprint, visualize plumes and wake flow structure	angle-of-attack, roll, Reynolds number, Mach number, RCS mass flow / thruster pairings	Global optical or discrete sensor heat transfer, flow-field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3408	Determine aftbody and payload heating environments in CO2 atmosphere	(4) convective aeroheating, (5) Flow Field Characterization	Measure payload & aeroshell backface heating, visualize wake flow structure	Reynolds number, angle-of-attack	Global optical or discrete sensor heating, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3409	Determine radiative heating environment in CO2 atmosphere	(12) Radiative heating environments	Measure radiative heat-transfer distributions on aeroshell and payload at high-enthalpy conditions and/or obtain fundamental radiation data	shock speed, pressure, gas composition	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	NASA EAST	CUBRC LENS
3.3410	Develop rarefied hypersonic aerodynamic performance database	(20) Rarefied Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.35	ADEPT Drag Modulated Aerocapture Flagship Ice Giant Orbiter/Probe Mission. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts							
3.3501	Develop supersonic aerodynamic performance database in H2/He atmosphere	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.3502	Develop supersonic dynamic aero database in H2/He atmosphere	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization (7) RCS performance and interactions	Measure unsteady aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization, free-flight observations (range)	supersonic wind tunnel, ballistic range	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
3.3503	Develop supersonic RCS performance database in H2/He atmosphere	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure RCS effects on aero forces and moments, visualize plume and shock shapes	angle-of-attack, roll, Reynolds number, Mach number, RCS mass flow / thruster pairings	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.3504	Develop hypersonic aerodynamic performance database in H2/He atmosphere	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3505	Determine baseline, smooth-OML aeroshell convective heating in H2/He atmosphere	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3506	Define TPS roughness effect on convective heating and BL transition in H2/He atmosphere	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack, roughness parameters	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3507	Determine RCS interaction effects on payload heating in H2/He atmosphere	(4) convective heating, (5) Flow Field Characterization (7) RCS performance and interactions	Measure payload & aeroshell backface heating and RCS interaction footprint, visualize plumes and wake flow structure	angle-of-attack, roll, Reynolds number, Mach number, RCS mass flow / thruster pairings	Global optical or discrete sensor heat transfer, flow-field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3508	Determine aftbody and payload heating environments in H2/He atmosphere	(4) convective aeroheating, (5) Flow Field Characterization	Measure payload & aeroshell backface heating, visualize wake flow structure	Reynolds number, angle-of-attack	Global optical or discrete sensor heating, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.3509	Determine radiative heating environment in H2/He atmosphere	(12) Radiative heating environments	Measure radiative heat-transfer distributions on aeroshell and payload at high-enthalpy conditions and/or obtain fundamental radiation data	shock speed, pressure, gas composition	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	NASA EAST	CUBRC LENS
3.3510	Develop rarefied hypersonic aerodynamic performance database	(20) Rarefied Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.36	Large scale deployable aeroshell for Human rated Mars missions							
3.4	**Advanced Rigid Aeroshell Capsule configurations**							
3.41	Geometric scaling of standard MSL / Orion type aeroshells							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.4101	Develop supersonic aerodynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.4102	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.4103	Develop Hypersonic aeroheating database for Aeroshell smooth OML	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.4104	Define TPS roughness effect on convective heating and BL transition in CO2 atmosphere	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack, roughness parameters	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.4105	Determine radiative heating database	(12) Radiative heating environments	Measure radiative heat-transfer distributions on aeroshell and payload at high-enthalpy conditions and/or obtain fundamental radiation data	shock speed, pressure, gas composition	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	NASA EAST	CUBRC LENS
3.42	Asymmetric rigid Aeroshell - AFE, ACV optimized shapes, elliptical/hyperboloid cross-section, etc.							
3.4201	Develop supersonic aerodynamic static performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.4202	Develop supersonic aerodynamic dynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure unsteady aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.4203	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.4204	Develop Hypersonic aeroheating database for Aeroshell smooth OML	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.4205	Define TPS roughness effect on convective heating and BL transition in CO2e atmosphere	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack, roughness parameters	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.4206	Determine radiative heating database	(12) Radiative heating environments	Measure radiative heat-transfer distributions on aeroshell and payload at high-enthalpy conditions and/or obtain fundamental radiation data	shock speed, pressure, gas composition	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	NASA EAST	CUBRC LENS
3.43	Aerodynamic Trim Tabs							
3.4301	Develop supersonic aerodynamic static performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.4302	Develop supersonic aerodynamic dynamic performance database	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure unsteady aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A
3.4303	Develop hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.4304	Develop Hypersonic aeroheating database for Aeroshell smooth OML	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.4305	Define TPS roughness effect on convective heating and BL transition in CO2 atmosphere	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack, roughness parameters	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.4306	Determine radiative heating database	(12) Radiative heating environments	Measure radiative heat-transfer distributions on aeroshell and payload at high-enthalpy conditions and/or obtain fundamental radiation data	shock speed, pressure, gas composition	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	NASA EAST	CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.4307	Define control surface supersonic aerodynamic performance	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform static aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA, Control deflections	Surface pressure, flow visualization around controls, static force & moment	supersonic wind tunnel	LaRC UPWT, ARC UPWT	AEDC VKF-A, CUBRC LENS
3.4308	Define hypersonic control surface aerodynamic effectiveness	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization,	Perform dynamic aero force & moment measurements and flow visualization	Mach, pitch, sideslip, Reynolds, AoA, Control deflections	Surface pressure, flow visualization, static force & moment	High-enthalpy shock/impulse facility, hypersonic wind tunnel,	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF-B/C, CUBRC LENS
3.4309	Define hypersonic control surface aeroheating environments	(4) convective heating (5) Flow Field Characterization	Perform testing at multiple AoA & control deflections to obtain shock-shape imagery and heating data on control surfaces	Control deflections, pitch-roll-yaw deflections, Reynolds number	Flow visualization, control surface heating	blow down hypersonic tunnel, shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9, AEDC VKF-B/C
3.44	Large scale rigid-TPS aeroshell for Human rated Mars missions utilizing any/all advance options listed under advanced rigid-aeroshell capsule development path							
3.5	**Super/Hypersonic Retropropulsion Technology Development and Demonstration**							
3.51	Evaluation of CFD capability for SRP		Supersonic WT with high-pressure air simulant gas feed and control; mass-flow order of magnitude (add); optical access; physical scale (e.g. test section or model scale accommodation)					
3.5101	Obtain surface pressure, flow visualization, and aerodynamic data on SRP system for CFD evaluations	(2) Supersonic Aerodynamic Performance, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions	Supersonic WT with high-pressure air simulant gas feed and control; mass-flow order of magnitude (add); optical access; physical scale (e.g. test section or model scale accommodation)		Force & moment, surface pressure, flow visualization	Supersonic wind tunnel (LaRC UPWT, GRC 10x10 WT)	LaRC UPWT, GRC 10x10 WT	DLR facilities

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.52	RP System ground testing capability development and unit-problem testing							
3.5201	Hot inert gas RP systems testing	(2) Supersonic Aerodynamic Performance, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions, (18) Test Technique Development	Uses NASA SSC portable ethane cart to provide heated ethane as the inert RP simulant gas in supersonic WT test	Mach, Re, thrust coefficients. CT and/or pressure ratio, AoA, roll, nozzle firings and single/multiple configurations	Force & moment, surface pressure, flow visualization, surface heat transfer	blow down super/hypersonic wind tunnels	GRC 10x10 WT, LaRC TDT and LaRC UPWT (remote possibility)	
3.5202	Sub-scale engine testing	(2) Supersonic Aerodynamic Performance, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions, (11) High-Enthalpy Kinetics for Propulsion, (18) Test Technique Development	Sea-level risk reduction testing prior to engine integration into ground test facility or into flight test vehicle.	Fixed thrust set points	Engine health monitoring, including mass flow, chamber pressure, temperature	Indoor/outdoor engine test stand	MSFC TS115	
3.5203	Flow-through balance development	(2) Supersonic Aerodynamic Performance, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions, (18) Test Technique Development	Will integrate flow-through balance in 2022 AETC SRP WT test	Mach, Re, thrust coefficients CT and/or pressure ratio, AoA, roll, nozzle firings and single/multiple configurations	Force & moment direct measurement	blow down super/hypersonic wind tunnels	LaRC UPWT	DLR
3.5204	RP testing in CO2 flow	(2) Supersonic Aerodynamic Performance, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions, (10) High-enthalpy kinetics, (11) High-Enthalpy Kinetics for Propulsion, (18) Test Technique Development	Measure aerodynamic F/M, surface pressure and heat transfer, and observe flow field structure and behavior in a supersonic CO2 freestream flow	Mach, Re, thrust coefficients CT and/or pressure ratio, AoA, roll, nozzle firings and single/multiple configurations	Force & moment, surface pressure, flow visualization, surface heat transfer (if hot-fire test)	blow down CO2 tunnel (?), high-enthalpy CO2 facility	None	CUBRC

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.5205	Flow field dynamics validation - unsteady RP/shock/plume interactions	(2) Supersonic Aerodynamic Performance, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions	Supersonic WT with high-pressure simulant gas feed and control; mass-flow order of magnitude (add); optical access; physical scale (e.g. test section or model scale accommodation); more than just high-pressure air	Mach, Re, thrust coefficients CT and/or pressure ratio, AoA, roll, nozzle firings and single/multiple configurations, hot vs cold fire	high-speed off-body flow visualization (PLIF, PIV, BOS)	blow down or closed-circuit super/hypersonic wind tunnels	LaRC UPWT, GRC 10x10, ARC 9x7	
3.5206	Turbulence model validation for separated unsteady flows with RP/shock interactions	(3) Boundary-layer characterization, (5) Flow field characterization, (8) Retropropulsion Performance and Interactions, (16) CFD Model development and validation	Primarily unit experiments.	Mach, Re, thrust coefficients CT and/or pressure ratio, AoA, roll, nozzle firings, hot vs cold fire	Unsteady surface pressures, Delta-aero coefficients, high-speed off-body flow visualization (PLIF, PIV, BOSS), high-frequency surface heating	Small-scale (e.g. lab scale) blow down or closed-circuit supersonic wind tunnels		University tunnels with specialized diagnostics, e.g. University of Washington
3.5207	Validation of kinetics for RP exhaust interactions with flow field	(5) Flow field characterization, (8) Retropropulsion Performance and Interactions, (11) High-Enthalpy Kinetics for Propulsion, (16) CFD Model development and validation	Hot-fire propulsion test in supersonic WT; Options beyond GRC 10x10 prop tunnel? different propulsion fuel/ox combinations affects facility choice/ops, parameters in the test	Mach, Re, thrust coefficients CT and/or pressure ratio, AoA, roll, nozzle firings, hot vs cold fire. May need to do as unit test for kinetics (EAST)	Post-shock species compositions, T/Tv rates, etc.	blow down super/hypersonic wind tunnels, shock tube?		
3.5208	Validation data for RP/shock/plume/surface interaction heating	(5) Flow field characterization, (8) Retropropulsion Performance and Interactions, (11) High-Enthalpy Kinetics for Propulsion, (16) CFD Model development and validation	Hot-fire propulsion test in supersonic WT	Mach, Re, thrust coefficients CT and/or pressure ratio, AoA, roll, nozzle firings, hot vs cold fire	Unsteady surface heating	blow down super/hypersonic wind tunnels	GRC 10x10, LaRC 8' HTT	
3.5209	Validation data for wake flow interactions with RP plumes	(5) Flow field characterization, (8) Retropropulsion Performance and Interactions, (16) CFD Model development and validation	May be difficult if not impossible to achieve in ground testing due to model support hardware, etc. Moving to larger test section in a facility like 8' HTT and instrument model support hardware.	Mach, Re, thrust coefficients CT and/or pressure ratio, AoA, roll, nozzle firings,	Steady/unsteady pressures and aero loads	Unknown	Unknown	Unknown

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.53	SRP Architecture Configuration Evaluation for Mars Application		Will be CFD-based and heavily leverage data products and analysis from 2022 AETC SRP testing					
3.5301	Task 1	TBD						
3.5302	Task 2	TBD						
3.54	Earth reentry flight tests and system demonstration							
3.5401	Configuration hypersonic aerodynamics	(1) Hypersonic Aerodynamic Performance	Hypersonic WT with optical access and direct force & moment measurement capability	Mach, Re, angle of attack, sideslip, and roll	Surface pressure, flow visualization, force & moment	hypersonic wind tunnel		
3.5402	Configuration supersonic aerodynamics	(2) Supersonic Aerodynamic Performance	Supersonic WT with optical access and direct force & moment measurement capability	Mach, Re, angle of attack, sideslip, and roll	Aero F/M, shock shape	Supersonic tunnel		
3.5403	Retropropulsion aerodynamics & interactions	(2) Supersonic Aerodynamic Performance, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions	Supersonic WT with high-pressure simulant gas feed and control; mass-flow order of magnitude (add); optical access; physical scale (e.g. test section or model scale accommodation); more than just high-pressure air	Mach, Re, thrust coefficients CT and/or pressure ratio, AoA, roll, nozzle firings and single/multiple configurations, hot vs cold fire	Surface pressure, flow visualization, RP performance, force & moment	Supersonic tunnel	LaRC UPWT, GRC 10x10	
3.5404	Configuration aeroheating environments	(3) Boundary-layer characterization, (4) Convective Heating Environments, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions	Perform retropropulsion testing on relevant configuration(s) and in relevant [scaled] environments to obtain shock-shape imagery and heating data on aerodynamic surfaces	Control deflections, pitch-roll-yaw deflections, Reynolds number	Flow visualization, control surface heating	blow down hypersonic tunnel, shock/impulse facility	LaRC 20-Inch Mach 6, LaRC 31-Inch Mach 10	CUBRC LENS, AEDC Tunnel 9, AEDC VKF-B/C

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.55	Mars reentry flight tests and system demonstration	(2) Supersonic Aerodynamic Performance, (4) Convective Heating Environments, (5) Flow field Characterization, (8) Retropropulsion Performance and Interactions	WT testing should be completed with the flight system configuration and operating conditions; may be limited to scaled conditions as informed by Earth-based flight testing			supersonic wind tunnel	GRC 10x10 and other GRC propulsion wind tunnels	Potential facilities at DLR (Cologne)
3.6	**Aerocapture**							
3.61	Trade studies on aerocapture options for EDL exploration missions							
3.6101	Develop rarefied hypersonic aerodynamic performance database	(20) Rarefied Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6102	Develop continuum hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6103	Develop Hypersonic aeroheating database	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6104	Determine radiative heating database	(12) Radiative heating environments	Measure radiative heat-transfer distributions on aeroshell and payload at high-enthalpy conditions and/or obtain fundamental radiation data	shock speed, pressure, gas composition	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	NASA EAST	CUBRC LENS
3.62	Sub-scale Earth flight test for TRL advancement to mission application of aerocapture							
3.6201	Develop rarefied hypersonic aerodynamic performance database	(20) Rarefied Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.6202	Develop continuum hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6203	Develop Hypersonic aeroheating database	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6204	Define TPS roughness effect on convective heating and BL transition	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack, roughness parameters	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.63	Small planet or satellite Mission (Venus, Titan, Mars, etc.) or Ice Giant (Uranus, Neptune)							
3.6301	Develop rarefied hypersonic aerodynamic performance database	(20) Rarefied Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6302	Develop continuum hypersonic aerodynamic performance database	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6303	Develop continuum supersonic aerodynamic performance database	(1) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure static aerodynamic forces & moments, surface pressures and shock shapes	angle-of-attack, roll, Reynolds number	Force and moment, surface pressure, flow field visualization	Supersonic Wind tunnel	LaRC UPWT, ARC UPWT	AEDC Tunnel A
3.6304	Develop Hypersonic aeroheating database	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6305	Define TPS roughness effect on convective heating and BL transition	(3) Boundary-layer characterization, (4) convective heating	Measure aeroshell surface heating and BL transition onset locations	Reynolds number, angle-of-attack, roughness parameters	Global optical heat transfer and BL transition	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6, Ames HFFAF	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
3.6306	Determine radiative heating database	(12) Radiative heating environments	Measure radiative heat-transfer distributions on aeroshell and payload at high-enthalpy conditions and/or obtain fundamental radiation data	shock speed, pressure, gas composition	surface heating, spectroscopy and flow field diagnostics	high-enthalpy shock/impulse facility	NASA EAST	CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
3.7	**MHD Control of Flow Field**							
3.71	Fundamental Research on aerodynamic aeroheating and BL transition effects							
3.7101	Evaluate MHD performance to generate large Lorentz Forces for increasing L/D ratios and for steering a spacecraft through its planned entry corridor	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics (5) Flow field Characterization, (14) Electro-Magnetic Environments, (16) CFD Development and Validation (18) test technique development	Measure aerodynamic forces & moments in the presence of EM fields	TBD	Aerodynamic forces and moments, electro-magnetic properties	Requirements are yet to be determined	N/A	likely pilot facilities in Academia
3.7102	Evaluate MHD effects on surface heating and BL transition	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics (5) Flow field Characterization, (14) Electro-Magnetic Environments, (16) CFD Development and Validation (18) test technique development	Measure surface heating and BL transition in the presence of EM fields	TBD	Surface heating and BL transition, electro-magnetic properties	Requirements are yet to be determined	N/A	likely pilot facilities in Academia

Table 36. Test Requirements for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
3	**NASA and Partners EDL Technology and Architecture Development**							
3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**							
3.11	HIAD - LOFTID demonstration mission for TPS performance							
3.1101	Develop hypersonic aerodynamic performance database	Hypersonic conditions-chemical kinetic effects are small for LOFTID trajectory	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers	30 runs / 1 week in NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	30 runs = 1 - 2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.1102	Develop supersonic aerodynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers	30 runs / 1 week in NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	30 runs = 1 - 2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
3.1103	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	15 test points ~ 1 week in any facility	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	15 test points ~ 1 week in any facility	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
3.1104	Determine aeroshell heating augmentation due to flexible TPS scalloping over supporting toroids	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Rapid turnaround time for multiple roughness parametric changes	3 AoA over range of 0-10-deg, 6 Reynolds numbers over laminar-to-turbulent ranges, 12 scallop heights. Total 216 test points	LaRC 20inM6 = 108 runs / 18 days.	3 AoA over range of 0-10-deg, 6 Reynolds numbers over laminar-to-turbulent ranges, 12 scallop heights. Total 216 test points	AEDC T9 (continuous pitch) = 72 runs / 36 days. CUBRC 216 runs = 108 days. AEDC VKF continuous ops not compatible with multiple parameter variations for heating tests	global optical techniques for measurement of heating distributions and BL transition onset	ability to accurately replicate scalloped OML in cast ceramic or machined metal

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3.1105	Determine aftbody and payload heating environments	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. High stagnation temperature to produce sensible heating in wake	3 AoA over range of 0-10-deg, 5 Reynolds numbers over laminar-to-turbulent ranges	LaRC 31InM10 = 15 runs / 4 days.	3 AoA over range of 0-10-deg, 5 Reynolds numbers over laminar-to-turbulent ranges	AEDC T9 (continuous sweep) 3 runs = 3 days. CUBRC = 15 runs, 8 days	Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors	cast ceramic or machined metallic models
3.1106	Determine wake flow-field structure	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. High stagnation temperature to produce sensible heating in wake	3 AoA over range of 0-10-deg, 3 rolls over 0-90 deg, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeats runs with each diagnostic technique to provide complete flow field imaging	27 test points x 3 techniques x 3 repeat each = 243 runs / 60 days	3 AoA over range of 0-10-deg, 3 rolls over 0-90 deg, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	27 test points x 3 techniques x 3 repeat each. Pitch sweep in AEDC Tunnel 9 reduces to 81 runs / 8 weeks	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
3.12	HIAD: ISS down mass							
3.1201	Develop hypersonic aerodynamic performance database	High Mach / high-enthalpy capability	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.1202	Determine hypersonic aerodynamic influence of payload	High Mach / high-enthalpy capability	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances	Metallic force & moment model with blade mount & offset sting
3.1203	Develop supersonic aerodynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
3.1204	Define supersonic RCS performance and interactions	Flight-relevant Mach/Re range, mass flow for RCS firing	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	UPWT assume cont. AoA sweep, 45 runs = 2 weeks	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from RCS
3.1205	Determine supersonic aerodynamic influence of payload	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances using blade mount & offset sting	Metallic force & moment model fabrication

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3.1206	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	15 test points ~ 1 week in any facility	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	12 test points ~ 1 week in any facility	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
3.1207	Determine aeroshell heating augmentation due to flexible TPS deflections	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Rapid turnaround time for multiple roughness parametric changes	3 AoA over range of 0-10-deg, 6 Reynolds numbers over laminar-to-turbulent ranges, 12 scallop heights. Total 216 test points	LaRC 20inM6 = 108 runs / 18 days.	3 AoA over range of 0-10-deg, 6 Reynolds numbers over laminar-to-turbulent ranges, 12 scallop heights. Total 216 test points	AEDC T9 (continuous pitch) = 72 runs / 36 days. CUBRC 216 runs = 108 days. AEDC VKF continuous ops not compatible with multiple parameter variations for heating tests	global optical techniques for measurement of heating distributions and BL transition onset	ability to accurately replicate scalloped OML in cast ceramic or machined metal
3.1208	Determine aftbody and payload heating environments	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. High stagnation temperature to produce sensible heating in wake	5 AoA over range of 0-20-deg, 5 Reynolds numbers over laminar-to-turbulent range. Heating + flow visualization runs = 50 test points	LaRC 31InM10 = 50 points, 9 days	5 AoA over range of 0-20-deg, 5 Reynolds numbers over laminar-to-turbulent range. Heating + flow visualization runs = 50 test points	AEDC T9 (continuous sweep) = 10 runs/ 5 days. CUBRC = 50 runs / 30 days	Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors. Laser seeding and schlieren flow visualization for wake	cast ceramic or machined metallic models with blade mount and offset sting
3.13	HIAD: launch vehicle booster recovery							
3.1301	Develop hypersonic aerodynamic performance database	High Mach / high-enthalpy capability	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.1302	Determine hypersonic aerodynamic influence of payload	High Mach / high-enthalpy capability	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances	Metallic force & moment model with blade mount & offset sting
3.1303	Develop supersonic aerodynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
3.1304	Define supersonic RCS performance and interactions	Flight-relevant Mach/Re range, mass flow for RCS firing	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	UPWT assume cont. AoA sweep, 45 runs = 2 weeks	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from RCS

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3.1305	Determine supersonic aerodynamic influence of payload	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	~ 1 week in any NASA facilities	3 AoA over range of 0-deg, 5 Reynolds numbers over laminar-to-turbulent range, 2 Mach numbers = 30 runs	2 weeks in non-NASA	measure static aerodynamics with force-and-moment balances using blade mount & offset sting	Metallic force & moment model fabrication
3.1306	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	15 test points ~ 1 week in any facility	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	12 test points ~ 1 week in any facility	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
3.1307	Determine aeroshell heating augmentation due to flexible TPS deflections	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow. Rapid turnaround time for multiple roughness parametric changes	3 AoA over range of 0-10-deg, 6 Reynolds numbers over laminar-to-turbulent ranges, 12 scallop heights. Total 216 test points	LaRC 20inM6 = 108 runs / 18 days.	3 AoA over range of 0-10-deg, 6 Reynolds numbers over laminar-to-turbulent ranges, 12 scallop heights. Total 216 test points	AEDC T9 (continuous pitch) = 72 runs / 36 days. CUBRC 216 runs = 108 days. AEDC VKF continuous ops not compatible with multiple parameter variations for heating tests	global optical techniques for measurement of heating distributions and BL transition onset	ability to accurately replicate scalloped OML in cast ceramic or machined metal
3.1308	Determine aftbody and payload heating environments	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment. High stagnation temperature to produce sensible heating in wake	5 AoA over range of 0-20-deg, 5 Reynolds numbers over laminar-to-turbulent range. Heating + flow visualization runs = 50 test points	LaRC 31InM10 = 50 points, 9 days	5 AoA over range of 0-20-deg, 5 Reynolds numbers over laminar-to-turbulent range. Heating + flow visualization runs = 50 test points	AEDC T9 (continuous sweep) = 10 runs/ 5 days. CUBRC = 50 runs / 30 days	Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors. Laser seeding and schlieren flow visualization for wake	cast ceramic or machined metallic models with blade mount and offset sting
3.14	Asymmetric aeroshell morphing for aerodynamic control and performance							
3.1401	Evaluate supersonic aerodynamic static performance and validate CFD predictions	Supersonic M2-M4 with wide range of Reynolds numbers	5 morphed shapes x 1 AoA sweep x 5 Reynolds numbers x 3 yaw x 3 Mach = 450 points	225 points = 38 days / 8 weeks	5 morphed shapes x 1 AoA sweep x 5 Reynolds numbers x 3 yaw x 3 Mach = 450 points	225 points = 38 days / 8 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.1402	Evaluate hypersonic aerodynamic static performance and validate CFD predictions	Mach 6-10 with range of Reynolds numbers	5 morphed shapes x 3 AoA x 5 Reynolds numbers x 3 yaw = 450 points	225 points = 38 days / 8 weeks	5 morphed shapes x 3 AoA x 5 Reynolds numbers x 3 yaw = 450 points	225 points = 38 days / 8 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.1403	Configuration specific evaluation of morphed aeroshell heating and BL transition	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions	5 morphed shapes x 3 AoA x 5 Reynolds numbers x 3 yaw = 150 points	225 points = 38 days / 8 weeks	5 morphed shapes x 3 AoA x 5 Reynolds numbers x 3 yaw = 150 points	225 points = 38 days / 8 weeks	global optical techniques for measurement of heating distributions and BL transition onset	cast ceramic or machined metallic models
3.24	HIAD skirt / inflatable tab extension to rigid aeroshell nose cap							

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3.2401	Evaluate supersonic aerodynamic static performance and validate CFD predictions	Supersonic M2-M4 with wide range of Reynolds numbers	5 skirt/tab shapes x 1 AoA sweep x 5 Reynolds numbers x 3 yaw x 3 Mach = 450 points	225 points = 38 days / 8 weeks	5 skirt/tab shapes x 1 AoA sweep x 5 Reynolds numbers x 3 yaw x 3 Mach = 450 points	225 points = 38 days / 8 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.2402	Evaluate hypersonic aerodynamic static performance and validate CFD predictions	Mach 6-10 with range of Reynolds numbers	5 skirt/tab shapes x 3 AoA x 5 Reynolds numbers x 3 yaw = 450 points	225 points = 38 days / 8 weeks	5 skirt/tab shapes x 3 AoA x 5 Reynolds numbers x 3 yaw = 450 points	225 points = 38 days / 8 weeks	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.2403	Configuration specific evaluation of skirt/tab aeroshell heating and BL transition	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions	5 skirt/tab shapes x 3 AoA x 5 Reynolds numbers x 3 yaw = 150 points	225 points = 38 days / 8 weeks	5 skirt/tab shapes x 3 AoA x 5 Reynolds numbers x 3 yaw = 150 points	225 points = 38 days / 8 weeks	global optical techniques for measurement of heating distributions and BL transition onset	cast ceramic or machined metallic models
3.15	HIAD: Human Mars Exploration mission							
3.2	**Mid L/D Lifting Body**							
3.21	Mid L/D Lifting-Body Architecture Configuration Evaluation for Mars Application							
3.2101	Parametric evaluation of configuration acreage convective aeroheating and BL transition	Sufficient Reynolds number/model scale to obtain laminar-to-turbulent data. High-enthalpy CO2 kinetic	5 configurations, 4 AoA, 5 Reynolds numbers = 100 test points	LaRC = 100 runs / 3 weeks	5 configurations, 4 AoA, 5 Reynolds numbers = 100 test points	AEDC Tunnel (continuous pitch) = 25 runs / 4 weeks. CUBRC LENS = 100 runs / 10 weeks	Global optical and / or discrete surface heating measurements	Cast ceramic or machined metallic models
3.2102	Parametric evaluation of configuration acreage radiative heating	NASA EAST not large enough for full OML testing, EAST permits unit-problem testing	N/A	N/A	5 configurations, 4 AoA, 5 enthalpies = 80 test points	80 days	Discrete surface heat-flux and radiation gages, flow field spectral imaging	metallic model with radiation sensors
3.2103	Hypersonic control surface aerodynamic effectiveness	Rapid turnaround time for multiple configuration / parametric changes. Sufficient Reynolds number/model scale to obtain laminar-to-turbulent data. High-enthalpy CO2 kinetics	4 AoA, 5 Reynolds number, 4 control deflections, 2 yaw/roll = 160 test points	LaRC (continuous aero pitch) 80 runs = 3 weeks.	4 AoA, 5 Reynolds number, 4 control deflections, 2 yaw/roll = 160 test points	AEDC Tunnel 9 (continuous pitch) 80 runs / 8 weeks. CUBRC LENS = 160 runs / 16 weeks. AEDC VKF B/C (continuous pitch / roll / Re sweep) = 4 runs / 1 week	Force & moment balances, surface pressure sensors, schlieren flow imaging	machined metallic models with variable control surfaces
3.2104	Hypersonic control surface aeroheating environments	Rapid turnaround time for multiple configuration / parametric changes. Sufficient Reynolds number/model scale to obtain laminar-to-turbulent data. High-enthalpy CO2 kinetics	4 AoA, 5 Reynolds number, 4 control deflections, 2 yaw/roll = 160 test points	LaRC = 160 runs/ 5 weeks	4 AoA, 5 Reynolds number, 4 control deflections, 2 yaw/roll = 160 test points	AEDC Tunnel 9 (cont. pitch) = 80 runs / 8 weeks. CUBRC LENS = 160 runs / 16 weeks. AEDC VKF B/C not suitable for aeroheating testing of multiple configs/deflections	Global optical and / or discrete surface heating measurements	Cast ceramic or machined metallic models - multiple configurations for all control deflections

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3.2105	Supersonic Control surface effectiveness evaluation	Sufficient Mach/Reynolds number range to evaluate control effectiveness. CO2 for compressibility effects	3 Mach, 3 Reynolds, 4 control deflections, 4 yaw/roll, 4 AoA = 144 test points	assume continuous pitch in all facilities - 36 runs = 2 weeks	3 Mach, 3 Reynolds, 4 control deflections, 4 yaw/roll, 4 AoA = 144 test points	assume continuous pitch in all facilities - 36 runs = 2 weeks	Force & moment balances, surface pressure sensors, schlieren flow imaging	machined metallic models with variable control surfaces
3.2106	Supersonic Retro-Propulsion performance and interactions	Sufficient Mach/Re capability for flight relevance. CO2 for compressibility effects	3 thruster configs x 3 mass flow x 3 AoA x 3 Mach = 81 points	assume adjust mass flow rates. 27 runs = 1 weeks	3 thruster configs x 3 mass flow x 3 AoA x 3 Mach = 81 points	assume adjust mass flow rates. 27 runs = 1 weeks	Force & moment balances, surface pressure sensors, schlieren flow imaging	Metallic model with plumbing for operational SRP firing
3.22	Evaluation of CFD capability for Mid L/D Aero/Aeroheating prediction for Mars entry							
3.2201	Obtain surface pressure, flow visualization and aerodynamic data on COBRA w/ body flaps for CFD evaluation	Sufficient Mach/Re to simulate flight effects	1000+ points including Mach, Re aileron and elevon deflections, pitch and roll, BL tripping	10 weeks	N/A	N/A	N/A	N/A
3.2202	Obtain acreage laminar and turbulent convective heating data for CFD evaluation	High-enthalpy for CO2 kinetics, Re range for BL transition	5 Reynolds x 5 AoA = 25 runs	25 runs = 1 weeks	5 Enthalpies x 5 AoA = 25 runs in CUBRC or 5 Reynolds x 1 pitch sweep in AEDC	2 weeks CUBRC, 1-week AEDC	Discrete or global optical heating	Ceramic or metallic aeroheating models
3.2203	Obtain heating data on / around / between / behind control flaps for CFD evaluation	High--enthalpy for CO2 kinetics, Re range for BL transition ahead of flaps	5 Reynolds x 5 AoA x 5 flap parameters = 75 runs	75 runs = 2 weeks	3 Enthalpies x 3 Reynolds x 3 AoA x 3 flap parameters = 81 test points in CUBRC. 5 Reynolds x 5 flaps x 1 pitch sweep = 25 test points in AEDC	81 points = 10 weeks in CUBRC. 25 points = 2 weeks in AEDC	Discrete or global optical heating, Detailed discrete sensors in areas with no optical view path	Ceramic or metallic aeroheating models
3.2204	Obtain "thrust-off" heating and flow field data on / around SRP installations for CFD evaluation	High-enthalpy for CO2 kinetics, Re range for BL transition	5 Reynolds x 5 AoA x 3 SRP nozzles= 50 runs	50 runs = 1 weeks	3 enthalpies x 3 Reynolds x 3 AoA x 3 SRP nozzles = 81 points in CUBRC. 5 Reynolds numbers x 1 pitch sweep x 3 SRP nozzles = 15 runs in AEDC	81 points = 10 weeks in CUBRC. 15 points = 2 weeks in AEDC	Discrete or global optical heating. Detailed discrete sensors in areas with no optical view path	Ceramic or metallic aeroheating models
3.2205	Obtain data on integrated SRP / vehicle performance for CFD evaluation	CO2 compressibility effects, sufficient Mach/Re to simulate flight effects. Ability to perform jet-on testing	3 Mach x 3 AoA x 3 Reynolds x 5 mass flows x 5 thrust pairings = 675 test points	Assume mass flow and pitch sweeps = 45 runs / 2 weeks	3 Mach x 3 AoA x 3 Reynolds x 5 mass flows x 5 thrust pairings = 675 test points	Assume mass flow and pitch sweeps = 45 runs / 2 weeks	High resolution aero force & moment balance to capture SRP deltas, high-speed schlieren	Metallic model with SRP firing capability
3.2206	Obtain data on dynamic aero pitch / sideslip for CFD evaluation	CO2 compressibility effects, sufficient Mach/Re to simulate flight effects	5 Mach x 3 AoA x 3 slip x 3 Reynolds = 145 test points in WT. 20 points in range	45 runs with continuous pitch = 2 weeks in WT. 20 points in range = 2 weeks	5 Mach x 3 AoA x 3 slip x 3 Reynolds = 145 test points in WT. 20 points in range	45 runs with continuous pitch = 2 weeks in WT. 20 points in range = 2 weeks	Ability to measure dynamic aero	Metallic force & moment models
3.23	Mid L/D Lifting Body - sub-scale flight test for aerodynamics and aeroheating							

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3.2301	Develop supersonic static aerodynamic performance database	flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points	Assume cont. AoA sweep, 27 runs = 1 weeks	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points	AEDC assumes cont. AoA sweep, 27 runs = 1 week. CUBRC 145 points = 15 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models
3.2302	Develop supersonic dynamic aero response to pitch and sideslip	Flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points in UPWT. 10 shots (AoA limited) in HFFAF	UPWT Assume cont. AoA sweep, 27 runs = 1 week. HFFAF = 2 weeks	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points in UPWT. 10 shots (AoA limited) in Aberdeen	AEDC assumes cont. AoA sweep, 27 runs = 1 week. CUBRC 145 points = 15 weeks. 10 shots (AoA limited) in Aberdeen	dynamic force & moment balances or range photography, discrete surface pressure	Metallic force & moment models
3.2303	Define supersonic control surface aerodynamic effectiveness	Flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 450 points	UPWT assume cont. AoA sweep, 90 runs = 4 weeks	3 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 450 points	AEDC assume cont. AoA sweep, 90 runs = 4 weeks. CUBRC 450 points = 45 weeks	static force & moment balances, schlieren, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with interchangeable or moveable control surfaces
3.2304	Define supersonic RCS performance and interactions	Flight-relevant Mach/Re range, mass flow for RCS firing	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	UPWT assume cont. AoA sweep, 45 runs = 2 weeks	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from RCS
3.2305	Develop hypersonic aerodynamic database	Flight-relevant Mach/re range	2 x Mach x 5 AoA x 3 slip x 5 AoA = 150 points	Assume cont. AoA sweep, 30 runs = 1 week	2 x Mach/enthalpy x 5 AoA x 3 slip x 5 AoA = 150 points	AEDC Assume cont. AoA sweep, 30 runs = 1 week. CUBRC 30 shots = 4 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models
3.2306	Define hypersonic control surface aerodynamic effectiveness	Flight-relevant Mach/re range	2 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 300 points	Assume cont. AoA sweep 60 runs = 2 weeks	2 x Mach/enthalpy x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 300 points	AEDC assume cont. AoA sweep, 60 runs = 6 weeks. CUBRC 300 points = 30 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models with interchangeable or moveable control surfaces
3.2307	Develop hypersonic smooth-OML acreage convective heating	Flight-relevant Mach/re range to produce laminar, transitional and turbulent flow	5 x Re x 3 AoA x 2 slip = 30 points	30 runs = 1 week	5 Mach/enthalpy x 3 AoA x 2 slip = 30 points	AEDC assume cont. pitch, 10 runs = 1 weeks. CUBRC 30 runs = 3 weeks	global optical and/or discrete surface heating	instrumented metallic or cast ceramic heating models
3.2308	Define control surface convective heating environments	Flight-relevant Mach/re range	5 x Re x 3 AoA x 5 control deflections = 45 points	45 runs = 2 weeks	5 x Re x 3 AoA x 5 control deflections = 45 points	AEDC assume cont. pitch 15 points = 2 weeks. CUBRC 45 points = 4 weeks	global optical and/or discrete surface heating. Small-scale discrete gages required between/under split flaps	instrumented metallic or cast ceramic heating models
3.2309	Define RCS jet/surface interaction effects on heating	Flight-relevant Mach/re range	3 x Mach x 3 Re x 5 AoA x 5 SRP firing parameters pairings = 175 points	175 runs = 6 weeks	3 x Mach/enthalpy x 3 Re x 5 AoA x 5 SRP firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	global optical and/or discrete surface heating	instrumented metallic or cast ceramic heating models with active blowing from RCS
3.24	Mid L/D Lifting Body - sub-scale flight test for SRP performance							
3.2401	Develop supersonic static aerodynamic performance database	flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points	Assume cont. AoA sweep, 27 runs = 1 week	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points	AEDC assumes cont. AoA sweep, 27 runs = 1 week. CUBRC 145 points = 15 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models

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3.2402	Develop supersonic dynamic aero response to pitch and sideslip	Flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points in UPWT. 10 shots (AoA limited) in HFFAF	UPWT Assume cont. AoA sweep, 27 runs = 1 week. HFFAF = 2 weeks	3 x Mach x 3 Re x 5 AoA x 3 sideslip = 145 points in UPWT. 10 shots (AoA limited) in Aberdeen	AEDC assumes cont. AoA sweep, 27 runs = 1 week. CUBRC 145 points = 15 weeks. 10 shots (AoA limited) in Aberdeen	dynamic force & moment balances or range photography, discrete surface pressure	Metallic force & moment models
3.2403	Define supersonic control surface aerodynamic effectiveness	Flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 450 points	UPWT assume cont. AoA sweep, 90 runs = 4 weeks	3 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 450 points	AEDC assume cont. AoA sweep, 90 runs = 4 weeks. CUBRC 450 points = 45 weeks	static force & moment balances, schlieren, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with interchangeable or moveable control surfaces
3.2404	Define supersonic RCS performance and interactions	Flight-relevant Mach/Re range, mass flow for RCS firing	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	UPWT assume cont. AoA sweep, 45 runs = 2 weeks	3 x Mach x 3 Re x 5 AoA x 5 RCS firing parameters pairings = 175 points	AEDC assumes cont. AoA sweep, 45 runs = 2 weeks. CUBRC 175 points = 18 weeks	static force & moment balances, schlieren and PLIF, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with active blowing from RCS
3.25	Mid L/D Lifting Body - full-scale Mars flight test and/or missions							
3.3	**Deployable Aerodynamic Decelerator Technology Development and Demonstration**							
3.31	SNC Deployable							
3.3101	Preliminary evaluation of hypersonic aerodynamic performance	Hypersonic conditions-chemical kinetic effects are negligible for concept evaluation	3 AoA, 3 Reynolds numbers over laminar-to-turbulent range ~ 30 runs	~ 1 week	N/A	N/A	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.3102	Preliminary evaluation of aeroheating effects on aeroshell	Hypersonic conditions-chemical kinetic effects are negligible for concept evaluation	3 AoA, 3 Reynolds numbers over laminar-to-turbulent range ~ 30 runs	~ 1 week	N/A	N/A	global surface heating	cast ceramic models
3.3103	Detailed supersonic aerodynamic performance for flight mission	Supersonic at relevant Mach / Reynolds	3 x AoA, 3 x roll, 2 x Mach, 4 x control deflection, 3 x Re = 216 points	~ 3 weeks	3 x AoA, 3 x roll, 2 x Mach, 4 x control deflection, 3 x Re = 216 points	~ 3 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models
3.3104	Detailed hypersonic aerodynamic performance for flight mission	Hypersonic at relevant Mach / Reynolds	3 x AoA, 3 x roll, 4 x control deflection, 3 x Re = 108 points	~ 2 weeks	3 x AoA, 3 x roll, 4 x control deflection, 3 x Re = 108 points	~ 2 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models
3.3105	Detailed aeroshell aeroheating for flight mission	Hypersonic at relevant Mach / Reynolds	3 x AoA, 3 x roll, 4 x control deflection, 3 x Re = 108 points	~ 4 weeks	3 x AoA, 3 x roll, 4 x control deflection, 3 x Re = 108 points	~ 4 weeks	global optical surface heating and/or discrete sensors	ceramic or metallic heating models
3.32	Pterodactyl Control Systems for DEVs Sample Return							
3.3201	Develop supersonic aerodynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 5 Reynolds numbers over laminar-to-turbulent range x 2 Mach numbers = 30 runs	~ 1 week in any NASA facility	3 AoA x 5 Reynolds numbers over laminar-to-turbulent range x 2 Mach numbers = 30 runs	1 week in non-NASA	measure static aerodynamics with force-and-moment balance	Metallic force & moment model fabrication

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3.3202	Develop hypersonic aerodynamic performance database	Hypersonic M5-M10 (chemical kinetic effects are small for trajectory)	3 AoA x 5 Reynolds numbers over laminar-to-turbulent range ~ 15 points	~ 1 week in any NASA facility	3 AoA x 5 Reynolds numbers over laminar-to-turbulent range ~ 15 points	1 week in non-NASA	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
3.3203	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at relevant Reynolds numbers to produce laminar-to-turbulent range of conditions	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	~ 1 week in any NASA facility	3 AoA x 5 Reynolds numbers over laminar-to-turbulent range ~ 15 points	1 week in non-NASA	Global surface and/or discrete heating measurements	cast ceramic or machined metallic models
3.3204	Determine aftbody and payload heating environments	Hypersonic facility with flight-relevant operating conditions and sufficient test time for wake flow establishment.	3 AoA x 5 Reynolds numbers sufficient to span laminar to turbulent flow	~ 1 week in any NASA facility	3 AoA x 5 Reynolds numbers over laminar-to-turbulent range ~ 15 points	1 week in non-NASA	Global optical techniques for measurement of payload/aftbody heating and/or discrete sensors	cast ceramic or machined metallic models
3.33	ADEPT Drag Modulated Aerocapture Demonstration (Earth GTO). ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts							
3.3301	Develop supersonic aerodynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.3302	Develop supersonic dynamic aero database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	Dynamic aero balance and/or free flight imagery, flow field visualization	Metallic force & moment model fabrication
3.3303	Develop supersonic RCS performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 3 Mach x 3 Re x 6 RCS parameters = 154 points	4 weeks	3 AoA x 3 Mach x 3 Re x 6 RCS parameters = 154 points	4 weeks	Static aerodynamic balances, flow field visualization, RCS mass flow measurement, plume visualization	Metallic force & moment model fabrication
3.3304	Develop hypersonic aerodynamic performance database	Hypersonic conditions - assume chemical kinetic effects are small for this mission	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week AEDC, 3 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.3305	Determine baseline, smooth-OML aeroshell convective heating	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week AEDC, 4 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models

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3.3306	Define TPS roughness effect on convective heating and BL transition	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions	3 AoA x 5 Re x 5 roughness parameters = 75 points	2 weeks	3 AoA x 5 Re x 5 roughness parameters = 75 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models, ability to machine/cast small-scale roughness features
3.3307	Determine RCS interaction effects on payload heating	Hypersonic facility with relevant Mach / Re range and sufficient test time for wake flow establishment	3 AoA x 2 roll x 3 Re x 2 Mach x 6 RCS parameters = 210 points	4 weeks	3 AoA x 2 roll x 3 Re x 2 Mach x 6 RCS parameters = 210 points	4 weeks AEDC, 12 weeks CUBRC	optical thermography and/or discrete heat-flux sensors, RCS mass flow measurements, plume and flow field visualization	cast ceramic or machined metallic models
3.3308	Determine aftbody and payload heating environments	Hypersonic facility with relevant Mach / Re range and sufficient test time for wake flow establishment	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors, flow field visualization	cast ceramic or machined metallic models
3.34	ADEPT Drag Modulated Aerocapture SmallSat Venus/Mars Orbiter. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts							
3.3401	Develop supersonic aerodynamic performance database in CO2 atmosphere	Supersonic M2-M4 with wide range of Reynolds numbers. CO2 test gas	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.3402	Develop supersonic dynamic aero database in CO2 atmosphere	Supersonic M2-M4 with wide range of Reynolds numbers. CO2 test gas	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	Dynamic aero balance and/or free flight imagery, flow field visualization	Metallic force & moment model fabrication
3.3403	Develop supersonic RCS performance database in CO2 atmosphere	Supersonic M2-M4 with wide range of Reynolds numbers. CO2 test gas	3 AoA x 3 Mach x 3 Re x 6 RCS parameters = 154 points	4 weeks	3 AoA x 3 Mach x 3 Re x 6 RCS parameters = 154 points	4 weeks	Static aerodynamic balances, flow field visualization, RCS mass flow measurement, plume visualization	Metallic force & moment model fabrication
3.3404	Develop hypersonic aerodynamic performance database in CO2 atmosphere	Hypersonic conditions - high-enthalpy CO2 test gas	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week AEDC, 3 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.3405	Determine baseline, smooth-OML aeroshell convective heating in CO2 atmosphere	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. High-enthalpy CO2 test gas	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1-week AEDC, 4 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models

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3.3406	Define TPS roughness effect on convective heating and BL transition	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. CO2 not necessary for fluid dynamics of transition	3 AoA x 5 Re x 5 roughness parameters = 75 points	2 weeks	3 AoA x 5 Re x 5 roughness parameters = 75 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models, ability to machine/cast small-scale roughness features
3.3407	Determine RCS interaction effects on payload heating in CO2 atmosphere	Hypersonic facility with relevant Mach / Re range and sufficient test time for wake flow establishment. High-enthalpy CO2 test gas	3 AoA x 2 roll x 3 Re x 2 Mach x 6 RCS parameters = 210 points	4 weeks	3 AoA x 2 roll x 3 Re x 2 Mach x 6 RCS parameters = 210 points	4 weeks AEDC, 12 weeks CUBRC	optical thermography and/or discrete heat-flux sensors, RCS mass flow measurements, plume and flow field visualization	cast ceramic or machined metallic models
3.3408	Determine aftbody and payload heating environments in CO2 atmosphere	Hypersonic facility with relevant Mach / Re range and sufficient test time for wake flow establishment. High-enthalpy CO2 test gas	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors, flow field visualization	cast ceramic or machined metallic models
3.3409	Determine radiative heating environment in CO2 atmosphere	Appropriate press / species / velocity for CO2 atmosphere	pressure, velocity and composition relevant to destination	2 months	Appropriate press / species / velocity for CO2 atmosphere	pressure, velocity and composition relevant to destination	Discrete surface heat-flux and radiation gages, flow field spectral imaging	metallic model with radiation sensors
3.341	Develop rarefied hypersonic aerodynamic performance database	Hypersonic conditions in rarefied flight regimes	3 AoA x 3 Re x 2 Mach = 18 points	1 week	3 AoA x 3 Re x 2 Mach = 18 points	1 week	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.35	ADEPT Drag Modulated Aerocapture Flagship Ice Giant Orbiter/Probe Mission. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts							
3.3501	Develop supersonic aerodynamic performance database in H2/He atmosphere	Supersonic M2-M4 with wide range of Reynolds numbers in Helium test gas	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.3502	Develop supersonic dynamic aero database in H2/He atmosphere	Supersonic M2-M4 with wide range of Reynolds numbers in Helium test gas	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	Dynamic aero balance and/or free flight imagery, flow field visualization	Metallic force & moment model fabrication

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3.3503	Develop supersonic RCS performance database in H2/He atmosphere	Supersonic M2-M4 with wide range of Reynolds numbers in Helium test gas	3 AoA x 3 Mach x 3 Re x 6 RCS parameters = 154 points	4 weeks	3 AoA x 3 Mach x 3 Re x 6 RCS parameters = 154 points	4 weeks	Static aerodynamic balances, flow field visualization, RCS mass flow measurement, plume visualization	Metallic force & moment model fabrication
3.3504	Develop hypersonic aerodynamic performance database in H2/He atmosphere	Hypersonic conditions - high-enthalpy H2/Helium test gas	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week AEDC, 3 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.3505	Determine baseline, smooth-OML aeroshell convective heating in H2/He atmosphere	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. High-enthalpy H2/Helium test gas	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week AEDC, 4 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models
3.3506	Define TPS roughness effect on convective heating and BL transition in H2/He atmosphere	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions in Helium test gas	3 AoA x 5 Re x 5 roughness parameters = 75 points	2 weeks	3 AoA x 5 Re x 5 roughness parameters = 75 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models, ability to machine/cast small-scale roughness features
3.3507	Determine RCS interaction effects on payload heating in H2/He atmosphere	Hypersonic facility with relevant Mach / Re range and sufficient test time for wake flow establishment in Helium test gas	3 AoA x 2 roll x 3 Re x 2 Mach x 6 RCS parameters = 210 points	4 weeks	3 AoA x 2 roll x 3 Re x 2 Mach x 6 RCS parameters = 210 points	4 weeks AEDC, 12 weeks CUBRC	optical thermography and/or discrete heat-flux sensors, RCS mass flow measurements, plume and flow field visualization	cast ceramic or machined metallic models
3.3508	Determine aftbody and payload heating environments in H2/He atmosphere	Hypersonic facility with relevant Mach / Re range and sufficient test time for wake flow establishment in Helium test gas	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors, flow field visualization	cast ceramic or machined metallic models
3.3509	Determine radiative heating environment in H2/He atmosphere	Appropriate press / species / velocity for H2/He atmosphere	pressure, velocity and composition relevant to destination	2 months	Appropriate press / species / velocity for H2/He atmosphere	pressure, velocity and composition relevant to destination	Discrete surface heat-flux and radiation gages, flow field spectral imaging	metallic model with radiation sensors
3.351	Develop rarefied hypersonic aerodynamic performance database	Hypersonic conditions in rarefied flight regimes	3 AoA x 3 Re x 2 Mach = 18 points	1 week	3 AoA x 3 Re x 2 Mach = 18 points	1 week	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.36	Large scale deployable aeroshell for Human rated Mars missions							

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3.4	**Advanced Rigid Aeroshell Capsule configurations**							
3.41	Geometric scaling of standard MSL / Orion type aeroshells							
3.4101	Develop supersonic aerodynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.4102	Develop hypersonic aerodynamic performance database	Hypersonic conditions with wide range of Re	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week AEDC, 3 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.4103	Develop Hypersonic aeroheating database for Aeroshell smooth OML	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. High-enthalpy test capability	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week AEDC, 4 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models
3.4104	Define TPS roughness effect on convective heating and BL transition in CO2 atmosphere	Hypersonic conditions with wide range of Re to produce laminar-to-turbulent flow. Sufficient model size to resolve roughness features	3 AoA x 5 Re x 5 roughness parameters = 75 points	2 weeks	3 AoA x 5 Re x 5 roughness parameters = 75 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models, ability to machine/cast small-scale roughness features
3.4105	Determine radiative heating database	Appropriate press / species / velocity for designated atmosphere	pressure, velocity and composition relevant to destination	2 months	Appropriate press / species / velocity for H2/He atmosphere	pressure, velocity and composition relevant to destination	Discrete surface heat-flux and radiation gages, flow field spectral imaging	metallic model with radiation sensors
3.42	Asymmetric rigid Aeroshell - AFE, ACV optimized shapes, elliptical/hyperboloid cross-section, etc.							
3.4201	Develop supersonic aerodynamic static performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.4202	Develop supersonic aerodynamic dynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	Dynamic aero balance and/or free flight imagery, flow field visualization	Metallic force & moment model fabrication

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3.4203	Develop hypersonic aerodynamic performance database	Hypersonic conditions with wide range of Re	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week AEDC, 3 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.4204	Develop Hypersonic aeroheating database for Aeroshell smooth OML	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. High-enthalpy test capability	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week AEDC, 4 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models
3.4205	Define TPS roughness effect on convective heating and BL transition in CO2e atmosphere	Hypersonic conditions with wide range of Re to produce laminar-to-turbulent flow. Sufficient model size to resolve roughness features	3 AoA x 5 Re x 5 roughness parameters = 75 points	2 weeks	3 AoA x 5 Re x 5 roughness parameters = 75 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models, ability to machine/cast small-scale roughness features
3.4206	Determine radiative heating database	Appropriate press / species / velocity for designated atmosphere	pressure, velocity and composition relevant to destination	2 months	Appropriate press / species / velocity for H2/He atmosphere	pressure, velocity and composition relevant to destination	Discrete surface heat-flux and radiation gages, flow field spectral imaging	metallic model with radiation sensors
3.43	Aerodynamic Trim Tabs							
3.4301	Develop supersonic aerodynamic static performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	3 AoA x 3 Roll x 3 Mach x 3 Re = 81 points	2 weeks	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.4302	Develop supersonic aerodynamic dynamic performance database	Supersonic M2-M4 with wide range of Reynolds numbers	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	3 AoA x 3 Roll x 5 Mach x 3 Re = 135 points	3 weeks	Dynamic aero balance and/or free flight imagery, flow field visualization	Metallic force & moment model fabrication
3.4303	Develop hypersonic aerodynamic performance database	Hypersonic conditions with wide range of Re	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week AEDC, 3 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.4304	Develop Hypersonic aeroheating database for Aeroshell smooth OML	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. High-enthalpy test capability	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week AEDC, 4 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models
3.4305	Define TPS roughness effect on convective heating and BL transition in CO2 atmosphere	Hypersonic conditions with wide range of Re to produce laminar-to-turbulent flow. Sufficient model size to resolve roughness features	3 AoA x 5 Re x 5 roughness parameters = 75 points	2 weeks	3 AoA x 5 Re x 5 roughness parameters = 75 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models, ability to machine/cast small-scale roughness features

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3.4306	Determine radiative heating database	Appropriate press / species / velocity for designated atmosphere	pressure, velocity and composition relevant to destination	2 months	Appropriate press / species / velocity for H2/He atmosphere	pressure, velocity and composition relevant to destination	Discrete surface heat-flux and radiation gages, flow field spectral imaging	metallic model with radiation sensors
3.4307	Define control surface supersonic aerodynamic performance	Flight-relevant Mach/Re range	3 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 450 points	UPWT assume cont. AoA sweep, 90 runs = 4 weeks	3 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 450 points	AEDC assume cont. AoA sweep, 90 runs = 4 weeks. CUBRC 450 points = 45 weeks	static force & moment balances, schlieren, discrete surface pressure - all with high-speed dynamic response	Metallic force & moment models with interchangeable or moveable control surfaces
3.4308	Define hypersonic control surface aerodynamic effectiveness	Flight-relevant Mach/re range	2 x Mach x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 300 points	Assume cont. AoA sweep 60 runs = 2 weeks	2 x Mach/enthalpy x 3 Re x 5 AoA x 2 slip x 5 BF deflection pairings = 300 points	AEDC assume cont. AoA sweep, 60 runs = 6 weeks. CUBRC 300 points = 30 weeks	static force & moment balances, schlieren, discrete surface pressure	Metallic force & moment models with interchangeable or moveable control surfaces
3.4309	Define hypersonic control surface aeroheating environments	Rapid turnaround time for multiple configuration / parametric changes. Sufficient Reynolds number/model scale to obtain laminar-to-turbulent data. High-enthalpy kinetics	4 AoA, 5 Reynolds number, 4 control deflections, 2 yaw/roll = 160 test points	LaRC = 160 runs/ 5 weeks	4 AoA, 5 Reynolds number, 4 control deflections, 2 yaw/roll = 160 test points	AEDC Tunnel 9 (cont. pitch) = 80 runs / 8 weeks. CUBRC LENS = 160 runs / 16 weeks. AEDC VKF B/C not suitable for aeroheating testing of multiple configs/deflections	Global optical and / or discrete surface heating measurements	Cast ceramic or machined metallic models - multiple configurations for all control deflections
3.44	Large scale rigid-TPS aeroshell for Human rated Mars missions utilizing any/all advance options listed under advanced rigid-aeroshell capsule development path							
3.5	**Super/Hypersonic Retropropulsion Technology Development and Demonstration**							
3.51	Evaluation of CFD capability for SRP							
3.5101	Obtain surface pressure, flow visualization, and aerodynamic data on SRP system for CFD evaluations	Supersonic freestream conditions up to Mach 4 with ability to run high-pressure simulant gas through model	see AETC run matrix	8-10 weeks	N/A	N/A	PSP, direct F/M measurement, off-body flow visualization (optical access), steady/unsteady pressure measurement	
3.52	RP System ground testing capability development and unit-problem testing							

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3.5201	Hot inert gas RP systems testing	Supersonic freestream conditions up to Mach 4 with ability to run high-pressure, heated (>500K) inert simulant gas through model	Pressure ratio (pe/p0,2) and CT below 1.0 to greater than 10.0 if possible; angle of attack up to 8 degrees; multiple SRP nozzle configurations	6-8 weeks	N/A	N/A	Direct F/M measurement, off-body flow visualization (optical access), steady/unsteady pressure and temperature measurements	
3.5202	Sub-scale engine testing	Hot-fire engine testing at sea-level conditions	No applied flow field as testing is conducted in an outdoor test stand or test cell.	2 weeks	N/A	N/A	Engine control and diagnostics/monitoring to verify propulsion test article performance	
3.5203	Flow-through balance development	N/A	see AETC test matrix; AETC testing in LaRC UPWT should demonstrate balance capability and identify any further development needs	6+ weeks	N/A	N/A	Integration of 6-component flow-through F/M balance	
3.5204	RP testing in CO2 flow	Supersonic CO2 freestream conditions up to Mach 4 with ability to run high-pressure, heated (>500K) inert simulant gas through model, if not combustion products	Limited multiple-nozzle configurations, conditions should span over-expanded to under-expanded nozzle flow transitions, limited AOA sweep (no greater than 10 deg)	8 weeks	N/A	N/A		
3.5205	Flow field dynamics validation - unsteady RP/shock/plume interactions	Supersonic freestream conditions up to Mach 4 with ability to run high-pressure, heated (>500K) inert simulant gas through model, if not combustion products	Overlap and significant duplication of 3.521; all ground testing will obtain data for validation of unsteady flow dynamics	Overlaps with above testing - no additional time required.				
3.5206	Turbulence model validation for separated unsteady flows with RP/shock interactions	Supersonic freestream conditions up to Mach 4 with ability to run high-pressure inert simulant gas through model; optical and diagnostics access as required for data acquisition	Non-NASA facilities (academia) are better suited than NASA facilities for these unit experiments.	TBD - significant unit experiment efforts and specialized diagnostics exist in academia				

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3.5207	Validation of kinetics for RP exhaust interactions with flow field	Hot-fire propulsion test in supersonic WT	Reduced matrix as compared to inert gas testing; limited to 1 or 2 model configurations; will still need to test with over-expanded and under-expanded nozzle flows unless vehicle designs and performance analyses change significantly	8 weeks; build-up and integration likely adds at least another month				
3.5208	Validation data for RP/shock/plume/surface interaction heating	Hot-fire propulsion test in supersonic WT	Should overlap with 3.527 in same test effort					
3.5209	Validation data for wake flow interactions with RP plumes	Hot-fire propulsion test in supersonic WT	Should overlap with 3.527 in same test effort					
3.53	SRP Architecture Configuration Evaluation for Mars Application							
3.5301	Task 1							
3.5302	Task 2							
3.54	Earth reentry flight tests and system demonstration							
3.5401	Configuration hypersonic aerodynamics	Hypersonic wind tunnel	Non-blowing model(s), AOA sweep based on flight-mechanics analysis					
3.5402	Configuration supersonic aerodynamics	supersonic wind tunnel	Test points will be included in the above RP testing for any SRP test to obtain baseline aero characteristics; Flight est article-specific geometry should be used if significantly different from those tested previously					
3.5403	Retropropulsion aerodynamics & interactions	supersonic wind tunnel	Flight system-specific geometry and scaled conditions; propulsion test recommended due to observations of significant chemistry in external flow					

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
3.5404	Configuration aeroheating environments	Hypersonic wind tunnel	Flight system-specific geometry and scaled conditions; propulsion test recommended due to observations of significant chemistry in external flow and no existing aerothermal data					
3.55	Mars reentry flight tests and system demonstration	Supersonic wind tunnel with propulsion capability	TBD					
3.6	**Aerocapture**							
3.61	Trade studies on aerocapture options for EDL exploration missions							
3.6101	Develop rarefied hypersonic aerodynamic performance database	Hypersonic conditions in rarefied flight regimes	3 AoA x 3 Re x 2 Mach = 18 points	1 week	3 AoA x 3 Re x 2 Mach = 18 points	1 week	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.6102	Develop continuum hypersonic aerodynamic performance database	Hypersonic conditions with wide range of Re	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week AEDC, 3 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.6103	Develop Hypersonic aeroheating database	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. High-enthalpy test capability	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week AEDC, 4 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models
3.6104	Determine radiative heating database	Appropriate press / species / velocity for destination atmosphere	TBD points at atmosphere relevant conditions	1 month	Appropriate press / species / velocity for destination atmosphere	TBD points at atmosphere relevant conditions	Discrete surface heat-flux and radiation gages, flow field spectral imaging	metallic model with radiation sensors
3.62	Sub-scale Earth flight test for TRL advancement to mission application of aerocapture							
3.6201	Develop rarefied hypersonic aerodynamic performance database	Hypersonic conditions in rarefied flight regimes	3 AoA x 3 Re x 2 Mach = 18 points	1 week	3 AoA x 3 Re x 2 Mach = 18 points	1 week	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.6202	Develop continuum hypersonic aerodynamic performance database	Hypersonic conditions with wide range of Re	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week	3 AoA x 2 roll x 3 Re x 2 Mach = 36 points	1 week AEDC, 3 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
3.6203	Develop Hypersonic aeroheating database	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. High-enthalpy test capability	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 30 points	1 week	3 AoA x 2 roll x 5 Reynolds numbers sufficient to span laminar to turbulent flow = 50 points	1 week AEDC, 4 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models
3.6204	Define TPS roughness effect on convective heating and BL transition	Hypersonic conditions with wide range of Re to produce laminar-to-turbulent flow. Sufficient model size to resolve roughness features	3 AoA x 5 Re x 5 roughness parameters = 75 points	2 weeks	3 AoA x 5 Re x 5 roughness parameters = 75 points	1 weeks AEDC, 2 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models, ability to machine/cast small-scale roughness features
3.63	Small planet or satellite Mission (Venus, Titan, Mars, etc.) or Ice Giant (Uranus, Neptune)							
3.6301	Develop rarefied hypersonic aerodynamic performance database	Hypersonic conditions in rarefied flight regimes	3 AoA x 3 Re x 2 Mach x 2 roll= 36 points	2 weeks	3 AoA x 3 Re x 2 Mach x 2 roll= 36 points	2 weeks AEDC, 4 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.6302	Develop continuum hypersonic aerodynamic performance database	Hypersonic conditions with wide range of Re	3 AoA x 2 roll x 6 Re x 2 Mach = 72 points	3 weeks	3 AoA x 2 roll x 6 Re x 2 Mach = 72 points	3 weeks AEDC, 6 weeks CUBRC	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.6303	Develop continuum supersonic aerodynamic performance database	Supersonic conditions with wide range of Re and Mach	3 AoA x 2 roll x 6 Re x 4 Mach = 142 points	4 weeks	3 AoA x 2 roll x 6 Re x 4 Mach = 142 points	4 weeks	Static aerodynamic balances, flow field visualization, surface pressure	Metallic force & moment model fabrication
3.6304	Develop Hypersonic aeroheating database	Hypersonic facility operating at high Reynolds numbers to produce laminar-to-turbulent range of conditions. High-enthalpy test capability	3 AoA x 2 roll x 5 Reynolds x 2 Mach numbers sufficient to span laminar to turbulent flow = 60 points	3 weeks	3 AoA x 2 roll x 5 Reynolds x 2 Mach numbers sufficient to span laminar to turbulent flow = 60 points	3 weeks AEDC, 6 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models
3.6305	Define TPS roughness effect on convective heating and BL transition	Hypersonic conditions with wide range of Re to produce laminar-to-turbulent flow. Sufficient model size to resolve roughness features	3 AoA x 5 Re x 5 roughness parameters x 2 roll = 150 points	4 weeks	3 AoA x 5 Re x 5 roughness parameters = 75 points	4 weeks AEDC, 8 weeks CUBRC	optical thermography and/or discrete heat-flux sensors	cast ceramic or machined metallic models, ability to machine/cast small-scale roughness features
3.6306	Determine radiative heating database	Appropriate press / species / velocity for destination atmosphere	TBD points at atmosphere relevant conditions	1 month	Appropriate press / species / velocity for destination atmosphere	TBD points at atmosphere relevant conditions	Discrete surface heat-flux and radiation gages, flow field spectral imaging	metallic model with radiation sensors

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
3.7	**MHD Control of Flow Field**							
3.71	Fundamental Research on aerodynamic aeroheating and BL transition effects							
3.7101	Evaluate MHD performance to generate large Lorentz Forces for increasing L/D ratios and for steering a spacecraft through its planned entry corridor	ability to generate EM effects at relevant test conditions	TBD	Estimate months of development work for new technologies	TBD	Estimate months of development work for new technologies	Force & moment balances for aerodynamics, sensors for EM measurements	Design of model with EM generation capability
3.7102	Evaluate MHD effects on surface heating and BL transition	ability to generate EM effects at relevant test conditions	TBD	Estimate months of development work for new technologies	TBD	Estimate months of development work for new technologies	Global optical surface heating and/or discrete surface heating, sensors for EM measurements	Design of model with EM generation capability

Table 37. Gaps List for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development.

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3	**NASA and Partners EDL Technology and Architecture Development**					
3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**					
3.11	HIAD - LOFTID demonstration mission for TPS performance					
3.1101	Develop hypersonic aerodynamic performance database	none expected	Scheduling and cost in non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-12
3.1102	Develop supersonic aerodynamic performance database	Reynolds/Mach number ranges of NASA facilities and Aberdeen range	Scheduling and cost in non-NASA facilities. Potential for LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12, Inst-Aero-02, Inst-Aero-06
3.1103	Determine baseline, smooth-OML aeroshell convective heating	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on smooth OML	Scheduling and cost in non-NASA facilities	Discrete sensor models have minimal internal volume for discrete gage wiring	None expected	EDL-12
3.1104	Determine aeroshell heating augmentation due to flexible TPS scalloping over supporting toroids	NASA facilities may lack operational Reynolds number to generate turbulence at roughness scales	Cost at non-NASA facilities. Inability to schedule large NASA test programs at non-NASA facilities. Lack of rapid turnaround/parametric changes in non-NASA facilities	Optical access and validation of global aeroheating techniques at AEDC and CUBRC, Discrete sensor models have minimal internal volume for discrete gage wiring	none expected	EDL-09, EDL-12, Inst-Heat-01
3.1105	Determine aftbody and payload heating environments	CUBRC LENS may not provide sufficient test time for wake flow establishment	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Discrete sensor models have minimal internal volume for discrete gage wiring	None expected	EDL-07, EDL-12
3.1106	Determine wake flow-field structure	CUBRC LENS may not provide sufficient test time for wake flow establishment	Scheduling large test program in NASA facilities	Techniques are well-established in supersonic flows, but development implementation in hypersonic tunnels	ability to machine model with internal plumbing to specifications for flow seeding	EDL-07, EDL-12
3.12	HIAD: ISS down mass					
3.1201	Develop hypersonic aerodynamic performance database	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-02, EDL-12, Inst-Aero-01

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.1202	Determine hypersonic aerodynamic influence of payload	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities. Potential for LaRC UPWT closure	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-02, EDL-07, EDL-11, EDL-12, Inst-Aero-01
3.1203	Develop supersonic aerodynamic performance database	Reynolds/Mach number ranges of NASA facilities and Aberdeen range	Scheduling and cost in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-12, Inst-Aero-06
3.1204	Define supersonic RCS performance and interactions	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Scheduling and cost in non-NASA facilities	none	ability to machine model with internal plumbing for RCS jets	EDL-08, EDL-12
3.1205	Determine supersonic aerodynamic influence of payload	Reynolds/Mach number ranges of NASA facilities and Aberdeen range	Scheduling and cost in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12
3.1206	Determine baseline, smooth-OML aeroshell convective heating	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on smooth OML. Lack of NASA high-enthalpy capability may impact aeroheating	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.1207	Determine aeroshell heating augmentation due to flexible TPS deflections	NASA facilities may lack operational Reynolds number to generate turbulence at roughness scales. Ames HFFAF has limited AoA range	Scheduling and cost in non-NASA facilities	Optical access and validation of global aeroheating techniques at AEDC and CUBRC	1) Ability to 3D print/machine or cast detailed TPS roughness features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12
3.1208	Determine aftbody and payload heating environments	CUBRC LENS may not provide sufficient test time for wake flow establishment. Lack of high-enthalpy capability in NASA & AEDC facilities	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-01, EDL-07, EDL-12
3.13	HIAD: launch vehicle booster recovery					
3.1301	Develop hypersonic aerodynamic performance database	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-02, EDL-12, Inst-Aero-01
3.1302	Determine hypersonic aerodynamic influence of payload	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities. Potential for LaRC UPWT closure	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	EDL-02, EDL-07, EDL-12, Inst-Aero-01
3.1303	Develop supersonic aerodynamic performance database	Reynolds/Mach number ranges of NASA facilities and Aberdeen range	Scheduling and cost in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.1304	Define supersonic RCS performance and interactions	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Scheduling and cost in non-NASA facilities	none	none	EDL-08, EDL-12
3.1305	Determine supersonic aerodynamic influence of payload	Reynolds/Mach number ranges of NASA facilities and Aberdeen range	Scheduling and cost in non-NASA facilities	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	EDL-11, EDL-12
3.1306	Determine baseline, smooth-OML aeroshell convective heating	NASA facilities may lack operational Reynolds number / model scale to generate turbulent flow on smooth OML. Lack of NASA high-enthalpy capability may impact aeroheating	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.1307	Determine aeroshell heating augmentation due to flexible TPS deflections	NASA facilities may lack operational Reynolds number to generate turbulence at roughness scales. Ames HFFAF has limited AoA range	Scheduling and cost in non-NASA facilities	Optical access and validation of global aeroheating techniques at AEDC and CUBRC	1) Ability to 3D print/machine or cast detailed TPS roughness features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12, Inst-Heat-02
3.1308	Determine aftbody and payload heating environments	CUBRC LENS may not provide sufficient test time for wake flow establishment. Lack of high-enthalpy capability in NASA & AEDC facilities	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-01, EDL-07, EDL-12
3.14	Asymmetric aeroshell morphing for aerodynamic control and performance					
3.1401	Evaluate supersonic aerodynamic static performance and validate CFD predictions	none expected	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-12
3.1402	Evaluate hypersonic aerodynamic static performance and validate CFD predictions	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
3.1403	Configuration specific evaluation of morphed aeroshell heating and BL transition	NASA facilities may lack operational Reynolds number to generate turbulence at aeroshell scales	Scheduling and cost in non-NASA facilities	none expected	1) Ability to 3D print/machine or cast detailed TPS roughness features for global techniques. 2) Model design and fabrication with large number of discrete sensors	EDL-01, EDL-09, EDL-12, Inst-Heat-02
3.24	HIAD skirt / inflatable tab extension to rigid aeroshell nose cap					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.2401	Evaluate supersonic aerodynamic static performance and validate CFD predictions	none expected	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-12
3.2402	Evaluate hypersonic aerodynamic static performance and validate CFD predictions	Lack of high-enthalpy NASA and AEDC capability may impact aerodynamics	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
3.2403	Configuration specific evaluation of skirt/tab aeroshell heating and BL transition	NASA facilities may lack operational Reynolds number to generate turbulence at aeroshell scales	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-01, EDL-09, EDL-12, Inst-Heat-02
3.15	HIAD: Human Mars Exploration mission					
3.2	**Mid L/D Lifting Body**					
3.21	Mid L/D Lifting-Body Architecture Configuration Evaluation for Mars Application					
3.2101	Parametric evaluation of configuration acreage convective aeroheating and BL transition	NASA facilities may lack Reynolds number range / model scale to obtain turbulent data on smooth OML. NASA and AEDC facilities lack high-enthalpy CO2 capability	Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation	validation of global optical aeroheating techniques in non-NASA facilities	none expected	EDL-01, EDL-02, EDL-12
3.2102	Parametric evaluation of configuration acreage radiative heating	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, EDL-12
3.2103	Hypersonic control surface aerodynamic effectiveness	No high-enthalpy CO2 capability in NASA facilities	Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation	none expected	none expected	EDL-02, EDL-12
3.2104	Hypersonic control surface aeroheating environments	No high-enthalpy CO2 capability in NASA facilities	Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation	validation of global optical aeroheating techniques in non-NASA facilities	none expected	EDL-02, EDL-12
3.2105	Supersonic Control surface effectiveness evaluation	No high-enthalpy CO2 capability in NASA facilities	Potential closure of LaRC UPWT. Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation. No CO2 effects	none expected	none expected	EDL-06, EDL-12
3.2106	Supersonic Retro-Propulsion performance and interactions	No high-enthalpy CO2 capability in NASA facilities. Ability to simulate flight relevant SRP mass flow	Potential closure of LaRC UPWT. Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation. No CO2 effects	none expected	Expensive and complicated models with SRP capability	EDL-06, EDL-08, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.22	Evaluation of CFD capability for Mid L/D Aero/Aeroheating prediction for Mars entry					
3.2201	Obtain surface pressure, flow visualization and aerodynamic data on COBRA w/ body flaps for CFD evaluation	NASA facilities do not have CO2, using perfect-gas air for CFD "assessment"	Schedule and cost in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-06, EDL-12
3.2202	Obtain acreage laminar and turbulent convective heating data for CFD evaluation	NASA facilities do not have CO2, using perfect-gas air for CFD "assessment" NASA facilities may not have sufficient Re to assure fully-turbulent flow	Schedule and cost in non-NASA facilities	none	none	EDL-06, EDL-12
3.2203	Obtain heating data on / around / between / behind control flaps for CFD evaluation	NASA facilities do not have CO2, using perfect-gas air for CFD "assessment" NASA facilities may not have sufficient Re to assure fully-turbulent flow	Schedule and cost in non-NASA facilities	Discrete heating sensors for NASA facilities	none	EDL-06, EDL-09, EDL-12, Inst-Heat-02
3.2204	Obtain "thrust-off" heating and flow field data on / around SRP installations for CFD evaluation	NASA facilities do not have CO2, using perfect-gas air for CFD "assessment"	Schedule and cost in non-NASA facilities	Discrete heating sensors for NASA facilities	none	EDL-08, EDL-12
3.2205	Obtain data on integrated SRP / vehicle performance for CFD evaluation	NASA facilities do not have CO2, using perfect-gas air for CFD "assessment"	Schedule and cost in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-08, EDL-12, inst-Aero-03
3.2206	Obtain data on dynamic aero pitch / sideslip for CFD evaluation	NASA facilities do not have CO2, using perfect-gas air for CFD "assessment"	Schedule and cost in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-12, Inst-Aero-02
3.23	Mid L/D Lifting Body - sub-scale flight test for aerodynamics and aeroheating					
3.2301	Develop supersonic static aerodynamic performance database	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation"	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-06, EDL-12
3.2302	Develop supersonic dynamic aero response to pitch and sideslip	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation"	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-06, EDL-12, Inst-Aero-02
3.2303	Define supersonic control surface aerodynamic effectiveness	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-06, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.2304	Define supersonic RCS performance and interactions	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-06, EDL-07, EDL-12, Inst-Aero-03
3.2305	Develop hypersonic aerodynamic database	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-02, EDL-12
3.2306	Define hypersonic control surface aerodynamic effectiveness	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-02, EDL-12
3.2307	Develop hypersonic smooth-OML acreage convective heating	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation", NASA facilities may lack Re range to produce turbulent flow	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-01, EDL-02, EDL-12
3.2308	Define control surface convective heating environments	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define heating-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	lack of small, discrete sensor fab capability for instrumentation between/under gaps	EDL-01, EDL-02, EDL-12
3.2309	Define RCS jet/surface interaction effects on heating	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define heating-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities	none	none	EDL-01, EDL-02, EDL-12
3.24	Mid L/D Lifting Body - sub-scale flight test for SRP performance					
3.2401	Develop supersonic static aerodynamic performance database	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation"	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-06, EDL-12
3.2402	Develop supersonic dynamic aero response to pitch and sideslip	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation"	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-06, EDL-11, EDL-12, Inst-Aero-02, Inst-Aero-06
3.2403	Define supersonic control surface aerodynamic effectiveness	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities. Potential for LaRC UPWT closure	none	none	EDL-06, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.2404	Define supersonic RCS performance and interactions	NASA and AEDC facilities do not replicate air kinetics, using perfect-gas air for CFD "assessment/validation" and to define aero-deltas to scale to flight	Assume cost not relevant for crewed mission. Schedule capacity issues in non-NASA facilities, Potential for LaRC UPWT closure	none	none	EDL-06, EDL-07, EDL-12, Inst-Aero-03
3.25	Mid L/D Lifting Body - full-scale Mars flight test and/or missions					
3.3	**Deployable Aerodynamic Decelerator Technology Development and Demonstration**					
3.31	SNC Deployable					
3.3101	Preliminary evaluation of hypersonic aerodynamic performance	none expected	N/A	none expected	none expected	EDL-12
3.3102	Preliminary evaluation of aeroheating effects on aeroshell	none expected	N/A	none expected	none expected	EDL-12
3.3103	Detailed supersonic aerodynamic performance for flight mission	none expected	N/A	none expected	none expected	EDL-12
3.3104	Detailed hypersonic aerodynamic performance for flight mission	none expected	Access to DoD facilitates unlikely for commercial mission	none expected	none expected	EDL-12
3.3105	Detailed aeroshell aeroheating for flight mission	required Reynolds number ranges are TBD	Access to DoD facilitates unlikely for commercial mission	none expected	none expected	EDL-12
3.32	Pterodactyl Control Systems for DEVs Sample Return					
3.3201	Develop supersonic aerodynamic performance database	none expected	Scheduling and cost in non-NASA facilities. Potential for LaRC UPWT closure	none expected	none expected	EDL-12
3.3202	Develop hypersonic aerodynamic performance database	none expected	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-12
3.3203	Determine baseline, smooth-OML aeroshell convective heating	none expected	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-12
3.3204	Determine aftbody and payload heating environments	none expected	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-07, EDL-12, Inst-Heat0-2

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.33	ADEPT Drag Modulated Aerocapture Demonstration (Earth GTO). ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts					
3.3301	Develop supersonic aerodynamic performance database	none expected	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none expected	none expected	EDL-12
3.3302	Develop supersonic dynamic aero database	range capability to provide relevant Mach/Re	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	ability to perform dynamic measures	none expected	EDL-11, EDL-12, Inst-Aero-02, Inst-Aero-06
3.3303	Develop supersonic RCS performance database	none expected	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	ability to measure small RCS aero deltas	none expected	EDL-12, Inst-Aero-03
3.3304	Develop hypersonic aerodynamic performance database	none expected	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-12
3.3305	Determine baseline, smooth-OML aeroshell convective heating	NSA facilities may lack Reynolds number range to produce turbulent flow	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-12
3.3306	Define TPS roughness effect on convective heating and BL transition	NASA facilities may lack Reynolds number range to produce turbulent flow, model scale sufficient to resolve surface features	Scheduling and cost in non-NASA facilities	none expected	ability to replicate roughness features at model scale	EDL-01, EDL-09, EDL-12
3.3307	Determine RCS interaction effects on payload heating	sufficient stagnation temperature to produce sensible aftbody heating	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-07, EDL-12
3.3308	Determine aftbody and payload heating environments	sufficient stagnation temperature to produce sensible aftbody heating	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-07, EDL-12
3.34	ADEPT Drag Modulated Aerocapture SmallSat Venus/Mars Orbiter. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.3401	Develop supersonic aerodynamic performance database in CO2 atmosphere	NASA and AEDC facilities lack CO2 test capability	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none expected	none expected	EDL-06, EDL-12
3.3402	Develop supersonic dynamic aero database in CO2 atmosphere	range capability to provide relevant Mach/Re	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	ability to perform dynamic measures without strut interference	none expected	EDL-06, EDL-11, EDL-12, Inst-Aero-02, Inst-Aero-06
3.3403	Develop supersonic RCS performance database in CO2 atmosphere	NASA and AEDC facilities lack CO2 test capability	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none expected	none expected	EDL-06, EDL-12, Inst-Aero-03
3.3404	Develop hypersonic aerodynamic performance database in CO2 atmosphere	NASA and AEDC facilities lack CO2 test capability	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
3.3405	Determine baseline, smooth-OML aeroshell convective heating in CO2 atmosphere	NSA facilities may lack Reynolds number range to produce turbulent flow. NASA and AEDC facilities lack CO2 test capability	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.3406	Define TPS roughness effect on convective heating and BL transition	NASA facilities may lack Reynolds number range to produce turbulent flow, model scale sufficient to resolve surface features	Scheduling and cost in non-NASA facilities	none expected	ability to replicate roughness features at model scale	EDL-01, EDL-09, EDL-12
3.3407	Determine RCS interaction effects on payload heating in CO2 atmosphere	sufficient stagnation temperature to produce sensible aftbody heating. NASA and AEDC facilities lack CO2 test capability	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-06, EDL-07, EDL-12
3.3408	Determine aftbody and payload heating environments in CO2 atmosphere	sufficient stagnation temperature to produce sensible aftbody heating. NASA and AEDC facilities lack CO2 test capability	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-07, EDL-12
3.3409	Determine radiative heating environment in CO2 atmosphere	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-03, EDL-12, Inst-Heat-03, Inst-Heat-04
3.341	Develop rarefied hypersonic aerodynamic performance database	No US facilities can provide rarefied operating conditions	Cost and schedule are likely prohibitive in non-NASA facilities for trade study	none expected	none expected	EDL-10
3.35	ADEPT Drag Modulated Aerocapture Flagship Ice Giant Orbiter/Probe Mission. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.3501	Develop supersonic aerodynamic performance database in H2/He atmosphere	NASA and AEDC facilities lack H2/He test capability	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none expected	none expected	EDL-03, EDL-12
3.3502	Develop supersonic dynamic aero database in H2/He atmosphere	range capability to provide relevant Mach/Re. NASA and AEDC facilities lack H2/He test capability	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	ability to perform dynamic measures	none expected	EDL-03, EDL-11, EDL-12, inst-Aero-02
3.3503	Develop supersonic RCS performance database in H2/He atmosphere	NASA and AEDC facilities lack H2/He test capability	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none expected	none expected	EDL-03, EDL-12, Inst-Aero-03
3.3504	Develop hypersonic aerodynamic performance database in H2/He atmosphere	NASA and AEDC facilities lack H2/He test capability	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-01, EDL-03, EDL-12
3.3505	Determine baseline, smooth-OML aeroshell convective heating in H2/He atmosphere	NSA facilities may lack Reynolds number range to produce turbulent flow. NASA and AEDC facilities lack H2/He test capability	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-03, EDL-12
3.3506	Define TPS roughness effect on convective heating and BL transition in H2/He atmosphere	NASA facilities may lack Reynolds number range to produce turbulent flow, model scale sufficient to resolve surface features. NASA and AEDC facilities lack H2/He test capability	Scheduling and cost in non-NASA facilities	none expected	ability to replicate roughness features at model scale	EDL-01, EDL-03, EDL-09, EDL-12
3.3507	Determine RCS interaction effects on payload heating in H2/He atmosphere	sufficient stagnation temperature to produce sensible aftbody heating. NASA and AEDC facilities lack H2/He test capability	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-03, EDL-07, EDL-08, Inst-Heat-03
3.3508	Determine aftbody and payload heating environments in H2/He atmosphere	sufficient stagnation temperature to produce sensible aftbody heating, NASA and AEDC facilities lack H2/He test capability	Scheduling and cost in non-NASA facilities	Global optical techniques need further development for low-temperature conditions. Models have minimal internal volume for discrete gage wiring	None expected	EDL-03, EDL-07, EDL-12, Inst-Heat-03
3.3509	Determine radiative heating environment in H2/He atmosphere	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-03, EDL-06, EDL-12, Inst-Heat-03, Inst-Heat-04
3.351	Develop rarefied hypersonic aerodynamic performance database	No US facilities can provide rarefied operating conditions	Cost and schedule are likely prohibitive in non-NASA facilities for trade study	none expected	none expected	EDL-10, EDL-12
3.36	Large scale deployable aeroshell for Human rated Mars missions					
3.4	**Advanced Rigid Aeroshell Capsule configurations**					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.41	Geometric scaling of standard MSL / Orion type aeroshells					
3.4101	Develop supersonic aerodynamic performance database	Destination dependent - lack of NASA/AEDC high-enthalpy, non-air test facilities may be gap	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none expected	none expected	EDL-06, EDL-12
3.4102	Develop hypersonic aerodynamic performance database	Destination dependent - lack of NASA/AEDC high-enthalpy, non-air test facilities may be gap	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
3.4103	Develop Hypersonic aeroheating database for Aeroshell smooth OML	NSA facilities may lack Reynolds number range to produce turbulent flow. NASA and AEDC facilities lack high-enthalpy test capability	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.4104	Define TPS roughness effect on convective heating and BL transition in CO2 atmosphere	NASA facilities may lack Reynolds number range to produce turbulent flow, model scale sufficient to resolve surface features. NASA and AEDC facilities	Scheduling and cost in non-NASA facilities	none expected	ability to replicate roughness features at model scale	EDL-01, EDL-02, EDL-09, EDL-12
3.4105	Determine radiative heating database	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, EDL-12, Inst-Heat-03, Inst-Heat-04
3.42	Asymmetric rigid Aeroshell - AFE, ACV optimized shapes, elliptical/hyperboloid cross-section, etc.					
3.4201	Develop supersonic aerodynamic static performance database	Destination dependent - lack of NASA/AEDC high-enthalpy, non-air test facilities may be gap	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none expected	none expected	EDL-06, EDL-12
3.4202	Develop supersonic aerodynamic dynamic performance database	range capability to provide relevant Mach/Re. non-air test facilities may be gap	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	ability to perform dynamic measures	none expected	EDL-06, EDL-11, EDL-12, Inst-Aero-02
3.4203	Develop hypersonic aerodynamic performance database	Destination dependent - lack of NASA/AEDC high-enthalpy, non-air test facilities may be gap	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
3.4204	Develop Hypersonic aeroheating database for Aeroshell smooth OML	NSA facilities may lack Reynolds number range to produce turbulent flow. NASA and AEDC facilities lack high-enthalpy test capability	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.4205	Define TPS roughness effect on convective heating and BL transition in CO2e atmosphere	NASA facilities may lack Reynolds number range to produce turbulent flow, model scale sufficient to resolve surface features. NASA and AEDC facilities	Scheduling and cost in non-NASA facilities	none expected	ability to replicate roughness features at model scale	EDL-01, EDL-02, EDL-09, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.4206	Determine radiative heating database	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Cost and schedule are likely prohibitive in non-NASA facilities for architectural evaluation	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, EDL-12, Inst-Heat-03, Inst-Heat-04
3.43	Aerodynamic Trim Tabs					
3.4301	Develop supersonic aerodynamic static performance database	Destination dependent - lack of NASA/AEDC high-enthalpy, non-air test facilities may be gap	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none expected	none expected	EDL-06, EDL-12
3.4302	Develop supersonic aerodynamic dynamic performance database	range capability to provide relevant Mach/Re. non-air test facilities may be gap	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	ability to perform dynamic measures	none expected	EDL-06, EDL-11, EDL-12, Inst-Aero-02
3.4303	Develop hypersonic aerodynamic performance database	Destination dependent - lack of NASA/AEDC high-enthalpy, non-air test facilities may be gap	Scheduling and cost in non-NASA facilities	none expected	none expected	EDL-02, EDL-12
3.4304	Develop Hypersonic aeroheating database for Aeroshell smooth OML	NSA facilities may lack Reynolds number range to produce turbulent flow. NASA and AEDC facilities lack high-enthalpy test capability	Scheduling and cost in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.4305	Define TPS roughness effect on convective heating and BL transition in CO2 atmosphere	NASA facilities may lack Reynolds number range to produce turbulent flow, model scale sufficient to resolve surface features. NASA and AEDC facilities	Scheduling and cost in non-NASA facilities	none expected	ability to replicate roughness features at model scale	EDL-01, EDL-02, EDL-09, EDL-12
3.4306	Determine radiative heating database	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Scheduling and cost in non-NASA facilities	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-04, EDL-12, Inst-Heat-03, Inst-Heat-04
3.4307	Define control surface supersonic aerodynamic performance	NASA and AEDC facilities do not replicate non-air atmosphere performance	potential for LaRC UPWT closure, cost and schedule in non-NASA facilities	none	none	EDL-06, EDL-12
3.4308	Define hypersonic control surface aerodynamic effectiveness	NASA and AEDC facilities do not replicate high-enthalpy kinetic effects	Scheduling and cost in non-NASA facilities	none	none	EDL-01, EDL-02, EDL-12
3.4309	Define hypersonic control surface aeroheating environments	NASA and AEDC facilities do not replicate high-enthalpy kinetic effects	Scheduling and cost in non-NASA facilities	validation of global optical aeroheating techniques in non-NASA facilities	none expected	EDL-01, EDL-02, EDL-12
3.44	Large scale rigid-TPS aeroshell for Human rated Mars missions utilizing any/all advance options listed under advanced rigid-aeroshell capsule development path					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.5	**Super/Hypersonic Retropropulsion Technology Development and Demonstration**					
3.51	Evaluation of CFD capability for SRP					
3.5101	Obtain surface pressure, flow visualization, and aerodynamic data on SRP system for CFD evaluations	Facility availability and non-continuous operational status; limitation to slightly heated high-pressure air	Test schedules are full for all relevant facilities, up to and including past scheduled end of utilization	Direct F/M measurement now addressed but gaps remain in off-body flow diagnostics to provide quantitative data products for CFD validation	None noted	EDL-08, EDL-12
3.52	RP System ground testing capability development and unit-problem testing					
3.5201	Hot inert gas RP systems testing	No existing integration capability for NASA SSC portable heated ethane cart; integration is possible, just costly	Cost and availability for NASA supersonic wind tunnels with propulsion capability are major challenges	off-body flow diagnostics accommodations are unknown	None noted	EDL-08, EDL-12, Inst-Flow-01
3.5202	Sub-scale engine testing	None noted	None noted	None noted	None noted	EDL-12
3.5203	Flow-through balance development	None noted	None noted	None noted	None noted	EDL-12
3.5204	RP testing in CO2 flow	No NASA facility with CO2 freestream flow capability	Requires cost and schedule challenges associated with testing at CUBRC	None noted	None noted	EDL-06, EDL-12
3.5205	Flow field dynamics validation - unsteady RP/shock/plume interactions	For anything other than high-pressure air as simulant gas, NASA has no present capability (capability can be added to facilities like GRC 10x10)	Facility availability remains a major challenge	off-body flow diagnostics accommodations are unknown	None noted	EDL-08, EDL-12
3.5206	Turbulence model validation for separated unsteady flows with RP/shock interactions	Work best completed in collaboration with universities and their test facilities	Requires reliable grant mechanisms for direct university collaboration	off-body flow diagnostics accommodations are challenging	None noted	EDL-12, Inst-Flow-01
3.5207	Validation of kinetics for RP exhaust interactions with flow field	Hot-fire test capability for supersonic WTs at NASA requires significant integration cost and complexity	Facility availability and cost remain major challenges	Not currently much overlap in diagnostics uses in blow-down and continuous circuit facilities and those used in outdoor propulsion testing	Thermal management with models will be a challenge	EDL-08, EDL-12, Inst-Flow-01
3.5208	Validation data for RP/shock/plume/surface interaction heating	Hot-fire test capability for supersonic WTs at NASA requires significant integration cost and complexity	Facility availability and cost remain major challenges	Not currently much overlap in diagnostics uses in blow-down and continuous circuit facilities and those used in outdoor propulsion testing	Thermal management with models will be a challenge	EDL-08, EDL-12, Inst-Flow-01
3.5209	Validation data for wake flow interactions with RP plumes	May be difficult if not impossible to achieve in ground testing due to model support hardware	Unknown	Unknown	Test article design due to support hardware and plumbing considerations are greater challenges than fabrication	EDL-08, EDL-12

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.53	SRP Architecture Configuration Evaluation for Mars Application	N/A	N/A	N/A	N/A	
3.5301	Task 1					
3.5302	Task 2					
3.54	Earth reentry flight tests and system demonstration					
3.5401	Configuration hypersonic aerodynamics	Current facilities must remain operational	Scheduling becomes a concern as NASA closes facilities	None noted	None noted	EDL-12
3.5402	Configuration supersonic aerodynamics	Current facilities must remain operational	Scheduling becomes a concern as NASA closes facilities	None noted	None noted	EDL-12
3.5403	Retropropulsion aerodynamics & interactions	For anything other than high-pressure air as simulant gas, capability must be added to existing facilities	Facility availability is an increasing concern	Need continued development and demonstration of diagnostics for quantitative off-body flow data	None noted	EDL-08, EDL-12, Inst-Flow-01
3.5404	Configuration aeroheating environments	Freestream conditions are generally too high-speed for SRP operating conditions; Very limited options for propulsion testing in supersonic tunnels	Facility availability is an increasing concern; external facilities are almost inaccessible due to both cost and schedule	Unknown	Thermal management will be a challenge	EDL-08, EDL-12
3.55	Mars reentry flight tests and system demonstration	For anything other than high-pressure air as simulant gas, capability must be added to existing facilities	Supersonic wind tunnel availability is an increasing challenge; external facilities are almost inaccessible due to both cost and schedule	Need continued development and demonstration of diagnostics for quantitative off-body flow data	None noted	
3.6	**Aerocapture**					
3.61	Trade studies on aerocapture options for EDL exploration missions					
3.6101	Develop rarefied hypersonic aerodynamic performance database	No US facilities can provide rarefied operating conditions	Cost and schedule are likely prohibitive in non-NASA facilities for trade study	none expected	none expected	EDL-10
3.6102	Develop continuum hypersonic aerodynamic performance database	Destination dependent - lack of NASA/AEDC high-enthalpy, non-air test facilities may be gap	Cost and schedule are likely prohibitive in non-NASA facilities for trade study	none expected	none expected	EDL2, EDL-12
3.6103	Develop Hypersonic aeroheating database	NSA facilities may lack Reynolds number range to produce turbulent flow. NASA and AEDC facilities lack high-enthalpy test capability	Cost and schedule are likely prohibitive in non-NASA facilities for trade study	none expected	None expected	EDL-01, EDL-02, EDL-12
3.6104	Determine radiative heating database	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Cost and schedule are likely prohibitive in non-NASA facilities for trade study	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-03, EDL-12, Inst-Heat-02, Inst-Heat-03

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.62	Sub-scale Earth flight test for TRL advancement to mission application of aerocapture					
3.6201	Develop rarefied hypersonic aerodynamic performance database	No US facilities can provide rarefied operating conditions	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	none expected	EDL-10
3.6202	Develop continuum hypersonic aerodynamic performance database	Lack of NASA/AEDC high-enthalpy, non-air test facilities may be gap	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	none expected	EDL2, EDL-12
3.6203	Develop Hypersonic aeroheating database	NASA facilities may lack Reynolds number range to produce turbulent flow. NASA and AEDC facilities lack high-enthalpy test capability	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.6204	Define TPS roughness effect on convective heating and BL transition	NASA facilities may lack Reynolds number range to produce turbulent flow, model scale sufficient to resolve surface features. NASA and AEDC facilities	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	ability to replicate roughness features at model scale	EDL-01, EDL-02, EDL-09, EDL-12
3.63	Small planet or satellite Mission (Venus, Titan, Mars, etc.) or Ice Giant (Uranus, Neptune)					
3.6301	Develop rarefied hypersonic aerodynamic performance database	No US facilities can provide rarefied operating conditions	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	none expected	EDL-10
3.6302	Develop continuum hypersonic aerodynamic performance database	Lack of NASA/AEDC high-enthalpy, non-air test facilities	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	none expected	EDL2, EDL-12
3.6303	Develop continuum supersonic aerodynamic performance database	None Expected	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	none expected	EDL-12
3.6304	Develop Hypersonic aeroheating database	NASA facilities may lack Reynolds number range to produce turbulent flow. NASA and AEDC facilities lack high-enthalpy test capability	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	None expected	EDL-01, EDL-02, EDL-12
3.6305	Define TPS roughness effect on convective heating and BL transition	NASA facilities may lack Reynolds number range to produce turbulent flow, model scale sufficient to resolve surface features. NASA and AEDC facilities	Cost and schedule are likely prohibitive in non-NASA facilities	none expected	ability to replicate roughness features at model scale	EDL-01, EDL-02, EDL-09, EDL-12
3.6306	Determine radiative heating database	Ability to produce sufficient enthalpy for radiative emissions at relevant Mach/Re at CUBRC. NASA EAST can only provide fundamental physics data, not vehicle configuration testing	Cost and schedule are likely prohibitive in non-NASA facilities for trade study	Generic heat-flux sensors do not separate radiative components; radiation sensors may not have spectral range to perform measurements	none expected	EDL-03, EDL-12, Inst-Heat-02, Inst-Heat-03

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
3.7	**MHD Control of Flow Field**					
3.71	Fundamental Research on aerodynamic aeroheating and BL transition effects					
3.7101	Evaluate MHD performance to generate large Lorentz Forces for increasing L/D ratios and for steering a spacecraft through its planned entry corridor	NASA and AEDC facilities lack high-enthalpy test capability	ability to generate EM effects	measurement of EM effects	ability to develop, package, operate EM generation equipment	EDL-02, EDL-12, EDL-13
3.7102	Evaluate MHD effects on surface heating and BL transition	NASA facilities may lack Reynolds number range to produce turbulent flow.	ability to generate EM effects	measurement of EM effects	ability to develop, package, operate EM generation equipment	EDL-01, EDL-12, EDL-13

Table 38. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic EDL, Customer: NASA and Partners Technology and Architecture Development.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3	**NASA and Partners EDL Technology and Architecture Development**					
3.1	**Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development and Demonstration**					
3.11	HIAD - LOFTID demonstration mission for TPS performance					
3.1101	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation	Sufficient
3.1102	Develop supersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for dynamic aero measurements. Potential for LaRC UPWT closure	Minimal: dynamic aero properties may not have large influence due to small payload and lack of impingement	Use CFD to obtain supersonic static aerodynamics and legacy data for dynamic properties	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.1103	Determine baseline, smooth-OML aeroshell convective heating	Scheduling and cost in non-NASA facilities	Low. CFD sufficient validated for smooth-OML blunt body heating	Use CFD to define baseline smooth-OML heating, Use non-NASA facilities. Develop higher-Reynolds number NASA facility	CFD capability for baseline (smooth) OML is well developed	Sufficient
3.1104	Determine aeroshell heating augmentation due to flexible TPS scalloping over supporting toroids	non-NASA facilities likely not available for large NASA programs or cost-prohibitive	high - cannot complete all flight test goals without a priori design information for TPS	Use CFD and historical data to design TPS with higher margins. Use non-NASA facilities. Develop higher-Reynolds number NASA facility	Lacking validated/functional models for roughness transition and heating augmentation	sufficient
3.1105	Determine aftbody and payload heating environments	Instrumentation for very low temperature / heating environments not well developed. CFD is unvalidated for these flow fields and carries high margins	High. HIAD vehicles have minimal (or no) TPS on back of aeroshell, so ever low heating environments are a critical issue for flight safety. Use of CFD would include up to 100% margins, which impact mission performance	Test technique development program for low temperature / heating conditions required to support HIAD applications. Develop database for validation of CFD	CFD capability for massively, separated wake flows are unvalidated. RANS may be insufficient, requiring LES/DES	Extremely CPU-intensive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.1106	Determine wake flow-field structure	Practical implementation of flow-field diagnostic techniques in hypersonic tunnels. CFD is unvalidated for these flow fields and carries high margins	High. HIAD vehicles have minimal (or no) TPS on back of aeroshell, so ever low heating environments are a critical issue for flight safety. Use of CFD would include up to 100% margins, which impact mission performance	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	CFD capability for massively, separated wake flows are unvalidated. RANS may be insufficient, requiring LES/DES	Extremely CPU-intensive
3.12	HIAD: ISS down mass					
3.1201	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation	Sufficient
3.1202	Determine hypersonic aerodynamic influence of payload	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Moderate: CFD capability is lacking, but payload effects should be small at hypersonic conditions	Use CFD to estimate payload deltas on aerodynamics	CFD capability to compute massively separated hypersonic wake flows is unvalidated with high uncertainty	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.1203	Develop supersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for dynamic aero measurements. Potential for LaRC UPWT closure	Moderate: dynamic aero properties could have larger influence than for LOFTID because of larger payload with potential for shear layer impingement	Use CFD to obtain supersonic static aerodynamics and legacy data for dynamic properties	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.1204	Define supersonic RCS performance and interactions	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and potential for RCS / flow / surface interactions	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.1205	Determine supersonic aerodynamic influence of payload	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for dynamic aero measurements. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and potential for shear - layer / payload interaction	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	CFD capability to compute unsteady supersonic wake flows is unvalidated with high uncertainty	Dense grids and unsteady flow simulations require extensive CPU time
3.1206	Determine baseline, smooth-OML aeroshell convective heating	Scheduling and cost in non-NASA facilities	Low. CFD sufficient validated for smooth-OML blunt body heating	Use CFD to define baseline smooth-OML heating, Use non-NASA facilities. Develop high-Reynolds number NASA facility	CFD capability for baseline (smooth) OML is well developed	Sufficient
3.1207	Determine aeroshell heating augmentation due to flexible TPS deflections	non-NASA facilities likely not available for large NASA programs or cost-prohibitive	high - cannot complete all flight test goals without design information for TPS	Use CFD and historical data to design TPS with higher margins. Use non-NASA facilities. Develop high-Reynolds number NASA facility	Lacking validated/functional models for roughness transition and heating augmentation	
3.1208	Determine aftbody and payload heating environments	Instrumentation for very low temperature / heating environments not well developed. CFD is unvalidated for these flow fields and carries high margins	High. Protection of payload is primary mission. Use of CFD would include up to 100% margins, which impact mission performance	Test technique development program for low temperature / heating conditions required to support HIAD applications.	CFD capability to compute massively separated hypersonic wake flows is unvalidated with high uncertainty	Extensive CPU/memory capacity required for unsteady aerodynamic simulations

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.13	HIAD: launch vehicle booster recovery					
3.1301	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation	Sufficient
3.1302	Determine hypersonic aerodynamic influence of payload	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Moderate: CFD capability is lacking, but payload effects should be small at hypersonic conditions	Use CFD to estimate payload deltas on aerodynamics	CFD capability to compute massively separated hypersonic wake flows is unvalidated with high uncertainty	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.1303	Develop supersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for dynamic aero measurements. Potential for LaRC UPWT closure	Moderate: dynamic aero properties could have larger influence than for LOFTID because of larger payload with potential for shear layer impingement	Use CFD to obtain supersonic static aerodynamics and legacy data for dynamic properties	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.1304	Define supersonic RCS performance and interactions	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and potential for RCS / flow / surface interactions	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.1305	Determine supersonic aerodynamic influence of payload	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for dynamic aero measurements. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and potential for shear - layer / payload interaction	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	CFD capability to compute unsteady supersonic wake flows is unvalidated with high uncertainty	Dense grids and unsteady flow simulations require extensive CPU time
3.1306	Determine baseline, smooth-OML aeroshell convective heating	Scheduling and cost in non-NASA facilities	Low. CFD sufficient validated for smooth-OML blunt body heating	Use CFD to define baseline smooth-OML heating, Use non-NASA facilities. Develop high-Reynolds number NASA facility	CFD capability for baseline (smooth) OML is well developed	Sufficient
3.1307	Determine aeroshell heating augmentation due to flexible TPS deflections	non-NASA facilities likely not available for large NASA programs or cost-prohibitive	high - cannot complete all flight test goals without design information for TPS	Use CFD and historical data to design TPS with higher margins. Use non-NASA facilities. Develop high-Reynolds number NASA facility	Lacking validated/functional models for roughness transition and heating augmentation	
3.1308	Determine aftbody and payload heating environments	Instrumentation for very low temperature / heating environments not well developed. CFD is unvalidated for these flow fields and carries high margins	High. Protection of payload is primary mission. Use of CFD would include up to 100% margins, which impact mission performance	Test technique development program for low temperature / heating conditions required to support HIAD applications.	CFD capability to compute massively separated hypersonic wake flows is unvalidated with high uncertainty	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.14	Asymmetric aeroshell morphing for aerodynamic control and performance					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.1401	Evaluate supersonic aerodynamic static performance and validate CFD predictions	Scheduling and cost in non-NASA facilities	Minimal: goal is to gather data to develop data for TRL maturation and CFD validation	CFD development & validation using exp. Data	CFD capability validated for smooth, axisymmetric OML validated, asymmetric aeroshell TBD	Sufficient
3.1402	Evaluate hypersonic aerodynamic static performance and validate CFD predictions	Scheduling and cost in non-NASA facilities	Minimal: goal is to gather data to develop data for TRL maturation and CFD validation	CFD development & validation using exp. Data	CFD capability validated for smooth, axisymmetric OML validated, asymmetric aeroshell TBD	Sufficient
3.1403	Configuration specific evaluation of morphed aeroshell heating and BL transition	Scheduling and cost in non-NASA facilities, Reynolds number range of NASA facilities	Minimal: goal is to gather data to develop data for TRL maturation and CFD validation	Development of high-Re NASA facility. CFD development & validation using exp. Data	Lacking validated/functional models for roughness transition and heating augmentation	Sufficient
3.24	HIAD skirt / inflatable tab extension to rigid aeroshell nose cap					
3.2401	Evaluate supersonic aerodynamic static performance and validate CFD predictions	Scheduling and cost in non-NASA facilities	Minimal: goal is to gather data to develop data for TRL maturation and CFD validation	CFD development & validation using exp. Data	CFD capability validated for smooth, axisymmetric OML validated, skirt/tab aeroshell TBD	Sufficient
3.2402	Evaluate hypersonic aerodynamic static performance and validate CFD predictions	Scheduling and cost in non-NASA facilities	Minimal: goal is to gather data to develop data for TRL maturation and CFD validation	CFD development & validation using exp. Data	CFD capability validated for smooth, axisymmetric OML validated, skirt/tab TBD	Sufficient
3.2403	Configuration specific evaluation of skirt/tab aeroshell heating and BL transition	Scheduling and cost in non-NASA facilities, Reynolds number range of NASA facilities	Minimal: goal is to gather data to develop data for TRL maturation and CFD validation	Development of high-Re NASA facility. CFD development & validation using exp. Data	Lacking validated/functional models for roughness transition and heating augmentation	Sufficient
3.15	HIAD: Human Mars Exploration mission					
3.2	**Mid L/D Lifting Body**					
3.21	Mid L/D Lifting-Body Architecture Configuration Evaluation for Mars Application					
3.2101	Parametric evaluation of configuration acreage convective aeroheating and BL transition	Reynolds number range of NASA facilities. Lack of CO2 in NASA and AEDC. Cost & scheduling in non-NASA facilities	Minimal - CFD sufficient for baseline acreage aeroheating for architectural evaluation	Rely on CFD and/or testing in external facilities. Develop NASA high-enthalpy CO2 and high-Reynolds test capabilities	Acceptable for architectural evaluation, but configuration specific validation / verification required for flight missions	Sufficient
3.2102	Parametric evaluation of configuration acreage radiative heating	Cannot test OML in NASA facilities. Radiation sensors may not have spectral range to be useful. Cost & scheduling in non-NASA facilities	Minimal: radiation transport simulations sufficient for architectural evaluation	Rely on radiation transport simulations, extrapolation of any experimental data to flight conditions	Acceptable for architectural evaluation, but configuration specific validation / verification required for flight missions	Sufficient
3.2103	Hypersonic control surface aerodynamic effectiveness	Reynolds number range of NASA facilities and lack of CO2. Cost & scheduling in non-NASA facilities	Minimal: deflected control surface flow fields rely on BL state which is hard to predict with CFD but uncertainties acceptable for architectural studies	Rely on CFD and/or testing in external facilities. Develop NASA high-enthalpy CO2 test capability	High uncertainty margins, but acceptable for architectural evaluation, but configuration specific validation / verification required for flight missions	Sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.2104	Hypersonic control surface aeroheating environments	Reynolds number range of NASA facilities and lack of CO2. Cost & scheduling in non-NASA facilities	Minimal: deflected control surface flow fields rely on BL state which is hard to predict with CFD but uncertainties acceptable for architectural studies	Rely on CFD and/or testing in external facilities. Develop NASA high-enthalpy CO2 and high-Reynolds test capabilities	High uncertainty margins, but acceptable for architectural evaluation, but configuration specific validation / verification required for flight missions	Sufficient
3.2105	Supersonic Control surface effectiveness evaluation	Reynolds number range of NASA facilities and lack of CO2. Cost & scheduling in non-NASA facilities. Potential for LaRC UPWT closure	Minimal: deflected control surface flow fields rely on BL state which is hard to predict with CFD but uncertainties acceptable for architectural studies	Rely on CFD and/or testing in external facilities. Develop NASA high-enthalpy CO2 test capability	High uncertainty margins, but acceptable for architectural evaluation, but configuration specific validation / verification required for flight missions	Sufficient
3.2106	Supersonic Retro-Propulsion performance and interactions	Reynolds number range of NASA facilities and lack of CO2. Cost & scheduling in non-NASA facilities. Potential for LaRC UPWT closure	Moderate: SRP performance is likely a mission requirement	Rely on CFD with high uncertainties and/or testing in external facilities. Develop NASA high-enthalpy CO2 test capability	High uncertainty margins, but acceptable for architectural evaluation, but configuration specific validation / verification required for flight missions	Sufficient
3.22	Evaluation of CFD capability for Mid L/D Aero/Aeroheating prediction for Mars entry					
3.2201	Obtain surface pressure, flow visualization and aerodynamic data on COBRA w/ body flaps for CFD evaluation	Lack of CO2 in NASA and AEDC Facilities. Schedule and cost in non-NASA facilities	TBD depending on CFD validation. Inability to predict control deflection aero would be moderate to major gap	Rely on non-NASA testing, CFD with potentially high uncertainties. Develop NASA high-enthalpy CO2 test capability. Invest in CFD development / validation using flight & WT data	TBD based on testing, but assuming uncertainties are sufficiently high to require this activity	Sufficient
3.2202	Obtain acreage laminar and turbulent convective heating data for CFD evaluation	Lack of CO2 in NASA and AEDC Facilities. Schedule and cost in non-NASA facilities	TBD depending on CFD validation. Unlikely to rise above minimal given success of previous Mars missions	Rely on non-NASA testing, CFD with potentially high uncertainties. Develop NASA high-enthalpy CO2 and high Reynolds test capability. Invest in CFD development / validation using flight & WT data	Expected to be sufficient, but lacking direct validation/verification for specific vehicle architecture	Sufficient
3.2203	Obtain heating data on / around / between / behind control flaps for CFD evaluation	Lack of CO2 in NASA and AEDC Facilities. Schedule and cost in non-NASA facilities. Lack of discrete sensors in NASA facilities	TBD depending on CFD validation. Inability to predict control deflection heating would be moderate to major gap	Rely on non-NASA testing, CFD with potentially high uncertainties. Develop NASA high-enthalpy CO2 and high Reynolds test capability. Invest in CFD development / validation using flight & WT data	TBD based on testing, but assuming uncertainties are sufficiently high to require this activity	Will require dense grids in/around flaps with extensive CPU time
3.2204	Obtain "thrust-off" heating and flow field data on / around SRP installations for CFD evaluation	Lack of CO2 in NASA and AEDC Facilities. Schedule and cost in non-NASA facilities. Lack of discrete sensors in NASA facilities	TBD depending on CFD validation. Minimal to moderate with expectation of localized TPS increase to bound uncertainties	Rely on non-NASA testing, CFD with potentially high uncertainties. Develop NASA CO2 test capability. Invest in CFD development / validation using flight & WT data	TBD based on testing, but assuming uncertainties are sufficiently high to require this activity	Will require dense grids in/around SRP installations with extensive CPU time
3.2205	Obtain data on integrated SRP / vehicle performance for CFD evaluation	Lack of CO2 in NASA and AEDC Facilities. Schedule and cost in non-NASA facilities. Potential for LaRC UPWT closure	TBD depending on CFD validation. Likely moderate to high as CFD is unvalidated/expensive and ground testing does not capture all flight conditions	Rely on non-NASA testing, CFD with potentially high uncertainties. Invest in CFD development / validation using flight & WT data	TBD based on testing, but assuming uncertainties are sufficiently high to require this activity	Will require dense grids to capture SRP/flow field interactions and fully unsteady simulations resulting in huge (massive?) CPU time

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.2206	Obtain data on dynamic aero pitch / sideslip for CFD evaluation	Lack of CO2 in NASA and AEDC Facilities. Schedule and cost in non-NASA facilities. Potential for LaRC UPWT closure	TBD depending on CFD validation. Inability to predict dynamic aero would be moderate to major gap	Rely on non-NASA testing, CFD with potentially high uncertainties. Invest in CFD development / validation using flight & WT data	TBD based on testing, but assuming uncertainties are sufficiently high to require this activity	Sufficient
3.23	Mid L/D Lifting Body - sub-scale flight test for aerodynamics and aeroheating					
3.2301	Develop supersonic static aerodynamic performance database	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Minimal due to lack of CFD validation for specific vehicle	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	CFD as primary source, but would require validation data for human rating	Sufficient
3.2302	Develop supersonic dynamic aero response to pitch and sideslip	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Ability to capture dynamics in all tunnels / sufficient AoA in ranges. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and importance of dynamic aero	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic/separated flow would require extensive validation data. RANS likely insufficient so LES/DES required	Dense grids and unsteady flow simulations require extensive CPU time
3.2303	Define supersonic control surface aerodynamic effectiveness	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation for specific vehicle / control configuration	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in unsteady shock/control interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.2304	Define supersonic RCS performance and interactions	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Minimal due to lack of CFD validation for specific RCS configurations	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.2305	Develop hypersonic aerodynamic database	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities	Minimal due to lack of CFD validation for specific vehicle configuration	Accept higher margins on unvalidated CFD. Develop NASA high-enthalpy capability. Invest in CFD development/validation using flight & WT data	CFD as primary source, but would require validation data for human rating	Sufficient
3.2306	Define hypersonic control surface aerodynamic effectiveness	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities	Minimal due to lack of CFD validation for specific vehicle / control configuration	Accept higher margins on unvalidated CFD. Develop NASA high-enthalpy capability. Invest in CFD development/validation using flight & WT data	High uncertainty margins for CFD in unsteady shock/control interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.2307	Develop hypersonic smooth-OML acreage convective heating	No high-enthalpy air kinetic effects in NASA or AEDC facilities, schedule for non-NASA facilities	Minimal due to lack of CFD validation for specific vehicle configuration	Accept higher margins on unvalidated CFD. Develop NASA high-enthalpy / high Re capability. Invest in CFD development/validation using flight & WT data	CFD as primary source, but would require validation data on kinetic/catalytic effects for human rating	Sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.2308	Define control surface convective heating environments	No high-enthalpy air kinetic effects in NASA or AEDC facilities, schedule for non-NASA facilities	Minimal due to lack of CFD validation for specific vehicle /control configuration	Accept higher margins on unvalidated CFD. Develop NASA high-enthalpy / high Re capability. Invest in CFD development/validation using flight & WT data	CFD as primary source but would require validation data. Disparate scales of external flow and flow between/under flaps may require DSMC	Dense grids and unsteady flow simulations required extensive CPU time
3.2309	Define RCS jet/surface interaction effects on heating	No high-enthalpy air kinetic effects in NASA or AEDC facilities, schedule for non-NASA facilities	Minimal due to lack of CFD validation for specific RCS configurations	Accept higher margins on unvalidated CFD. Develop NASA high-enthalpy capability. Invest in CFD development/validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS jet/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.24	Mid L/D Lifting Body - sub-scale flight test for SRP performance					
3.2401	Develop supersonic static aerodynamic performance database	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Minimal due to lack of CFD validation for specific vehicle	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	CFD as primary source, but would require validation data for human rating	Sufficient
3.2402	Develop supersonic dynamic aero response to pitch and sideslip	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Ability to capture dynamics in all tunnels / sufficient AoA in ranges. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and importance of dynamic aero	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic/separated flow would require extensive validation data. RANS likely insufficient so LES/DES required	Dense grids and unsteady flow simulations require extensive CPU time
3.2403	Define supersonic control surface aerodynamic effectiveness	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation for specific vehicle / control configuration	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in unsteady shock/control interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.2404	Define supersonic RCS performance and interactions	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	Minimal due to lack of CFD validation for specific RCS configurations	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.25	Mid L/D Lifting Body - full-scale Mars flight test and/or missions					
3.3	**Deployable Aerodynamic Decelerator Technology Development and Demonstration**					
3.31	SNC Deployable					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.3101	Preliminary evaluation of hypersonic aerodynamic performance	None expected	None expected	N/A	Expected to be sufficient for preliminary evaluations, but lacking direct validation for flight operations	Sufficient
3.3102	Preliminary evaluation of aeroheating effects on aeroshell	None expected	None expected	N/A	TBD based on results - asymmetric panel geometries present heating and BL transition challenges	Sufficient
3.3103	Detailed supersonic aerodynamic performance for flight mission	No technical gaps, access to AEDC for commercial mission is unlikely	None expected	N/A	Asymmetric geometry with embedded control surface will be required extensive CFD validations	Sufficient
3.3104	Detailed hypersonic aerodynamic performance for flight mission	No technical gaps, access to AEDC for commercial mission is unlikely	None expected	N/A	Asymmetric geometry with embedded control surface will be required extensive CFD validations	Sufficient
3.3105	Detailed aeroshell aeroheating for flight mission	Potential issues with Reynolds number ranges	TBD - minimal to moderate?	TBD	Asymmetric geometry with embedded control surface will be required extensive CFD validations	Sufficient
3.32	Pterodactyl Control Systems for DEVs Sample Return					
3.3201	Develop supersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Potential for LaRC UPWT closure	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation	Sufficient
3.3202	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Potential for LaRC UPWT closure	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation	Sufficient
3.3203	Determine baseline, smooth-OML aeroshell convective heating	Non-NASA facility may not be available/affordable within project scope. Potential for LaRC UPWT closure	Low. CFD sufficiently validated for smooth-OML blunt body heating	Use CFD to define baseline smooth-OML heating	CFD capability for baseline (smooth) OML is well developed	Sufficient
3.3204	Determine aftbody and payload heating environments	Instrumentation for very low temperature / heating environments not well developed. CFD is unvalidated for these flow fields and carries high margins. Non-NASA facility may not be available/affordable within project scope.	Low - this is a concept evaluation	Test technique development program for low temperature / heating conditions required to support wake flow applications.	CFD capability for massively, separated wake flows are unvalidated	Extremely CPU/memory-intensive
3.33	ADEPT Drag Modulated Aerocapture Demonstration (Earth GTO). ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.3301	Develop supersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. Potential for LaRC UPWT closure	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation for non-asymmetric shapes	Sufficient
3.3302	Develop supersonic dynamic aero database	Non-NASA facility may not be available/affordable within project scope. Potential for LaRC UPWT closure. Ranges may not meet operational conditions	Moderate due to lack of CFD validation and importance of dynamic aero	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.3303	Develop supersonic RCS performance database	Non-NASA facility may not be available/affordable within project scope. Potential for LaRC UPWT closure	Moderate due to lack of CFD validation and importance of RCS attitude control	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.3304	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope.	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation for non-asymmetric shapes	Sufficient
3.3305	Determine baseline, smooth-OML aeroshell convective heating	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body smooth-surface aeroheating	Use CFD to define baseline smooth-OML heating. Use non-NASA facilities. Invest in NASA high-Reynolds test capability	Expected to be sufficient, but lacking direct validation for non-asymmetric shapes	Sufficient
3.3306	Define TPS roughness effect on convective heating and BL transition	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence	Moderate due to lack of CFD capability, but effects should be small	Accept higher margins on unvalidated CFD. Develop NASA high Re capability. Invest in CFD development/validation using flight & WT data	Lacking validated/functional models for roughness transition and heating augmentation	unknown
3.3307	Determine RCS interaction effects on payload heating	Non-NASA facility may not be available/affordable within project scope. All facilities challenged to measure low heating levels on aftbody	Moderate due to lack of CFD capability and importance of RCS interaction effects on payload heating	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.3308	Determine aftbody and payload heating environments	Non-NASA facility may not be available/affordable within project scope. All facilities challenged to measure low heating levels on aftbody	Moderate due to lack of CFD capability and importance for wake flows	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	CFD capability for massively, separated wake flows are unvalidated and carry high uncertainty	Extremely CPU/memory-intensive
3.34	ADEPT Drag Modulated Aerocapture SmallSat Venus/Mars Orbiter. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.3401	Develop supersonic aerodynamic performance database in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack CO2 test capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation for non-asymmetric shapes	Sufficient
3.3402	Develop supersonic dynamic aero database in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. Ranges may not meet operational conditions. NASA and AEDC facilities lack CO2 test capability	Moderate due to lack of CFD validation and importance of dynamic aero	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.3403	Develop supersonic RCS performance database in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack CO2 test capability	Moderate due to lack of CFD validation and importance of RCS attitude control	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.3404	Develop hypersonic aerodynamic performance database in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. NASA and AEDC facilities lack CO2 test capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for blunt bodies	Expected to be sufficient, but lacking direct validation for non-asymmetric shapes	Sufficient
3.3405	Determine baseline, smooth-OML aeroshell convective heating in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack CO2 test capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body smooth-surface aeroheating	Use CFD to define baseline smooth-OML heating. Use non-NASA facilities. Invest in NASA high-Reynolds test capability	Expected to be sufficient, but lacking direct validation for non-asymmetric shapes	Sufficient
3.3406	Define TPS roughness effect on convective heating and BL transition	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence	Moderate due to lack of CFD capability, but effects should be small	Accept higher margins on unvalidated CFD. Develop NASA high Re capability. Invest in CFD development/validation using flight & WT data	Lacking validated/functional models for roughness transition and heating augmentation	unknown
3.3407	Determine RCS interaction effects on payload heating in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. All facilities challenged to measure low heating levels on aftbody. NASA and AEDC facilities lack CO2 test capability	Moderate due to lack of CFD capability and importance of RCS interaction effects on payload heating	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.3408	Determine aftbody and payload heating environments in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. All facilities challenged to measure low heating levels on aftbody. NASA and AEDC facilities lack CO2 test capability	Moderate due to lack of CFD capability and importance for wake flows	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	CFD capability for massively, separated wake flows are unvalidated and carry high uncertainty	Extremely CPU/memory-intensive
3.3409	Determine radiative heating environment in CO2 atmosphere	Cannot test OML in NASA facilities. Radiation sensors may not have spectral range to be useful. Cost & scheduling in non-NASA facilities	Minimal: can likely overdesign TPS to accommodate uncertainties for robotic mission	Rely on radiation transport simulations, extrapolation of any experimental data to flight conditions	TBD - aerocapture radiative properties may differ from standard EDL profile	Sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.341	Develop rarefied hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. No US facilities can provide rarefied operating conditions	Minimal for trade study level	Use rarefied CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA rarefied test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.35	ADEPT Drag Modulated Aerocapture Flagship Ice Giant Orbiter/Probe Mission. ADEPT is a mechanically deployed hypersonic decelerator with 3d woven carbon fabric supported by rib/struts					
3.3501	Develop supersonic aerodynamic performance database in H2/He atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack H2/He test capability	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body supersonic aerodynamics. However, H2/He atmosphere has little heritage/validation	Use CFD to obtain supersonic static aerodynamics for blunt bodies	Lacking direct validation for non-asymmetric shapes. No validation data / little development work for H2/He atmospheres	Sufficient
3.3502	Develop supersonic dynamic aero database in H2/He atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. Ranges may not meet operational conditions. NASA and AEDC facilities lack H2/He test capability	Moderate due to lack of CFD validation and importance of dynamic aero. H2/He atmosphere has little heritage/validation	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects. No validation data / little development work for H2/He atmospheres	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.3503	Develop supersonic RCS performance database in H2/He atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack H2/He test capability	Moderate due to lack of CFD validation and importance of RCS attitude control. H2/He atmosphere has little heritage/validation	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required. No validation data / little development work for H2/He atmospheres	Dense grids and unsteady flow simulations require extensive CPU time
3.3504	Develop hypersonic aerodynamic performance database in H2/He atmosphere	Non-NASA facility may not be available/affordable within project scope. NASA and AEDC facilities lack H2/He test capability	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body hypersonic aerodynamics. However, H2/He atmosphere has little heritage/validation	Use CFD to obtain hypersonic static aerodynamics for blunt bodies. Invest in high-enthalpy H2/He test capability	Lacking direct validation for non-asymmetric shapes. No validation data / little development work for H2/He atmospheres	Sufficient
3.3505	Determine baseline, smooth-OML aeroshell convective heating in H2/He atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack H2/He test capability	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for blunt body smooth-surface aeroheating. However, H2/He atmosphere has little heritage/validation	Use CFD to define baseline smooth-OML heating. Use non-NASA facilities. Invest in high-enthalpy H2/He test capability and high-Reynolds capability	Lacking direct validation for non-asymmetric shapes. No validation data / little development work for H2/He atmospheres	Sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.3506	Define TPS roughness effect on convective heating and BL transition in H2/He atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack H2/He test capability	Moderate due to lack of CFD capability. H2/He atmosphere has little heritage/validation	Accept higher margins on unvalidated CFD. Invest in CFD development/validation using flight & WT data. Invest in high-enthalpy H2/He test capability and high-Reynolds capability	Lacking validated/functional models for roughness transition and heating augmentation. No validation data / little development work for H2/He atmospheres	unknown
3.3507	Determine RCS interaction effects on payload heating in H2/He atmosphere	Non-NASA facility may not be available/affordable within project scope. All facilities challenged to measure low heating levels on aftbody. NASA and AEDC facilities lack H2/He test capability	Moderate due to lack of CFD capability and importance of RCS interaction effects on payload heating. H2/He atmosphere has little heritage/validation	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in dynamic RCS plume/flow/surface interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required. No validation data / little development work for H2/He atmospheres	Dense grids and unsteady flow simulations require extensive CPU time
3.3508	Determine aftbody and payload heating environments in H2/He atmosphere	Non-NASA facility may not be available/affordable within project scope. All facilities challenged to measure low heating levels on aftbody. NASA and AEDC facilities lack H2/He test capability	Moderate due to lack of CFD capability and importance for wake flows. H2/He atmosphere has little heritage/validation	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data. Invest in high-enthalpy H2/He test capability and high-Reynolds capability	CFD capability for massively, separated wake flows are unvalidated and carry high uncertainty. No validation data / little development work for H2/He atmospheres	Extremely CPU/memory-intensive
3.3509	Determine radiative heating environment in H2/He atmosphere	Cannot test OML in NASA facilities. Radiation sensors may not have spectral range to be useful. Cost & scheduling in non-NASA facilities	Moderate: H2/He atmosphere has little heritage/validation	Rely on radiation transport simulations, extrapolation of any experimental data to flight conditions	Probably very little data available for H2/He atmospheres	Sufficient
3.351	Develop rarefied hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. No US facilities can provide rarefied operating conditions	Minimal for trade study level	Use rarefied CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA rarefied test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.36	Large scale deployable aeroshell for Human rated Mars missions					
3.4	**Advanced Rigid Aeroshell Capsule configurations**					
3.41	Geometric scaling of standard MSL / Orion type aeroshells					
3.4101	Develop supersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack high-enthalpy test capability	Minimal: at trade study level, CFD can rely on heritage from smaller-scale vehicle analyses	Use CFD to obtain supersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.4102	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack high-enthalpy test capability	Minimal: at trade study level, CFD can rely on heritage from smaller-scale vehicle analyses	Use CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.4103	Develop Hypersonic aeroheating database for Aeroshell smooth OML	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack high-enthalpy test capability	Minimal: at trade study level, CFD can rely on heritage from smaller-scale vehicle analyses	Use CFD to define baseline smooth-OML heating. Develop NASA high-Re and high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.4104	Define TPS roughness effect on convective heating and BL transition in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence.	Minimal: at trade study level, CFD can rely on heritage from smaller-scale vehicle analyses	Use heritage data to define roughness effects. Develop NASA high-Re and high-enthalpy test capability	Lacking validated/functional models for roughness transition and heating augmentation.	unknown
3.4105	Determine radiative heating database	Cannot test OML in NASA facilities. Radiation sensors may not have spectral range to be useful. Cost & scheduling in non-NASA facilities	Minimal: at trade study level, CFD can rely on heritage from smaller-scale vehicle analyses	Rely on radiation transport simulations, extrapolation of any experimental data to flight conditions	destination/trajectory/scale dependent	Sufficient
3.42	Asymmetric rigid Aeroshell - AFE, ACV optimized shapes, elliptical/hyperboloid cross-section, etc.					
3.4201	Develop supersonic aerodynamic static performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack high-enthalpy test capability	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Use CFD to obtain supersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.4202	Develop supersonic aerodynamic dynamic performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. Ranges may not meet operational conditions. NASA and AEDC facilities lack H2/He test capability	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.4203	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack high-enthalpy test capability	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Use CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.4204	Develop Hypersonic aeroheating database for Aeroshell smooth OML	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack high-enthalpy test capability	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Use CFD to define baseline smooth-OML heating. Develop NASA high-Re and high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.4205	Define TPS roughness effect on convective heating and BL transition in CO2e atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence.	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Use heritage data to define roughness effects. Develop NASA high-Re and high-enthalpy test capability	Lacking validated/functional models for roughness transition and heating augmentation.	unknown
3.4206	Determine radiative heating database	Cannot test OML in NASA facilities. Radiation sensors may not have spectral range to be useful. Cost & scheduling in non-NASA facilities	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Rely on radiation transport simulations, extrapolation of any experimental data to flight conditions	destination/trajectory/scale dependent	Sufficient
3.43	Aerodynamic Trim Tabs					
3.4301	Develop supersonic aerodynamic static performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack high-enthalpy test capability	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Use CFD to obtain supersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.4302	Develop supersonic aerodynamic dynamic performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. Ranges may not meet operational conditions. NASA and AEDC facilities lack H2/He test capability	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty- requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations
3.4303	Develop hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack high-enthalpy test capability	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Use CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.4304	Develop Hypersonic aeroheating database for Aeroshell smooth OML	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack high-enthalpy test capability	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Use CFD to define baseline smooth-OML heating. Develop NASA high-Re and high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.4305	Define TPS roughness effect on convective heating and BL transition in CO2 atmosphere	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence.	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Use heritage data to define roughness effects. Develop NASA high-Re and high-enthalpy test capability	Lacking validated/functional models for roughness transition and heating augmentation.	unknown
3.4306	Determine radiative heating database	Cannot test OML in NASA facilities. Radiation sensors may not have spectral range to be useful. Cost & scheduling in non-NASA facilities	Moderate: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes	Rely on radiation transport simulations, extrapolation of any experimental data to flight conditions	destination/trajectory/scale dependent	Sufficient

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.4307	Define control surface supersonic aerodynamic performance	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities. Potential for LaRC UPWT closure	High: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes or for aerodynamic trim-tabs	Accept higher margins on unvalidated CFD. Invest in CFD development / validation using flight & WT data	High uncertainty margins for CFD in unsteady shock/control interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.4308	Define hypersonic control surface aerodynamic effectiveness	No high-enthalpy air compressibility effects in NASA or AEDC facilities, schedule for non-NASA facilities	High: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes or for aerodynamic trim-tabs	Accept higher margins on unvalidated CFD. Develop NASA high-enthalpy capability. Invest in CFD development/validation using flight & WT data	High uncertainty margins for CFD in unsteady shock/control interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.4309	Define hypersonic control surface aeroheating environments	Reynolds number range of NASA and AEDC facilities and lack of high-enthalpy. Cost & scheduling in non-NASA facilities	High: even for trade-study / TRL advancement, there is minimal heritage/analyses for asymmetric shapes or for aerodynamic trim-tabs	Accept higher margins on unvalidated CFD. Develop NASA high-enthalpy capability. Invest in CFD development/validation using flight & WT data	High uncertainty margins for CFD in unsteady shock/control interactions would require extensive validation data. RANS may be insufficient so LES/DES may be required	Dense grids and unsteady flow simulations require extensive CPU time
3.44	Large scale rigid-TPS aeroshell for Human rated Mars missions utilizing any/all advance options listed under advanced rigid-aeroshell capsule development path					
3.5	**Super/Hypersonic Retropropulsion Technology Development and Demonstration**					
3.51	Evaluation of CFD capability for SRP					
3.5101	Obtain surface pressure, flow visualization, and aerodynamic data on SRP system for CFD evaluations	Cost & scheduling in non-NASA facilities, limitations on SRP test capabilities	High: even for trade-study / TRL advancement, there is minimal validation for flight-like configurations, scales, and environments		Some codes validated against 2010/2011 subscale, air WT data; Capability increases substantially with completion of 2022 AETC efforts and will benchmark subscale, inert-gas CFD for multiple-nozzle configurations	Computational cost is a limiting factor for all codes, and all codes in AETC effort report long queue times and challenges with availability of computing resources
3.52	RP System ground testing capability development and unit-problem testing					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.5201	Hot inert gas RP systems testing	Cost & scheduling in non-NASA facilities, limitations on SRP test capabilities	High: Simulations indicate significant afterburning for SRP, external to the nozzles, complicating aerothermal environments and reduced-fidelity computational simulation accuracy		Unvalidated for anything but inert gas WT case. CFD cost/CPU is challenging. May be OK for trades	Computational cost increases with multiple fluid composition; long queue times and challenges with computing resource availability remain an issue
3.5202	Sub-scale engine testing	Cost & scheduling in non-NASA facilities,	Moderate: Any propulsion system should conduct sea-level risk reduction testing before integration into a ground test facility to characterize performance and reduce risk to the facility		CFD capability exists with LociCHEM and FUN3D to simulate hot-fire propulsion systems	Existing capabilities are tractable from a computing resource standpoint
3.5203	Flow-through balance development	Cost & scheduling in non-NASA facilities,	Low: Largely addressed for inert-gas testing. No solution at present for hot-fire testing.		CFD capability exists and has been applied in design of the internal flow path of the new 6-component flow-through balance for SRP	N/A
3.5204	RP testing in CO2 flow	Cost & scheduling in non-NASA facilities, lack of NASA supersonic CO2 capability	Moderate: Due to the large variation in CO2 thermodynamic properties, even at low temperatures (200K - 1000K), certain operating conditions will be more difficult to consistently predict and may result in large flow structure transitions in flight.		No validation data exist; best practices have been applied in exploratory flight-scale CO2 analyses; FUN3D utilizes CO2 data and models from LAURA	As the number of chemical species increases, the computational cost increases substantially, challenging throughout and fidelity of CFD solutions
3.5205	Flow field dynamics validation - unsteady RP/shock/plume interactions	Cost & scheduling in non-NASA facilities, limitations on SRP test capabilities. Lack of flow field diagnostics	High: Mission applications have substantial aerodynamic surface area over which unsteady flow field dynamics resolve, with simulations indicating low-frequency dynamics at flight-scales.		Unvalidated for anything but inert gas WT case with very limited multiple-nozzle configuration. CFD capability will be benchmarked with completion of the 2022 AETC SRP effort	Configuration complexity and moving beyond subscale, inert gas WT testing generally leads to near-prohibitive computational costs. Databases are feasible with lower-fidelity methods
3.5206	Turbulence model validation for separated unsteady flows with RP/shock interactions	Cost & scheduling in non-NASA facilities, limitations on SRP test capabilities, lack of flow field diagnostics	Moderate: Turbulence modeling continues to be a driver for large differences in code-to-code comparisons and consistent prediction of SRP aero interference across the design space.		RANS is not generally appropriate, so need validation data for DES and eventually LES. Completely unvalidated except for cold air gas firings	Increasing computational fidelity increases computing costs, but unit problem validation is likely feasible with current capacity
3.5207	Validation of kinetics for RP exhaust interactions with flow field	Cost & scheduling in non-NASA facilities, lack of NASA supersonic CO2 capability	Moderate: Largely unknown how far off current mechanisms in use are, but most mechanisms do not account for substantial high-temperature mixing with CO2 from the atmosphere.		Lacks validation data, but FUN3D and LociCHEM have the ability to model kinetics with success on large-scale plume interference problems with similar physics	Computing costs with finite-rate chemistry for accurate aerothermal evaluations are approaching prohibitive with NASA resources. Solutions without chemistry are expensive, but tractable
3.5208	Validation data for RP/shock/plume/surface interaction heating	Cost & scheduling in non-NASA facilities, lack of NASA supersonic CO2 capability	High: No significant knowledge or relevant data exist on aerothermal effects, but LV base heating and re-usable LV testing indicate localized aerothermal effects can be non-negligible.		Lacking validation data, unsteady effects not suited for RANS, high CPU cost. Big unknowns	Computing costs with finite-rate chemistry for accurate aerothermal evaluations are approaching prohibitive with NASA resources. Solutions without chemistry are expensive, but tractable

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.5209	Validation data for wake flow interactions with RP plumes	Cost & scheduling in non-NASA facilities, lack of NASA supersonic CO2 capability	Moderate: The assumption is that the entry environments will be most severe for the payloads due to wake heating, but this remains a major unknown with the vehicle largely flying through engine exhaust, not atmosphere.		Unsteady wake effects not suitable with RANS approaches. Multiple codes have demonstrated success in modeling separated wake flows. No validation data presently exist.	For grids that must capture both RP interference and separated wake flows, computational cost becomes a concern.
3.53	SRP Architecture Configuration Evaluation for Mars Application		Moderate: Large uncertainties remain, but it is clear that RP configuration plays a major role in predictive accuracy and vehicle performance effects.		Multiple NASA tools have been applied to subscale and flight-scale parametric studies, but there is no validation data, and large code-to-code differences are observed	Unless done with RANS and highly simplified, parametric studies of flight configurations are not practical, due to computational cost and present fidelity characterization
3.5301	Task 1					
3.5302	Task 2					
3.54	Earth reentry flight tests and system demonstration					
3.5401	Configuration hypersonic aerodynamics	Cost & scheduling in non-NASA facilities	Low: Capability to predict hypersonic aerodynamics without RP exists.		Should be sufficient, might need configuration specific validation	ok
3.5402	Configuration supersonic aerodynamics	Cost & scheduling in non-NASA facilities	Low: Capability to predict supersonic aerodynamics without RP exists.		Should be sufficient, might need configuration specific validation	ok
3.5403	Retropropulsion aerodynamics & interactions	Cost & scheduling in non-NASA facilities, limitations on SRP test capabilities. Lack of flow field diagnostics	High: Flight test required to validate free-flight effects arising from RP interference and integrated aerodynamics.		Unvalidated for anything beyond subscale and inert-gas, with very limited validation for multiple nozzle configurations	Expensive, but simplifying assumptions (unknown if many current assumptions are acceptable) permit coarse database development with significant computing resources and priority
3.5404	Configuration aeroheating environments	Cost & scheduling in non-NASA facilities, limitations on SRP test capabilities.	High: Aerothermal environments arising from powered flight with significant aerodynamic surface area remains a major unknown. Effects may be negligible or minor, but they are, at present, completely unknown.		No validation data for aerothermal effects during powered descent; unclear if recent advancements with unstructured solvers will yield reliable aerothermal environments	Aerothermal environments require finite-rate chemistry. If coupled with non-RANS CFD methods, only FUN3D currently has computing capability for GPUs to permit some reasonable expectation of a minimum required solution set
3.55	Mars reentry flight tests and system demonstration		Moderate: Moderate if the above gaps are addressed to mature and validate predictive capabilities and relevant validation data products are obtained, across physical scale and configuration and system complexity.		No validation beyond subscale, inert gas, basic configurations, but capabilities at varying fidelity are advancing and will eventually support database and model development with multiple tools and varying fidelity approaches	Flight database development may require computing resources and computing hardware beyond what NASA presently has, as many other important programs and project all share these resources
3.6	**Aerocapture**					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.61	Trade studies on aerocapture options for EDL exploration missions					
3.6101	Develop rarefied hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. No US facilities can provide rarefied operating conditions	Minimal for trade study level	Use rarefied CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA rarefied test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.6102	Develop continuum hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack high-enthalpy test capability	Minimal for trade study level	Use CFD to obtain hypersonic continuum aerodynamics. Develop NASA high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.6103	Develop Hypersonic aeroheating database	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack high-enthalpy test capability	Minimal for trade study level	Use CFD to define baseline convective heating. Develop NASA high-Re and high-enthalpy test capability	Destination dependent - CFD may be lacking validation data	Sufficient
3.6104	Determine radiative heating database	Cannot test full OML in NASA EAST. Radiation sensors may not have spectral range to be useful. Cost & scheduling in non-NASA facilities	Minimal for trade study level	Rely on radiation transport simulations, extrapolation of any experimental data to flight conditions	destination/trajectory/scale dependent	Sufficient
3.62	Sub-scale Earth flight test for TRL advancement to mission application of aerocapture					
3.6201	Develop rarefied hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. No US facilities can provide rarefied operating conditions	Dependent on mission architecture - moderate	Use rarefied CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA rarefied test capability	Highly architecture dependent - CFD may be lacking validation data for configuration/trajectory	unknown
3.6202	Develop continuum hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. NASA and AEDC facilities lack high-enthalpy test capability	Dependent on mission architecture - moderate	Use CFD to obtain hypersonic continuum aerodynamics. Develop NASA high-enthalpy test capability	Highly architecture dependent - CFD may be lacking validation data for configuration/trajectory	unknown
3.6203	Develop Hypersonic aeroheating database	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack high-enthalpy test capability	Dependent on mission architecture - moderate	Use CFD to define baseline convective heating. Develop NASA high-Re and high-enthalpy test capability	Highly architecture dependent - CFD may be lacking validation data for configuration/trajectory	unknown
3.6204	Define TPS roughness effect on convective heating and BL transition	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence.	Dependent on mission architecture - moderate	Use heritage data to define roughness effects. Develop NASA high-Re and high-enthalpy test capability	Highly architecture dependent - CFD may be lacking validation data for configuration/trajectory	unknown

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.63	Small planet or satellite Mission (Venus, Titan, Mars, etc.) or Ice Giant (Uranus, Neptune)					
3.6301	Develop rarefied hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. No US facilities can provide rarefied operating conditions	Dependent on mission architecture - moderate	Use rarefied CFD to obtain hypersonic static aerodynamics for blunt bodies. Develop NASA rarefied test capability	Highly architecture dependent - CFD may be lacking validation data for configuration/trajectory	sufficient
3.6302	Develop continuum hypersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. NASA and AEDC facilities lack high-enthalpy test capability	Dependent on mission architecture - moderate	Use CFD to obtain hypersonic continuum aerodynamics. Develop NASA high-enthalpy test capability	Highly architecture dependent - CFD may be lacking validation data for configuration/trajectory	sufficient
3.6303	Develop continuum supersonic aerodynamic performance database	Non-NASA facility may not be available/affordable within project scope. LARC UPWT subject to potential closure. NASA and AEDC facilities lack high-enthalpy test capability	Dependent on mission architecture - moderate	Use CFD to obtain supersonic continuum aerodynamics.	Highly architecture dependent - CFD may be lacking validation data for configuration/trajectory	sufficient
3.6304	Develop Hypersonic aeroheating database	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence. NASA and AEDC facilities lack high-enthalpy test capability	Dependent on mission architecture - moderate	Use CFD to define baseline convective heating. Develop NASA high-Re and high-enthalpy test capability	Highly architecture dependent - CFD may be lacking validation data for configuration/trajectory	sufficient
3.6305	Define TPS roughness effect on convective heating and BL transition	Non-NASA facility may not be available/affordable within project scope. LARC hypersonic tunnels may lack Reynolds number range for turbulence.	Dependent on mission architecture - moderate	Use heritage data to define roughness effects. Develop NASA high-Re and high-enthalpy test capability	Lacking validated/functional models for roughness transition and heating augmentation.	sufficient
3.6306	Determine radiative heating database	Cannot test OML in NASA facilities. Radiation sensors may not have spectral range to be useful. Cost & scheduling in non-NASA facilities	Minimal for trade study level	Rely on radiation transport simulations, extrapolation of any experimental data to flight conditions	destination/trajectory/scale dependent	sufficient
3.7	**MHD Control of Flow Field**					
3.71	Fundamental Research on aerodynamic aeroheating and BL transition effects					
3.7101	Evaluate MHD performance to generate large Lorentz Forces for increasing L/D ratios and for steering a spacecraft through its planned entry corridor	Facility with MHD testing capability at relevant conditions, fabrication of models with EM generation, instrumentation to measure EM effects	TBD - must first develop computational and experimental analysis methods to define usefulness of MHD control	Intensive experimental and computational development program	Multi-physics tools with MHD capabilities under development in Academia	Multi-physics tools with MHD capabilities under development in Academia

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
3.7102	Evaluate MHD effects on surface heating and BL transition	Facility with MHD testing capability at relevant conditions, fabrication of models with EM generation, instrumentation to measure EM effects	TBD - must first develop computational and experimental analysis methods to define usefulness of MHD control	Intensive experimental and computational development program	Multi-physics tools with MHD capabilities under development in Academia	Multi-physics tools with MHD capabilities under development in Academia

Appendix F Database for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development

Table 39. Programs List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development.

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
Hypersonic Atmospheric Flight and Access-to-Space	**4**	**NASA Hypersonic Atmospheric Flight Technology Development**	**NASA led development of hypersonic flight systems for civilian applications**		**NASA policy statements and Administration directives; independent advisory groups (e.g. National Academy of Sciences)**	
	4.1	**Vehicle Architecture**	**vehicle concept trades, analysis, development**	**TBD based on future NASA goals**		
	4.11	Airbreathing Sub-scale Demonstration Vehicle (e.g. Aether-derived), but a technology/point design concept	Design and testing of one or more technology demonstration vehicles. Mission requirements are based on the technologies to be demonstrated.	Assumed to be like a Hyper-X follow on program with vertical and horizontal control surfaces	NASA AAVP/HTP goals	
	4.12	Point-2-Point Vehicle (cruise - sustained hypersonic flight - air breathing) - no space access	Design and testing of one or more demonstration vehicles that will fly point-to-point. Payload and range are determined by project design requirements.	Requirements as per 4.11	NASA AAVP/HTP goals.	
	4.13	Air-breathing Access-to-space vehicle	Design and testing of one or more demonstration vehicles using hypersonic air-breathing propulsion for access to space (low earth orbit). Payload and orbit to be determined by project design requirements. Could be single or multi-stage to orbit, TBCC or RBCC (or a combination).	Requirements as per 4.11	NASA AAVP/HTP goals.	
	4.14	Rocket-Based Access to Space	Design and testing of one or more demonstration vehicles using rocket-based propulsion for access to space. Payload and orbit to be determined by project design requirements. Could be single or multi-stage to orbit.	Requirements as per 4.11, without airbreathing requirements	NASA STMD/HEO goals.	
	4.2	**System Components**	**Focus on components of overall hypersonic airbreathing propulsions system**	Targeted test objective to advance knowledge in specific areas		

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	4.21	Forebody/Inlet/isolator performance and operability	Determine performance metrics and operability bounds for a vehicle forebody/inlet/isolator with a back-pressure plug to simulate the combustion pressure rise.	Pattern after 4.11 Inlet characterization test requirements	NASA AAVP/HTP goals.	
	4.22	Engine exhaust interactions with vehicle aft-body and control surfaces.	Determine performance metrics and operability bounds for the aft portion of a hypersonic vehicle. Evaluate the interaction of the engine exhaust plume with the external aerodynamics and the effects on control surfaces.	Pattern after 4.11 Plume/exhaust characterization test requirements	NASA AAVP/HTP goals.	
	4.3	**Fundamental Hypersonics Research**	**Experimentally investigate hypersonic flow phenomena (natural and forced boundary layer transition, shock/boundary layer interactions, shock/shock interactions, etc.).**	**Focus on unit problem investigation of hypersonic flow phenomena**	**NASA AAVP/HTP goals.**	
	4.31	Hypersonic Boundary Layer Characterization and/or control				
	4.32	Supersonic Boundary Layer Characterization and/or control		Need for detailed roadmap/test plan here		
	4.33	Hypersonic, Perfect Gas Shock Interactions				
	4.34	Hypersonic, Non-equilibrium Shock Interactions				
	4.35	Fluid Structure Interactions and Deformations				
	4.36	RCS Jet Interactions	Determine interactions between reaction control system jet plumes and local flow field on a hypersonic vehicle.			

Table 40. Database Objectives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development.

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4	**NASA Hypersonic Atmospheric Flight Technology Development**							
4.1	**Vehicle Architecture**							
4.11	Airbreathing Sub-scale Demonstration Vehicle (e.g. Aether-derived), but a technology/point design concept							
4.1101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
4.1102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
4.1103	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1104	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.1105	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1106	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
4.1107	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1108	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.1109	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	(1) Hypersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
4.1110	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
4.1111	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
4.12	Point-2-Point Vehicle (cruise - sustained hypersonic flight - air breathing) - no space access							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.1201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
4.1202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
4.1203	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1204	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1205	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.1206	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
4.1207	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1208	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
4.1209	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.1210	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
4.1211	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
4.13	Air-breathing Access-to-space vehicle							
4.1301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
4.1302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.1303	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1304	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1305	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1306	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
4.1307	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1308	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.1309	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
4.1310	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
4.1311	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
4.14	Rocket-Based Access to Space							
4.1401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.1402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
4.1403	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.1404	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.2	**System Components**							
4.21	Forebody/Inlet/isolator performance and operability							
4.2101	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.2102	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.22	Engine exhaust interactions with vehicle aft-body and control surfaces.							
4.2201	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.2202	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
4.3	**Fundamental Hypersonics Research**							
4.31	Hypersonic Boundary Layer Characterization and/or control	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	TBD	TBD	Optical and discrete surface and flow field measurements	Hypersonic Wind Tunnels	LAL, New M6QT(?)	BAM6QT, TAMU M6QT
4.3101	Tunnel Noise/Receptivity	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Perform non-intrusive flow field diagnostics to measure freestream and boundary layer disturbances	Mach, Reynolds numbers, vehicle alpha/beta	Hot-wires, optical flow diagnostic techniques	Conventional and Quiet Tunnels	LAL, New M6QT?	BAM6QT, TAMU M6QT
4.3102	Instability Growth/Breakdown	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Perform non-intrusive flow field diagnostics to measure boundary layer disturbances and growth	Mach, Reynolds numbers, vehicle alpha/beta	Hot-wires, optical flow diagnostic techniques, high speed surface instrumentation	Conventional and Quiet Tunnels	LAL, New M6QT?	BAM6QT, TAMU M6QT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.3103	By-pass Mechanisms	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition	Mach, Reynolds numbers, vehicle alpha/beta, roughness type, size, distribution	phosphor thermography, IR, TSP, discrete thin-film sensors	Conventional and Quiet Tunnels	LAL, New M6QT?	BAM6QT, TAMU M6QT
4.3104	Flight Data Analysis (might be captured in other sheets)	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	TBD	TBD	TBD	Conventional and Quiet Tunnels	TBD	TBD
4.32	Supersonic Boundary Layer Characterization and/or control	3,4,5,13			Optical and discrete surface and flow field measurements	Supersonic Wind Tunnels		
4.3201	Tunnel Noise/Receptivity	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Perform non-intrusive flow field diagnostics to measure freestream and boundary layer disturbances	Mach, Reynolds numbers, vehicle alpha/beta	Hot-wires, optical flow diagnostic techniques	Conventional and Quiet Tunnels	UPWT, SLDT, SWT	No QT available
4.3202	Instability Growth/Breakdown	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Perform non-intrusive flow field diagnostics to measure boundary layer disturbances and growth	Mach, Reynolds numbers, vehicle alpha/bet, small roughness	Hot-wires, optical flow diagnostic techniques, high speed surface instrumentation	Conventional and Quiet Tunnels	UPWT, SLDT, SWT	No QT available
4.3203	By-pass Mechanisms	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure surface heating associated with roughness effects on supersonic boundary-layer transition	Mach, Reynolds numbers, vehicle alpha/beta, roughness type, size, distribution	phosphor thermography, IR, TSP, discrete thin-film sensors	Conventional and Quiet Tunnels	UPWT, SLDT, SWT	No QT available

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.3204	Flight Data Analysis (might be captured in other sheets)	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	TBD	TBD	TBD	Conventional and Quiet Tunnels	TBD	TBD
4.33	Hypersonic, Perfect Gas Shock Interactions	3,4,5,13			Optical and discrete surface and flow field measurements	Hypersonic Wind Tunnels		
4.3301	2D Shock-Shock Interaction (e.g. shock on cowl)	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure heating to cowl leading edge from (bow) shock interactions, visualize flow structure of interaction type	Mach, Reynolds number, angle-of-attack, shock inclination angle and location	Global optical or discrete sensor heating, flow field visualization	Hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.3302	3D Shock-Shock Interaction (e.g. shock on wing, fin)	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure heating to leading edge of swept wing or fin from shock interactions, visualize flow structure due to shock interaction	Mach, Reynolds number, angle-of-attack, shock inclination angle and location	Global optical or discrete sensor heating, flow field visualization	Hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.3303	Shock - BL Interaction	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure heating along body from shock impingement, visualize flow structure due to shock interaction	Mach, Reynolds number, angle-of-attack, shock inclination angle and location	Global optical or discrete sensor heating, flow field visualization	Hypersonic wind tunnel	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.34	Hypersonic, Non-equilibrium Shock Interactions	3,4,5,13			Optical and discrete surface and flow field measurements	Hypersonic Wind Tunnels		
4.3401	2D Shock-Shock Interaction (e.g. shock on cowl)	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure heating to cowl from shock interactions under high-enthalpy conditions, visualize flow structure due to shock interaction	Mach, Reynolds number, angle-of-attack, shock inclination angle and location, flow enthalpy	Global optical or discrete sensor heating, flow field visualization	Hypersonic high-enthalpy facility	N/A	AEDC Tunnel 9, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.3402	3D Shock-Shock Interaction (e.g. shock on wing, fin)	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure heating to leading edge of swept wing or fin from shock interactions under high-enthalpy conditions, visualize flow structure due to shock interaction	Mach, Reynolds number, angle-of-attack, shock inclination angle and location, flow enthalpy	Global optical or discrete sensor heating, flow field visualization	Hypersonic high-enthalpy facility	N/A	AEDC Tunnel 9, CUBRC LENS
4.3403	Shock - BL Interaction	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure heating along body from shock impingement under high-enthalpy conditions, visualize flow structure due to shock interaction	Mach, Reynolds number, angle-of-attack, shock inclination angle and location, flow enthalpy	Global optical or discrete sensor heating, flow field visualization	Hypersonic high-enthalpy facility	N/A	AEDC Tunnel 9, CUBRC LENS
4.35	Fluid Structure Interactions and Deformations	3,4,5,9			Optical and discrete surface and flow field measurements	Hypersonic Wind Tunnels		
4.3501	Surface deformations due to thermal effects	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (9) Fluid-Structures interactions	Measure heating and pressure for deforming surface due to thermal effects, visualize flow structure	Mach, Reynolds number, angle-of-attack, material stiffness and temperatures	Global optical or discrete sensor heating, flow field visualization, photogrammetry	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.3502	Corner flow 3D interactions with compliant surfaces	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (9) Fluid-Structures interactions	Measure heating and pressure for deflecting surface (static and dynamic) due to shock-BL interactions, visualize flow structure	Mach, Reynolds number, angle-of-attack, shock inclination angle and location, material stiffness and temperatures	Global optical or discrete sensor heating, flow field visualization, photogrammetry	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.3503	Shock-BL interaction with compliant panels	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (9) Fluid-Structures interactions	Measure heating and pressure for deflecting surface (static and dynamic) due to shock-BL interactions, visualize flow structure	Mach, Reynolds number, angle-of-attack, shock inclination angle and location, material stiffness and temperatures	Global optical or discrete sensor heating, flow field visualization, photogrammetry	Hypersonic wind tunnel or high-enthalpy facility	LaRC 31-Inch Mach 10, 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
4.36	RCS Jet Interactions	3,4,5,13						

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.3601	Supersonic aerodynamic jet interactions	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure force & moment with 5 or 6-component flow-thru balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure sensitive paint. Measure model plenum pressure/temperature, supplied mass flow rate using calibrated venturis or Coriolis meters. Infrared imaging to assess boundary layer state.	angle-of-attack, sideslip angle, Reynolds number, Mach number, jet-to-local static pressure ratio, jet-to-freestream momentum ratio	force/moment, discrete pressure, PSP, discrete temperature, schlieren, mass flow rate, infrared imaging	Supersonic wind tunnels	LaRC UPWT, ARC 9x7, GRC 8x6, GRC 10x10	AEDC VKF A, AEDC 16S, Boeing PSWT, Lockheed Martin HSWT
4.3602	Hypersonic aerodynamic jet interactions	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure force & moment with 5 or 6-component flow-thru balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure sensitive paint. Measure model plenum pressure/temperature, supplied mass flow rate using calibrated venturis or Coriolis meters. Infrared imaging to assess boundary layer state.	angle-of-attack, sideslip angle, Reynolds number, Mach number, jet-to-local static pressure ratio, jet-to-freestream momentum ratio	force/moment, discrete pressure, discrete temperature, schlieren, mass flow rate, infrared imaging	Hypersonic wind tunnels	LAL	AEDC VKF B/C, Tunnel 9, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
4.3603	Plume flow field studies for CFD validation.	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure plume characteristics using non-intrusive laser diagnostic methods along with schlieren visualization. Pressure measurements using discrete sensors and pressure sensitive paint. Infrared imaging to assess boundary layer state.	Mach number, angle of attack, nozzle pressure ratio, nozzle exit Mach number	discrete pressure, PSP, high-speed schlieren, PLIF, mass flow rate, other laser diagnostic methods, infrared imaging	Supersonic/hypersonic wind tunnels	LaRC UPWT, GRC 1x1, LAL	AEDC VKF A/D
4.3604	Simulant gases study	(3) Boundary-layer characterization, (4) Convective heating environments, (5) Flow-field characterization, (13) Aero-optical environments	Measure force & moment with 5 or 6-component flow-thru balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure sensitive paint. Measure model plenum pressure/temperature, supplied mass flow rate using calibrated venturis or Coriolis meters. Infrared imaging to assess boundary layer state.	Mach number, nozzle pressure ratio, simulant gas type, nozzle shape	force/moment, discrete pressure, PSP, discrete temperature, schlieren, mass flow rate, PLIF, infrared imaging	Supersonic/hypersonic wind tunnels	LaRC UPWT, GRC 1x1, LAL	AEDC VKF A/D

Table 41. Test Requirements for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
4	**NASA Hypersonic Atmospheric Flight Technology Development**							
4.1	**Vehicle Architecture**							
4.11	Airbreathing Sub-scale Demonstration Vehicle (e.g. Aether-derived), but a technology/point design concept							
4.1101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
4.1102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
4.1103	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.1104	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
4.1105	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1106	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1107	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
4.1108	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1109	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
4.111	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
4.1111	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
4.12	Point-2-Point Vehicle (cruise - sustained hypersonic flight - air breathing) - no space access							
4.1201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
4.1202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
4.1203	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.1204	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

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4.1205	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1206	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1207	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
4.1208	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1209	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.

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4.121	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
4.1211	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
4.13	Air-breathing Access-to-space vehicle							
4.1301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
4.1302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
4.1303	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.1304	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

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4.1305	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1306	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1307	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
4.1308	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.1309	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.

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4.131	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
4.1311	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
4.14	Rocket-Based Access to Space							
4.1401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
4.1402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
4.1403	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.1404	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.2	**System Components**							
4.21	Forebody/Inlet/isolator performance and operability							

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4.2101	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.2102	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.22	Engine exhaust interactions with vehicle aft-body and control surfaces.							
4.2201	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
4.2202	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
4.3	**Fundamental Hypersonics Research**							

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4.31	Hypersonic Boundary Layer Characterization and/or control	Sufficient Mach and Reynolds number ranges to produce transition for problem of interest under flight-relevant disturbance environment	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Global optical or highly spatially-resolved surface heating / pressure / temperature instrumentation. Laser-based flow field measurements	Models with precision surface quality
4.3101	Tunnel Noise/Receptivity	Sufficient Mach and Reynolds number ranges to produce transition for problem of interest under flight-relevant disturbance environment	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Dynamic measurements (megahertz range)	Highly polished models, typically
4.3102	Instability Growth/Breakdown	Sufficient Mach and Reynolds number ranges to produce transition for problem of interest under flight-relevant disturbance environment	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Dynamic measurements (megahertz range)	Highly polished models, typically
4.3103	By-pass Mechanisms	Sufficient Mach and Reynolds number ranges to produce transition for problem of interest under flight-relevant disturbance environment	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Dynamic measurements (megahertz range)	Highly polished models, typically
4.3104	Flight Data Analysis (might be captured in other sheets)	TBD	TBD	TBD	TBD	TBD	TBD	TBD
4.32	Supersonic Boundary Layer Characterization and/or control							
4.3201	Tunnel Noise/Receptivity	Range of supersonic freestream conditions	TBD	TBD (significant)	TBD	TBD (significant)	Dynamic measurements (100s kHz range)	Highly polished models, typically
4.3202	Instability Growth/Breakdown	Range of supersonic freestream conditions	TBD	TBD (significant)	TBD	TBD (significant)	Dynamic measurements (100s kHz range)	Highly polished models, typically
4.3203	By-pass Mechanisms	Range of supersonic freestream conditions	TBD	TBD (significant)	TBD	TBD (significant)	Dynamic measurements (100s kHz range)	Highly polished models, typically
4.3204	Flight Data Analysis (might be captured in other sheets)	Range of supersonic freestream conditions	TBD	TBD (significant)	TBD	TBD (significant)	Dynamic measurements (100s kHz range)	Highly polished models, typically
4.33	Hypersonic, Perfect Gas Shock Interactions							
4.3301	2D Shock-Shock Interaction (e.g. shock on cowl)	Hypersonic facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, shock angle and location	Assume a few weeks in the tunnel.	TBD	TBD	Requirement for discrete sensor spacing resolution on the order of 0.001". Temperature range capability on the order of 1000's of degrees.	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

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4.3302	3D Shock-Shock Interaction (e.g. shock on wing, fin)	Hypersonic facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, shock angle and location	Assume a few weeks in the tunnel.	TBD	TBD	Requirement for discrete sensor spacing resolution on the order of 0.001". Temperature range capability on the order of 1000's of degrees.	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.3303	Shock - BL Interaction	Hypersonic facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, shock angle and location	Assume a few weeks in the tunnel.	TBD	TBD	Dynamic measurements (100s kHz range)	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.34	Hypersonic, Non-equilibrium Shock Interactions							
4.3401	2D Shock-Shock Interaction (e.g. shock on cowl)	Hypersonic high-enthalpy facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, shock angle and location, and enthalpy	N/A	Assume many weeks in facilities that typically get no more than two runs per day	On the order of months	Requirement for discrete sensor spacing resolution on the order of 0.001". Temperature range capability on the order of 1000's of degrees.	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.3402	3D Shock-Shock Interaction (e.g. shock on wing, fin)	Hypersonic high-enthalpy facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, shock angle and location, and enthalpy	N/A	Assume many weeks in facilities that typically get no more than two runs per day	On the order of months	Requirement for discrete sensor spacing resolution on the order of 0.001". Temperature range capability on the order of 1000's of degrees.	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.3403	Shock - BL Interaction	Hypersonic high-enthalpy facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, shock angle and location, and enthalpy	N/A	Assume many weeks in facilities that typically get no more than two runs per day	On the order of months	Dynamic measurements (100s kHz range)	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
4.35	Fluid Structure Interactions and Deformations							
4.3501	Surface deformations due to thermal effects	Hypersonic facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, surface deformations and temperatures	Assume a few weeks in the tunnel.	TBD	TBD	Real time and dynamic surface photogrammetry	Thermally responsive material for model substrates
4.3502	Corner flow 3D interactions with compliant surfaces	Hypersonic facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, surface deformations and temperatures	Assume a few weeks in the tunnel.	TBD	TBD	Real time and dynamic surface photogrammetry	Thermally responsive material for model substrates

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4.3503	Shock-BL interaction with compliant panels	Hypersonic facility with sufficient Reynolds numbers to study laminar, transitional, & turbulent conditions	For any given Mach, sweep of Re, AoA, surface deformations and temperatures	Assume a few weeks in the tunnel.	TBD	TBD	Real time and dynamic surface photogrammetry	Thermally responsive material for model substrates
4.36	RCS Jet Interactions							
4.3601	Supersonic aerodynamic jet interactions	Supersonic conditions over a range of Reynolds numbers. Propulsion simulation capability with high-pressure air or other simulant gas, with ability to control pressure, temperature, mass flow rate.	Multiple combinations of Mach number, angle of attack, angle of sideslip, RCS jet location on model, nozzle pressure ratio, and control surface deflection (if control surfaces would be influenced by RCS plumes).	2-4 weeks	Multiple combinations of Mach number, angle of attack, angle of sideslip, RCS jet location on model, nozzle pressure ratio, and control surface deflection (if control surfaces would be influenced by RCS plumes).	1-2 weeks	force balance measurements, multi-channel pressure measurements, high-speed data system (tens of kHz range), high-speed schlieren imagery, laser diagnostics including optical windows on test section and plume seeding, infrared imaging.	Metallic model fabrication with high pressure plenum and internal plumbing for nozzles. Wire or plunge electrical discharge machining (EDM) capability to accurately fabricate small-scale nozzles for wind tunnel models.
4.3602	Hypersonic aerodynamic jet interactions	Hypersonic conditions over a range of Reynolds numbers. Propulsion simulation capability with high-pressure air or other simulant gas, with ability to control pressure, temperature, mass flow rate.	Multiple combinations of Mach number, angle of attack, angle of sideslip, RCS jet location on model, nozzle pressure ratio, and control surface deflection (if control surfaces would be influenced by RCS plumes).	3-4 weeks	Multiple combinations of Mach number, angle of attack, angle of sideslip, RCS jet location on model, nozzle pressure ratio, and control surface deflection (if control surfaces would be influenced by RCS plumes).	1 week (VKF), 2-3 weeks T9/CUBRC	force balance measurements, multi-channel pressure measurements, high-speed data system (tens of kHz range), high-speed schlieren imagery, laser diagnostics including optical windows on test section and plume seeding, infrared imaging.	Metallic model fabrication with high pressure plenum and internal plumbing for nozzles. Wire or plunge electrical discharge machining (EDM) capability to accurately fabricate small-scale nozzles for wind tunnel models.
4.3603	Plume flow field studies for CFD validation.	Supersonic/hypersonic conditions over a range of Reynolds numbers. Propulsion simulation capability with high-pressure air or other simulant gas, with ability to control pressure, temperature, mass flow rate.	Several combinations of Mach number, angle of attack, RCS nozzle shape, nozzle pressure ratio, unit Reynolds number, and boundary layer trips.	2-3 weeks	Several combinations of Mach number, angle of attack, RCS nozzle shape, nozzle pressure ratio, unit Reynolds number, and boundary layer trips.	1 week (VKF A), 2-3 weeks (VKF D)	force balance measurements, multi-channel pressure measurements, high-speed data system (tens of kHz range), high-speed schlieren imagery, laser diagnostics including optical windows on test section and plume seeding, infrared imaging.	Metallic model fabrication with high pressure plenum and internal plumbing for nozzles. Wire or plunge electrical discharge machining (EDM) capability to accurately fabricate small-scale nozzles for wind tunnel models.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
4.3604	Simulant gases study	Supersonic/hypersonic conditions over a range of Reynolds numbers. Propulsion simulation capability with high-pressure air or other simulant gas, with ability to control pressure, temperature, mass flow rate.	Several combinations of Mach number, angle of attack, RCS nozzle shape, nozzle pressure ratio, simulant gas type, simulant gas temperature, unit Reynolds number.	2-3 weeks	Several combinations of Mach number, angle of attack, RCS nozzle shape, nozzle pressure ratio, simulant gas type, simulant gas temperature, unit Reynolds number.	1 week (VKF A), 2-3 weeks (VKF D)	force balance measurements, multi-channel pressure measurements, high-speed data system (tens of kHz range), high-speed schlieren imagery, laser diagnostics including optical windows on test section and plume seeding, infrared imaging.	Metallic model fabrication with high pressure plenum and internal plumbing for nozzles. Wire or plunge electrical discharge machining (EDM) capability to accurately fabricate small-scale nozzles for wind tunnel models.

Table 42. Gaps List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development.

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4	**NASA Hypersonic Atmospheric Flight Technology Development**					
4.1	**Vehicle Architecture**					
4.11	Airbreathing Sub-scale Demonstration Vehicle (e.g. Aether-derived), but a technology/point design concept					
4.1101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia hypersonic wind tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
4.1102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
4.1103	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
4.1104	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
4.1105	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia hypersonic wind tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.1106	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1107	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1108	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1109	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Full 10X scale facilities unavailable. NASA Facilities lack high-Reynolds number capabilities. NASA facilities lack high -enthalpy conditions	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
4.111	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
4.1111	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
4.12	Point-2-Point Vehicle (cruise - sustained hypersonic flight - air breathing) - no space access					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.1201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
4.1202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
4.1203	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
4.1204	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
4.1205	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1206	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1207	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.1208	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1209	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable. NASA Facilities lack high-Reynolds number capabilities. NASA facilities lack high -enthalpy conditions	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
4.121	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
4.1211	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
4.13	Air-breathing Access-to-space vehicle					
4.1301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
4.1302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
4.1303	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.1304	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
4.1305	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1306	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1307	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1308	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.1309	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable. NASA Facilities lack high-Reynolds number capabilities. NASA facilities lack high -enthalpy conditions	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
4.131	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.1311	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
4.14	Rocket-Based Access to Space					
4.1401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
4.1402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
4.1403	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
4.1404	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
4.2	**System Components**					
4.21	Forebody/Inlet/isolator performance and operability					
4.2101	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.2102	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.22	Engine exhaust interactions with vehicle aft-body and control surfaces.					
4.2201	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.2202	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
4.3	**Fundamental Hypersonics Research**					
4.31	Hypersonic Boundary Layer Characterization and/or control	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds / enthalpy ranges / material surface interactions in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Currently no hypersonic quiet tunnel within NASA. Unlikely to obtain extensive test time in non-NASA facilities	Off-body flow-field diagnostics for hypersonic tunnels.	Potential issues with replicating roughness patterns at model scale.	HTP-02, HTP-03, HTP-04, HTP-05, HTP-08, Inst-Flow-01
4.3101	Tunnel Noise/Receptivity	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds / enthalpy ranges / material surface interactions in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Currently no hypersonic quiet tunnel within NASA. Unlikely to obtain extensive test time in non-NASA facilities	Off-body flow-field diagnostics for hypersonic tunnels.	Potential issues with replicating roughness patterns at model scale.	HTP-02, HTP-03, HTP-04, HTP-05, HTP-08, Inst-Flow-01

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.3102	Instability Growth/Breakdown	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds / enthalpy ranges / material surface interactions in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Currently no hypersonic quiet tunnel within NASA. Unlikely to obtain extensive test time in non-NASA facilities	Off-body flow-field diagnostics for hypersonic tunnels.	Potential issues with replicating roughness patterns at model scale.	HTP-02, HTP-03, HTP-04, HTP-05, HTP-08, Inst-Flow-01
4.3103	By-pass Mechanisms	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds / enthalpy ranges / material surface interactions in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Currently no hypersonic quiet tunnel within NASA. Unlikely to obtain extensive test time in non-NASA facilities	Off-body flow-field diagnostics for hypersonic tunnels.	Potential issues with replicating roughness patterns at model scale.	HTP-02, HTP-03, HTP-04, HTP-05, HTP-08, Inst-Flow-01
4.3104	Flight Data Analysis (might be captured in other sheets)	TBD	TBD	TBD	TBD	TBD
4.32	Supersonic Boundary Layer Characterization and/or control	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Current supersonic quiet tunnel at NASA is a pilot tunnel. Unlikely able to test blunt or large models in SLDT.	TBD	TBD	HTP-04, HTP-08
4.3201	Tunnel Noise/Receptivity	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Current supersonic quiet tunnel at NASA is a pilot tunnel. Unlikely able to test blunt or large models in SLDT.	TBD	TBD	HTP-04, HTP-08
4.3202	Instability Growth/Breakdown	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Current supersonic quiet tunnel at NASA is a pilot tunnel. Unlikely able to test blunt or large models in SLDT.	TBD	TBD	HTP-04, HTP-08
4.3203	By-pass Mechanisms	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Current supersonic quiet tunnel at NASA is a pilot tunnel. Unlikely able to test blunt or large models in SLDT.	TBD	TBD	HTP-04, HTP-08
4.3204	Flight Data Analysis (might be captured in other sheets)	TBD	TBD	TBD	TBD	TBD

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.33	Hypersonic, Perfect Gas Shock Interactions					
4.3301	2D Shock-Shock Interaction (e.g. shock on cowl)	Possible Reynolds Number deficiency	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-03, HTP-08
4.3302	3D Shock-Shock Interaction (e.g. shock on wing, fin)	Possible Reynolds Number deficiency	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-03, HTP-08
4.3303	Shock - BL Interaction	Need to investigate impact of "quiet" and conventional tunnel on transition process. Potential lack of Mach / Reynolds / enthalpy ranges / material surface interactions in wind tunnels to duplicate flight relevant conditions	Currently no hypersonic quiet tunnel within NASA. Unlikely to obtain extensive test time in non-NASA facilities	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-03, HTP-04, HTP-08
4.34	Hypersonic, Non-equilibrium Shock Interactions					
4.3401	2D Shock-Shock Interaction (e.g. shock on cowl)	Short duration runs	Would have a difficult time gaining access and/or be able to afford to test in these facilities	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors.	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-05, HTP-06, HTP-08
4.3402	3D Shock-Shock Interaction (e.g. shock on wing, fin)	Short duration runs	Would have a difficult time gaining access and/or be able to afford to test in these facilities	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors.	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-05, HTP-06, HTP-08
4.3403	Shock - BL Interaction	Short duration runs	Would have a difficult time gaining access and/or be able to afford to test in these facilities	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors.	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-05, HTP-06, HTP-08
4.35	Fluid Structure Interactions and Deformations					
4.3501	Surface deformations due to thermal effects	Possible Reynolds Number deficiency	Low priority in non-NASA facilities	Need for research into low temperature ablator materials	Ability to fabricate models from materials that are thermal responsive or deformative	HTP-03, HTP-05, HTP-08
4.3502	Corner flow 3D interactions with compliant surfaces	Possible Reynolds Number deficiency	Low priority in non-NASA facilities		Ability to fabricate models from materials that are thermal responsive or deformative	HTP-03, HTP-05, HTP-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
4.3503	Shock-BL interaction with compliant panels	Possible Reynolds Number deficiency	Low priority in non-NASA facilities		Ability to fabricate models from materials that are thermal responsive or deformative	HTP-03, HTP-05, HTP-08
4.36	RCS Jet Interactions					
4.3601	Supersonic aerodynamic jet interactions	None expected.	The AEDC facilities in particular are heavily scheduled and costly to operate, so it is unlikely that NASA would be able to perform a test there, from both a schedule and cost standpoint. LaRC UPWT may be closed in 2022.	None expected.	Ability to accurately fabricate small-scale RCS nozzles to the required tolerances.	HTP-02, HTP-08
4.3602	Hypersonic aerodynamic jet interactions	LAL lacks a dedicated high-pressure gas delivery/measurement system for propulsion simulation, with an ability to control pressure, temperature, and mass flow rate.	The AEDC facilities in particular are heavily scheduled and costly to operate, so it is unlikely that NASA would be able to perform a test there, from both a schedule and cost standpoint.	LAL lacks a dedicated high-speed data system for dynamic measurements beyond 32-channel capability	Ability to accurately fabricate small-scale RCS nozzles to the required tolerances.	HTP-02, HTP-07, HTP-08
4.3603	Plume flow field studies for CFD validation.	LAL lacks a dedicated high-pressure gas delivery/measurement system for propulsion simulation, with an ability to control pressure, temperature, and mass flow rate.	AEDC VKF A is heavily scheduled and costly to operate, so it is unlikely that NASA would be able to perform a test there, from both a schedule and cost standpoint. LaRC UPWT may be closed in 2022.	LAL lacks a dedicated high-speed data system for dynamic measurements beyond 32-channel capability	Ability to accurately fabricate small-scale RCS nozzles to the required tolerances.	HTP-02, HTP-07, HTP-08
4.3604	Simulant gases study	LAL lacks a dedicated high-pressure gas delivery/measurement system for propulsion simulation, with an ability to control pressure, temperature, and mass flow rate. The use of any propulsion simulant gas other than air may be difficult for large volumes of gas usage.	AEDC VKF A is heavily scheduled and costly to operate, so it is unlikely that NASA would be able to perform a test there, from both a schedule and cost standpoint. LaRC UPWT may be closed in 2022.	LAL lacks a dedicated high-speed data system for dynamic measurements beyond 32-channel capability	Ability to accurately fabricate small-scale RCS nozzles to the required tolerances.	HTP-02, HTP-07, HTP-08

Table 43. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: NASA Hypersonic Atmospheric Flight Technology Development.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4	**NASA Hypersonic Atmospheric Flight Technology Development**					
4.1	**Vehicle Architecture**					
4.11	Airbreathing Sub-scale Demonstration Vehicle (e.g. Aether-derived), but a technology/point design concept					
4.1101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
4.1102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
4.1103	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
4.1104	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.1105	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
4.1106	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
4.1107	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
4.1108	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
4.1109	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
4.111	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.1111	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
4.12	Point-2-Point Vehicle (cruise - sustained hypersonic flight - air breathing) - no space access					
4.1201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
4.1202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
4.1203	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
4.1204	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.1205	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
4.1206	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
4.1207	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
4.1208	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
4.1209	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
4.121	Supersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.1211	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
4.13	Air-breathing Access-to-space vehicle					
4.1301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
4.1302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
4.1303	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
4.1304	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.1305	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
4.1306	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
4.1307	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
4.1308	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
4.1309	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
4.131	Supersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.1311	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
4.14	Rocket-Based Access to Space					
4.1401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
4.1402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
4.1403	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
4.1404	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
4.2	**System Components**					
4.21	Forebody/Inlet/isolator performance and operability					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.2101	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
4.2102	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
4.22	Engine exhaust interactions with vehicle aft-body and control surfaces.					
4.2201	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
4.2202	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
4.3	**Fundamental Hypersonics Research**					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.31	Hypersonic Boundary Layer Characterization and/or control	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest. Inability to make spatiotemporally resolved noise measurements in ground facilities and accurately measure low-amplitude freestream noise in quiet environment	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Improving capability to predict transition onset via physics-based approaches, still reliant on supplementary data from ground facilities and (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux. Tunnel disturbance characterization limited to DNS approach	Increase in CFD capacity critical to enable broad parameter studies and to compensate for the lack of detail in hypersonic experiments via high-fidelity simulations
4.3101	Tunnel Noise/Receptivity	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest. Inability to make spatiotemporally resolved noise measurements in ground facilities and accurately measure low-amplitude freestream noise in quiet environment	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Improving capability to predict transition onset via physics-based approaches, still reliant on supplementary data from ground facilities and (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux. Tunnel disturbance characterization limited to DNS approach	Increase in CFD capacity critical to enable broad parameter studies and to compensate for the lack of detail in hypersonic experiments via high-fidelity simulations
4.3102	Instability Growth/Breakdown	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest. Inability to make spatiotemporally resolved noise measurements in ground facilities and accurately measure low-amplitude freestream noise in quiet environment	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Improving capability to predict transition onset via physics-based approaches, still reliant on supplementary data from ground facilities and (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux. Tunnel disturbance characterization limited to DNS approach	Increase in CFD capacity critical to enable broad parameter studies and to compensate for the lack of detail in hypersonic experiments via high-fidelity simulations

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.3103	By-pass Mechanisms	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest. Inability to make spatiotemporally resolved noise measurements in ground facilities and accurately measure low-amplitude freestream noise in quiet environment	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Improving capability to predict transition onset via physics-based approaches, still reliant on supplementary data from ground facilities and (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux. Tunnel disturbance characterization limited to DNS approach	Increase in CFD capacity critical to enable broad parameter studies and to compensate for the lack of detail in hypersonic experiments via high-fidelity simulations
4.3104	Flight Data Analysis (might be captured in other sheets)	TBD	TBD	TBD	TBD	TBD
4.32	Supersonic Boundary Layer Characterization and/or control	Lack of NASA quiet-flow capability, non-NASA facilities unavailable	TBD	TBD	Improving capability to predict transition onset via physics-based approaches, still reliant on supplementary data from ground facilities and (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations
4.3201	Tunnel Noise/Receptivity	Lack of NASA quiet-flow capability, non-NASA facilities unavailable	TBD	TBD	Improving capability to predict transition onset via physics-based approaches, still reliant on supplementary data from ground facilities and (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations
4.3202	Instability Growth/Breakdown	Lack of NASA quiet-flow capability, non-NASA facilities unavailable	TBD	TBD	Improving capability to predict transition onset via physics-based approaches, still reliant on supplementary data from ground facilities and (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations
4.3203	By-pass Mechanisms	Lack of NASA quiet-flow capability, non-NASA facilities unavailable	TBD	TBD	Improving capability to predict transition onset via physics-based approaches, still reliant on supplementary data from ground facilities and (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.3204	Flight Data Analysis (might be captured in other sheets)	TBD	TBD	TBD	TBD	TBD
4.33	Hypersonic, Perfect Gas Shock Interactions					
4.3301	2D Shock-Shock Interaction (e.g. shock on cowl)	Some NASA facilities may not have high enough Reynolds number; non-NASA facilities may not be available/affordable within project scope. Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest.	Minimal: CFD may lack extensive direct validation for specific vehicle / conditions but is generally accepted for shock on cowl problems	Use CFD to obtain hypersonic aerothermodynamics for slender airbreathing configurations	Higher confidence in CFD for shock/shock interaction flows.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for the lack of detail in hypersonic experiments via high-fidelity simulations
4.3302	3D Shock-Shock Interaction (e.g. shock on wing, fin)	Some NASA facilities may not have high enough Reynolds number; non-NASA facilities may not be available/affordable within project scope. Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest.	Minimal: CFD may lack extensive direct validation for specific vehicle / conditions but is generally accepted for on fin/wing problems	Use CFD to obtain hypersonic aerothermodynamics for slender airbreathing configurations	Higher confidence in CFD for shock/shock interaction flows.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for the lack of detail in hypersonic experiments via high-fidelity simulations
4.3303	Shock - BL Interaction	Lack of NASA quiet-flow capability, non-NASA facilities unlikely to be available and do not have adequate Re range.	High: cannot rely on unvalidated CFD at this time to predict BLT effects, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine shock-BLT effects on aeroheating	Lower confidence in CFD for shock/shock interaction flows with influence of boundary layer state.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations
4.34	Hypersonic, Non-equilibrium Shock Interactions					
4.3401	2D Shock-Shock Interaction (e.g. shock on cowl)	Non-NASA facilities may not be available or affordable within project scope.	Minimal: CFD may lack extensive direct validation for specific vehicle / conditions but is generally accepted for shock on cowl problems	Use CFD to obtain hypersonic aerothermodynamics for slender airbreathing configurations	Higher confidence in CFD for shock/shock interaction flows.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for the lack of detail in hypersonic experiments via high-fidelity simulations
4.3402	3D Shock-Shock Interaction (e.g. shock on wing, fin)	Non-NASA facilities may not be available or affordable within project scope.	Minimal: CFD may lack extensive direct validation for specific vehicle / conditions but is generally accepted for on fin/wing problems	Use CFD to obtain hypersonic aerothermodynamics for slender airbreathing configurations	Higher confidence in CFD for shock/shock interaction flows.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for the lack of detail in hypersonic experiments via high-fidelity simulations
4.3403	Shock - BL Interaction	Non-NASA facilities may not be available or affordable within project scope.	High: cannot rely on unvalidated CFD at this time to predict BLT effects, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine shock-BLT effects on aeroheating	Lower confidence in CFD for shock/shock interaction flows with influence of boundary layer state.	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations
4.35	Fluid Structure Interactions and Deformations					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.3501	Surface deformations due to thermal effects	Non-NASA facilities may not be available or affordable within project scope.	High: cannot rely on unvalidated CFD at this time to predict material response under aerothermal loads, thus inducing increased TPS design margins to account for uncertainties	Rely on unvalidated CFD and/or legacy data from similar vehicles with known material response effects on aeroheating	Lower confidence in ability to compute thermal responsiveness of material under aerothermal loading	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations
4.3502	Corner flow 3D interactions with compliant surfaces	Non-NASA facilities may not be available or affordable within project scope.	High: cannot rely on unvalidated CFD at this time to predict material response under aerothermal loads, thus inducing increased TPS design margins to account for uncertainties	Rely on unvalidated CFD and/or legacy data from similar vehicles with known material response effects on aeroheating	Lower confidence in ability to compute thermal responsiveness of material under aerothermal loading	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations
4.3503	Shock-BL interaction with compliant panels	Non-NASA facilities may not be available or affordable within project scope.	High: cannot rely on unvalidated CFD at this time to predict material response under aerothermal loads, thus inducing increased TPS design margins to account for uncertainties	Rely on unvalidated CFD and/or legacy data from similar vehicles with known material response effects on aeroheating	Lower confidence in ability to compute thermal responsiveness of material under aerothermal loading	Increase in CFD capacity critical to enable broad parameter studies and to compensate for limited detail in high-speed experiments via high-fidelity simulations
4.36	RCS Jet Interactions					
4.3601	Supersonic aerodynamic jet interactions	Non-NASA facilities may not be available or affordable for NASA programs involving RCS jet interactions. Fabricating small-scale RCS nozzles for small nozzles is difficult and costly.	Moderate: reliance on unvalidated CFD and/or legacy data will require increased RCS thruster and propellant margins, thus increasing the overall mass of the vehicle. Use of unsteady CFD will lead to increased cost/schedule and larger aerodynamic database uncertainties.	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine RCS jet interaction effects	Prediction of force and moment increments predicted with reasonable uncertainty compared to test data. RANS model heating prediction has excessive uncertainty. Scale-resolving simulations required to reduce uncertainty and better predict unsteady effects.	RCS jet and plume physics are almost always unsteady, which requires more complex physics and more resources. Symmetry assumptions may by invalid.
4.3602	Hypersonic aerodynamic jet interactions	Non-NASA facilities may not be available or affordable for NASA programs involving RCS jet interactions. Fabricating small-scale RCS nozzles for small nozzles is difficult and costly.	Moderate: reliance on unvalidated CFD and/or legacy data will require increased RCS thruster and propellant margins, thus increasing the overall mass of the vehicle. Use of unsteady CFD will lead to increased cost/schedule and larger aerodynamic database uncertainties.	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine RCS jet interaction effects	Prediction of force and moment increments predicted with reasonable uncertainty compared to test data. RANS model heating prediction has excessive uncertainty. Scale-resolving simulations required to reduce uncertainty and better predict unsteady effects.	RCS jet and plume physics are almost always unsteady, which requires more complex physics and more resources. Symmetry assumptions may by invalid.
4.3603	Plume flow field studies for CFD validation.	Non-NASA facilities may not be available or affordable for NASA programs involving RCS jet interactions. Fabricating small-scale RCS nozzles for small nozzles is difficult and costly.	Moderate: reliance on unvalidated CFD and/or legacy data will require increased RCS thruster and propellant margins, thus increasing the overall mass of the vehicle. Use of unsteady CFD will lead to increased cost/schedule and larger aerodynamic database uncertainties.	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine RCS jet interaction effects	Averaged flow features predicted with small uncertainty compared to experimental uncertainty. Scale resolution of flow features have high prediction uncertainty.	RCS jet and plume physics are almost always unsteady, which requires more complex physics and more resources. Symmetry assumptions may by invalid.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
4.3604	Simulant gases study	Non-NASA facilities may not be available or affordable for NASA programs involving RCS jet interactions. Fabricating small-scale RCS nozzles for small nozzles is difficult and costly. Use of alternative gases in large volumes may be difficult.	Moderate: reliance on unvalidated CFD and/or legacy data will require increased RCS thruster and propellant margins, thus increasing the overall mass of the vehicle. Use of unsteady CFD will lead to increased cost/schedule and larger aerodynamic database uncertainties.	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine RCS jet interaction effects	Prediction of force and moment increments predicted with reasonable uncertainty compared to test data. RANS model heating prediction has uncertainty excessive. Scale-resolving simulations required to reduce uncertainty and better predict unsteady effects.	RCS jet and plume physics are almost always unsteady, which requires more complex physics and more resources. Symmetry assumptions may by invalid.

Appendix G Database for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support

Table 44. Programs List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support.

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
Hypersonic Atmospheric Flight and Access-to-Space	**5**	**Commercial Hypersonic Flight with NASA Support**	**Collaborative work with commercial partners that benefits NASA or directed reimbursable work for customers in the development of hypersonic atmospheric flight systems for commercial purposes**		**NASA collaborative programs, public statements by commercial entities**	
	5.1	**Commercial Airbreathing-Based Access-to-Space - some portion of trajectory includes sustained atmospheric flight (horizontal landing?)**	**This is not limited to SSTO, likely TSTO**	**Does not seem to be current market. Placeholder only**		
	5.11	Placeholder only				
	5.2	**Commercial Rocket-Based Access-to-Space**	**Rocket launch of payload to space, ops plan may include recovery and reuse of stages or complete vehicle using SRP, HIAD, controlled lifting flight**	**Multiple commercial vendors developing or planning. Speculative but reasonable to extrapolate several programs over the next decade. Anticipated that this will become a market in the future.**	**Public statements by vendors**	
	5.21	SpaceX	Design and testing of company-specific proprietary hypersonic vehicles for commercial access to space using rocket propulsion. Intended to be fully reusable.	Speculative	company website & PR	2020-
	5.22	Blue Origin	Design and testing of company-specific proprietary hypersonic vehicles for commercial access to space using rocket propulsion.	Speculative	company website & PR	2020-
	5.23	Virgin Galactic	Design and testing of company-specific proprietary hypersonic vehicles for commercial access to space using rocket propulsion.	Speculative	company website & PR	2020-

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	5.24	Rocket Lab	Design and testing of company-specific proprietary hypersonic vehicles for commercial access to space using rocket propulsion.	Speculative	company website & PR	2020-
	5.25	Other marketplace entrants	As the market develops it is expected additional companies will enter the field. Design and testing of company-specific proprietary hypersonic vehicles for commercial access to space using rocket propulsion.	Speculative	company website & PR	2020-
	5.30	**Commercial Point-to-Point - both sustained atmospheric and airbreathing**	**Development of proprietary commercial point-to-point vehicles. Payload and range to be set by external partners. Potential for supersonic to low hypersonic regime**	**Assume multiple entrants. NASA role will likely be limited to specific issues, not complete analysis**	**Public statements by vendors**	
	5.31	Hermeus	Development of proprietary commercial point-to-point vehicles. Payload and range to be set by external partners	Specific requirements TBD based on vendor inputs, template based on NASA airbreathing vehicle 4.11	company website & PR	2020-2030
	5.32	Boeing	Development of proprietary commercial point-to-point vehicles. Payload and range to be set by external partners	Specific requirements TBD based on vendor inputs, template based on NASA airbreathing vehicle 4.11	company website & PR	2020-2030
	5.33	Spaceship Company	Development of proprietary commercial point-to-point vehicles. Payload and range to be set by external partners	Specific requirements TBD based on vendor inputs, template based on NASA airbreathing vehicle 4.11	company website & PR	2020-2030
	5.34	Aerion	Development of proprietary commercial point-to-point vehicles. Payload and range to be set by external partners	Specific requirements TBD based on vendor inputs, template based on NASA airbreathing vehicle 4.11	company website & PR	2020-2030
	5.35	Ursa Major	Development of proprietary commercial point-to-point vehicles. Payload and range to be set by external partners	Specific requirements TBD based on vendor inputs, template based on NASA airbreathing vehicle 4.11	company website & PR	2020-2030
	5.40	**Commercial R&D Testbed**	**Use of large, but conventional aircraft to launch small payloads to orbit or for hypersonic flight R&D**	**NASA analysis would focus on supersonic/hypersonic flight of carried payloads**	**Public statements by vendors**	
	5.41	StratoLaunch	Proprietary commercial research and development testbed vehicles. Small payload hypersonic flight testbed.	Specific requirements TBD based on vendor inputs, template based on NASA airbreathing vehicle 4.11	company website & PR. Stratolaunch.com	2020-2025

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	5.42	Another entrant?	Proprietary commercial research and development testbed vehicles. Small payload hypersonic flight testbed.	Placeholder		2020-2025

Table 45. Database Objectives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support.

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5	**Commercial Hypersonic Flight with NASA Support**							
5.1	**Commercial Airbreathing-Based Access-to-Space - some portion of trajectory includes sustained atmospheric flight (horizontal landing?)**							
5.11	Placeholder only							
5.2	**Commercial Rocket-Based Access-to-Space**							
5.21	SpaceX							
5.2101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
5.2102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.2103	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.2104	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.2105	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.22	Blue Origin							
5.2201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
5.2202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.2203	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.2204	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.2205	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.23	Virgin Galactic							
5.2301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
5.2302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.2303	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.2304	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.2305	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.24	Rocket Lab							
5.2401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
5.2402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.2403	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.2404	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.2405	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.25	Other marketplace entrants							
5.2501	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
5.2502	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.2503	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.2504	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.2505	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.3	**Commercial Point-to-Point - both sustained atmospheric and airbreathing**							
5.31	Hermeus							
5.3101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
5.3102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3103	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3104	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3105	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3106	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3107	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3108	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3109	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	(1) Hypersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
5.3110	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
5.3111	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.32	Boeing							
5.3201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3203	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3204	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3205	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3206	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3207	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3208	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3209	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	(1) Hypersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
5.3210	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3211	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.33	Spaceship Company							
5.3301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
5.3302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3303	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3304	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3305	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3306	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3307	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3308	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3309	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	(1) Hypersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
5.3310	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
5.3311	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.34	Aerion							
5.3401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3403	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3404	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3405	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3406	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3407	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3408	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3409	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	(1) Hypersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
5.3410	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3411	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.35	Ursa Major							
5.3501	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel
5.3502	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3503	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3504	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3505	Flow field Characteristics - Inlet - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3506	Flow field Characteristics - Inlet - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine boundary layer characteristics, separated flow, temporal variations towards understanding inlet performance	angle-of-attack, sideslip angle, Reynolds number, Mach number, back pressure, boundary layer bleed	Boundary layer visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.3507	Flow field Characteristics - Plume Effects - Hypersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Hypersonic wind tunnel	LaRC 20-Inch Mach 6, 8-FT HTT	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.3508	Flow field Characteristics - Plume Effects - Supersonic	(5) flow field characterization, (6) Propulsion System Flow path Interactions, (16) CFD development and validation (18) test technique development	Perform non-intrusive flow field diagnostics to determine separated flow, mixing, temporal variations, control surface interactions towards understanding plume effects	angle-of-attack, sideslip angle, Reynolds number, Mach number, nozzle pressure ratio	Wake flow visualization - Non-intrusive diagnostic	Supersonic wind tunnel	LaRC UPWT TS1&2, Ames 9x7, GRC 8x6, GRC 10x10	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.3509	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	(1) Hypersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
5.3510	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with six-component balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
5.3511	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.4	**Commercial R&D Testbed**							
5.41	StratoLaunch							
5.4101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, Sandia Hypersonic Wind Tunnel

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
5.4102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	(2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure force & moment with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number, OML variation	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
5.4103	Boundary Layer Characterization	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition or design trips to tailor BL for the inlet	Trip types, Trip sizes, Mach, Reynolds numbers, vehicle alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.4104	Convective Aeroheating, Shock Interactions, etc.	(4) Convective aeroheating environments, (5) Flow field characterization	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	phosphor thermography, IR, TSP, discrete thin-film sensors	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6, 31-Inch Mach 10	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
5.4105	Stage Separation and Interactions	(1) Hypersonic/ (2) Supersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with six-component balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic/Supersonic Wind Tunnels	LAL / UPWT	VKF-A/B
5.42	Another entrant?							

Table 46. Test Objectives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5	**Commercial Hypersonic Flight with NASA Support**							
5.1	**Commercial Airbreathing-Based Access-to-Space - some portion of trajectory includes sustained atmospheric flight (horizontal landing?)**							
5.11	Placeholder only							
5.2	**Commercial Rocket-Based Access-to-Space**							
5.21	SpaceX							
5.2101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.2102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.2103	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2104	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.2105	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.22	Blue Origin							
5.2201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.2202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.2203	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2204	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2205	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.23	Virgin Galactic							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.2301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.2302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.2303	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2304	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2305	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.24	Rocket Lab							
5.2401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.2402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.2403	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2404	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2405	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.25	Other marketplace entrants							
5.2501	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.2502	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.2503	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2504	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF -??? CUBRC - 1.5 runs/day	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.2505	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.3	**Commercial Point-to-Point - both sustained atmospheric and airbreathing**							
5.31	Hermeus							
5.3101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3103	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

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5.3104	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.3105	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3106	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3107	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
5.3108	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques

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5.3109	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
5.311	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
5.3111	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.32	Boeing							
5.3201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3203	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

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5.3204	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.3205	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3206	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3207	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
5.3208	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques

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5.3209	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
5.321	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
5.3211	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.33	Spaceship Company							
5.3301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3303	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

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5.3304	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.3305	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3306	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3307	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
5.3308	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques

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5.3309	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
5.331	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
5.3311	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.34	Aerion							
5.3401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3403	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.3404	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.3405	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3406	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3407	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
5.3408	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.3409	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
5.341	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
5.3411	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.35	Ursa Major							
5.3501	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3502	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.3503	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.3504	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.3505	Flow field Characteristics - Inlet - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3506	Flow field Characteristics - Inlet - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques
5.3507	Flow field Characteristics - Plume Effects - Hypersonic	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	18 test points x 3 techniques x 3 repeat each = 162 runs / 40 days	3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed wake flow with NO for optical techniques
5.3508	Flow field Characteristics - Plume Effects - Supersonic	Supersonic conditions over a range of Reynolds numbers	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	LaRC: 3 Mach x 18 test points x 3 techniques x 3 repeat each = 486 runs / 120 days; GRC = similar	3 Mach, 3 AoA over range, 2 sideslip, 3 Reynolds numbers over laminar-to-turbulent ranges. Multiple repeat runs with each diagnostic technique to provide complete flow field imaging	162 runs. AEDC Tunnel 9 and CUBRC avg 1.5 shots/day - 108 days; AEDC VKF - 2/3 shift operations, much less calendar time	Non-intrusive flow-field diagnostics including PLIF, FLEET and hi-frequency Schlieren	Fabrication of models with internal plumbing and exhaust ports to seed boundary layer with NO for optical techniques

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.3509	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 tests/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
5.351	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 tests/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
5.3511	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.4	**Commercial R&D Testbed**							
5.41	StratoLaunch							
5.4101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	100 runs, 2 weeks per test/Mach including test installation ==> 200 runs, 4 weeks	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	200 runs, 1.5 week including test installation (AEDC VKF); Sandia similar to LAL; Tunnel 9 approx. 30 weeks	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.4102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition), with control surface deflections	500 runs, 6 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	500 runs, 3 weeks including test installation (AEDC VKF); Boeing/Lockheed - TBD	measure static aerodynamics with force-and-moment balances, standard and fast-response pressure sensors, Schlieren	Metallic force & moment model
5.4103	Boundary Layer Characterization	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
5.4104	Convective Aeroheating, Shock Interactions, etc.	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent on slender-body flows	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta), control surface effects on the order of 25 runs, total 75 runs	Baseline heating could be completed in 1 week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta). control surface effects on the order of 25 runs, total 75 runs	T9 - 1.5 runs/day but AoA sweeps possible VKF - AoA sweeps possible CUBRC - 1.5 runs/day multiple weeks in tunnel required	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
5.4105	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
5.42	Another entrant?							

Table 47. Gaps List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support.

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5	**Commercial Hypersonic Flight with NASA Support**					
5.1	**Commercial Airbreathing-Based Access-to-Space - some portion of trajectory includes sustained atmospheric flight (horizontal landing?)**					
5.11	Placeholder only					
5.2	**Commercial Rocket-Based Access-to-Space**					
5.21	SpaceX					
5.2101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-03, HTP-08
5.2102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.2103	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2104	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2105	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.22	Blue Origin					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.2201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-03, HTP-08
5.2202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.2203	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2204	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2205	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.23	Virgin Galactic					
5.2301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-03, HTP-08
5.2302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.2303	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.2304	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2305	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.24	Rocket Lab					
5.2401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-03, HTP-08
5.2402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.2403	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2404	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2405	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.25	Other marketplace entrants					
5.2501	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-03, HTP-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.2502	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.2503	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2504	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
5.2505	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.3	**Commercial Point-to-Point - both sustained atmospheric and airbreathing**					
5.31	Hermeus					
5.3101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
5.3102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.3103	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.3104	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.3105	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3106	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3107	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3108	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3109	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Full 10X scale facilities unavailable. NASA Facilities lack high-Reynolds number capabilities. NASA facilities lack high -enthalpy conditions	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
5.311	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
5.3111	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.32	Boeing					
5.3201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.3202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.3203	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.3204	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.3205	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3206	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3207	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3208	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3209	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Full 10X scale facilities unavailable. NASA Facilities lack high-Reynolds number capabilities. NASA facilities lack high -enthalpy conditions	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
5.321	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.3211	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.33	Spaceship Company					
5.3301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
5.3302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.3303	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.3304	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.3305	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3306	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3307	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.3308	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3309	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Full 10X scale facilities unavailable. NASA Facilities lack high-Reynolds number capabilities. NASA facilities lack high -enthalpy conditions	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
5.331	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
5.3311	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.34	Aerion					
5.3401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
5.3402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.3403	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.3404	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.3405	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3406	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3407	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3408	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3409	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Full 10X scale facilities unavailable. NASA Facilities lack high-Reynolds number capabilities. NASA facilities lack high -enthalpy conditions	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
5.341	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
5.3411	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.35	Ursa Major					
5.3501	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.3502	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.3503	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.3504	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.3505	Flow field Characteristics - Inlet - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Inefficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3506	Flow field Characteristics - Inlet - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3507	Flow field Characteristics - Plume Effects - Hypersonic	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-01, HTP-02, HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3508	Flow field Characteristics - Plume Effects - Supersonic	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	Test techniques well-established in supersonic flows, but development required for hypersonic tunnels, optical methods not applicable for internal flows	ability to machine model with internal plumbing to specifications for flow seeding, optical access for internal flow	HTP-03, HTP-08, Inst-Flow-01, Inst-Flow-02
5.3509	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Full 10X scale facilities unavailable. NASA Facilities lack high-Reynolds number capabilities. NASA facilities lack high -enthalpy conditions	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
5.351	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
5.3511	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.4	**Commercial R&D Testbed**					
5.41	StratoLaunch					
5.4101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	NASA facilities lack test capability between Mach 4.6 and 6.0; Insufficient Reynolds number range in NASA facilities	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia Hypersonic Wind Tunnel) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
5.4102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Possible Reynolds Number deficiency	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-03, HTP-08
5.4103	Boundary Layer Characterization	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.4104	Convective Aeroheating, Shock Interactions, etc.	Insufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08, Inst-Heat-01
5.4105	Stage Separation and Interactions	Limited Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
5.42	Another entrant?					

Table 48. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Commercial Hypersonic Flight with NASA Support.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5	**Commercial Hypersonic Flight with NASA Support**					
5.1	**Commercial Airbreathing-Based Access-to-Space - some portion of trajectory includes sustained atmospheric flight (horizontal landing?)**					
5.11	Placeholder only					
5.2	**Commercial Rocket-Based Access-to-Space**					
5.21	SpaceX					
5.2101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2103	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.2104	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.2105	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.22	Blue Origin					
5.2201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2203	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.2204	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.2205	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.23	Virgin Galactic					
5.2301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.2302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2303	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.2304	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.2305	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.24	Rocket Lab					
5.2401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2403	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.2404	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.2405	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.25	Other marketplace entrants					
5.2501	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2502	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.2503	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.2504	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.2505	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.3	**Commercial Point-to-Point - both sustained atmospheric and airbreathing**					
5.31	Hermeus					
5.3101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3103	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.3104	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3105	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3106	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3107	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3108	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3109	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
5.311	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3111	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.32	Boeing					
5.3201	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3202	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3203	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.3204	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3205	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3206	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3207	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3208	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3209	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
5.321	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3211	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.33	Spaceship Company					
5.3301	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3302	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3303	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.3304	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3305	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3306	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3307	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3308	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3309	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
5.331	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3311	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.34	Aerion					
5.3401	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3402	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3403	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.3404	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3405	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3406	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3407	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3408	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3409	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
5.341	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3411	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.35	Ursa Major					
5.3501	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3502	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.3503	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.3504	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3505	Flow field Characteristics - Inlet - Hypersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3506	Flow field Characteristics - Inlet - Supersonic	Given non-intrusive measurement limitations for inlet configurations, must infer information from surface, flow field ahead of inlet coupled with CFD predictions which have large uncertainties	Medium: These are likely piggy-back techniques on inlet performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Low confidence in CFD for transition and operability prediction, moderate confidence for inlet performance. Standard is to use RANS. Using other scale resolving techniques would require even more CPU's than the RANS case.	Extremely CPU-intensive
5.3507	Flow field Characteristics - Plume Effects - Hypersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3508	Flow field Characteristics - Plume Effects - Supersonic	Ground-based testing limitations common for plume simulation (cold gas vs combustion products in a smaller-scale facility like LAL), coupled with CFD predictions which have large uncertainties. Possible Reynolds number deficiency in NASA facilities	Medium: These are likely piggy-back techniques on nozzle performance tests. This data is useful for CFD comparison/modeling	Test technique development program for hypersonic flow-field diagnostics. Develop database for validation of CFD	Moderate confidence in CFD for plume simulations/wake flows using RANS. Using other scale resolving techniques (if required) would require even more CPU's than the RANS case.	CPU-intensive
5.3509	Propulsive Aerodynamic Effects Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
5.351	Supersonic aerodynamics, propulsive aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.3511	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.4	**Commercial R&D Testbed**					
5.41	StratoLaunch					
5.4101	Hypersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.4102	Supersonic Aerodynamic Performance, Stability/Control, Flow Field Visualization	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Possible Reyolds number deficiency in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies	Capability expected to be sufficient for aerodynamics	Cannot compete with experimental productivity
5.4103	Boundary Layer Characterization	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	High: cannot rely on unvalidated CFD at this time to predict the onset of BLT, thus inducing increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive
5.4104	Convective Aeroheating, Shock Interactions, etc.	Some NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	Laminar and turbulent solutions are certainly appropriate for smooth surfaces, but computations on surface features that require complex details and an assessment of transition onset would be cost prohibitive

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
5.4105	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Access to 10X facilities. NASA facilities lack high-Reynolds and Mach 4.6-6.0 capability	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
5.42	Another entrant?					

Appendix H Database for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support

Table 49. Programs List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support.

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
Hypersonic Atmospheric Flight and Access-to-Space	**6**	**Defense Hypersonics with NASA Support**	Collaborative work with Defense partners on dual-use technologies or directed reimbursable work for Defense in the development of hypersonic flight systems for Defense applications		**Open-source public information from the Defense and advisory/consulting groups**	
	6.1	**Defense Fundamental/Applied R&D Activities**	**NASA participation in flight testing, technology development, specific missions**	**NASA provides expertise in hypersonic analysis/testing**	**These are open-source projects**	
	6.11	BOLT-2	BOLT 1 follow on to include turbulent boundary layers	active program. Several more tests conducted since than listed in spreadsheet	AIAA publications	2020-2024
	6.12	BOLT-3	BOLT 2 follow on to include transitional and turbulent boundary layers as well as shock interactions	Assume brand new shape, cannot use legacy data	AIAA publications	2022-2026
	6.13	HIFiRE-X+1	additional HIFiRE (or similar program with new acronym) flights	Extrapolate from support for previous HIFIRE missions	Open source - assume continuation of current program	2020+
	6.14	HIFiRE-X+2	additional HIFiRE (or similar program with new acronym) flights	Extrapolate from support for previous HIFIRE missions	Open source - assume continuation of current program	2020+
	6.15	HIFiRE-X+3	additional HIFiRE (or similar program with new acronym) flights	Extrapolate from support for previous HIFIRE missions	Open source - assume continuation of current program	2020+
	6.16	HIFLiRE	follow on to the HIFiRE program	Extrapolate support from previous programs such as HIFIRE and BOLT	AIAA conferences	2025+
	6.17	Southern Cross Integrated Flight Research Experiment (SCIFiRe)	R&D with test flights to mature SCRAMJET systems. Multiple vendor contracts	Extrapolate support from previous programs such as HIFIRE and BOLT	Aviation Week	20225+
	6.2	**Defense Operational System Development: Glide Vehicles**	**Hypersonic vehicle with glide (unpowered) trajectory**	**Assume multiple development activities over next 25+ years**	**Open sources, e.g. Defense press releases, Aviation Week, etc.**	**2025-2050**
	6.21	Glide vehicles program #1	Hypersonic vehicle with glide (unpowered) trajectory	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2025-2050
	6.22	Glide vehicles program #2	Hypersonic vehicle with glide (unpowered) trajectory	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2025-2050
	6.23	Glide vehicles program #3	Hypersonic vehicle with glide (unpowered) trajectory	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2025-2050

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	6.3	**Defense Operational System Development: Airbreathing Vehicles**	**Hypersonic vehicle with air-breathing propulsion system**	**Assume multiple development activities over next 25+ years**	**Open sources, e.g. Defense press releases, Aviation Week, etc.**	**2025-2050**
	6.31	Airbreathing vehicle program #1	Hypersonic vehicle with air-breathing propulsion system	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2025-2050
	6.32	Airbreathing vehicle program #2	Hypersonic vehicle with air-breathing propulsion system	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2025-2050
	6.33	Airbreathing vehicle program #3	Hypersonic vehicle with air-breathing propulsion system	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2025-2050
	6.4	**Defense Operational System Develop: Intelligence, Surveillance and Reconnaissance (Point-to-point)**	**Hypersonic vehicle for ISR mission following development of airbreathing systems**	**Assume multiple development activities over next 25+ years**	**Open sources, e.g. Defense press releases, Aviation Week, etc.**	**2030-2050**
	6.41	ISR Program #1	Hypersonic vehicle for ISR mission following development of airbreathing systems	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2030-2050
	6.42	ISR Program #2	Hypersonic vehicle for ISR mission following development of airbreathing systems	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2030-2050
	6.5	**Defense Operational System Develop: Access-to-space**	**Hypersonic vehicle for space access mission following development of ISR system**	**Assuming reusable system for delivery/return of small to medium payloads as in X-37**	**Open sources, e.g. Defense press releases, Aviation Week, etc.**	**2035-2050**
	6.51	Access to Space: Program #1	Hypersonic vehicle for space access mission following development of ISR system	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2035-2050
	6.52	Access to Space: Program #2	Hypersonic vehicle for space access mission following development of ISR system	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2035-2050
	6.6	**Flight Testbeds**	**Hypersonic system used to carry or deploy new technologies for test and evaluation**	**Industry & Defense demand for increased flight test cadence as per Mach-TB program**	**Open sources, e.g. Defense press releases, Aviation Week, etc.**	**2020-**
	6.61	Flight Testbed #1	Potentially classified, but could include vehicles like X-60A and follow on vehicle programs	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2020-
	6.62	Flight Testbed #2	Potentially classified, but could include vehicles like X-60A and follow on vehicle programs	Does NOT assume analyses to be performed by NASA, but speaks to overall National demand for facilities	Open sources, e.g. Defense press releases, Aviation Week, etc.	2020-

Table 50. Database Objectives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support.

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6	**Defense Hypersonics with NASA Support**							
6.1	**Defense Fundamental/Applied R&D Activities**							
6.11	BOLT-2		Extrapolation from current and past test requirements.					
6.1101	Aerothermal Performance	(3) Boundary-layer characterization, (4) convective heating			Surface temperatures / heat flux	Hypersonic Wind Tunnels		
6.12	BOLT-3		Extrapolation from current and past test requirements.					
6.1201	Hypersonic testing of vehicle and possibly vehicle plus stack	(1) Hypersonic Aerodynamic Performance (5) Flow Field Characterization	Measure F&M with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors.	angle-of-attack, sideslip angle, Reynolds number, Mach number	Force and moment, surface pressure, flow-field visualization	Hypersonic Wind Tunnels	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS, Sandia HWT
6.1202	Supersonic Testing of vehicle plus stack, with consideration of any required stage separations	(2) Supersonic Aerodynamic Performance (5) Flow Field Characterization	Measure F&M with 6-component balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	Supersonic Wind Tunnels	LaRC UPWT TS1&2, Ames 9x7	AEDC VKF Tunnel A, Boeing PSWT, Lockheed Martin HSWT
6.1203	Transonic Testing of launch vehicle stack.	(19) Transonic Aerodynamic Performance	Measure F&M with 6-component balances. Measure surface pressure with standard and fast-response pressure sensors, pressure-sensitive paint.	angle-of-attack, sideslip angle, Reynolds number, Mach number	Force and moment, surface pressure, flow field visualization	Transonic Wind Tunnels	Ames 11-Foot, LaRC NTF, GRC 8x6	Calspan 8-Foot TWT, Boeing PSWT, LM HSWT
6.1204	Hypersonic testing of vehicle to define baseline heating	(4) Convective heating environments	Measure surface heating on baseline surface	Roughness size, Reynolds number, possibly vehicle shape and range of alpha/beta	TSP, phosphor thermography, thin-film, optical	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.1205	Hypersonic testing of vehicle to investigate roughness effects	(3) Boundary-layer characterization	Measure surface heating associated with roughness effects on hypersonic boundary-layer transition and turbulent heating augmentation		TSP, phosphor thermography, thin-film, optical	hypersonic wind tunnel, high-enthalpy shock/impulse facility	LaRC 20-Inch Mach 6	AEDC Tunnel 9, AEDC VKF B/C, CUBRC LENS
6.13	HIFiRE-X+1		Extrapolation from current and past test requirements.					
6.1301	Hypersonic Aerodynamic performance	(1) Hypersonic Aerodynamic Performance, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.1302	Aerothermal performance	(3) Boundary-layer characterization, (4) Convective aeroheating environments	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.14	HIFiRE-X+2		Extrapolation from current and past test requirements.					
6.1401	Hypersonic Aerodynamic performance	(1) Hypersonic Aerodynamic Performance, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.1402	Aerothermal performance	(3) Boundary-layer characterization, (4) Convective aeroheating environments	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.15	HIFiRE-X+3		Extrapolation from current and past test requirements.					
6.1501	Hypersonic Aerodynamic performance	(1) Hypersonic Aerodynamic Performance, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.1502	Aerothermal performance	(3) Boundary-layer characterization, (4) Convective aeroheating environments	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.16	HIFLiRE		Extrapolation from current and past test requirements.					
6.1601	Hypersonic Aerodynamic performance	(1) Hypersonic Aerodynamic Performance, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.1602	Aerothermal performance	(3) Boundary-layer characterization, (4) Convective aeroheating environments	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.17	Southern Cross Integrated Flight Research Experiment (SCIFiRe)		Extrapolation from current and past test requirements.					
6.1701	Hypersonic Aerodynamic performance	(1) Hypersonic Aerodynamic Performance, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.1702	Aerothermal performance	(3) Boundary-layer characterization, (4) Convective aeroheating environments	Requirements TBD based on Defense inputs	TBD	TBD	TBD	TBD	TBD
6.2	**Defense Operational System Development: Glide Vehicles**							
6.21	Glide vehicles program #1		Extrapolation from current and past test requirements.					
6.2101	Hypersonic Aerodynamic Performance	(1) Hypersonic Aerodynamic Performance, (3) Boundary-layer characterization, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, Surface measurements to infer BL state, Surface pressures	Hypersonic Wind Tunnels	TBD	TBD
6.2102	Supersonic Aerodynamic Performance	(2) Supersonic Aerodynamic Performance, (3) Boundary-layer characterization, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, Surface measurements to infer BL state, Surface pressures	Supersonic Wind Tunnels	TBD	TBD
6.2103	Aerothermal Performance	(3) Boundary-layer characterization, (4) Convective aeroheating environments	Requirements TBD based on Defense inputs	TBD	Surface temperatures/heat flux	Hypersonic Wind Tunnels	TBD	TBD
6.2104	Stage Separation and Interactions	(1) Hypersonic Aerodynamic Performance, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	TBD	TBD
6.22	Glide vehicles program #2		Extrapolation from current and past test requirements.					

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.2201	Hypersonic Aerodynamic Performance	(1) Hypersonic Aerodynamic Performance, (3) Boundary-layer characterization, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, Surface measurements to infer BL state, Surface pressures	Hypersonic Wind Tunnels	TBD	TBD
6.2202	Supersonic Aerodynamic Performance	(2) Supersonic Aerodynamic Performance, (3) Boundary-layer characterization, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, Surface measurements to infer BL state, Surface pressures	Supersonic Wind Tunnels	TBD	TBD
6.2203	Aerothermal Performance	(3) Boundary-layer characterization, (4) Convective aeroheating environments	Requirements TBD based on Defense inputs	TBD	Surface temperatures/heat flux	Hypersonic Wind Tunnels	TBD	TBD
6.2204	Stage Separation and Interactions	(1) Hypersonic Aerodynamic Performance, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	TBD	TBD
6.23	Glide vehicles program #3		Extrapolation from current and past test requirements.					
6.2301	Hypersonic Aerodynamic Performance	(1) Hypersonic Aerodynamic Performance, (3) Boundary-layer characterization, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, Surface measurements to infer BL state, Surface pressures	Hypersonic Wind Tunnels	TBD	TBD
6.2302	Supersonic Aerodynamic Performance	(2) Supersonic Aerodynamic Performance, (3) Boundary-layer characterization, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, Surface measurements to infer BL state, Surface pressures	Supersonic Wind Tunnels	TBD	TBD
6.2303	Aerothermal Performance	(3) Boundary-layer characterization, (4) Convective aeroheating environments	Requirements TBD based on Defense inputs	TBD	Surface temperatures/heat flux	Hypersonic Wind Tunnels	TBD	TBD
6.2304	Stage Separation and Interactions	(1) Hypersonic Aerodynamic Performance, (5) Flow Field Characterization	Requirements TBD based on Defense inputs	TBD	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	TBD	TBD

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.3	**Defense Operational System Development: Airbreathing Vehicles**							
6.31	Airbreathing vehicle program #1		Extrapolation from current and past test requirements.					
6.3101	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
6.3102	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
6.3103	Stage Separation and Interactions	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B
6.3104	Hypersonic aeroheating and BL transition	(3) Boundary-layer transition, (4) convective aeroheating	Measure surface heating and BL transition	Mach, Re, alpha	Global optical and/or discrete surface heating/transition measurements	Hypersonic Wind Tunnels, High-Enthalpy facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC VKF-B/C, AEDC Tunnel 9, CUBRC LENS
6.32	Airbreathing vehicle program #2		Extrapolation from current and past test requirements.					

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.3201	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
6.3202	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
6.3203	Stage Separation and Interactions	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B
6.3204	Hypersonic aeroheating and BL transition	(3) Boundary-layer transition, (4) convective aeroheating	Measure surface heating and BL transition	Mach, Re, alpha	Global optical and/or discrete surface heating/transition measurements	Hypersonic Wind Tunnels, High-Enthalpy facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC VKF-B/C, AEDC Tunnel 9, CUBRC LENS
6.33	Airbreathing vehicle program #3		Extrapolation from current and past test requirements.					

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.3301	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
6.3302	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
6.3303	Stage Separation and Interactions	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B
6.3304	Hypersonic aeroheating and BL transition	(3) Boundary-layer transition, (4) convective aeroheating	Measure surface heating and BL transition	Mach, Re, alpha	Global optical and/or discrete surface heating/transition measurements	Hypersonic Wind Tunnels, High-Enthalpy facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC VKF-B/C, AEDC Tunnel 9, CUBRC LENS
6.4	**Defense Operational System Develop: Intelligence, Surveillance and Reconnaissance (Point-to-point)**							
6.41	ISR Program #1		Extrapolation from current and past test requirements.					

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.4101	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
6.4102	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
6.4103		(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B
6.42	ISR Program #2		Extrapolation from current and past test requirements.					
6.4201	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.4202	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
6.4203		(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B
6.5	**Defense Operational System Develop: Access-to-space**							
6.51	Access to Space: Program #1		Extrapolation from current and past test requirements (e.g. X-37).					
6.5101	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
6.5102	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.5103	Stage Separation and Interactions	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B
6.5104	Hypersonic aeroheating and BL transition	(3) Boundary-layer transition, (4) convective aeroheating, (10) High-enthalpy kinetics	Measure surface heating and BL transition	Mach, Re, alpha	Global optical and/or discrete surface heating/transition measurements	Hypersonic Wind Tunnels, High-Enthalpy facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC VKF-B/C, AEDC Tunnel 9, CUBRC LENS
6.52	Access to Space: Program #2		Extrapolation from current and past test requirements (e.g. X-37).					
6.5201	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Surface and internal heat flux/thermal couple gauges. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT	CUBRC LENS, AEDC APTU
6.5202	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
6.5203	Stage Separation and Interactions	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.5204	Hypersonic aeroheating and BL transition	(3) Boundary-layer transition, (4) convective aeroheating, (10) High-enthalpy kinetics	Measure surface heating and BL transition	Mach, Re, alpha	Global optical and/or discrete surface heating/transition measurements	Hypersonic Wind Tunnels, High-Enthalpy facilities	LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6	AEDC VKF-B/C, AEDC Tunnel 9, CUBRC LENS
6.6	**Flight Testbeds**							
6.61	Flight Testbed #1		Extrapolation from current and past test requirements.					
6.6101	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT, LAL	CUBRC LENS, AEDC APTU
6.6102	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
6.6103	Stage Separation and Interactions	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B
6.62	Flight Testbed #2		Extrapolation from current and past test requirements.					

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
6.6201	Hypersonic aerodynamics and Propulsion/Airframe Integration	(1) Hypersonic Aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, total enthalpy, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces, surface temperatures/heat flux	Hypersonic Wind Tunnels	LaRC 8' HTT, LAL	CUBRC LENS, AEDC APTU
6.6202	Supersonic aerodynamics and Propulsion/Airframe Integration	(2) Supersonic aerodynamic performance, (6) Propulsion system flow path interactions, (9) Fluid-structures interactions	Measure forces and moments with 2/3 axis balances. Use Schlieren photography for shock shape. Measure surface pressure with required spatial resolution. Secondary fast-response pressure sensors for transient effects	angle-of-attack, Reynolds number, Mach number, Propulsion exhaust system control	Force and Moment, Surface measurements to infer BL state, Surface pressures. Inlet mass capture, surface and field measurements to determine exhaust plume interactions with the vehicle and control surfaces	Supersonic Wind Tunnels	LaRC UPWT, ARC UPWT	AEDC VKF-A, US Army Aberdeen range
6.6203	Stage Separation and Interactions	(1) Hypersonic aerodynamic performance, (5) Flow field characterization	Measure forces and moments with 2/3 axis balances. Schlieren photography for shock shape. Measure surface pressure with fast-response pressure sensors	alpha, beta of each body, relative Euler, relative position, Re, M, control surface deflection (other actuation)	Force and Moment, surface pressures, flow field characterization	Hypersonic Wind Tunnels	LAL / UPWT	VKF-A/B

Table 51. Test Requirements for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
6	**Defense Hypersonics with NASA Support**							
6.1	**Defense Fundamental/Applied R&D Activities**							
6.11	BOLT-2							
6.1101	Aerothermal Performance							
6.12	BOLT-3							
6.1201	Hypersonic testing of vehicle and possibly vehicle plus stack	Hypersonic conditions over a range of Reynolds number	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition).	40 runs. 1.5 weeks including test installation.	2 Mach numbers, 4 Reynolds numbers, 3 sideslip angles, at least 12 angles of attack (can get more using continuous-sweep data acquisition).	40 runs. 1.5 weeks including test installation.	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
6.1202	Supersonic Testing of vehicle plus stack, with consideration of any required stage separations	Supersonic conditions over a range of Reynolds numbers	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	100 runs. 1.5 weeks including test installation.	5 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 15 angles of attack (can get more using continuous-sweep data acquisition).	100 runs. 1.5 weeks including test installation.	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
6.1203	Transonic Testing of launch vehicle stack.	Transonic conditions over a range of Reynolds numbers	8 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 25 angles of attack (can get more using continuous-sweep data acquisition).	120 runs. 1.5 weeks including test installation.	8 Mach numbers, 3 Reynolds numbers, 5 sideslip angles, at least 25 angles of attack (can get more using continuous-sweep data acquisition).	120 runs. 1.5 weeks including test installation.	measure static aerodynamics with force-and-moment balances	Metallic force & moment model
6.1204	Hypersonic testing of vehicle to define baseline heating	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta).	Baseline heating could be completed in a week in the 20m6.	For baseline heating, on the order of 50 runs (5 alpha, 4 Re, & 2+ beta).	Baseline heating could be completed in a week in the 20m6.	Global aeroheating measurement and/or high-density discrete measurement to determine convective heating environments	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
6.1205	Hypersonic testing of vehicle to investigate roughness effects	Hypersonic facility with sufficient Reynolds numbers to produce transition/turbulent blunt-body flow	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	For developing roughness database, on the order of 200 runs (baseline above plus range of trip heights and locations).	Typical roughness testing would require a multi week entry into the 20m6.	Global aeroheating measurement and/or high-density discrete measurement to identify transition onset	1) ceramic or other low conductivity material models; or 2) highly-instrumented discrete sensors on metallic models
6.13	HIFiRE-X+1							
6.1301	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.1302	Aerothermal performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
6.14	HIFiRE-X+2							
6.1401	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.1402	Aerothermal performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.15	HIFiRE-X+3							
6.1501	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.1502	Aerothermal performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.16	HIFLiRE							
6.1601	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.1602	Aerothermal performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.17	Southern Cross Integrated Flight Research Experiment (SCIFiRe)							
6.1701	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.1702	Aerothermal performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2	**Defense Operational System Development: Glide Vehicles**							
6.21	Glide vehicles program #1							
6.2101	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2102	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2103	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2104	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.22	Glide vehicles program #2							
6.2201	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2202	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2203	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2204	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.23	Glide vehicles program #3							
6.2301	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2302	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2303	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6.2304	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD	TBD	TBD

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
6.3	**Defense Operational System Development: Airbreathing Vehicles**							
6.31	Airbreathing vehicle program #1							
6.3101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.3102	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
6.3103	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
6.3104	Hypersonic aeroheating and BL transition	Re/Mach sufficient to produce laminar through turbulent flow conditions, flight-like enthalpies	TBD	TBD (significant)	TBD	TBD (significant)	global and/or discrete heat-transfer capabilities	cast ceramic and/or instrumented metallic models
6.32	Airbreathing vehicle program #2							
6.3201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.3202	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
6.3203	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
6.3204	Hypersonic aeroheating and BL transition	Re/Mach sufficient to produce laminar through turbulent flow conditions, flight-like enthalpies	TBD	TBD (significant)	TBD	TBD (significant)	global and/or discrete heat-transfer capabilities	cast ceramic and/or instrumented metallic models
6.33	Airbreathing vehicle program #3							
6.3301	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.3302	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
6.3303	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
6.3304	Hypersonic aeroheating and BL transition	Re/Mach sufficient to produce laminar through turbulent flow conditions, flight-like enthalpies	TBD	TBD (significant)	TBD	TBD (significant)	global and/or discrete heat-transfer capabilities	cast ceramic and/or instrumented metallic models
6.4	**Defense Operational System Develop: Intelligence, Surveillance and Reconnaissance (Point-to-point)**							
6.41	ISR Program #1							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
6.4101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.4102	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
6.4103		Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
6.42	ISR Program #2							
6.4201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.4202	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
6.4203		Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
6.5	**Defense Operational System Develop: Access-to-space**							
6.51	Access to Space: Program #1							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
6.5101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.5102	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
6.5103	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
6.5104	Hypersonic aeroheating and BL transition	Re/Mach sufficient to produce laminar through turbulent flow conditions, flight-like enthalpies	TBD	TBD (significant)	TBD	TBD (significant)	global and/or discrete heat-transfer capabilities	cast ceramic and/or instrumented metallic models
6.52	Access to Space: Program #2							
6.5201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.5202	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
6.5203	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
6.5204	Hypersonic aeroheating and BL transition	Re/Mach sufficient to produce laminar through turbulent flow conditions, flight-like enthalpies	TBD	TBD (significant)	TBD	TBD (significant)	global and/or discrete heat-transfer capabilities	cast ceramic and/or instrumented metallic models
6.6	**Flight Testbeds**							
6.61	Flight Testbed #1							
6.6101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf. dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.6102	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf. dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf. dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
6.6103	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication
6.62	Flight Testbed #2							
6.6201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Hypersonic conditions at flight enthalpies with simulated propulsion effects.	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	Mach 4-8 testing, angle of attack -10 to 10 deg., 3 side-slip angles, 500 - 3000 psf dynamic pressure	~100 runs/6-months (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps. localized thermal response measurements	Thermally protected model made of resilient and reusable materials and/or with cooling. (APTU and 8' HTT) Embedded stress measurements for FTSI.
6.6202	Supersonic aerodynamics and Propulsion/Airframe Integration	Supersonic M2-M5 with wide range of Reynolds numbers	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	Mach 2-5 testing, angle of attack -10 to 10 deg., 5 side-slip angles, 500 - 3000 psf dynamic pressure	~1500 runs/6-months which includes tests of inlet operability (Project requirements and dependent on uncertainty)	measure static aerodynamics with force-and-moment balances. Acreage and flow path pressure distributions with static pressure taps.	Metallic force & moment model fabrication
6.6203	Stage Separation and Interactions	Mach numbers up to M10/12, range of Re, multi-body capable (remote motion), store separation (ejection / free-flight)	TBD	TBD (significant)	TBD	TBD (significant)	measure static aerodynamics with force-and-moment balances, measure dynamic aerodynamics with force-and-moment balances	Metallic force & moment model fabrication

Table 52. Gaps List for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support.

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
6	**Defense Hypersonics with NASA Support**					
6.1	**Defense Fundamental/Applied R&D Activities**					
6.11	BOLT-2					
6.1101	Aerothermal Performance					
6.12	BOLT-3					
6.1201	Hypersonic testing of vehicle and possibly vehicle plus stack	NASA facilities lack test capability between Mach 4.6 and 6.0	Hypersonic facilities in the U.S. are currently heavily scheduled, so gaining access for non-NASA facilities may be an issue. Non-NASA facilities (with the possible exception of Sandia HWT) may be prohibitively expensive to test in.	none expected	none expected	HTP-01, HTP-08
6.1202	Supersonic Testing of vehicle plus stack, with consideration of any required stage separations	Capability exists, no gap identified	Potential LaRC UPWT closure. Only NASA supersonic facility for this kind of testing with a wide Mach number range (1.5 < M < 4.6). Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-08
6.1203	Transonic Testing of launch vehicle stack.	Capability exists, no gap identified	Non-NASA facilities may be prohibitively expensive relative to project budget.	none expected	none expected	HTP-08
6.1204	Hypersonic testing of vehicle to define baseline heating	Sufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
6.1205	Hypersonic testing of vehicle to investigate roughness effects	Sufficient Reynolds number range in NASA facilities	Depending on facility chosen, could be a prioritization issue for gaining access?	Cost, schedule, sensor spacing and internal wiring volume constraints for large numbers of discrete sensors. Optical access and validate global aeroheating techniques at AEDC VKF	1) Ability to 3D print/machine or cast detailed surface features for global techniques. 2) Model design and fabrication with large number of discrete sensors	HTP-02, HTP-03, HTP-08
6.13	HIFiRE-X+1					
6.1301	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1302	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.14	HIFiRE-X+2					
6.1401	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1402	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.15	HIFiRE-X+3					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
6.1501	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1502	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.16	HIFLiRE					
6.1601	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1602	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.17	Southern Cross Integrated Flight Research Experiment (SCIFiRe)					
6.1701	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1702	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.2	**Defense Operational System Development: Glide Vehicles**					
6.21	Glide vehicles program #1					
6.2101	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2102	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2103	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD
6.2104	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD
6.22	Glide vehicles program #2					
6.2201	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2202	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2203	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD
6.2204	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD
6.23	Glide vehicles program #3					
6.2301	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2302	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2303	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD
6.2304	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD
6.3	**Defense Operational System Development: Airbreathing Vehicles**					
6.31	Airbreathing vehicle program #1					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
6.3101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
6.3102	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-02
6.3103	Stage Separation and Interactions	Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-03, HTP-08, Inst-Aero-01
6.3104	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	Availability of non-NASA facilities	TBD	model scale sufficient for numerous discrete sensors	HTP-02, HTP-03, HTP-06, HTP-08
6.32	Airbreathing vehicle program #2					
6.3201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
6.3202	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-02
6.3203	Stage Separation and Interactions	Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	0	HTP-03, HTP-08, Inst-Aero-01
6.3204	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	Availability of non-NASA facilities	TBD	model scale sufficient for numerous discrete sensors	HTP-02, HTP-03, HTP-06, HTP-08
6.33	Airbreathing vehicle program #3					
6.3301	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
6.3302	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
6.3303	Stage Separation and Interactions	Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	0	HTP-03, HTP-08, Inst-Aero-01
6.3304	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	Availability of non-NASA facilities	TBD	model scale sufficient for numerous discrete sensors	HTP-02, HTP-03, HTP-06, HTP-08
6.4	**Defense Operational System Develop: Intelligence, Surveillance and Reconnaissance (Point-to-point)**					
6.41	ISR Program #1					
6.4101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
6.4102	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
6.4103		Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-03, HTP-08, Inst-Aero-02
6.42	ISR Program #2					
6.4201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
6.4202	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
6.4203		Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	0	HTP-03, HTP-08, Inst-Aero-02

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
6.5	**Defense Operational System Develop: Access-to-space**					
6.51	Access to Space: Program #1					
6.5101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
6.5102	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
6.5103	Stage Separation and Interactions	Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-02, HTP-03, HTP-08, Inst-Aero-02
6.5104	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	Availability of non-NASA facilities	TBD	model scale sufficient for numerous discrete sensors	HTP-02, HTP-03, HTP-06, HTP-08
6.52	Access to Space: Program #2					
6.5201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
6.5202	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
6.5203	Stage Separation and Interactions	Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	0	HTP-02, HTP-03, HTP-08, Inst-Aero-02
6.5204	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	Availability of non-NASA facilities	TBD	model scale sufficient for numerous discrete sensors	HTP-02, HTP-03, HTP-06, HTP-08
6.6	**Flight Testbeds**					
6.61	Flight Testbed #1					
6.6101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
6.6102	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
6.6103	Stage Separation and Interactions	Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response		HTP-03, HTP-08, Inst-Aero-02
6.62	Flight Testbed #2					
6.6201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Access to high-enthalpy test facility within program schedule and cost	fast-response force & moment balance suitable for short-duration impulse facility operation	none expected	HTP-02, HTP-06, HTP-08, Inst-Aero-01
6.6202	Supersonic aerodynamics and Propulsion/Airframe Integration	Full 10X scale facilities unavailable.	Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	none expected	HTP-02, HTP-08, Inst-Aero-02
6.6203	Stage Separation and Interactions	Reynolds/Mach number ranges of NASA facilities. Scale becomes a factor as some of the most unsteady / dynamic / least understood flow is at close proximity (full scale), difficult to mimic at model scale	Cost and scheduling at AEDC. Potential LaRC UPWT closure	force and moment balances with high-frequency response for dynamic pitch-response measurement. Inability to separate strut/balance effects from dynamic response	0	HTP-03, HTP-08, Inst-Aero-02

Table 53. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Atmospheric Flight and Access to Space, Customer: Defense Hypersonics with NASA Support.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
6	**Defense Hypersonics with NASA Support**					
6.1	**Defense Fundamental/Applied R&D Activities**					
6.11	BOLT-2					
6.1101	Aerothermal Performance					
6.12	BOLT-3					
6.1201	Hypersonic testing of vehicle and possibly vehicle plus stack	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Lack of M4-6 test capability in NASA facilities	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body hypersonic aerodynamics	Use CFD to obtain hypersonic static aerodynamics for slender bodies		
6.1202	Supersonic Testing of vehicle plus stack, with consideration of any required stage separations	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for slender bodies		
6.1203	Transonic Testing of launch vehicle stack.	Non-NASA facilities may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements	Minimal: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for slender body transonic aerodynamics	Use CFD to obtain transonic static aerodynamics for slender bodies		
6.1204	Hypersonic testing of vehicle to define baseline heating	NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of TPS roughness	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine TPS roughness effects on aeroheating	Inability to model highly-complex topologies with structured grids. Inability to predict heating on unstructured grids	
6.1205	Hypersonic testing of vehicle to investigate roughness effects	NASA facilities may not have high enough Reynolds number, non-NASA facilities may not be available/affordable within project scope, Fabrication capability may not be sufficient to resolve small surface features and/or install sufficient sensors in regions of interest	Moderate: reliance on unvalidated CFD and/or legacy data will require increased TPS design margins to account for effects of BLT on aeroheating	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine BLT effects on aeroheating	Inability to predict roughness bypass transition onset.	
6.13	HIFiRE-X+1					
6.1301	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1302	Aerothermal performance	TBD	TBD	TBD	TBD	TBD

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
6.14	HIFiRE-X+2					
6.1401	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1402	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.15	HIFiRE-X+3					
6.1501	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1502	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.16	HIFLiRE					
6.1601	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1602	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.17	Southern Cross Integrated Flight Research Experiment (SCIFiRe)					
6.1701	Hypersonic Aerodynamic performance	TBD	TBD	TBD	TBD	TBD
6.1702	Aerothermal performance	TBD	TBD	TBD	TBD	TBD
6.2	**Defense Operational System Development: Glide Vehicles**					
6.21	Glide vehicles program #1					
6.2101	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2102	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2103	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD
6.2104	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD
6.22	Glide vehicles program #2					
6.2201	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2202	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2203	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD
6.2204	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD
6.23	Glide vehicles program #3					
6.2301	Hypersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2302	Supersonic Aerodynamic Performance	TBD	TBD	TBD	TBD	TBD
6.2303	Aerothermal Performance	TBD	TBD	TBD	TBD	TBD
6.2304	Stage Separation and Interactions	TBD	TBD	TBD	TBD	TBD

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
6.3	**Defense Operational System Development: Airbreathing Vehicles**					
6.31	Airbreathing vehicle program #1					
6.3101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements, NASA Facilities lack high-enthalpy capability. Lack of 10X facility	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
6.3102	Supersonic aerodynamics and Propulsion/Airframe Integration	. Lack of 10X facility	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources
6.3103	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Lack of Re/M capability in NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
6.3104	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	TBD	TBD	TBD	TBD
6.32	Airbreathing vehicle program #2					
6.3201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements, NASA Facilities lack high-enthalpy capability. Lack of 10X facility	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
6.3202	Supersonic aerodynamics and Propulsion/Airframe Integration	. Lack of 10X facility	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
6.3203	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Lack of Re/M capability in NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
6.3204	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	TBD	TBD	TBD	TBD
6.33	Airbreathing vehicle program #3					
6.3301	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements, NASA Facilities lack high-enthalpy capability. Lack of 10X facility	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
6.3302	Supersonic aerodynamics and Propulsion/Airframe Integration	. Lack of 10X facility	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources
6.3303	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Lack of Re/M capability in NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
6.3304	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	TBD	TBD	TBD	TBD
6.4	**Defense Operational System Develop: Intelligence, Surveillance and Reconnaissance (Point-to-point)**					
6.41	ISR Program #1					
6.4101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Lack of 10x facilities. NASA facilities lack high-enthalpy capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
6.4102	Supersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field. Lack of 10X facilities	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources
6.4103		Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Re/M range of NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
6.42	ISR Program #2					
6.4201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Lack of 10x facilities. NASA facilities lack high-enthalpy capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
6.4202	Supersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field. Lack of 10X facilities	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources
6.4203		Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Re/M range of NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
6.5	**Defense Operational System Develop: Access-to-space**					
6.51	Access to Space: Program #1					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
6.5101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Lack of 10 facilities. NASA facilities lack high-enthalpy capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
6.5102	Supersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field. Lack of 10x facilities	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources
6.5103	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Re/M range of NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
6.5104	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	TBD	TBD	TBD	TBD
6.52	Access to Space: Program #2					
6.5201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Lack of 10 facilities. NASA facilities lack high-enthalpy capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
6.5202	Supersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field. Lack of 10x facilities	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources
6.5203	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field. Re/M range of NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
6.5204	Hypersonic aeroheating and BL transition	Re/M range of NASA facilities. Lack of flight-like enthalpy in NASA facilities	TBD	TBD	TBD	TBD
6.6	**Flight Testbeds**					
6.61	Flight Testbed #1					
6.6101	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Lack of 10X facilities. NASA facilities lack high-enthalpy capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
6.6102	Supersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field. Lack of 10x facilities	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources
6.6103	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field, Re/M range of NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable
6.62	Flight Testbed #2					
6.6201	Hypersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facility may not be available/affordable within project scope. Instrumentation may not be adequate for short-duration aerodynamic measurements. Lack of 10X facilities. NASA facilities lack high-enthalpy capability	High: CFD with thermal response lacks direct validation for specific vehicle / conditions but is generally accepted for hypersonic aerodynamics. FTSI is an emerging capability with no validation quality data.	Use CFD to obtain hypersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient for aerodynamics, but lacking direct validation. FTSI for hypersonics is an emerging capability, with insufficient validation data.	Capacity on sufficiently resolved grids limited by computational resources
6.6202	Supersonic aerodynamics and Propulsion/Airframe Integration	Non-NASA facilities may not be available within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to separate strut interference from flow field. Lack of 10x facilities	Moderate: CFD lacks direct validation for specific vehicle / conditions but is generally accepted for supersonic aerodynamics	Use CFD to obtain supersonic static aerodynamics for aerodynamic database development and maximum combustor pressure capability	Capability expected to be sufficient, but lacking direct validation.	Capacity on sufficiently resolved grids limited by computational resources

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
6.6203	Stage Separation and Interactions	Non-NASA facilities may not be available/affordable within project scope. NASA facilities may be closed. Instrumentation may not be sufficient to resolve unsteady wake dynamics and to separate strut interference from flow field, Re/M range of NASA facilities	Moderate: unsteady supersonic CFD for blunt bodies will lead to increased simulation cost/schedule, and higher aero database uncertainties	significant amounts of CFD / schedule to replace facility, likely untenable	Requires validation data for dynamic aero parameters (Cmq) and unsteady wake effects.	Extensive CPU/memory capacity required for unsteady aerodynamic simulations. Number of independent variables given two bodies makes CFD based database likely untenable

Appendix I Database for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation

Table 54. Programs List for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation.

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
Hypersonic Tools and Methods	**7**	**Modeling and Simulation Code Development and Validation**	**Ground test programs conducted to obtain high-fidelity data on phenomena for which CFD capabilities are nonexistent, impractical or unvalidated for CFD tool development and validation**		**Surveys of NASA and external (DoD, Academia) subject matter experts in computational fluid dynamics**	
	7.1	**Wakes and separated flows**	**Validation data for Simulation of separated wake flows, including unsteady flow, shear-layer transition & turbulence, flow rarefication, shear-layer/aftbody interactions, parachute dynamics, etc.**	**Requires surface heating, surface pressure, flow field imagery**		
	7.11	Unsteady, massively-separated hypersonic wake flows	Capsule wake flow structure. BL separation / shear-layer impingements, aftbody heating / pressure / aero, low-density flows	NASA TM 103935, Inflatable & Deployable decelerator requirements, Human-Mars EDL architecture, NESC Aerosciences	CFD SME team members	2020-2030
	7.12	Aftbody / wake flow influence on supersonic dynamics	Wake rarefaction, supersonic influence of aftbody, shear-layer payload interaction effects		CFD SME team members	
	7.13	Parachute modeling	High-speed parachute modeling, including dynamic loads during inflation; drag performance for fully inflated parachutes at high supersonic and subsonic speeds; interactions of multiple parachutes; interactions of sounding rocket and parachute for flight test comparisons.	ESM portfolio, NESC Aerosciences	CFD SME team members	2020-2030
	7.2	**Shock-Shock and Shock-BL Interactions**	**Validation data for complex flow fields created by shock interactions - separation, transition, unsteadiness, etc.**	**Will required high-frequence flow field data, surface heating, surface pressure**		
	7.21	Multi-body separation interactions	Shroud, payload, stage, abort system separation interaction effects on aerodynamics		CFD SME team members	2020-2035

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	7.22	Shock/shock and shock/boundary-layer interactions	Shock interaction effects on heating, pressure, aero-performance and BL transition effects of shock-shock and shock-BL interactions on control surfaces, leading edges, payloads, entropy layer swallowing, flight-relevant enthalpies, effects of boundary layer "history" (whether transitional, turbulent, or laminar, for how long, and what mechanism).	NASA TM 103935	CFD SME team members	2020-
	7.23	Shock/BL interactions, flow fields around local surface features	Protuberances such as antennas, sensors, feedlines, handles, part lines, compression pads, windows, and so forth.		CFD SME team members	2020-
	7.3	**Propulsion System Performance, Interactions and Integration**	**Includes RCS jets, Super/Hyper retropropulsion, airbreather inlets and flow paths, launch vehicle rocket nozzle flows, etc.**	**Requires surface heating, pressure, flow field visualization**		
	7.31	RCS performance	RCS performance and interactions with each other and surface, including multi-thruster interactions.	NESC Aerosciences	CFD SME team members	2020-2040
	7.32	Retropropulsion performance	Large-scale retropropulsion at super/hypersonic conditions	Mars Exploration Architecture, NESC Aerosciences	CFD SME team members	2020-2040
	7.33	Propulsion system inlet operability	Inlet and Isolator performance and shock train prediction: inlet self-starting requirements, inlet unstart (internal contraction ratio) limit, isolator backpressure operability limit, inlet/isolator overall static pressure rise and total pressure recovery, inlet mass capture	NASA TM 103935	CFD SME team members	2020-2040
	7.4	**Transition and Turbulence**	**The most challenging problems in physics - breakdown of smooth, laminar flow to chaotic turbulent flow**	**Highly dependent on surface roughness, free stream noise, Reynolds number, surface geometry, etc.**		

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	7.41	Turbulence modeling	Turbulence models for attached and separated slender/mid/blunt geometries. Effects of chemistry and atmosphere. Effect of surface roughness and blowing. Explore 3D relief effects, which may be more friendly to lower-fidelity turbulence modeling approaches than the 2D academic cases that have previously indicated that only high-fidelity techniques can be trusted. Separate from transition modeling under 7.42	NASA TM 103935	CFD SME team members	2020-
	7.42	Boundary-layer transition due to instability mechanisms	Non-"bypass" models for transition resulting from instability growth and affect by pressure gradients, crossflow, surface temperature, Mach and Reynolds numbers. Focus on transition onset separate from development of models for turbulent flow heating after transition. Separate from turbulence modeling under 7.41	NASA TM 103935	CFD SME team members	2020-
	7.43	Boundary-layer transition due to bypass mechanisms	"Bypass" transition models for surface-roughness (discrete, distributed, pattern, random). Focus on transition onset separate from development of models for turbulent flow heating with roughness. Separate from turbulence modeling under 7.41	ESM portfolio, NASA TM 103935, Artemis/Orion, LOFTID	CFD SME team members	2020-2030
	7.44	Boundary-layer transition control	Injection, bleeding, plasma/EM or other active mechanisms for controlling transition (off/on)		CFD SME team members	
	7.5	**Surface / Flow field Interactions**	**Interactions between flow field and surface affecting, shape, pressure load and thermal response of vehicle**	**Requires, flow field visualization, surface geometry tracking, surface pressure, shear, heating, etc.**		

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	7.51	FSI for rigid structures	Rigid body deformation from thermal and/or pressure loads; Effects on heating/aero/BLT; Vibration response to BLT; deformation due to asymmetric heating. Also, rigid body flight dynamics/stability/control estimation.		CFD SME team members	2020-
	7.52	FSI for inflatable/deployable structures	Material response: Surface deflection effects on heating/transition for inflatable (HIAD) or deployable (ADEPT) aeroshells		CFD SME team members	2020-2035
	7.53	TPS response and ablation modelling	Kinetics, shape-change, catalysis, injection-blowing etc. effects on thermal response and flow field. Properly an arc-jet problem, but unit-problem simulation in WT possible with cold-gas or low-temperature ablator.		CFD SME team members	2020-
	7.54	Massive ablation aero/heating/shape change effects	Effects of ablation/shape change on aero/aeroheating, BLT, radiation blockage, shape-change aero, mass injection.		CFD SME team members	2020-
	7.6	**Thermophysical and Radiative Properties**	**Data on high-temperature/pressure response of gases to shock-wave**	**Generally requires shock-tube testing**		
	7.61	Flow field radiation	Radiation in compressive shock layer and in backshell expansion regions. Tests are needed for different planetary atmospheres (Air, CO2/N2, N2/CH4, H2/He)	Artemis, Mars 2020, Mars Sample Return (SRL & EEV), ESM portfolio	CFD SME team members	2020-
	7.62	Shock Radiation-TPS interactions	Shock-layer radiation penetration within porous ablator (surface vs volume effects)	ESM portfolio	CFD SME team members	2025-2040
	7.63	Kinetic models for planetary atmospheres			CFD SME team members	
	7.64	Kinetic models for propulsion system products		Noted, but not in HEAC domain	CFD SME team members	
	7.65	Kinetic models for ablation products			CFD SME team members	

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	7.66	Shock layer non-equilibrium thermochemistry	Tests to validate new modeling practices, including non-Boltzmann behavior, pre-shock ionization, freestream-radiation interaction, ablation product impact and boundary layer reactivity	Artemis, Mars Sample Return EEV, ESM portfolio	CFD SME team members	2020-
	7.67	Surface catalysis effects	Surface or TPS properties that influence recombination rates and surface temperature / heating		CFD SME team members	
	7.7	**Multi-phase Flows and gas/solid interactions**	**Includes blowing, transpiration, ablation, recession, gas-surface chemistry etc.**			
	7.71	Transpiration cooling (for non-ablators)	Transpiration cooling	ESM portfolio	CFD SME team members	2025-2035
	7.72	Massive injection/blowing for aerodynamic control or aeroheating mitigation	injectants extend past BL; does not included combustion powered (e.g. retropropulsion) injection		CFD SME team members	2025-2035
	7.73	Particle flow subject to phase change	Dusty flow, spallation, droplet, surface interactions (degradation), shock-layer radiation interaction	ESM portfolio	CFD SME team members	2025-2035
	7.8	**Rarefied flow**	**Non-CFD techniques (DSMC, Boltzmann, etc.) Applicable to high orbit mission, high atmospheric entry, micro-structure flow, porous BL, property extractions for multi-scale stochastic CFD modeling**	**0**	**0**	
	7.81	Free molecule flow aerodynamics			CFD SME team members	2025-2040
	7.82	Rarefied aerodynamics and aeroheating			CFD SME team members	2025-2040
	7.83	Mixed regime flows	Continuum / rarefied overlap: in separated wake flows or thruster/flow interactions		CFD SME team members	2025-2040
	7.84	Internal flow through porous microstructure				2025-2040
	7.9	**Miscellaneous**	**other topics with potential growth areas for testing, code development**			
	7.91	"Free-flight" CFD simulations of vehicle dynamics	Time-accurate, adaptive grid CFD simulation of dynamic properties such as Cmq, RCS and SRP firings, wake flow structure, etc.	NESC Aerosciences	CFD SME team members	2020-

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	7.92	Passive vehicle dynamics	Dynamic flight characteristics of unpowered vehicle	ESM portfolio, LOFTID, ADEPT, Mars Sample Return Earth Entry Vehicle	CFD SME team members	2020-2035
	7.93	Vehicle trim	Predict near-zero moments, i.e., trim. This is a base-drag issue?	Shuttle Lessons Learned	CFD SME team members	2020-
	7.94	Stagnation region flow field prediction	Accurate shock shape predictions, including thermochemical nonequilibrium, convective and radiative heat transfer, thermal and entropy layers. Also include the impact of blowing on stagnation region heating.	NESC Aerosciences	CFD SME team members	2020-
	7.95	Aero-optics	Flow field effects on sensor performance, communication blackout, wake signatures		CFD SME team members	2020-
	7.96	Magneto-hydro dynamics			CFD SME team members	

Table 55. Database Objectives List for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation.

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7	**Modeling and Simulation Code Development and Validation**							
7.1	**Wakes and separated flows**							
7.11	Unsteady, massively-separated hypersonic wake flows	(1) Hypersonic Aerodynamics, (5) Flow-Field Characterization, (16) CFD Development and Validation	High frequency schlieren for turbulent flow structure visualization. Spatially resolved steady surface pressure measurements upstream, within, and downstream of the separated wake. High frequency pressure measurements in vicinity of separation point. Advanced diagnostics to extract unsteady off-body velocity components in sufficient quantity to compute 1st and 2nd-order statistics. Surface temperature and heat transfer measurements.	Total Enthalpy, Mach number, angle-of-attack, Reynolds number	Oil flow or shear stress to visualize recirculation patterns. Global and/or discrete sensor measurements of pressure levels using pressure taps, kulites, and/or PSP; Off body flow field diagnostics. Spatial thermocouple and/or total heat flux measurements. Optical heating measurements such as IR thermography.	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT	Variety of academic and DoD facilities
7.1101	Aeroshell back-face and vehicle payload measurements of heating distributions	(4) Convective aeroheating environments, (16) CFD development and validation	Surface temperature and heat transfer measurements (local gauges and/or thermal tomography)	Total Enthalpy, Mach number, angle-of-attack, Reynolds number	Global and/or discrete sensor measurements of heating levels	Hypersonic wind tunnel	LAL, LaRC UPWT	Variety of academic and DoD facilities
7.1102	Aeroshell back-face and vehicle payload measurements of pressure distributions and wake/payload effects on aerodynamics	(1) Hypersonic aerodynamics, (2) Supersonic aerodynamics, (16) CFD Development and validation	Spatially resolved steady surface pressure measurements. High frequency pressure measurements if unsteadiness is a concern.	Total Enthalpy, Mach number, angle-of-attack, Reynolds number	Global and/or discrete sensor measurements of pressure levels	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT	Variety of academic and DoD facilities

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.1103	Wake flow structure visualization	(5) Flow-field characterization, (16) CFD Development and Validation	High frequency schlieren for turbulent flow structure visualization. Advanced diagnostics to extract unsteady off-body velocity components in sufficient quantity to compute 1st and 2nd-order statistics.	Total Enthalpy, Mach number, angle-of-attack, Reynolds number	Nonintrusive flow field measurements, e.g., Schlieren, FLEET, PLIF	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT	Variety of academic and DoD facilities
7.12	Aftbody / wake flow influence on supersonic dynamics	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics (16) CFD Development and Validation	Forced oscillation wind tunnel tests, static force and moment tests with high frequency surface pressure measurements	Total Enthalpy, Mach number, angle-of-attack, Reynolds number, forced oscillation frequency	Static and dynamic forces and moments, static and dynamic surface pressures, schlieren imaging	Supersonic and high transonic Mach facility with accurate dynamic force/moment balances	LaRC UPWT, Ames UPWT, GRC 10x10	Desired information can be informed with instrumented ballistic range models shot at the Test and Evaluation Facility (ballistic range) at Aberdeen Proving Grounds, Aberdeen MD
7.1201	Objectives TBD							
7.1202	Objectives TBD							
7.13	Parachute modeling	(1) Hypersonic Aerodynamics, (5) Flow-Field Characterization , (9) Fluid-Structures Interactions, (16) CFD Development and Validation	Continuous deployment scenarios, as opposed to start-stop-repack are highly desirable, and currently being investigated at small scales. Methods to deploy for all test objectives require care to ensure dynamics do not lead to unstart scenarios or other operating problems. There is limited experience with this problem.		Stereo photogrammetry of deformed shape/strain. PIV of wake flow field. Novel strain sensors being developed for in situ fabric measurements. Standard pressure ports and cobra probes for calibration data.	High-speed wind tunnels with good optical access for non-intrusive measurements.	GRC 10x10 with improved optical access	
7.1301	Objectives TBD							
7.1302	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.2	**Shock-Shock and Shock-BL Interactions**							
7.21	Multi-body separation interactions	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics, (5) Flow-Field Characterization , (7) RCS Performance and Interactions, (16) CFD Development and Validation	Multi-balance force measurements, surface pressure via pressure-sensitive paint, schlieren imagery for shock locations	Mach number, Reynolds number, relative angles of pitch, yaw, and roll between bodies, relative positions of bodies, thrust coefficient(s) if motor plumes are present.	multi-component-force balances, global surface pressure measurements using PSP (steady for sure, unsteady desirable), off body flow field diagnostics such as velocimetry (including plume velocities).	Hypersonic and/or supersonic wind tunnels. Continuous flow are the desired type (LaRC UPWT and AEDC Tunnels A, B, and C), although long duration blow-down facilities (not pulse facilities) such as Boeing PSWT and the Lockheed Ft. Worth tunnel can be used.	LaRC UPWT, LAL	AEDC Tunnel 9, AEDC VKF
7.2101	Objectives TBD							
7.2102	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.22	Shock/shock and shock/boundary-layer interactions	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics, (3) Boundary-layer characterization, (4) Convective aeroheating, (5) Flow-Field Characterization, (6) Propulsion System Flow-path interactions, (10) High-enthalpy kinetics, (16) CFD development and validation	Schlieren imagery for shock/shock and shock/BL flow structure visualization. Spatially resolved steady surface pressure measurements along surfaces impacted by shocks. High frequency pressure measurements in vicinity of shock/BL interaction regions. Advanced diagnostics to extract unsteady off-body velocity components in sufficient quantity to compute 1st and 2nd-order statistics. Surface temperature and heat transfer measurements to quantify turbulence transition region and impact of shock heating.	Total Enthalpy, Mach number, angle-of-attack, angle-of-yaw, Reynolds number	Global and/or discrete sensor measurements of pressure levels using pressure taps, kulites, and/or PSP; Off body flow field diagnostics. Spatial thermocouple and/or total heat flux measurements. Optical heating measurements such as IR thermography.	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT	AEDC Tunnel 9, AEDC VKF, CUBRC LENS, and variety of academic facilities
7.2201	Characterize supersonic perfect gas shock/shock interactions.	(2) Supersonic Aerodynamics, (5) Flow-Field Characterization, (16) CFD development and validation	Schlieren imagery (BOSS, unsteady schlieren) for shock/shock flow structure visualization. Advanced non-intrusive flow field diagnostics (PLIF, PIV) for quantitative velocity measurements.	Mach number, angle-of-attack, angle-of-yaw	Off body flow field visualization (BOSS, unsteady schlieren) and more quantitative diagnostics for velocity field (PLIF, PIV).	Supersonic wind tunnels	LAL, LaRC UPWT	AEDC Tunnel 9, AEDC VKF, CUBRC LENS, and variety of academic facilities
7.2202	Characterize hypersonic perfect gas shock/shock interactions.	(1) Hypersonic Aerodynamics, (5) Flow-Field Characterization, (16) CFD development and validation	Schlieren imagery (BOSS, unsteady schlieren) for shock/shock flow structure visualization. Advanced non-intrusive flow field diagnostics (PLIF, PIV) for quantitative velocity measurements.	Mach number, angle-of-attack, angle-of-yaw	Off-body flow field visualization (BOSS, unsteady schlieren) and more quantitative diagnostics for velocity field (PLIF, PIV).	Hypersonic wind tunnels	LAL	AEDC Tunnel 9, AEDC VKF, CUBRC LENS, and variety of academic facilities

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.2203	Characterize hypersonic nonequilibrium gas shock/shock interactions.	(1) Hypersonic Aerodynamics, (5) Flow-Field Characterization, (10) High-enthalpy kinetics, (16) CFD development and validation	Schlieren imagery (BOSS, unsteady schlieren) for shock/shock flow structure visualization. Advanced non-intrusive flow field diagnostics (PLIF, PIV) for quantitative velocity and scalar (CARS, Raman spectroscopy) measurements.	Total Enthalpy, Mach number, angle-of-attack, angle-of-yaw	Off-body flow field visualization (BOSS, unsteady schlieren) and more quantitative diagnostics for velocity field (PLIF, PIV). Off-body diagnostics for scalar properties (CARS, Raman Spectroscopy) needed to quantify thermo-chemical non-equilibrium effects.	Hypersonic high enthalpy wind tunnels	AHSTF	AEDC Tunnel 9, CUBRC LENS
7.2204	Characterize shock-BL interactions	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics, (3) Boundary-layer characterization, (4) Convective aeroheating, (5) Flow-Field Characterization, (6) Propulsion System Flow-path interactions, (10) High-enthalpy kinetics, (16) CFD development and validation	Schlieren imagery (BOSS, unsteady schlieren) for shock/shock flow structure visualization. Advanced non-intrusive flow field diagnostics to measure boundary layer disturbances and growth. Spatially resolved steady surface pressure measurements along surfaces impacted by shocks. High frequency pressure measurements in vicinity of shock/BL interaction regions. Advanced diagnostics to extract unsteady off-body velocity components in sufficient quantity to compute 1st and 2nd-order statistics for turbulent SBLI. Surface temperature and heat transfer measurements to quantify turbulence transition region and impact of shock heating.	Total Enthalpy, Mach number, angle-of-attack, angle-of-yaw, Reynolds number	Off-body flow field visualization (BOSS, unsteady schlieren) and more quantitative diagnostics for velocity field (PLIF, PIV) to track BL disturbances and growth. Off-body diagnostics for scalar properties (CARS, Raman Spectroscopy) needed to quantify thermo-chemical non-equilibrium effects in the SBLI region. Global and/or discrete sensor measurements of pressure levels using pressure taps, kulites, and/or PSP. Spatial thermocouple and/or total heat flux measurements. Optical heating measurements such as IR thermography.	Hypersonic and/or supersonic wind tunnels (true enthalpy hypersonic tunnel needed for thermo-chemical nonequilibrium effects)	LAL, LaRC UPWT (perfect gas), AHSTF (possible for thermal non-equilibrium effects - but not previously used in this way)	AEDC Tunnel 9, AEDC VKF, CUBRC (LENS I, II, XX and others?), and variety of academic facilities

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.2205	Shock/BL interactions, flow fields around local surface features	(4) Convective aeroheating environments, (5) Flow-field characterization, (15) TPS response and characterization, (16) CFD Development and Validation, (17) Parametric configuration evaluation and screening	High frequency schlieren for turbulent flow structure visualization. Spatially resolved steady surface pressure measurements upstream, within, and downstream of the protuberance. High frequency pressure measurements in vicinity of protuberance. Advanced diagnostics to extract unsteady off-body velocity components in sufficient quantity to compute 1st and 2nd-order statistics in the region affected by the protuberance. Spatially resolved steady surface pressure measurements upstream, within, and downstream of the protuberance.	Total Enthalpy, Mach number, and Reynolds number	Oil flow or shear stress to characterize localized regions of flow separation. Global and/or discrete sensor measurements of pressure levels using pressure taps, kulites, and/or PSP; Off-body flow field diagnostics. Spatial thermocouple and/or total heat flux measurements. Optical thermal measurements such as TSP.	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT, AHSTF, DCSTF	Variety of academic and DoD facilities
7.2206	Objectives TBD							
7.2207	Objectives TBD							
7.3	**Propulsion System Performance, Interactions and Integration**							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.31	RCS performance	(1) Hypersonic Aerodynamics, (2) Supersonic aerodynamics, (4) Convective aeroheating, (5) Flow field characterization, (7) RCS Performance and interactions, (16) CFD development and validation	Measure force & moment with 5 or 6-component flow-thru balances. Use Schlieren photography for shock shape. Measure surface pressure with standard and fast-response pressure sensors, pressure sensitive paint. Measure model plenum pressure/temperature, supplied mass flow rate using calibrated venturis or Coriolis meters. Infrared imaging to assess boundary layer state.	angle-of-attack, sideslip angle, Reynolds number, Mach number, jet-to-local static pressure ratio, jet-to-freestream momentum ratio	force/moment, discrete pressure, PSP, discrete temperature, schlieren, mass flow rate, infrared imaging	Supersonic and Hypersonic wind tunnels	LaRC UPWT, ARC 9x7, GRC 8x6, GRC 10x10, LAL	AEDC VKF A, AEDC 16S, Boeing PSWT, Lockheed Martin HSWT, AEDC VKF B/C, Tunnel 9, CUBRC LENS
	Objectives TBD							
	Objectives TBD							
7.32	Retropropulsion performance	(1) Hypersonic Aerodynamics, (2) Supersonic aerodynamics, (3) Boundary-layer transition, (4) Convective aeroheating, (5) Flow field characterization, (8) Retropropulsion Performance and interactions, (16) CFD development and validation	Sub-scale wind tunnel test with inert gas (typically air) on relevant geometries with multiple engines.	Mach number, dynamic pressure, nozzle expansion ratio, nozzle exit pressure ratio	Discrete pressure (steady and unsteady), pressure-sensitive paint, temperature-sensitive paint, direct force and moment measurements, schlieren, qualitative off-body flow visualization, mass flow.	Supersonic wind tunnels	Langley UPWT, Langley TDT, Glenn 10x10, Ames 9x7	CUBRC, AEDC
7.3201	Objectives TBD							
7.3202	Objectives TBD							

7.33	Propulsion system inlet operability	(1) Hypersonic Aerodynamics, (2) Supersonic aerodynamics, (3) Boundary-layer transition, (5) Flow field characterization, (6) Propulsion system flow path interactions, (16) CFD development and validation	Facility with the ability to alter both freestream conditions and test model that provides isolator exit back pressure control during the course of a single test. Spatially resolved steady surface pressure measurements needed throughout the inlet/isolator internal flow path. High frequency kulite measurements desirable near the engine throat to examine unsteady dynamics at conditions close to unstart. Direct mass flow measurements needed at some station downstream of the isolator as well as through any boundary layer bleed regions to quantify the captured mass flow rate. Surface temperatures, heat flux gauges and/or surface shear sensors needed along the forebody to detect transition from laminar to turbulent flow. Pitot rakes required downstream of the isolator to quantify total pressure recovery. Pitot rakes desired on the forebody near the closeout of the captured inlet flow and near the engine throat to quantify the	Mach number, angle of attack (and beta), and Reynolds number. Also need to vary internal flow path back pressure.	Global and/or discrete sensor measurements of pressure levels in the inlet and isolator using pressure taps (including kulites for dynamic measurements). Spatial thermocouple, heat flux, and/or surface shear stress measurements of the inlet approach flow to detect transition from laminar to turbulent flow. Pitot surveys for distortion characterization and pressure recovery.	Hypersonic and/or supersonic wind tunnels. Continuous flow are the desired type (LaRC UPWT and AEDC Tunnels A, B, and C), although long duration blow-down facilities (not pulse facilities) such as Boeing PSWT and the Lockheed Ft. Worth tunnel can be used for screening inlet performance models.	LaRC UPWT for comprehensive inlet/isolator performance characterization, but LAL and GRC 1x1 could be used for small model screening inlet/isolator configuration performance testing.	For inlet/isolator performance characterization: AEDC Tunnels A, B, and C. For inlet/isolator screening tests: Boeing PSWT, Lockheed Ft. Worth, and AEDC Tunnel D. Also, a variety of small-scale academic facilities available for isolator backpressure characterization only

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
			distortion entering the inlet and isolator.					
7.3301	Objectives TBD							
7.3302	Objectives TBD							
7.4	**Transition and Turbulence**							
7.41	Turbulence modeling	(3) Boundary-layer transition, (4) Convective aeroheating, (5) Flow field characterization, (16) CFD development and validation	High frequency schlieren for turbulent flow structure visualization. Spatially resolved steady surface pressure measurements for wall bounded turbulent flows. High frequency pressure measurements in vicinity of separation point for separated wall-bounded flows. Advanced diagnostics to extract unsteady off-body velocity components in sufficient quantity to compute 1st and 2nd-order statistics. Surface temperature and heat transfer measurements.	Mach number, Reynold number, total enthalpy (when high temperature effects are included)	Oil flow or shear stress to visualize recirculation patterns. Global and/or discrete sensor measurements of pressure levels using pressure taps, kulites, and/or PSP; Off-body flow field diagnostics. Spatial thermocouple and/or total heat flux measurements. Optical heating measurements such as IR thermography.	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT, AHSTF, DCSTF	Variety of academic and DoD facilities
7.4101	Attached boundary-layers on smooth surfaces	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4102	Attached boundary-layers on rough surfaces	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4103	Separated shear layers and wakes	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4104	Boundary-layers with blowing and/or ablation	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.42	Boundary-layer transition due to instability mechanisms	(3) Boundary-layer transition, (4) Convective aeroheating, (5) Flow field characterization, (16) CFD development and validation	Highly spatially resolved measurements of surface temperature or heating to precisely identify transition onset location. Freestream noise measurements. Flow visualization of boundary-layer structure near transition	Mach number, Reynolds number, vehicle configuration, surface geometry (for linear and crossflow gradients)	Surface pressure, temperature, heat-flux. Flow field diagnostics in boundary-layer	Supersonic and hypersonic wind tunnels, high-enthalpy facilities, ballistics ranges	LaRC UPWT, LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6, ARC UPWT, ARC HFFAF, SWT, SLDT	AEDC VKF A/B/C. AEDC Tunnel 9, CUBRC LENS, Purdue BAMQT, TAMU M6QT
7.4201	As per 7.42 with focus on first-mode transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4202	As per 7.42 with focus on second-mode transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4203	As per 7.42 with focus on crossflow transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4204	As per 7.42 with focus on multiple-mode interactions	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4205	As per 7.42 with focus on ablative surfaces	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4206	As per 7.42 with focus on shock-shock and shock-BL transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.43	Boundary-layer transition due to bypass mechanisms	(3) Boundary-layer transition, (4) Convective aeroheating, (5) Flow field characterization, (16) CFD development and validation	Highly spatially resolved measurements of surface temperature or heating to precisely identify transition onset location. Flow visualization of boundary-layer structure near transition	Mach number, Reynolds number, roughness type (discrete, random, pattern, etc.), vehicle configuration	Surface pressure, temperature, heat-flux. Flow field diagnostics in boundary-layer	Supersonic and hypersonic wind tunnels, high-enthalpy facilities, ballistics ranges	LaRC UPWT, LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6, ARC UPWT, ARC HFFAF, SWT, SLDT	AEDC VKF A/B/C. AEDC Tunnel 9, CUBRC LENS, Purdue BAMQT, TAMU M6QT
7.4301	As per 7.43 with focus on Block-TPS Fence/Gap effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4302	As per 7.43 with focus on Woven TPS pattern effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.4303	As per 7.43 with focus on ablated hex comb pattern TPS effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4304	As per 7.43 with focus on distributed sand grain TPS effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4305	As per 7.43 with focus on isolated surface features such as pads, antennas, thruster ports, window, TPS damage sites	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.44	Boundary-layer transition control	(3) Boundary-layer transition, (4) Convective aeroheating, (5) Flow field characterization, (16) CFD development and validation	Highly spatially resolved measurements of surface temperature or heating to precisely identify transition onset location. Flow visualization of boundary-layer structure near transition	Mach number, Reynolds number, roughness type (discrete, random, pattern, etc.), vehicle configuration	Surface pressure, temperature, heat-flux. Flow field diagnostics in boundary-layer	Supersonic and hypersonic wind tunnels, high-enthalpy facilities, ballistics ranges	LaRC UPWT, LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6, ARC UPWT, ARC HFFAF, SWT, SLDT	AEDC VKF A/B/C. AEDC Tunnel 9, CUBRC LENS, Purdue BAMQT, TAMU M6QT
7.4401	Objectives TBD							
7.4402	Objectives TBD							
7.5	**Surface / Flow field Interactions**							

7.51	FSI for rigid structures	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics, (3) Boundary-layer transition, (4) Convective aeroheating, (5) Flow field characterization, (9) Fluid-Structures interactions, (16) CFD development and validation	Spatially resolved measurements of surface pressure (including kulites), high speed schlieren for unsteady flow visualization, high speed capacitive distance sensors to measure dynamic surface deformation, real time temperature imaging (IR or thermocouples). For studying effects from dynamic deformations, such as vibrating compliant panel in SWBLI, test at different laminar-turbulent conditions while controlling thin panel back pressure (to reduce confounding static deformation) with high-frequency measurements (5-50KHz), of surface deformation, pressure and temperature. For static deformations, such as from thermal and large pressure gradients on control surfaces, either simulate and build series of rigid pre-deformed test models or test with a mechanical deformation actuator. May need to augment surface heating to simulate flight material conditions.	Mach Number, Reynolds number, surface/panel material, total enthalpy, and relevant configuration variables such as attitude and control surface deflections.	Surface pressure (pressure taps, kulites, and/or PSP), surface temperature (thermocouples and/or IR thermography), high speed sensors or distributed (e.g., photogrammetry) surface deformation measurements.	Hypersonic and/or supersonic wind tunnels	LaRC UPWT, LaRC 31-Inch Mach 10, LaRC 20-Inch Mach 6, ARC UPWT, AHSTF, DCSTF	Variety of academic and DoD facilities
7.5101	Objectives TBD							
7.5102	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.52	FSI for inflatable/deployable structures	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics, (3) Boundary-layer transition, (4) Convective aeroheating, (5) Flow field characterization, (9) Fluid-Structures interactions, (16) CFD development and validation			Global surface heating & BL transition measurements	Hypersonic tunnels, ballistics ranges, high-enthalpy tunnels		
7.5201	Objectives TBD							
7.5202	Objectives TBD							
7.53	TPS response and ablation modelling	(1) Hypersonic Aerodynamics, (5) Flow field characterization, (9) Fluid-Structures interactions, (15) TSP response and characterization, (16) CFD development and validation	Roughness/Blowing: shock tunnel or blowdown facility. Complexity is in model design and instrumentation. Need ability to fabricate flight-like roughness and transpire uniformly through surfaces. Unit problems can be accomplished in low temperature tunnels. More broadly, kinetics, shape-change, catalysis, injection coupling effects are best suited to be studied in a high-temperature tunnel	Long duration (minutes). High enthalpy (10+ MJ/kg). Model scale ~1 ft. Clean freestream (not vitiated air). Should be able to use real materials. Air, CO2, H2/He, and methane test gas. Range of pressure to get equilibrium and non-equilibrium effects. Need ability to obtain subsonic and supersonic edge conditions	Heat flux (discrete and global). Pressure. Photogrammetry. Spectroscopy in the boundary layer (300-1000nm). Pyrometry. IR thermography.	Hypersonic shock tunnel and blowdown facility for unit problems. High-temperature tunnel for the rest	None	CUBRC lower-enthalpy and short duration unit tests. Rumored TAMU (DoD) funded large scale high-temperature tunnel
7.5301	Objectives TBD							
7.5302	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.54	Massive ablation aero/heating/shape change effects	(1) Hypersonic Aerodynamics, (2) Supersonic Aerodynamics, (3) Boundary-layer transition, (4) Convective aeroheating (5) Flow field characterization, (12) Radiative heating, (15) TSP response and characterization (16) CFD development and validation	Significant overlap with 7.53. Could also obtain coupled/massive shape change validation data using low-temperature ablators such as camphor and naphthalene. Recession patterns with these materials WILL NOT match flight patterns for charring thermochemical ablators, but coupled aerothermal-TPS model validation data can be obtained	For capsule testing, ~2ft model diameter will be necessary to meaningfully scale small geometric features such as seams between ablator blocks. Need ability to obtain laminar and turbulent flow at the 2 ft scale. Test times on order of minutes. Total temperature requirements are low (~800K), but pressure dependence should also be noted. Phase diagram below...	photogrammetry for transient shape measurements. Discrete and global heat flux measurements for reference/calibration models.	Hypersonic and/or supersonic wind tunnels	LaRC Mach 6	AEDC Tunnel C, AEDC Tunnel 9
7.5401	Objectives TBD							
7.5402	Objectives TBD							
7.6	**Thermophysical and Radiative Properties**							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.61	Flow field radiation	(5) Flow field characterization, (10) high-enthalpy kinetics, (12) Radiative heating, (15) TSP response and characterization (16) CFD development and validation	Obtain post-shock radiative intensity profiles in a shock-tube as a function of wavelength and distance behind the shock. Identify similarity conditions, matching density and velocity for stagnation line, streamline analysis off-stagnation	Velocity, density, test gas mixture. Free-stream chemical composition, which should cover Earth (N2-O2), Mars (CO2-N2), Titan (CH4-N2), Venus (CO2-N2), and Gas/Ice Giants (H2-He).	Emission spectroscopy	Shock tube, high enthalpy tunnel	NASA Ames EAST facility	CUBRC, X2 (Australia), HVST (JAXA), ESTHER (Lisbon), T6 (Oxford), University of Queensland
7.6101	Emission spectroscopy from VUV to IR				Emission spectroscopy	Shock tube, high enthalpy tunnel		
7.6102	Multi-temperature measurements				Emission & absorption spectroscopy	Shock tube, high enthalpy tunnel		
7.62	Shock Radiation-TPS interactions	(10) high-enthalpy kinetics, (12) Radiative heating, (15) TSP response and characterization (16) CFD development and validation						
7.6201	Reflectivity and Transmission Measurements		Measure sample reflectance and transmittance in laboratory apparatus	Wavelength, Temperature	Reflectance/Transmittance	Characterization Lab	Materials Characterization Lab (ARC)	SWRI, other vendors
7.6202	High Power Illumination Testing			Wavelength, Heat Flux/Fluence		High powered lasers, lamp banks, focused radiation sources	LEAF, JSC Radiant Heating Facility	LHEML, Sandia Solar Power Tower

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.63	Kinetic models for planetary atmospheres	(5) Flow field characterization, (10) high-enthalpy kinetics, (12) Radiative heating, (15) TSP response and characterization (16) CFD development and validation	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6301	Objectives TBD							
7.6302	Objectives TBD							
7.64	Kinetic models for propulsion system products	(5) Flow field characterization, (10) high-enthalpy kinetics, (12) Radiative heating, (15) TSP response and characterization (16) CFD development and validation	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6401	Objectives TBD							
7.6402	Objectives TBD							
7.65	Kinetic models for ablation products	(5) Flow field characterization, (10) high-enthalpy kinetics, (12) Radiative heating, (15) TSP response and characterization (16) CFD development and validation	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6501	Objectives TBD							
7.6502	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.66	Shock layer non-equilibrium thermochemistry	(5) Flow field characterization, (10) high-enthalpy kinetics, (12) Radiative heating, (14) Electromagnetic environments, (16) CFD development and validation	Perform experiments in shock tubes at different velocities (enthalpies), mixtures and densities to test reaction rate models	Temperature (enthalpy), collision time (pressure, density), gas mixture	See subcategories	Shock tube, high enthalpy tunnel	EAST, mini-Arc	Other shock tubes (see 7.61) or reacting flow environments such as plasma torches or plasma wind tunnels
7.6601	Emission spectroscopy from VUV to IR	(12) Radiative heating, (16) CFD development and validation	See 7.66	See 7.66	Emission spectroscopy	Shock tube, high enthalpy tunnel	See 7.66	See 7.66
7.6602	Multi-temperature measurements	(12) Radiative heating, (16) CFD development and validation	See 7.66	See 7.66	Emission & absorption spectroscopy	Shock tube, high enthalpy tunnel	See 7.66	See 7.66
7.6603	Population measurements	(12) Radiative heating, (16) CFD development and validation	See 7.66	See 7.66	Raman spectroscopy, CARS, laser spectroscopy	Shock tube, high enthalpy tunnel	See 7.66	See 7.66
7.6604	Electron number density	12) Radiative heating, (14) Electromagnetic environments, (16) CFD development and validation	See 7.66	See 7.66	Microwave interferometry	Shock tube, high enthalpy tunnel	See 7.66	See 7.66
7.67	Surface catalysis effects	(4) Convective aeroheating, (5) Flow field characterization, (10) high-enthalpy kinetics, (15) TSP response and characterization, (16) CFD development and validation	This test requires a heated model, which has been achieved by various researchers by passing a large current through an electrically resistive model. Because the free-stream velocity must be high enough to produce shock layer chemistry, these tests require a high enthalpy facility such as a shock tube or expansion tube.	Primarily free-stream velocity, density, atmospheric composition, and wall temperature. The geometry can be something simple like a sphere.	Various measurement techniques could be used to determine the catalytic efficiency, the simplest of which would simply obtain heat transfer measurements, using sensitive IR temperature measurements, to various models and determine the catalytic efficiency by tuning the model to the data. Other more sophisticated techniques could apply emission spectroscopy to measure N2, NO, C2, CO, CO2, or CN radiation profiles near the surface, which could be used to tune catalycity models.	Shock tube, high enthalpy tunnel	No NASA facilities are adequate.	CUBRC or University of Queensland
7.6701	Objectives TBD							
7.6702	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.7	**Multi-phase Flows and gas/solid interactions**							
7.71	Transpiration cooling (for non-ablators)	(3) Boundary-layer characterization, (4) Convective aeroheating, (5) Flow field characterization, (16) CFD Development and Validation	Spatially resolved steady surface pressure measurements upstream, within, and downstream of the transpiration cooling region. Advanced diagnostics to extract unsteady off-body velocity components and relevant scalars (temperature and/or coolant species) in sufficient quantity to compute 1st and 2nd-order statistics. Surface temperature and heat transfer	Mach number, dynamic pressure, porous area fraction, coolant flow rate	Off-body quantitative diagnostics for velocity field (PLIF, PIV) and scalar properties (CARS, Raman Spectroscopy) needed to quantify coolant mixing within the boundary layer. New diagnostics capable of measuring temperature and velocity simultaneously needed to directly validate models for the Reynolds heat flux vector. Global and/or discrete sensor measurements of pressure levels using pressure taps, kulites, and/or PSP. Spatial thermocouple and/or total heat flux measurements. Optical heating measurements such as IR thermography.	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT	AEDC Tunnel 9, AEDC VKF, CUBRC LENS, and variety of academic facilities
7.7101								
7.7102								

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.72	Massive injection/blowing for aerodynamic control or aeroheating mitigation	(3) Boundary-layer characterization, (4) Convective aeroheating, (5) Flow field characterization, (16) CFD Development and Validation	Spatially resolved steady surface pressure measurements upstream, within, and downstream of the fluid injection location. High frequency pressure measurements in vicinity of the fluid injection location. Advanced diagnostics to extract unsteady off-body velocity components and relevant scalars (temperature and/or coolant species) in sufficient quantity to compute 1st and 2nd-order statistics. Surface temperature and heat transfer	Mach number, dynamic pressure, injectant dynamic pressure and flow rate	Off-body quantitative diagnostics for velocity field (PLIF, PIV) and scalar properties (CARS, Raman Spectroscopy) needed to quantify flow structure in the injectant region. Global and/or discrete sensor measurements of pressure levels using pressure taps, kulites, and/or PSP. Spatial thermocouple and/or total heat flux measurements. Optical heating measurements such as IR thermography.	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT	AEDC Tunnel 9, AEDC VKF, CUBRC LENS, and variety of academic facilities
7.7201	Objectives TBD							
7.7202	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.73	Particle flow subject to phase change	(5) Flow field characterization, (12) Radiative heating, (16) CFD Development and Validation	Particle injection into freestream over test articles with variable mass loading. Flight enthalpy and/or models heated to flight temperature. Pre-test characterization of particle simulant shape and size distributions. Optical measurements of particle distributions in flow and effect on flow structure (e.g. shocks, transition). Surface pressure and heat transfer measurements. In situ and/or post-test measurements of surface recession.	Mach number, dynamic pressure, particle shape and size distributions (pre-test and in test), particle mass loading, model temperature.	Pitot, pressure transducers, co-axial thermocouples and/or heat flux gauges, optical (Schlieren/shadowgraph, background-oriented Schlieren, PIV), pre and post-test laser scans and micrographs of material erosion.	Hypersonic wind tunnel; arc jet; lab-scale apparatus for characterization of microscale effect of particle impacts	LAL; Ames arc jets; HYMETS	Various university lab-scale apparatus; TAMU; HET; Arc jets in construction at U Illinois/CHESS labs. DLR L2K arc jet
7.7301	Objectives TBD							
7.7302	Objectives TBD							
7.8	**Rarefied flow**							
7.81	Free molecule flow aerodynamics	(5) Flow field characterization, (16) CFD Development and Validation, (20) Rarefied aerodynamics	Measure forces and moments on scale models and any heat transfer if possible	Mach number, accommodation coefficient (if possible), surface temperatures.	Force and moment measurements	Vacuum chambers	NASA Glenn Vacuum Chamber	Vacuum facility VU-1 (Saint-Petersburg State University)
7.8101	Objectives TBD							
7.8102	Objectives TBD							
7.82	Rarefied aerodynamics and aeroheating	(5) Flow field characterization, (16) CFD Development and Validation, (20) Rarefied aerodynamics	Force and moment measurements on models (global) as well as spatially resolved pressure and temperature (heating) measurements.	Knudsen number, Mach number, accommodation coefficient (if possible), surface temperatures.	Surface (pressure/heating) and flow-field (translational/rotational/vibrational/electronic temperature) measurements	Vacuum chambers, hypersonic facilities	NASA Glenn Vacuum Chamber	MARHy tunnel (France), V2G tunnel (DLR Gottingen), HRWT (JAXA)
7.8201	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.8202	Objectives TBD							
7.83	Mixed regime flows	(5) Flow field characterization, (16) CFD Development and Validation, (20) Rarefied aerodynamics	Force and moment measurements on models (global) as well as spatially resolved pressure and temperature (heating) measurements. Measurement of off-body non-equilibrium measurements. Near-body velocity and temperature measurements to determine slip-effects.	Knudsen number, Mach number, accommodation coefficient (if possible), surface temperatures, free stream enthalpy to compare non-equilibrium temperatures and chemistry.	Surface (pressure/heating) and flow-field (translational/rotational/vibrational/electronic temperature) measurements	Hypersonic facilities	LaRC Mach 10 Tunnel	Variety of academic and DoD facilities
7.8301	Objectives TBD							
7.8302	Objectives TBD							
7.84	Internal flow through porous microstructure	(5) Flow field characterization, (16) CFD Development and Validation, (20) Rarefied aerodynamics						
7.8401	Objectives TBD							
7.8402	Objectives TBD							
7.8403	Objectives TBD							
7.9	**Miscellaneous**							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.91	"Free-flight" CFD simulations of vehicle dynamics	(2) Supersonic aerodynamics, (5) Flow field characterization, (6) Propulsion system flow path interactions, (7) RCS performance and interactions, (8) retropropulsion performance and interactions, (9) Fluid-structures interactions, (16) CFD development and validation, (18) Transonic Aerodynamics	Free Flight: Trajectory reconstruction of free flying models using a) Position/orientation data from ground-based cameras in instrumented range, b) onboard rate, acceleration, pressure sensors. Tunnel: dynamic strain gage balance	Mach number, oscillation amplitude, vehicle geometry, reduced frequency, Reynolds number, nozzle expansion ratio, nozzle exit pressure ratio	Free flight: Image or radar measurement of model position and orientation vs. time, body rates and accelerations, body surface pressures, time. Sting supported tunnel: dynamic force/moment histories.	Ballistic range, free or forced oscillation tunnel	Langley: TDT, UPWT, Ames: HFFAF, UPWT	Test and Evaluation Facility and Transonic Range at US Army Research Laboratory, Aberdeen MD
7.9101	Objectives TBD							
7.9102	Objectives TBD							
7.92	Passive vehicle dynamics	(1) Hypersonic Aerodynamics, (2) Supersonic aerodynamics, (3) Boundary-layer characterization, (5) Flow field, (16) CFD development and validation	Free Flight: Trajectory reconstruction of free flying models using a) Position/orientation data from ground-based cameras in instrumented range, b) onboard rate, acceleration, pressure sensors. Tunnel: dynamic strain gage balance	Mach number, oscillation amplitude, vehicle geometry, reduced frequency, Reynolds number	Free flight: Image or radar measurement of model position and orientation vs. time, body rates and accelerations, body surface pressures, time. Sting supported tunnel: dynamic force/moment histories.	Ballistic range, vertical spin tunnel, free or forced oscillation tunnel	Langley: VST, TDT, UPWT, Ames: HFFAF, UPWT	Test and Evaluation Facility and Transonic Range at US Army Research Laboratory, Aberdeen MD
7.9201	Objectives TBD							
7.9202	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.93	Vehicle trim	(1) Hypersonic Aerodynamics, (2) Supersonic aerodynamics, (3) Boundary-layer characterization, (5) Flow field characterization, (16) CFD development and validation	Schlieren for flow structure visualization. Spatially resolved steady surface pressure measurements. Direct force and moment measurements.	Mach number, angle-of-attack, Reynolds number	Oil flow to visualize recirculation patterns. Global and/or discrete sensor measurements of pressure levels using pressure taps and/or PSP.	Hypersonic and/or supersonic wind tunnels	LAL, LaRC UPWT, GRC 10x10	Variety of academic and DoD facilities
7.9301	Objectives TBD							
7.9302	Objectives TBD							
7.94	Stagnation region flow field prediction	1, 3, 4, 5, 10, 16 (1) Hypersonic Aerodynamics, (3) Boundary-layer characterization, (4) Convective aeroheating (5) Flow field characterization, (10) High-enthalpy kinetics, (16) CFD development and validation	Non-intrusive velocity and temperature measurements along stagnation streamline. High-speed, 3D shock location visualization. Unsteady free stream characterization including thermal energy state distributions. High frequency surface heat transfer measurements. High frequency boundary layer state measurements.	Mach number, stagnation pressure, stagnation temperature, gas composition, and their boundary layer profiles - pure nitrogen and Mars simulant are desired in addition to air. Surface blowing rates and chemical composition.	Three-dimensional laser velocimetry and temperature measurements; high frequency velocity and heat transfer measurements; spectral species concentration and thermal state distribution measurements.	Hypersonic wind tunnels, shock tube, high enthalpy tunnel	LAL, EAST	
7.9401	Measure 3-D shock shapes in Martian, Venusian, and other planet atmospheric compositions (principally carbon dioxide)	?	Flow field visualization	Gas composition and Reynolds number	Optical techniques	wind tunnel and shock tube		CUBRC
7.9402	Resolve the so-called stagnation point heat transfer anomaly		High frequency and high accuracy heat transfer gauges	Mach and Reynolds number	high accuracy gauges	wind tunnel	LAL	
7.9403	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
7.95	Aero-optics	(5) Flow field characterization, (13) Aero-optical environments, (16) CFD development and validation				Hypersonic wind tunnels, shock tube, high enthalpy tunnel		
7.9501	Objectives TBD							
7.9502	Objectives TBD							
7.96	Magneto-hydro dynamics	(1) Hypersonic aerodynamics, (4) Convective heating, (5) Flow field characterization, (14) Electromagnetic environments, (16) CFD development and validation						
7.9601	Objectives TBD							
7.9602	Objectives TBD							

Table 56. Test Requirements for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7	**Modeling and Simulation Code Development and Validation**							
7.1	**Wakes and separated flows**							
7.11	Unsteady, massively-separated hypersonic wake flows	Supersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required. Hypersonic facilities capable of enthalpies relevant to the true thermochemical environment required to validate high temperature effects. Long duration tunnels required for many off-body diagnostic techniques.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions is expected to take multiple months.	Measure static and dynamic surface pressures (pressure taps, Kulites, PSP), substantial optical access for advanced off-body flow diagnostics (velocity). Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access for thermal tomography, and/or surface temperature/pressure sensitive paint measurements.	Non-rigid structure causing shear layer dynamics (inflatables), metal models with thermal protection and relevant roughness patterns
7.1101	Aeroshell back-face and vehicle payload measurements of heating distributions	Hypersonic facilities capable of enthalpies relevant to the true thermochemical environment required to validate high temperature effects. Optical access required for thermal tomography.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Time to fully map out the validation information required (using a validation-centric test approach) to provide surface heating measurements and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple weeks.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Time to fully map out the validation information required (using a validation-centric test approach) to provide surface heating measurements and necessary measurements for all CFD boundary conditions is expected to take multiple weeks.	Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access required for thermal tomography, and/or TSP measurements.	Non-rigid structure causing shear layer dynamics (inflatables), metal models with thermal protection and relevant roughness patterns

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.1102	Aeroshell back-face and vehicle payload measurements of pressure distributions and wake/payload effects on aerodynamics	Supersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required. Hypersonic facilities capable of enthalpies relevant to the true thermochemical environment required to validate high temperature effects. Optical access required if pressure sensitive paint is used for surface resolved pressure measurements.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Time to fully map out the validation information required (using a validation-centric test approach) to provide surface pressure measurements and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple weeks.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Time to fully map out the validation information required (using a validation-centric test approach) to provide surface pressure measurements and necessary measurements for all CFD boundary conditions is expected to take multiple weeks.	Measure surface static and dynamic pressures (pressure taps, Kulites, PSP). Optical access required for PSP.	Non-rigid structure causing shear layer dynamics (inflatables), metal models with thermal protection and relevant roughness patterns
7.1103	Wake flow structure visualization	Supersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required. Hypersonic facilities capable of enthalpies relevant to the true thermochemical environment required to validate high temperature effects. Long duration tunnels required for the diagnostic techniques used to make nonintrusive off-body flow field measurements.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions is expected to take multiple months.	Advanced off-body flow diagnostics needed to measure instantaneous velocity values in sufficient quantity to extract 1st and 2nd order statistics in the wake and recirculation regions behind the aeroshell. Substantial optical access required to make these measurements.	Non-rigid structure causing shear layer dynamics (inflatables), metal models with thermal protection and relevant roughness patterns

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.12	Aftbody / wake flow influence on supersonic dynamics	Long duration supersonic facilities (Mach 1.0 up to 4.0) with forced oscillation test capability, dynamic & static force/moment measurements and Schlieren	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment as well as forced oscillation frequencies for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment as well as forced oscillation frequencies for the mission of interest (specific points that lead to this TBD)	To fully map out the validation information required (using a validation-centric test approach) would be difficult in ballistic range testing, but data spanning the operational space of interest can potentially be obtained in a single test with multiple launches attempted to address repeatability.	Static and dynamic strain gauge balances, high frequency flush mounted pressure transducers, traditional static pressure taps, and/or PSP, Schlieren imaging	Standard model fabrication and microphone/static pressure transducer installation
7.1201	Objectives TBD							
7.1202	Objectives TBD							
7.13	Parachute modeling	Long duration supersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required.	Minimum relevant Mach number is probably around 2. Bigger issue is tunnel scale. Require sufficient canopy size to achieve measurable deformation and strain. Will still not replicate flight but can provide useful validation data.	Complex tests that will require about 1 month of facility time for setup and execution.	Smaller facilities can be used for shakedown tests, but smaller canopy size limits utility of results unless we can develop novel materials that mimic flight article at smaller scale.	Complex tests that will require about 1 month of facility time for setup and execution.	Optical access is the most critical aspect, as photogrammetry is the most reliable mechanism currently for measuring deformation. Can be doubled up to provide PIV.	Canopy articles require specialized fabrication that should be contracted out for serious tests.
7.1301	Objectives TBD							
7.1302	Objectives TBD							
7.2	**Shock-Shock and Shock-BL Interactions**							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.21	Multi-body separation interactions	Long duration supersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required. High-pressure air (high-pressure air) simulation capability required for plume simulation (if present). Other simulant gas capability may be desirable.	Test points that populate the specific Mach number and Reynolds number flight environment for the mission of interest (specific points that lead to this TBD)	Complex tests that will require about 1-2 months of facility time for setup and execution.	Test points that populate the specific Mach number and Reynolds number flight environment for the mission of interest (specific points that lead to this TBD)	Complex tests that will require about 1-2 months of facility time for setup and execution.	Force-and-moment balances, static surface pressures (PSP), optical access for advanced off-body flow diagnostics (e.g. velocity).	Metal models with interchangeable parts, and possibly with internal flow paths to nozzles.
7.2101	Objectives TBD							
7.2102	Objectives TBD							
7.22	Shock/shock and shock/boundary-layer interactions	Supersonic facilities and hypersonic facilities (true enthalpy capabilities required to validate high temperature effects). Optical access required for off-body flow visualization and diagnostics, PSP, and thermal tomography.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Substantial optical access for advanced off-body flow diagnostics (velocity and/or scalars). Measure static and dynamic surface pressures (pressure taps, Kulites, PSP). Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access for thermal tomography, and/or surface temperature/pressure sensitive paint measurements.	Metal models (possibly with thermal protection)

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.2201	Characterize supersonic perfect gas shock/shock interactions.	Supersonic aerodynamic facilities. Optical access required for off-body flow visualization and diagnostics.	Test points that populate the specific Mach number range for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number range for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Substantial optical access for advanced off-body flow diagnostics for quantitative velocity field measurements.	Metal models
7.2202	Characterize hypersonic perfect gas shock/shock interactions.	Hypersonic aerodynamic facilities. Optical access required for off-body flow visualization and diagnostics.	Test points that populate the specific Mach number range for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number range for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Substantial optical access for advanced off-body flow diagnostics for quantitative velocity field measurements.	Metal models
7.2203	Characterize hypersonic nonequilibrium gas shock/shock interactions.	Hypersonic facilities capable of simulating true flight enthalpy conditions. Optical access required for off-body flow visualization and diagnostics.	Test points that populate the specific Mach number and flight enthalpy environment for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number and flight enthalpy environment for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Substantial optical access for advanced off-body flow diagnostics for quantitative velocity field measurements and scalar measurements to quantify thermo-chemical non-equilibrium effects.	Metal models (possibly with thermal protection)

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.2204	Characterize shock-BL interactions	Supersonic facilities and hypersonic facilities (true enthalpy capabilities required to validate high temperature effects). Optical access required for off-body flow visualization and diagnostics, PSP, and thermal tomography.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD).	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Substantial optical access for advanced off-body flow diagnostics (velocity and/or scalars). Measure static and dynamic surface pressures (pressure taps, Kulites, PSP). Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access for thermal tomography, and/or surface temperature/pressure sensitive paint measurements.	Metal models (possibly with thermal protection)
7.2205	Shock/BL interactions, flow fields around local surface features	Supersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required. Hypersonic facilities capable of enthalpies relevant to the true thermochemical environment required to validate high temperature effects. Long duration tunnels required for many off-body diagnostic techniques.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment that impacts the protuberance for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest near the protuberance and necessary measurements to characterize the upstream boundary layer for CFD boundary condition specification, the test time is expected to take at least a month.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment that impacts the protuberance for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest near the protuberance and necessary measurements to characterize the upstream boundary layer for CFD boundary condition specification is expected to take at least a month.	Measure static and dynamic surface pressures (pressure taps, Kulites, PSP) and surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) in the vicinity of the protuberance. Optical access required for thermal tomography, and/or surface temperature/pressure sensitive paint measurements. Advanced off-body flow diagnostics needed to measure instantaneous velocity values in sufficient quantity to extract 1st and 2nd order statistics in vicinity of the protuberance (optical access required).	Metal models with thermal protection
7.2206	Objectives TBD							
7.2207	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.3	**Propulsion System Performance, Interactions and Integration**							
7.31	RCS performance	Supersonic/Hypersonic conditions over a range of Reynolds numbers. Propulsion simulation capability with high-pressure air or other simulant gas, with ability to control pressure, temperature, mass flow rate.	Multiple combinations of Mach number, angle of attack, angle of sideslip, RCS jet location on model, nozzle pressure ratio, and control surface deflection (if control surfaces would be influenced by RCS plumes).	2-4 weeks	Multiple combinations of Mach number, angle of attack, angle of sideslip, RCS jet location on model, nozzle pressure ratio, and control surface deflection (if control surfaces would be influenced by RCS plumes).	1-3 weeks	force balance measurements, multi-channel pressure measurements, high-speed data system (tens of kHz range), high-speed schlieren imagery, laser diagnostics including optical windows on test section and plume seeding, infrared imaging.	Metallic model fabrication with high pressure plenum and internal plumbing for nozzles. Wire or plunge electrical discharge machining (EDM) capability to accurately fabricate small-scale nozzles for wind tunnel models.
	Objectives TBD							
	Objectives TBD							
7.32	Retropropulsion performance	Mach and Reynolds number, total enthalpy for aeroheating, secondary high-pressure gas delivery for engines, optical access for PSP/TSP, schlieren.	Test points that populate the specific Mach number, Reynolds number, nozzle exit pressure ratio, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements of the plume interaction region and necessary measurements for all CFD boundary conditions. The test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, nozzle exit pressure ratio, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements of the plume interaction region and necessary measurements for all CFD boundary conditions. The test time is expected to take multiple months.	Measure static and dynamic surface pressures (pressure taps, Kulites, PSP), high speed schlieren for unsteady plume interaction imagery, substantial optical access for advanced off-body flow diagnostics (velocity). Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access for thermal tomography, and/or surface temperature/pressure sensitive paint measurements.	Metal models with internal flow paths to engines.
7.3201	Objectives TBD							
7.3202	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.33	Propulsion system inlet operability	Supersonic and hypersonic facilities capable of simulating the Mach and Reynolds number environment for these applications. Full inlet/isolator testing also requires the ability to vary freestream conditions during the course of a single test. Long duration tunnels required to provide temporal histories of start/unstart transitions.	Test points that populate the specific Mach number, Reynolds number and angle of attack/sideslip variability expected in flight (specific points that lead to this TBD). Engine mode transition test points are also required. Inlet operability limit test points are required but have to be determined by testing through a range of Mach/alpha/beta for a specific inlet contraction ratio. The ability to vary the isolator back pressure during a test is also required to determine the isolator backpressure operability limit.	To fully map out the validation information required in a continuous flow facility (using a validation-centric test approach) is expected to take several weeks (3-10) per inlet/isolator configuration.	Test points that populate the specific Mach number, Reynolds number and angle of attack/sideslip variability expected in flight (specific points that lead to this TBD). The ability to vary the isolator back pressure during a test is also required.	To fully map out the validation information required in a continuous flow facility (using a validation-centric test approach) is expected to take several weeks (3-10) per inlet/isolator configuration.	Measure static and dynamic surface pressures (pressure taps, Kulites) and surface temperatures/heat transfer (thermocouples, heat transfer gauges, TSP) and/or surface shear along surfaces upstream of the inlet entrance (optical access required for TSP if used for this purpose). Mass flow meters required to accurately measured captured mass flow rate and any amount of flow removed by boundary layer bleed systems. Pitot rakes required for quantifying total pressure recovery and state of distortion entering the inlet and/or isolator.	Metal models (possibly with multiple moving parts). High temperature seals for testing above Mach 6.
7.3301	Objectives TBD							
7.3302	Objectives TBD							
7.4	**Transition and Turbulence**							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.41	Turbulence modeling	Supersonic facilities capable of simulating the Mach and Reynolds number environment of the given mission application. Hypersonic facilities capable of enthalpies relevant to the true thermochemical environment required to validate high temperature effects. Long duration tunnels required for many off-body diagnostic techniques.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions. The test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions. The test time is expected to take multiple months.	Measure static and dynamic surface pressures (pressure taps, Kulites, PSP), substantial optical access for advanced off-body flow diagnostics (velocity and possibly scalars when high temperature effects are desired). Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access for thermal tomography, and/or surface temperature/pressure sensitive paint measurements.	Metal models (possibly with thermal protection)
7.4101	Attached boundary-layers on smooth surfaces	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4102	Attached boundary-layers on rough surfaces	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4103	Separated shear layers and wakes	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4104	Boundary-layers with blowing and/or ablation	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.42	Boundary-layer transition due to instability mechanisms	Sufficient Mach and Reynolds number ranges to produce transition for problem of interest under flight-relevant disturbance environment	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Multiple operating points with statistical repeatability and known ground-to-flight scalability	Months per specific mission/vehicle type	Global optical or highly spatially-resolved surface heating / pressure / temperature instrumentation. Laser-based flow field measurements	Models with precision surface quality
7.4201	As per 7.42 with focus on first-mode transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4202	As per 7.42 with focus on second-mode transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4203	As per 7.42 with focus on crossflow transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4204	As per 7.42 with focus on multiple-mode interactions	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.4205	As per 7.42 with focus on ablative surfaces	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4206	As per 7.42 with focus on shock-shock and shock-BL transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.43	Boundary-layer transition due to bypass mechanisms	Sufficient Mach and Reynolds number ranges to produce transition for problem of interest under flight-relevant disturbance environment	Multiple operating points with statistical repeatability. Multiple roughness scales and known ground-to-flight scalability	Months per specific mission/vehicle/TPS type	Multiple operating points with statistical repeatability. Multiple roughness scales and known ground-to-flight scalability	Months per specific mission/vehicle/TPS type	Global optical or highly spatially-resolved surface heating / pressure / temperature instrumentation. Laser-based flow field measurements	Models with precision surface quality
7.4301	As per 7.43 with focus on Block-TPS Fence/Gap effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4302	As per 7.43 with focus on Woven TPS pattern effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4303	As per 7.43 with focus on ablated hex comb pattern TPS effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4304	As per 7.43 with focus on distributed sand grain TPS effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4305	As per 7.43 with focus on isolated surface features such as pads, antennas, thruster ports, window, TPS damage sites	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.44	Boundary-layer transition control	Sufficient Mach and Reynolds number ranges to produce transition for problem of interest under flight-relevant disturbance environment	Multiple operating points with statistical repeatability. Multiple roughness scales and known ground-to-flight scalability	Months per specific mission/vehicle/TPS type	Multiple operating points with statistical repeatability. Multiple roughness scales and known ground-to-flight scalability	Months per specific mission/vehicle/TPS type	Global optical or highly spatially-resolved surface heating / pressure / temperature instrumentation. Laser-based flow field measurements	Models with precision surface quality
7.4401	Objectives TBD							
7.4402	Objectives TBD							
7.5	**Surface / Flow field Interactions**							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.51	FSI for rigid structures	Supersonic facilities capable of simulating the Mach number and load environment encountered by the structure. Hypersonic facilities capable of enthalpies relevant to the true thermochemical environment required to validate high temperature effects (FTSI). Long duration tunnels required.	Test points that populate the specific Mach number and flight enthalpy environment for the mission of interest (specific points that lead to this TBD and dependent on specific FSI application, e.g., flutter, BLT, buckling, structural plasticity, etc.).	Depends on the density of diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide pressure and thermal loads, surface deformation and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number and flight enthalpy environment for the mission of interest (specific points that lead to this TBD and dependent on specific FSI application, e.g., flutter, BLT, buckling, structural plasticity, etc.).	Depends on the density of diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide pressure and thermal loads, surface deformation and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Measure static and dynamic surface pressures (pressure taps, Kulites, PSP), optical access for high speed schlieren flow visualization. Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access for thermal tomography, and/or surface temperature/pressure sensitive paint measurements. High speed capacitive distance sensors to measure dynamic surface deformation	Metal models, possibly with thermal protective coating or actively cooled. Composite models if FSI intended for non-metal components.
7.5101	Objectives TBD							
7.5102	Objectives TBD							
7.52	FSI for inflatable/deployable structures							
7.5201	Objectives TBD							
7.5202	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.53	TPS response and ablation modelling	Long duration (minutes). High enthalpy (10+ MJ/kg). Model scale ~1 ft. Clean freestream (not vitiated air). Should be able to use real materials. Air, CO2, H2/He, and methane test gas. Range of pressure to get equilibrium and non-equilibrium effects. Need ability to obtain subsonic and supersonic edge conditions	Mission dependent	Model validation for the collection of physics associated with this item could utilize the hypothetical facility for on the order of 5 years for model development and validation. Low enthalpy tests could be accomplished in existing non-NASA facilities for ~4 months per flight project	Mission dependent	Model validation for the collection of physics associated with this item could utilize the hypothetical facility for on the order of 5 years for model development and validation. Low enthalpy tests could be accomplished in existing non-NASA facilities for ~4 months per flight project	Heat flux (discrete and global). Pressure. Photogrammetry. Spectroscopy in the boundary layer (300-1000nm). Pyrometry. IR thermography.	No novel capabilities necessary. Ability to machine and integrate real TPS materials (ablators and non-ablators) into test fixtures. Low-enthalpy testing (ala CUBRC) needs standard machining, EDM, laser etching.
7.5301	Objectives TBD							
7.5302	Objectives TBD							
7.54	Massive ablation aero/heating/shape change effects	For capsule testing, ~2ft model diameter will be necessary to meaningfully scale small geometric features such as seams between ablator blocks. Need ability to obtain laminar and turbulent flow at the 2 ft scale. Test times on order of minutes. Total temperature requirements are low (~800K), but pressure dependence should also be noted. Phase diagram below...	Mission dependent	Model validation for the collection of physics associated with this item could utilize the hypothetical facility for on the order of 5 years for model development and validation. Low enthalpy tests could be accomplished in existing non-NASA facilities for ~4 months per flight project	Mission dependent	Model validation for the collection of physics associated with this item could utilize the hypothetical facility for on the order of 5 years for model development and validation. Low enthalpy tests could be accomplished in existing non-NASA facilities for ~4 months per flight project	Heat flux (discrete and global). Pressure. Photogrammetry. Spectroscopy in the boundary layer (300-1000nm). Pyrometry. IR thermography.	No novel capabilities necessary. Ability to machine and integrate real TPS materials (ablators and non-ablators) into test fixtures. Low-enthalpy testing (ala CUBRC) needs standard machining, EDM, laser etching.
7.5401	Objectives TBD							
7.5402	Objectives TBD							
7.6	**Thermophysical and Radiative Properties**							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.61	Flow field radiation	Velocity and density range to replicate areas of heating concern during entry. Test time must exceed several microsec	Mission dependent, informed by trajectories and streamline analyses	Full year occupancy given the breadth of entry scenarios at play for NASA	Cross-validation of selected test points (second source data)	As available	spectrometers that cover the wavelength range required for the mission of interest. Optical access for the spectrometers into the shock-tunnel, and a vacuum path if the vacuum-ultraviolet wavelength range is to be measured, Cameras, Optics, Vacuum systems and pumps	N/A
7.6101	Emission spectroscopy from VUV to IR							
7.6102	Multi-temperature measurements							
7.62	Shock Radiation-TPS interactions							
7.6201	Reflectivity and Transmission Measurements	Wavelengths relevant for radiation (100-10,000nm)	NA	NA	NA	NA	NA	Extinction measurements require transmission through thinly sliced samples
7.6202	High Power Illumination Testing	50-1000 W/cm2?	NA	NA	NA	NA	NA	NA
7.63	Kinetic models for planetary atmospheres	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6301	Objectives TBD							
7.6302	Objectives TBD							
7.64	Kinetic models for propulsion system products	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6401	Objectives TBD							
7.6402	Objectives TBD							
7.65	Kinetic models for ablation products	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6501	Objectives TBD							
7.6502	Objectives TBD							
7.66	Shock layer non-equilibrium thermochemistry	Temperature 3000-30,000K	NA	see 7.61	see 7.61	see 7.61	see 7.61	see 7.61
7.6601	Emission spectroscopy from VUV to IR	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66
7.6602	Multi-temperature measurements	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.6603	Population measurements	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66
7.6604	Electron number density	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66	See 7.66
7.67	Surface catalysis effects	This test requires a heated model, which has been achieved by various researchers by passing a large current through an electrically resistive model. Because the free-stream velocity must be high enough to produce shock layer chemistry, these tests require a high enthalpy facility such as a shock tube or expansion tube.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the problem of interest.	Test points that populate the specific Mach number, Reynolds number, and flight enthalpy environment for the mission of interest (specific points that lead to this TBD)	Depends on the problem of interest.	Various measurement techniques could be used to determine the catalytic efficiency, the simplest of which would simply obtain heat transfer measurements, using sensitive IR temperature measurements, to various models and determine the catalytic efficiency by tuning the model to the data. Other more sophisticated techniques could apply emission spectroscopy to measure N2, NO, C2, CO, CO2, or CN radiation profiles near the surface, which could be used to tune catalycity models.	Model should have a simple geometry and must be fabricated with materials appropriate to achieve a heated surface.
7.6701	Objectives TBD							
7.6702	Objectives TBD							
7.7	**Multi-phase Flows and gas/solid interactions**							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.71	Transpiration cooling (for non-ablators)	Hypersonic/Supersonic aerodynamic facilities. Secondary fluid system needed for coolant. Optical access required for off-body flow visualization and diagnostics.	Test points that populate the specific Mach number, Reynolds number, and range of coolant conditions needed for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, and range of coolant conditions needed for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Substantial optical access for advanced off-body flow diagnostics (velocity and/or scalars). Measure static and dynamic surface pressures (pressure taps, Kulites, PSP). Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access for thermal tomography, and/or surface temperature/pressure sensitive paint measurements.	Metal models (with thermal protection if tested in true enthalpy environment)
7.7101								
7.7102								
7.72	Massive injection/blowing for aerodynamic control or aeroheating mitigation	Hypersonic/Supersonic aerodynamic facilities. Secondary fluid system needed for injectant. Optical access required for off-body flow visualization and diagnostics.	Test points that populate the specific Mach number, Reynolds number, and range of injectant conditions needed for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, Reynolds number, and range of coolant conditions needed for the mission of interest (specific points that lead to this TBD)	Depends on the diagnostics employed, but to fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Substantial optical access for advanced off-body flow diagnostics (velocity and/or scalars). Measure static and dynamic surface pressures (pressure taps, Kulites, PSP). Measure surface temperatures and heat transfer (thermocouples, heat transfer gauges, TSP) and optical access for thermal tomography, and/or surface temperature/pressure sensitive paint measurements.	Metal models (with thermal protection if tested in true enthalpy environment)
7.7201	Objectives TBD							
7.7202	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.73	Particle flow subject to phase change	Hypersonic facilities capable of replicating some combination of flight Mach/dynamic pressure/enthalpy. Particle injection capability. Optical access for diagnostics.	Test points that populate the specific Mach number, dynamic pressure, and/or enthalpies needed to replicate trajectories near peak heating of Mars missions of interest, e.g. Sample Retrieval Lander and Human Mars architectures for reference.	1-2 months not accounting for effort to implement and verify test capability.	Test points that populate the specific Mach number, dynamic pressure, and/or enthalpies needed to replicate trajectories near peak heating of Mars missions of interest, e.g. Sample Retrieval Lander and Human Mars architectures for reference.	1-2 months not accounting for effort to implement and verify test capability.	Optical access for optical diagnostics; pressure and thermal measurements.	Thermal protection materials bonded to substructure with embedded pressure and thermal gauges.
7.7301	Objectives TBD							
7.7302	Objectives TBD							
7.8	**Rarefied flow**							
7.81	Free molecule flow aerodynamics	Kn > 10 (altitudes above 100 km)	Test points that populate the range of Mach numbers required. Exact conditions depend on facility (TBD)	Dependent on development time required and test techniques used	Test points that populate the range of Mach numbers required. Exact conditions depend on facility (TBD)	Dependent on development time required and test techniques used	Force and moment balance. Measurements of surface pressure and temperature/heating.	Depends on facility. Possibly metal, ceramic, or plastic.
7.8101	Objectives TBD							
7.8102	Objectives TBD							
7.82	Rarefied aerodynamics and aeroheating	0.25 < Kn < 10 (altitudes above 75 km)	Test points that populate the range of Mach numbers and Knudsen numbers required. Exact conditions depend on facility (TBD)	Dependent on facility. Dependent on development time required and test techniques used	Test points that populate the range of Mach numbers and Knudsen numbers required. Exact conditions depend on facility (TBD)	Dependent on facility. Dependent on development time required and test techniques used	Optical access for off-body measurements. Measurements of surface pressure and temperature/heating.	Depends on facility and operational conditions. Possibly metal, ceramic, or plastic.
7.8201	Objectives TBD							
7.8202	Objectives TBD							
7.83	Mixed regime flows	Kn < 0.25	Test points that populate the range of Mach numbers and Knudsen numbers required. Exact conditions depend on facility (TBD)	Facility dependent, but these tests may likely be able to be piggy-backed on continuum wake-flow experiments for certain flow conditions.	Test points that populate the range of Mach numbers and Knudsen numbers required. Exact conditions depend on facility (TBD)	Facility dependent, but these tests may likely be able to be piggy-backed on continuum wake-flow experiments for certain flow conditions.	Optical access for off-body measurements. Measurements of surface pressure and temperature/heating.	Depends on facility and operational conditions. Possibly metal, ceramic, or plastic.
7.8301	Objectives TBD							
7.8302	Objectives TBD							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.84	Internal flow through porous microstructure							
7.8401	Objectives TBD							
7.8402	Objectives TBD							
7.8403	Objectives TBD							
7.9	**Miscellaneous**							
7.91	"Free-flight" CFD simulations of vehicle dynamics	Subsonic, transonic and supersonic wind tunnels. Instrumented ballistic ranges or outdoor range with radar tracking and telemetry.	Test points that populate the specific Mach number, oscillation amplitudes, and Reynolds number for the mission of interest (specific points that lead to this TBD).	To fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, attitude oscillation amplitudes, and Reynolds number for the mission of interest (specific points that lead to this TBD)	o fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Free flight: Motion capture or orthogonal shadowgraph imaging system, or radar tracking and telemetry recording. Forced Oscillation: Dynamic strain gauge balance	Forced Oscillation Tunnel: metal model fabrication (3d printing or traditional machining), Subsonic Free flight: light weight fiberglass, wood, plastic fabrication, Supersonic Ballistic Range: specialize onboard instrumentation design/fabrication, traditional machining, 3d printed sabot (device to support model during launch).
7.9101	Objectives TBD							
7.9102	Objectives TBD							
7.92	Passive vehicle dynamics	Subsonic, transonic and supersonic wind tunnels. Instrumented ballistic ranges or outdoor range with radar tracking and telemetry.	Test points that populate the specific Mach number, oscillation amplitudes, and Reynolds number for the mission of interest (specific points that lead to this TBD).	To fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Test points that populate the specific Mach number, attitude oscillation amplitudes, and Reynolds number for the mission of interest (specific points that lead to this TBD)	o fully map out the validation information required (using a validation-centric test approach) to provide off-body measurements in the region of interest and necessary measurements for all CFD boundary conditions, the test time is expected to take multiple months.	Free flight: Motion capture or orthogonal shadowgraph imaging system, or radar tracking and telemetry recording. Forced Oscillation: Dynamic strain gauge balance	Forced Oscillation Tunnel: metal model fabrication (3d printing or traditional machining), Subsonic Free flight: light weight fiberglass, wood, plastic fabrication, Supersonic Ballistic Range: specialize onboard instrumentation design/fabrication, traditional machining, 3d printed sabot (device to support model during launch).

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
7.9201	Objectives TBD							
7.9202	Objectives TBD							
7.93	Vehicle trim	Supersonic and hypersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required.	Test points that populate the specific Mach number and Reynolds number for the mission of interest (specific points that lead to this TBD)	1 Day of testing per Mach and Reynolds number combination per facility. Testing in LaRC UPWT would expedite process due to in run variable Mach capability.	Test points that populate the specific Mach number and Reynolds number for the mission of interest (specific points that lead to this TBD)	1 Day of testing per Mach and Reynolds number combination per facility.	Measure static surface pressures (pressure taps, PSP), optical access for surface pressure sensitive paint measurements.	Rigid structure with remote actuated control surfaces.
7.9301	Objectives TBD							
7.9302	Objectives TBD							
7.94	Stagnation region flow field prediction	Supersonic and hypersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required.	Test points that populate the specific Mach number and Reynolds number for the mission of interest (specific points that lead to this TBD)	1 Day of testing per Mach and Reynolds number combination per facility.	Test points that populate the specific Mach number and Reynolds number for the mission of interest (specific points that lead to this TBD)	1 Day of testing per Mach and Reynolds number combination per facility.		Traditional methods.
7.9401	Measure 3-D shock shapes in Martian, Venusian, and other planet atmospheric compositions (principally carbon dioxide)	Supersonic and hypersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required.	Test points that populate the specific Mach number and Reynolds number for the mission of interest (specific points that lead to this TBD)	1 Day of testing per Mach and Reynolds number combination per facility.	Test points that populate the specific Mach number and Reynolds number for the mission of interest (specific points that lead to this TBD)	1 Day of testing per Mach and Reynolds number combination per facility.		Traditional methods.
7.9402	Resolve the so-called stagnation point heat transfer anomaly	Supersonic and hypersonic facilities capable of simulating the Mach and Reynolds number environment of these applications required.	Test points that populate the specific Mach number and Reynolds number for the mission of interest (specific points that lead to this TBD)	1 Day of testing per Mach and Reynolds number combination per facility.	Test points that populate the specific Mach number and Reynolds number for the mission of interest (specific points that lead to this TBD)	1 Day of testing per Mach and Reynolds number combination per facility.		Traditional methods.
7.9403	Objectives TBD							
7.95	Aero-optics							
7.9501	Objectives TBD							
7.9502	Objectives TBD							
7.96	Magneto-hydro dynamics							
7.9601	Objectives TBD							
7.9602	Objectives TBD							

Table 57. Gaps List for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation.

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7	**Modeling and Simulation Code Development and Validation**					
7.1	**Wakes and separated flows**					
7.11	Unsteady, massively-separated hypersonic wake flows	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aero+thermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access for true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics, ability to make near surface measurements (inner portion of boundary layer) is often problematic.	None expected (except possibly inflatable testing)	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat-08
7.1101	Aeroshell back-face and vehicle payload measurements of heating distributions	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aero+thermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Optical access for true flight enthalpy (hypersonic) facilities required for TSP and/or thermal tomography.	None expected (except possibly inflatable testing)	CFD-08, CFD-13, CFD-15, Inst-Heat-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.1102	Aeroshell back-face and vehicle payload measurements of pressure distributions and wake/payload effects on aerodynamics	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aero+thermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Optical access for true flight enthalpy (hypersonic) facilities required for PSP.	None expected (except possibly inflatable testing)	CFD-08, CFD-13, CFD-15
7.1103	Wake flow structure visualization	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aero+thermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access for true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics, ability to make near surface measurements (inner portion of boundary layer) is often problematic.	None expected (except possibly inflatable testing)	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08
7.12	Aftbody / wake flow influence on supersonic dynamics	Optical access is currently insufficient. Wall mounted forced oscillation system (like TDT) could enable many tests that might not be possible with fork-sting forced oscillation balance concepts.	There are customers (Mars, Titan flight projects and game changing ESM) for this type of testing. They can pay for model fab and test time, but it is not known if they have resources for tunnel modifications to enable tests.	Requires forced oscillation system like configuration used in TDT or sting mounted variant. Neither have been developed for LaRC UPWT or similar supersonic wind tunnels. Compact dynamic strain gage balances might need to be developed.	Fork-style forced oscillation sting/model support would require development effort using modern brushless motors and position control with possible active sting-oscillation damping.	CFD-08, CFD-10, CFD-13, CFD-15, Inst-Flow-01
7.1201	Objectives TBD					
7.1202	Objectives TBD					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.13	Parachute modeling	Optical access for larger scale high speed tunnels is almost non-existent. We are not looking to just measure 3 load components. The dynamics of parachutes, and potential for "things" to come apart during testing also pose challenges for operational safety that would need to be addressed.	If we could do these tests, and had the facilities, I think we could find sponsors willing to pay the costs.	Optical access. See other comments for more details.	I think it's best to leave the specialized fabrication of canopies and rigging to the experts, rather than trying to replicate.	CFD-13
7.1301	Objectives TBD					
7.1302	Objectives TBD					
7.2	**Shock-Shock and Shock-BL Interactions**					
7.21	Multi-body separation interactions	LaRC UPWT is currently limited to Mach 4.6. The UPWT TS2 nozzle was designed to operate up to Mach 5.87. An additional air compressor is required for this higher Mach number capability which is very desirable and would eliminate the dependency on AEDC Tunnel A. For NASA, a medium scale (~4 ft) continuous flow Mach 8 and Mach 10 wind tunnel would also eliminate the dependency on AEDC Tunnel B and C.	Access to supersonic/hypersonic test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Flow-thru balances that do not omit axial beam are costly and larger than desirable (and few available). Temperature-compensated PSP required when plume simulation present. Seeding techniques for plumes to enable plume velocity measurements.	None	CFD-04, CFD-13, CFD-15, Inst-Aero-05
7.2101	Objectives TBD					
7.2102	Objectives TBD					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.22	Shock/shock and shock/boundary-layer interactions	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic/hypersonic (aero) and high-enthalpy (aero+thermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access in true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics, ability to make near surface measurements (inner portion of boundary layer) is often problematic.	None	CFD-01, CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat-08
7.2201	Characterize supersonic perfect gas shock/shock interactions.	None	Access to supersonic test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	None	None	CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-08
7.2202	Characterize hypersonic perfect gas shock/shock interactions.	None	Access to hypersonic test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	None	None	CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-08
7.2203	Characterize hypersonic nonequilibrium gas shock/shock interactions.	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to hypersonic high-enthalpy (aerothermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access in true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics.	None	CFD-01, CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.2204	Characterize shock-BL interactions	Current true flight Reynolds Numbers, enthalpies; hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic/hypersonic (aero) and high-enthalpy (aerothermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access in true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics, ability to make near surface measurements (inner portion of boundary layer) is often problematic.	None	CFD-01, CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat-08
7.2205	Shock/BL interactions, flow fields around local surface features	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aerothermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access for true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics, ability to make near surface measurements (inner portion of boundary layer) is often problematic.	None expected (except possibly inflatable testing)	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat01, Inst-Heat-08
7.2206	Objectives TBD					
7.2207	Objectives TBD					
7.3	**Propulsion System Performance, Interactions and Integration**					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.31	RCS performance	None expected in supersonic facilities. LAL lacks a dedicated high-pressure gas delivery/measurement system for propulsion simulation, with an ability to control pressure, temperature, and mass flow rate.	The AEDC facilities in particular are heavily scheduled and costly to operate, so it is unlikely that NASA would be able to perform a test there, from both a schedule and cost standpoint. LaRC UPWT may be closed in 2022.	None expected at supersonic facilities. LAL lacks a dedicated high-speed data system for dynamic measurements beyond 32-channel capability	Ability to accurately fabricate small-scale RCS nozzles to the required tolerances.	CFD-03, CFD-13, CFD-15, Inst-Aero-04, Inst-Flow-40, Inst-Flow-08, Inst-Heat-08
	Objectives TBD					
	Objectives TBD					
7.32	Retropropulsion performance	CO2 for Mars applications, inert plume gas capability other than air for nozzle exhaust gas.	Access to supersonic (aero) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access required for quantitative off-body measurements, inert gas other than air (e.g., heated ethane) needed for plume simulant, direct measurement of aerodynamic forces & moments.	Well-characterized large area ratio nozzles with small throats (< 0.3 in. diameter).	CFD-03, CFD-13, CFD-15, CFD-16, Inst-Aero-04, Inst-Flow-04, Inst-Flow-08, Inst-Heat-08
7.3201	Objectives TBD					
7.3202	Objectives TBD					
7.33	Propulsion system inlet operability	LaRC UPWT is currently limited to Mach 4.6. The UPWT TS2 nozzle was designed to operate up to Mach 5.87. An additional air compressor is required for this higher Mach number capability which is very desirable and would eliminate the dependency on AEDC Tunnel A. For NASA, a medium scale (~4 ft) continuous flow Mach 8 and Mach 10 wind tunnel would also eliminate the dependency on AEDC Tunnel B and C.	Access to DoD facilities for validation needs unlikely. Requires access to NASA facilities. Isolator only characterization could be performed in smaller direct-connect facilities at NASA and academic institutions. AEDC Tunnel A is 3X to 4X the cost of testing in UPWT for the same test matrix.	Small, high temperature tolerant and temperature compensated inclinometers would be needed to measure any inlet variable geometry panel/flap angles if LaRC UPWT TS2 is upgraded to a Mach 5.87 capability, as well as for testing at Mach 8 and 10 at current AEDC or NASA facilities, due to the increasing model temperatures at higher hypersonic flight conditions.	No critical gaps, but overcoming the engineering challenges associated with the inclusion of movable parts introduce non-trivial challenges (e.g., leaks)	CFD-04, CFD-15, Inst-Flow-02
7.3301	Objectives TBD					
7.3302	Objectives TBD					
7.4	**Transition and Turbulence**					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.41	Turbulence modeling	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aerothermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access for true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics, ability to make near surface measurements (inner portion of boundary layer) is often problematic.	None	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat-08
7.4101	Attached boundary-layers on smooth surfaces	As per 7.41	As per 7.41	As per 7.41	As per 7.41	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat-08
7.4102	Attached boundary-layers on rough surfaces	As per 7.41	As per 7.41	As per 7.41	As per 7.41	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat-08
7.4103	Separated shear layers and wakes	As per 7.41	As per 7.41	As per 7.41	As per 7.41	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-08
7.4104	Boundary-layers with blowing and/or ablation	As per 7.41	As per 7.41	As per 7.41	As per 7.41	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat-08
7.42	Boundary-layer transition due to instability mechanisms	Lack of "quiet" tunnels to mitigate free stream influence. Potential lack of Mach / Reynolds / enthalpy ranges/ material surface interactions in wind tunnels to duplicate flight relevant conditions and freestream disturbances (particulates, electrostatic discharge)	Unlikely to obtain extensive test time in non-NASA facilities	Off-body flow-field diagnostics for hypersonic tunnels.	Potential issues with precision of surface manufacturing	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4201	As per 7.42 with focus on first-mode transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4202	As per 7.42 with focus on second-mode transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4203	As per 7.42 with focus on crossflow transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4204	As per 7.42 with focus on multiple-mode interactions	as per 7.42	as per 7.42	as per 7.42	as per 7.42	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.4205	As per 7.42 with focus on ablative surfaces	as per 7.42	as per 7.42	as per 7.42	as per 7.42	CFD-05, CFD-06, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4206	As per 7.42 with focus on shock-shock and shock-BL transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.43	Boundary-layer transition due to bypass mechanisms	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds / enthalpy ranges / material surface interactions in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Unlikely to obtain extensive test time in non-NASA facilities	Off-body flow-field diagnostics for hypersonic tunnels.	Potential issues with replicating roughness patterns at model scale.	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4301	As per 7.43 with focus on Block-TPS Fence/Gap effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4302	As per 7.43 with focus on Woven TPS pattern effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4303	As per 7.43 with focus on ablated hex comb pattern TPS effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4304	As per 7.43 with focus on distributed sand grain TPS effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4305	As per 7.43 with focus on isolated surface features such as pads, antennas, thruster ports, window, TPS damage sites	as per 7.43	as per 7.43	as per 7.43	as per 7.43	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.44	Boundary-layer transition control	Need to investigate impact of "quiet" and conventional tunnel on bypass transition. Potential lack of Mach / Reynolds / enthalpy ranges / material surface interactions in wind tunnels to duplicate flight relevant conditions (particulates, electrostatic discharge)	Unlikely to obtain extensive test time in non-NASA facilities	Off-body flow-field diagnostics for hypersonic tunnels and accurate characterization of control input	Potential issues with replicating roughness patterns at model scale and implementing actuation at requisite frequencies	CFD-05, CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.4401	Objectives TBD					
7.4402	Objectives TBD					
7.5	**Surface / Flow field Interactions**					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.51	FSI for rigid structures	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of some advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aerothermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access for true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics.	No critical gaps, but overcoming the engineering challenges associated with the inclusion of surface internal features may introduce non-trivial challenges (e.g., sophisticated cooling channels)	CFD-13, CFD-15, Inst-Flow-01, Inst-Heat-08
7.5101	Objectives TBD					
7.5102	Objectives TBD					
7.52	FSI for inflatable/deployable structures					CFD-13, CFD-15, Inst-Flow-01
7.5201	Objectives TBD					
7.5202	Objectives TBD					
7.53	TPS response and ablation modelling	No large scale, high temperature/enthalpy, clean air, long duration tunnel exists		Challenge to make discrete sensor surface measurements on hot surface. Maybe optical methods can get you everything you need.	None	CFD-01, CFD-06, CFD-08, CFD-13, CFD-14, CFD-15, Inst-Flow-01, Inst-Heat-08
7.5301	Objectives TBD					
7.5302	Objectives TBD					
7.54	Massive ablation aero/heating/shape change effects	While these tests were common in the ~60s, we are not aware of similar tests executed by NASA in the past few decades. Consequently, there would need to be some capability development to run tests on these materials.		Challenge to make discrete sensor surface measurements on hot surface. Maybe optical methods can get you everything you need.	fabricating camphor and naphthalene models with small geometric features can be challenging or impossible. May need to explore new fabrication techniques and or new materials. I think that historically these models have been cast.	CFD-01, CFD-06, CFD-08, CFD-13, CFD-14, CFD-15, Inst-Flow-01, Inst-Heat-08
7.5401	Objectives TBD					
7.5402	Objectives TBD					
7.6	**Thermophysical and Radiative Properties**					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.61	Flow field radiation	Long test times (10s of us), high velocity or low-pressure extrema. Constancy of shock conditions are often not achieved with significant attenuation of shock strength along the length of the tube	Facility produces one shot per day. With multi-year backlog of testing the facility may not meet capacity and tests need to be down selected. Insufficient effort has been put forth to maintain facility up-time	Pressure sensors are noisy and do not allow accurate measurement of post-shock conditions. Time of arrival from pressure measurements suffer from rise time limitations and sensor lag	N/A	CFD-02, CFD-08, CFD-15, CFD-17, CFD-18
7.6101	Emission spectroscopy from VUV to IR					TBD
7.6102	Multi-temperature measurements					TBD
7.62	Shock Radiation-TPS interactions					TBD
7.6201	Reflectivity and Transmission Measurements	Measurements almost always made at room temperature. No VUV (<200 nm) apparatus available	None	No VUV instrumentation	Often not possible to prepare thin samples of TPS or char due to their porous/brittle nature	TBD
7.6202	High Power Illumination Testing	Limited to only wavelengths provided	LEAF is customer and mission driven and would only be used for these tests under critical need	In-situ recession measurement	None.	TBD
7.63	Kinetic models for planetary atmospheres	see 7.66	see 7.66	see 7.66	see 7.66	CFD-02, CFD-08, CFD-15, CFD-17, CFD-18
7.6301	Objectives TBD					
7.6302	Objectives TBD					
7.64	Kinetic models for propulsion system products	see 7.66	see 7.66	see 7.66	see 7.66	CFD-01, CFD-08, CFD-15, CFD-17, CFD-18
7.6401	Objectives TBD					
7.6402	Objectives TBD					
7.65	Kinetic models for ablation products	see 7.66	see 7.66	see 7.66	see 7.66	CFD-01, CFD-08, CFD-15, CFD-17, CFD-18
7.6501	Objectives TBD					
7.6502	Objectives TBD					
7.66	Shock layer non-equilibrium thermochemistry	see 7.61	see 7.61	see 7.61	see 7.61	CFD-02, CFD-08, CFD-15, CFD-17, CFD-18, Inst-Heat-03
7.6601	Emission spectroscopy from VUV to IR	See 7.66	See 7.66	See 7.66	See 7.66	CFD-02, CFD-08, CFD-15, CFD-17, CFD-18, Inst-Heat-03
7.6602	Multi-temperature measurements	See 7.66	See 7.66	See 7.66	See 7.66	CFD-02, CFD-08, CFD-15, CFD-17, CFD-18, Inst-Heat-03
7.6603	Population measurements	See 7.66	See 7.66	See 7.66	See 7.66	CFD-02, CFD-08, CFD-15, CFD-17, CFD-18, Inst-Heat-03
7.6604	Electron number density	See 7.66	See 7.66	See 7.66	See 7.66	CFD-02, CFD-08, CFD-15, CFD-17, CFD-18, Inst-Heat-03

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.67	Surface catalysis effects	NASA facilities are not capable of achieving heat transfer measurements to heated models at velocities sufficient to produce chemistry.	N/A	N/A	Maybe fabricating a model capable of supporting a heated surface.	CFD-01, CFD-08, CFD-15, CFD-17, CFD-18, Inst-Heat-03
7.6701	Objectives TBD					
7.6702	Objectives TBD					
7.7	**Multi-phase Flows and gas/solid interactions**					
7.71	Transpiration cooling (for non-ablators)	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aero+thermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access for true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics, ability to make near surface measurements (inner portion of boundary layer) is often problematic. Diagnostic development desired to allow the simultaneous measurement of velocity and temperature for direct validation of Reynolds heat flux models.	None.	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-02, Inst-Flow-05, Inst-Flow-08, Inst-Heat-08
7.7101						
7.7102						
7.72	Massive injection/blowing for aerodynamic control or aeroheating mitigation	Current true flight enthalpy hypersonic facilities at Langley were built/designed primarily for hardware testing with little attention given to the precision required for CFD validation. Test time, ability to hold conditions fixed throughout test, and extensive optical access are limited, which hinders the use of many advanced diagnostic techniques for quantitative measurements required for validation purposes and boundary condition specifications.	Access to supersonic (aero) and high-enthalpy (aero+thermal) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Substantial optical access for true flight enthalpy (hypersonic) facilities required for nonintrusive diagnostics, ability to make near surface measurements (inner portion of boundary layer) is often problematic.	None.	CFD-08, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-08, Inst-Heat-08

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.7201	Objectives TBD					
7.7202	Objectives TBD					
7.73	Particle flow subject to phase change	No high-enthalpy NASA facilities currently allow particle injection.	None.	Optical tracking and characterization of particles in situ of high-speed flows remains low TRL.	None.	CFD-12, CFD-13, CFD-15, Inst-Flow-01, Inst-Flow-06, Inst-Heat-08
7.7301	Objectives TBD					
7.7302	Objectives TBD					
7.8	**Rarefied flow**					**CFD-09, CFD-15**
7.81	Free molecule flow aerodynamics	Probable design of nozzle and test stand.	Very difficult regime to test in ground-based facilities.	Any instrument used must be very sensitive due to very low pressure/temperature variations	None known.	CFD-09, CFD-15
7.8101	Objectives TBD					
7.8102	Objectives TBD					
7.82	Rarefied aerodynamics and aeroheating	Probable design of nozzle and test stand.	Few facilities remain that are capable of simulating rarefied flow.	Any instrument used must be very sensitive due to very low pressure/temperature variations for higher Kn. Also see 7.11	None known.	CFD-09, CFD-15
7.8201	Objectives TBD					
7.8202	Objectives TBD					
7.83	Mixed regime flows	See 7.11	See 7.11	See 7.11	See 7.11	CFD-08, CFD-09, CFD-13, CFD-15, Inst-Aero-01, Inst-Flow-01, Inst-Flow-02, Inst-Flow-08, Inst-Heat-08
7.8301	Objectives TBD					
7.8302	Objectives TBD					
7.84	Internal flow through porous microstructure					(Not sure on this one)
7.8401	Objectives TBD					
7.8402	Objectives TBD					
7.8403	Objectives TBD					
7.9	**Miscellaneous**					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.91	"Free-flight" CFD simulations of vehicle dynamics	Forced oscillation test capability in supersonic facilities does not exist at this time. Aberdeen ballistic range has half the stations of the range at Eglin AFB which was our default facility to measure dynamic stability for past planetary missions. HFFAF range is too short to measure the deceleration and consecutive oscillation cycles possible at Aberdeen.	Instrumented free flight models at Aberdeen are often prohibitively expensive.	Data stations in Aberdeen indoor range (TEF) are half of Eglin facility. Existing forced oscillation balances can be too large to fit within vehicle OML at model scale.	None.	CFD-10, CFD-11, Inst-Aero-07
7.9101	Objectives TBD					
7.9102	Objectives TBD					
7.92	Passive vehicle dynamics	Forced oscillation test capability in supersonic facilities does not exist at this time. Aberdeen ballistic range has half the stations of the range at Eglin AFB which was our default facility to measure dynamic stability for past planetary missions. HFFAF range is too short to measure the deceleration and consecutive oscillation cycles possible at Aberdeen.	Instrumented free flight models at Aberdeen are often prohibitively expensive.	Data stations in Aberdeen indoor range (TEF) are half of Eglin facility. Existing forced oscillation balances can be too large to fit within vehicle OML at model scale.	None.	CFD-10, CFD-11, Inst-Aero-07
7.9201	Objectives TBD					
7.9202	Objectives TBD					
7.93	Vehicle trim	None.	Access to supersonic (aero) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	None.	None.	CFD-13, CFD-15, Inst-Aero-04
7.9301	Objectives TBD					
7.9302	Objectives TBD					
7.94	Stagnation region flow field prediction	Ability to fully characterize the thermal state distribution of the free stream flow; non-air gas compositions.	Access to supersonic (aero) test facility within program schedule and cost. Access to DoD facilities for validation needs unlikely. Requires access to NASA/Academic facilities.	Ability to measure thermal state distributions and flow field temperatures along the stagnation streamline.	None.	CFD-01, CFD-03, CFD-08, CFD-13, CFD-14, CFD-16, Inst-Flow-01, Inst-Flow-07

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
7.9401	Measure 3-D shock shapes in Martian, Venusian, and other planet atmospheric compositions (principally carbon dioxide)	Non-air gas compositions	none	none	none	
7.9402	Resolve the so-called stagnation point heat transfer anomaly	none	none	none	none	
7.9403	Objectives TBD					
7.95	Aero-optics					
7.9501	Objectives TBD					
7.9502	Objectives TBD					
7.96	Magneto-hydro dynamics					
7.9601	Objectives TBD					
7.9602	Objectives TBD					

Table 58. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Tools and Methods, Customer: Modeling and Simulation Code Development and Validation.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7	**Modeling and Simulation Code Development and Validation**					
7.1	**Wakes and separated flows**					
7.11	Unsteady, massively-separated hypersonic wake flows	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles dependent on shear-layer dynamics/physics for mission success	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS model prediction uncertainty excessive. Scale-resolving simulations required to reduce uncertainty.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.1101	Aeroshell back-face and vehicle payload measurements of heating distributions	Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles dependent on shear-layer dynamics/physics for mission success	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS surface heating prediction uncertainty excessive. Local flow environment dependent on shear layer deflection downstream of aeroshell and subsequent separation zones that are formed are not accurately captured with Reynolds-averaged simulations (particularly if large scale unsteadiness is present). Full scale-resolving simulations (i.e., without wall-modeling) may be required to reduce model-form uncertainty to acceptable levels.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.1102	Aeroshell back-face and vehicle payload measurements of pressure distributions and wake/payload effects on aerodynamics	Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles dependent on shear-layer dynamics/physics for mission success	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS surface pressure prediction uncertainty excessive in the massively separated flow in the vicinity of the aeroshell back-face. Local flow environment dependent on shear layer deflection downstream of aeroshell and subsequent separation zones that are formed are not accurately captured with Reynolds-averaged simulations (particularly if large scale unsteadiness is present). Scale-resolving simulations with wall-modeling may be required to reduce model-form uncertainty to acceptable levels.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.1103	Wake flow structure visualization	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles dependent on shear-layer dynamics/physics for mission success.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS wake flow prediction uncertainty excessive due to the massively separated flow in the vicinity of the aeroshell back-face. Local wake flow properties are dependent on shear layer deflection downstream of aeroshell and subsequent separation zones that are formed are not accurately captured with Reynolds-averaged simulations (particularly if large scale unsteadiness is present). Scale-resolving simulations with wall-modeling may be required to reduce model-form uncertainty to acceptable levels.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.12	Aftbody / wake flow influence on supersonic dynamics	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties. Forced oscillation mechanism required.	Criticality high for missions/vehicles dependent on unsteady shear-layer dynamics/physics for mission success.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS wake flow prediction uncertainty excessive due to the unsteady massively separated flow in the vicinity of the aeroshell back-face. Local wake flow properties are dependent on shear layer deflection downstream of aeroshell and subsequent separation zones that are formed are not accurately captured with Reynolds-averaged simulations (particularly if large scale unsteadiness is present). Scale-resolving simulations with wall-modeling may be required to reduce model-form uncertainty to acceptable levels.	Unsteady simulations are required, which introduces more complex physics and extensively more resources than required for steady-state problems.
7.1201	Objectives TBD					
7.1202	Objectives TBD					
7.13	Parachute modeling	Optical access …	Parachute systems carry the most risk of any entry systems component, and we have essentially no predictive design capability to address faults when they inevitably appear. We currently rely upon trial and error and accepting unquantified risk.	Validate using lower speed facilities and data and allow CFD to provide extrapolation to higher-speed conditions.	CFD predictions are possible, but in order to be accepted by the engineering community, they require detailed local validation data of the type we are discussing here.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.1301	Objectives TBD					
7.1302	Objectives TBD					
7.2	**Shock-Shock and Shock-BL Interactions**					
7.21	Multi-body separation interactions	Optical access to enable flow diagnostics, temperature-independent PSP	May not be critical if sufficient control authority is present.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	Current RANS and URANS uncertainties acceptable, depending on control authority of the vehicles.	Not currently limited for this validation exercise; however, throughput *highly* dependent on overall NASA HPC utilization.
7.2101	Objectives TBD					
7.2102	Objectives TBD					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.22	Shock/shock and shock/boundary-layer interactions	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles dependent on accurate heating estimates in SBLI regions.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS surface heating prediction uncertainty for transitional and turbulent flow is excessive. Local flow environment dependent on SBLI strength and subsequent separation zones that are formed are not accurately captured with Reynolds-averaged simulations. Full scale-resolving simulations (i.e., without wall-modeling) may be required to reduce model-form uncertainty to acceptable levels for turbulent SBLI. Deviation from thermo-chemical equilibrium (which is dependent on shock strength) not always well predicted with standard multi-temperature models using empirical T/vibrational temperature relationships for kinetic effects.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.2201	Characterize supersonic perfect gas shock/shock interactions.	None	Criticality high for missions/vehicles dependent on accurate heating estimates due to shock-enhanced heating (particularly for Type IV shock-shock interactions).	Accept existing computational modeling uncertainties given existing models and testing capabilities.	Uncertainty minimal except for the prediction of turbulent shear layer development for certain shock-shock interactions (e.g., Type III and Type IV).	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.2202	Characterize hypersonic perfect gas shock/shock interactions.	None	Criticality high for missions/vehicles dependent on accurate heating estimates due to shock-enhanced heating (particularly for Type IV shock-shock interactions).	Accept existing computational modeling uncertainties given existing models and testing capabilities.	Uncertainty minimal except for the prediction of turbulent shear layer development for certain shock-shock interactions (e.g., Type III and Type IV)	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.2203	Characterize hypersonic nonequilibrium gas shock/shock interactions.	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles dependent on accurate heating estimates due to shock-enhanced heating (particularly for Type IV shock-shock interactions).	Accept existing computational modeling uncertainties given existing models and testing capabilities.	Current SOA modeling of thermo-chemical non-equilibrium effects across shocks have excessive uncertainties. Deviation from thermo-chemical equilibrium (which is dependent on shock strength) is not always well predicted with standard multi-temperature models using empirical T/vibrational temperature relationships for kinetic effects. Uncertainty in the prediction of turbulent shear layer development for certain shock-shock interactions (e.g., Type III and Type IV) can be excessive as well.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.2204	Characterize shock-BL interactions	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles dependent on accurate heating estimates in SBLI regions.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS surface heating prediction uncertainty for transitional and turbulent flow is excessive. Local flow environment dependent on SBLI strength and subsequent separation zones that are formed are not accurately captured with Reynolds-averaged simulations. Full scale-resolving simulations (i.e., without wall-modeling) may be required to reduce model-form uncertainty to acceptable levels for turbulent SBLI.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.2205	Shock/BL interactions, flow fields around local surface features	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for protuberances that may significantly alter the aero thermal environment in localized key areas (e.g., peak heating or unsteady forcing induced by protuberance).	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS model prediction uncertainty excessive (particularly if unsteady effects are sought). Scale-resolving simulations required to reduce uncertainty.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.2206	Objectives TBD					
7.2207	Objectives TBD					
7.3	**Propulsion System Performance, Interactions and Integration**					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.31	RCS performance	Non-NASA facilities may not be available or affordable for NASA programs involving RCS jet interactions. Fabricating small-scale RCS nozzles for small nozzles is difficult and costly.	Moderate: reliance on unvalidated CFD and/or legacy data will require increased RCS thruster and propellant margins, thus increasing the overall mass of the vehicle. Use of unsteady CFD will lead to increased cost/schedule and larger aerodynamic database uncertainties.	Rely on unvalidated CFD and/or legacy data from similar vehicles to determine RCS jet interaction effects	Prediction of force and moment increments predicted with reasonable uncertainty compared to test data. RANS model heating prediction has excessive uncertainty. Scale-resolving simulations required to reduce uncertainty and better predict unsteady effects.	RCS jet and plume physics are almost always unsteady, which requires more complex physics and more resources. Symmetry assumptions may by invalid.
	Objectives TBD					
	Objectives TBD					
7.32	Retropropulsion performance	Testing with more suitable plume gas (e.g., heated ethane) not yet possible, no direct measurement of aerodynamic forces & moments have been made yet, no suitable off-body flow measurements have been demonstrated.	Critically high. The amount of computer horsepower required to replace the capability offered by a facility like LaRC UPWT for this application will drastically increase the calendar time required to map out the operational space.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS model prediction uncertainty excessive. Scale-resolving simulations required to reduce uncertainty and better predict unsteady effects.	Plume physics is almost always unsteady, which requires more complex physics and more resources.
7.3201	Objectives TBD					
7.3202	Objectives TBD					
7.33	Propulsion system inlet operability	Maximum Mach number range currently limited to Mach 4.6 for continuous flow, medium scale or larger test facilities. Capability to extend the Mach number range of LaRC UPWT up to ~Mach 6 is highly desirable. A medium scale Mach 8 and Mach 10 aerodynamic test facility (long duration blow-down or continuous) would also fill a gap for NASA with regard to higher Mach hypersonic inlet performance testing, although the need for this capability has a longer timeline.	Critically high. The amount of computer horsepower required to replace the capability offered by LaRC UPWT for this application will drastically increase the calendar time required to map out the operational space.	Accept existing computational modeling uncertainties and a much coarser mapping of the operational space used to characterize inlet/isolator performance and operability. Accept the risk (NASA/Industry) of taking proposed multi-billion-dollar hypersonic airbreathing vehicle configurations straight to flight test programs without ground test verification.	RANS model prediction uncertainty excessive (particularly at conditions close to unstart where large scale flow separation is present caused by turbulent SBLI). Scale-resolving simulations required to reduce uncertainty (particularly at high back pressure conditions).	Very limited for this validation exercise due the inclusion of so many independent variables (freestream Mach, Re, angle of attack/sideslip, and back pressure condition). Moreover, geometry changes may be required introducing significant additional grid generation time. This is one area where testing in a facility like LaRC UPWT is significantly more efficient and cost effective at mapping out the entire operational space than performing CFD simulations to achieve the same goal.
7.3301	Objectives TBD					
7.3302	Objectives TBD					
7.4	**Transition and Turbulence**					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.41	Turbulence modeling	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles dependent on accurate turbulence model predictions for heating and drag prediction (particularly in separated flow regions).	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS model prediction uncertainty excessive. Scale-resolving simulations required to reduce uncertainty.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.4101	Attached boundary-layers on smooth surfaces	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4102	Attached boundary-layers on rough surfaces	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4103	Separated shear layers and wakes	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.4104	Boundary-layers with blowing and/or ablation	As per 7.41	As per 7.41	As per 7.41	As per 7.41	As per 7.41
7.42	Boundary-layer transition due to instability mechanisms	Lacking operating conditions that match flight/configuration parameters (enthalpy, Mach, Re, disturbance environment)	Minor to Major depending on specific mission. EDL mission may ignore transition and assume fully turbulent conditions. Airbreathing system may be entirely dependent on inlet BL state and/or overall drag effects of turbulence	Invest in comprehensive experimental / computational research projects targeted at specific mission-relevant cases	Limited capability to predict transition onset, mostly reliant on empirical, configuration-specific models based on ground or (highly limited) flight data. No reliable capability for prediction of breakdown zone and elevated heat flux.	Limited due to grid resolution requirements for obtaining high-quality basic state laminar solutions that are used for BL stability analysis.
7.4201	As per 7.42 with focus on first-mode transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4202	As per 7.42 with focus on second-mode transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4203	As per 7.42 with focus on crossflow transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4204	As per 7.42 with focus on multiple-mode interactions	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4205	As per 7.42 with focus on ablative surfaces	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42
7.4206	As per 7.42 with focus on shock-shock and shock-BL transition	as per 7.42	as per 7.42	as per 7.42	as per 7.42	as per 7.42

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.43	Boundary-layer transition due to bypass mechanisms	Operating conditions that match flight/configuration parameters	Minor to Moderate. Most distributed roughness is relevant to ablating TPS, so turbulent flows is assumed in design (does not speak to ability to predict roughness turbulent heating. Transition due to discrete features may be more problematic	Invest in comprehensive experimental / computational research projects targeted at specific mission-relevant cases	Limited capability to predict transition onset, mostly reliant on empirical, configuration-specific models based on ground or flight data	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.4301	As per 7.43 with focus on Block-TPS Fence/Gap effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4302	As per 7.43 with focus on Woven TPS pattern effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4303	As per 7.43 with focus on ablated hex comb pattern TPS effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4304	As per 7.43 with focus on distributed sand grain TPS effects	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.4305	As per 7.43 with focus on isolated surface features such as pads, antennas, thruster ports, window, TPS damage sites	as per 7.43	as per 7.43	as per 7.43	as per 7.43	as per 7.43
7.44	Boundary-layer transition control				Limited capability to predict transition onset, mostly reliant on empirical, configuration-specific models based on ground or flight data. Key will be understanding the forcing function (static/dynamic) for designing a control mechanism and/or approach.	
7.4401	Objectives TBD					
7.4402	Objectives TBD					
7.5	**Surface / Flow field Interactions**					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.51	FSI for rigid structures	Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties.	Criticality high for missions/vehicles that are sensitive to FSI and FTSI for mission success.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	Limited capability to predict the full coupled FTSI physics. Disparate time scales between fluid and structural analysis may allow loosely coupled analysis for some applications, but full coupling likely necessary for others (e.g., flutter).	Very limited for this application. The full FTSI requires coupling of up to 3 critical high-fidelity solvers (fluid, structural, thermal).
7.5101	Objectives TBD					
7.5102	Objectives TBD					
7.52	FSI for inflatable/deployable structures					
7.5201	Objectives TBD					
7.5202	Objectives TBD					
7.53	TPS response and ablation modelling	High temperature/enthalpy tunnel does not exist to obtain validation quality data that exercises most of relevant physics and relevant scales.	Blowing/roughness and shape change uncertainty are significant contributors to heating uncertainty for Orion, MSR EES & SRL, Davinci, etc. If designs cannot close with conservative margins, improved computational and testing techniques will be required.	Flight test and/or healthy design margin	CFD and material response models are coupled and appropriate physics modeled are implemented. However, capabilities are lacking validation to prove out modeling capabilities and develop modeling inputs. Therefore, we have no production capability. Running codes requires expertise usually only had by the code developers. Capabilities have been demonstrated and are currently at TRL3. Need test data and developers to help mature to TRL6.	Problem is physics/model limited and not computational capability limited
7.5301	Objectives TBD					
7.5302	Objectives TBD					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.54	Massive ablation aero/heating/shape change effects	High temperature/enthalpy tunnel does not exist to obtain validation quality data that exercises most of relevant physics and relevant scales.	Blowing/roughness and shape change uncertainty are significant contributors to heating uncertainty for Orion, MSR EES & SRL, Davinci, etc. If designs cannot close with conservative margins, improved computational and testing techniques will be required.	Flight test and/or healthy design margin	Coupled codes exist, but validation data with massive shape change does not exist, particularly with shape measured in a transient manner.	Problem is physics/model limited and not computational capability limited
7.5401	Objectives TBD					
7.5402	Objectives TBD					
7.6	**Thermophysical and Radiative Properties**					
7.61	Flow field radiation	High speed infrared spectroscopy equipment is limited and hard to find. S/N levels in vacuum ultraviolet could be improved	Probably low, but depends on mission	Invest in development of new and improved sensing technologies. SBIR and ECF calls, however much of spectroscopic technology is market driven, especially by DoD	Predictive CFD generates flow field variables that are then passed to a radiation solver. CFD solvers are now able to couple to radiation codes to correct for the impact of radiation on flow field enthalpy.	Capacity appears to be sufficient
7.6101	Emission spectroscopy from VUV to IR					
7.6102	Multi-temperature measurements					
7.62	Shock Radiation-TPS interactions				This is a material response problem. Most material response solvers are not designed to predict in depth radiative heating phenomena	NA
7.6201	Reflectivity and Transmission Measurements	No high temperature or VUV reflectance measurements available	Low	Construct new apparatus	NA	NA
7.6202	High Power Illumination Testing				NA	NA
7.63	Kinetic models for planetary atmospheres	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6301	Objectives TBD					
7.6302	Objectives TBD					
7.64	Kinetic models for propulsion system products	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6401	Objectives TBD					
7.6402	Objectives TBD					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.65	Kinetic models for ablation products	see 7.66	see 7.66	see 7.66	see 7.66	see 7.66
7.6501	Objectives TBD					
7.6502	Objectives TBD					
7.66	Shock layer non-equilibrium thermochemistry	see 7.61	see 7.61	see 7.61	see 7.61	see 7.61
7.6601	Emission spectroscopy from VUV to IR	see 7.61	see 7.61	see 7.61	See 7.66	See 7.66
7.6602	Multi-temperature measurements	Most lasers cannot scan fast enough to capture a significant portion of the spectrum on the time scales of reaction		Procure femtosecond laser. Investment via SBIR and ECF for diagnostic development. Procured supercontinuum laser to perform Fourier Dispersive Spectroscopy	See 7.66	See 7.66
7.6603	Population measurements	Speed of diagnostics may be insufficient to capture timescale of reaction		Investment via SBIR and ECF for diagnostic development	See 7.66	See 7.66
7.6604	Electron number density	Technology exists but does not in facility		Purchase Microwave Interferometry System	See 7.66	See 7.66
7.67	Surface catalysis effects	Test objective is to determine the catalytic rates/efficiencies for heterogenous (such as CO2 surface chemistry) and homogenous (such as O2 or N2 recombination) surface reactions. The rate of these reactions determine the species gradients near the wall, which have a first-order impact on the convective heating. Because these reactions are temperature dependent, these measurements should be at flight relevant surface temperatures, meaning above 1000 K.	Criticality high for missions/vehicles with significant shock layer chemistry, which is essentially all NASA mission with an atmospheric entry phase.	These measurements will drive the development of validated surface chemistry models at flight relevant temperatures. These new models will be implemented in NASA workhorse CFD codes.	Modeling catalycity in CFD is trivial. The challenge is to determine the appropriate rates to implement, which are to be determined in these tests.	No issue.
7.6701	Objectives TBD					
7.6702	Objectives TBD					
7.7	**Multi-phase Flows and gas/solid interactions**					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.71	Transpiration cooling (for non-ablators)	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties. This particular validation activity also needs diagnostic development to allow the simultaneous measurement of velocity and temperature for direct validation of Reynolds heat flux models.	Criticality high for missions/vehicles dependent on cooling for structural survivability.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS model prediction uncertainty excessive when combined with empirical models for transpiration cooling (this level of modeling inevitably requires tunnel tests for calibration). RANS model prediction with transpiration cooling passages included in the simulation offers improvements, but uncertainty is still excessive. Scale-resolving simulations required to reduce uncertainty.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.7101						
7.7102						
7.72	Massive injection/blowing for aerodynamic control or aeroheating mitigation	Limited optical access at true flight enthalpy conditions may restrict where off-body measurements can be made. Performing true validation quality experiments in current long-duration, hypersonic facilities designed/built for hardware testing may lead to excessive uncertainties. This particular validation activity likely needs diagnostic development to validate multiphase aspects.	May not be too critical given that this flow control option is not currently being heavily considered.	Accept existing computational modeling uncertainties given existing models and testing capabilities.	RANS model prediction uncertainty excessive for this unsteady flow problem. Prediction problem is amplified when liquid injectants (i.e., multi-phase) are considered. Scale-resolving simulations required to reduce uncertainty for single phase conditions but does little to reduce the uncertainty when liquid injectant is used.	Plume physics is almost always unsteady, which introduces more complex physics and more computational resources.
7.7201	Objectives TBD					
7.7202	Objectives TBD					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.73	Particle flow subject to phase change	No high-enthalpy NASA facilities currently allow particle injection of the kind needed to replicate atmospheric particulates. Optical diagnostics for in situ measurement of particle shape and size distributions at high speed remain low TRL.	Entry at Mars during global dust storm remains a potential risk with currently unquantified consequence. Spallation typically not included in TPS sizing analysis. Surface impact damage models not available for TPS materials such as PICA.	Accept modeling uncertainty and potential mission risk.	Full CFD models are in place for coupled particle simulations and erosion. Models are largely unvalidated with primary concerns for quantifying particle-fluid coupling (e.g. particle drag and heating) and particle erosion rates for thermal protection materials of interest.	CFD capacity is sufficient.
7.7301	Objectives TBD					
7.7302	Objectives TBD					
7.8	**Rarefied flow**					
7.81	Free molecule flow aerodynamics	Testing limited to development of hardware to install in vacuum chamber	Low/moderate. Main uncertainty in FM aero is accommodation coefficient and flight conditions.	Study flight data	Current NASA capabilities include analytical FM equations for force & moment and heating as well as DSMC simulation	These simulations require low levels of resources and have compared well to flight data. The main uncertainties in these computations are free stream conditions
7.8101	Objectives TBD					
7.8102	Objectives TBD					
7.82	Rarefied aerodynamics and aeroheating	Testing limited to development of hardware to install in vacuum chamber	Moderate. Same concerns as FM, but uncertainties in relaxation models (rotation/vibration/electronic) also become important	Comparison to previous wind tunnel data and flight data.	Current NASA capabilities are DSMC codes MAP and DAC but could be expanded to non-NASA codes (e.g. SPARTA). Comparisons to flight data have been favorable.	Resource requirements vary depending on Kn. Higher Kn cases (higher altitude) are currently well within current capacity. Transitional flows (lower altitude/Kn cases) take more time to solution. Currently exploring HPC options.
7.8201	Objectives TBD					
7.8202	Objectives TBD					
7.83	Mixed regime flows	See 7.11	See 7.11	Comparison to previous wind tunnel data and flight data.	For larger Kn (~0.01-0.001) DSMC is capable of simulating flows. More continuum-type flows require input from CFD and DSMC (hybrid) solutions.	Current capability of CFD/DSMC hybrid solutions is limited to one-way CFD-to-DSMC simulations for two-temperature CFD models. More accurate hybrid simulations would require two-way coupling where information is passed between CFD and DSMC between continuum/transitional regions with up to five temperature (trans/rot/vib/electronic/electron) models

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.8301	Objectives TBD					
7.8302	Objectives TBD					
7.84	Internal flow through porous microstructure					
7.8401	Objectives TBD					
7.8402	Objectives TBD					
7.8403	Objectives TBD					
7.9	**Miscellaneous**					
7.91	"Free-flight" CFD simulations of vehicle dynamics	None.	Not critical (can often be engineered around)	Accept modeling uncertainty and potential mission risk.	Unsteady, LES DDES CFD codes are in development attempting to model/predict dynamic stability across desired Mach range. Progress has been made in recent years, but no validation confirming predictive ability to date.	Unsteady nature of this application introduces more complex physics and considerably more computational resources than steady-state activities.
7.9101	Objectives TBD					
7.9102	Objectives TBD					
7.92	Passive vehicle dynamics	None.	Not critical (can often be engineered around)	Accept modeling uncertainty and potential mission risk.	Unsteady, LES DDES CFD codes are in development attempting to model/predict dynamic stability across desired Mach range. Progress has been made in recent years, but no validation confirming predictive ability to date.	Unsteady nature of this application introduces more complex physics and considerably more computational resources than steady-state activities.
7.9201	Objectives TBD					
7.9202	Objectives TBD					
7.93	Vehicle trim	None.	Not critical.	N/A	RANS model prediction uncertainty maybe acceptable assuming potential large-scale separation is not impacting control surfaces.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.9301	Objectives TBD					
7.9302	Objectives TBD					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
7.94	Stagnation region flow field prediction	None.	Not critical.	N/A	This is an unknown-unknown. The belief was that the governing equations were known and being correctly solved, but without detailed measurement of boundary layer profile at the stagnation region, the mismatch between simulations and measurements cannot be properly characterized. Anomalous measurements of the impact of blowing on stagnation region convective heating have persisted through a number of independent measurement campaigns. The current theory is that this anomaly is the result of stagnation region turbulence resulting from blowing.	Not currently limited for this validation exercise; however, throughput dependent on overall NASA HPC utilization.
7.9401	Measure 3-D shock shapes in Martian, Venusian, and other planet atmospheric compositions (principally carbon dioxide)	None.	Not critical.	N/A	Data needed for validation	not limited
7.9402	Resolve the so-called stagnation point heat transfer anomaly	None.	Not critical.	N/A	Unknown source of discrepancies needs to be resolved	not limited
7.9403	Objectives TBD					
7.95	Aero-optics					
7.9501	Objectives TBD					
7.9502	Objectives TBD					
7.96	Magneto-hydro dynamics					
7.9601	Objectives TBD					
7.9602	Objectives TBD					

Appendix J Database for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development

Table 59. Programs List for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development.

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
Hypersonic Tools and Methods	**8**	**Ground Test Technique Development**	**Ground test programs conducted to develop and validate advanced new measurement capabilities**	**Facility time spent on calibration, diagnostics and instrumentation development counts against capacity for programmatic testing**	**Surveys of NASA facility operations staff, test engineers and experimental researchers**	
	8.1	**Global optical Surface Measurement Techniques**	**Global techniques for heating, temperature, pressure, shear**			
	8.11	High-temperature phosphor thermography				
	8.12	Infrared thermography				
	8.13	Pressure sensitive paint				
	8.14	Temperature sensitive paint				
	8.2	**Flow Field Optical Diagnostics**	**Steady & fluctuating flow field measurements for temperature, velocity etc.**			
	8.21	Laser-Based Velocimetry	Femtosecond Laser Electronic Excitation Tagging (FLEET) or PLIF - Improve on existing PLIF or demonstrate FLEET technique in hypersonic flows		AETC Strategic Plan for LAL	2020-
	8.22	Laser-Based Temperature measurements	Planar Laser Induced Fluorescence (PLIF) - Visualize boundary layers/wakes (laminar/turbulent state, BL edge and wake closure), potential to determine velocity/temperature, want to upgrade to current 10 -1000 kHz hardware		AETC Strategic Plan for LAL	2020-
	8.23	3D Flow field Density Measurements	Tomographic Background Oriented Schlieren (BOS) - Time resolved possible with high-speed cameras		AETC Strategic Plan for LAL	2021-
	8.24	Flow field Density Fluctuations/Velocity in 2+ points	Multi-Focal Focused Laser Differential Interferometry (FLDI) - Characterize noise environment, instability waves, velocity field, BL measurements		AETC Strategic Plan for LAL	2022-

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	8.25	Broadband absorption spectroscopy	Requires light sources with sufficient brightness to overcome shock luminosity, multi-channel detectors with high data sampling rate/low integration times			
	8.26	Microwave interferometry	Electron density measurement in shock tubes			
	8.3	**Discrete Sensor Development**	**Discrete sensors for temperature, pressure, shear, heating, etc.**			
	8.31	Advanced high-frequency pressure/temperature/noise instrumentation				
	8.32	Shock time of arrival/pressure sensors	Improve upon state-of-the-art piezoelectric which display significant resonance noise and thermal drifts. There are promising results for MEMS based sensors that were produced as part of a Phase II SBIR			
	8.33	Fiber-optic temperature / heat transfer sensors				
	8.34	Development of injection systems for film cooling and BLT control				
	8.35	Miniaturized Spectrometer	Develop and test miniaturized spectrometer options, including fiber bragg gratings, and VUV and MWIR capable grating spectrometers. Challenges include heat shield integration, mitigation of ablation product impact, thermal re-radiation from TPS, data and bandwidth requirements			
	8.36	Shear stress sensor	Direct skin friction coefficient measurements from 0.0003 to 0.0060.			
	8.37	Displacement sensor	Measurement of material thermal growth and gap closure at sealed interfaces			
	8.38	Strain gages	high temperature capable strain gages (above 500 F)			
	8.4	**Aerodynamic Force & Angle Measurement**	**Advanced techniques for aerodynamic force & moment measurements**			

Theme	ID	Customer / Categories / Programs	Description	Notes	Sources	Time Frame
	8.41	Free-flight magnetic suspension	Support-free test cell for free-flight measurements			
	8.42	Rapid Development of force & moment balances	validation of additive manufacturing balance components			
	8.43	High-frequency response balances	high-frequency response for short-duration impulse facilities			
	8.44	Angle Measurements	Development of angle measurement technologies			
	8.45	Flow Through Balances				

Table 60. Database Objectives for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
8	**Ground Test Technique Development**							
8.1	**Global optical Surface Measurement Techniques**							
8.11	High-temperature phosphor thermography							
8.1101	Phosphor Thermography	(3) Boundary-layer characterization, (4) Convective aeroheating, (15) TPS response and characterization, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Variety of test conditions including range of alpha, beta, and Re # using updated ceramic and colloidal materials	Phosphor Thermography	Hypersonic Blowdown Tunnels	20" M6, 31" M10	AEDC Tunnel 9
8.1102	High Temperature Phosphor Thermography	(3) Boundary-layer characterization, (4) Convective aeroheating, (15) TPS response and characterization, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Variety of test conditions for shock-shock interaction studies at any Mach number, high Reynolds numbers at high Mach numbers	Phosphor Thermography	Hypersonic Blowdown Tunnels	20" M6, 31" M10	AEDC Tunnel 9
8.12	Infrared thermography							
8.1201	Development of Quantitative IR Capability	(3) Boundary-layer characterization, (4) Convective aeroheating, (15) TPS response and characterization, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Ability to go to high AoA, variety of test conditions	High Speed discrete temperatures	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
8.1202	Development of High-Speed IR Capability	(3) Boundary-layer characterization, (4) Convective aeroheating, (15) TPS response and characterization, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Ability to go to high AoA, variety of test conditions	High Speed discrete temperatures	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C
8.13	Pressure sensitive paint							
8.1301	Development of Advanced Pressure Sensitive Paints	(7) RCS Performance and interaction, (8) Retropropulsion performance and interactions, (15) TPS response and characterization, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Variety of test conditions	Pressure Sensitive Paints	Hypersonic Blowdown Tunnels	20" M6, 31" M10	AEDC Tunnel 9
8.14	Temperature sensitive paint							
8.1401	Development of Advanced Temperature Sensitive Paints	(3) Boundary-layer characterization, (4) Convective aeroheating, (8) Retropropulsion performance and interactions, (15) TPS response and characterization, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Variety of test conditions for a range of Mach numbers (comparable conditions to phosphor thermography)	Temperature Sensitive Paints	Hypersonic Blowdown Tunnels	20" M6, 31" M10	AEDC Tunnel 9
8.2	**Flow Field Optical Diagnostics**							
8.21	Laser-Based Velocimetry							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
8.2101	Planar Laser Induced Fluorescence	(3) Boundary-layer characterization, (4) Convective aeroheating, (5) Flow-field characterization, (7) RCS Performance and interaction, (13) aero-optical environments, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Variety of test conditions	Planar Laser Induced Fluorescence	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C
8.2102	Femtosecond Laser Electronic Excitation Tagging	(3) Boundary-layer characterization, (4) Convective aeroheating, (5) Flow-field characterization, (7) RCS Performance and interaction, (130 Aero-optical environments, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Variety of test conditions	Femtosecond Laser Electronic Excitation Tagging	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C
8.22	Laser-Based Temperature measurements							
8.2201	Planar Laser Induced Fluorescence	(3) Boundary-layer characterization, (4) Convective aeroheating, (5) Flow-field characterization, (7) RCS Performance and interaction, (13) aero-optical environments, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Technique Development	Variety of test conditions	Planar Laser Induced Fluorescence	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C
8.23	3D Flow field Density Measurements							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
8.2301	Focusing schlieren capability	(1) Hypersonic aerodynamics, (3) Boundary-layer characterization, (5) Flow-field characterization, (7) RCS Performance and interaction, (8) Retropropulsion performance and interactions, (9) Fluid-structures interactions, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Flow field diagnostics in plane of density gradient (as opposed to integrated schlieren across flow field)	Variety of test conditions, including shock interactions and cases with localized phenomenon	Focusing schlieren capability	Hypersonic blowdown and continuous flow tunnels	20" M6, 31" M10, other tunnels with visual access on both sides	AEDC Tunnel 9
8.2302	Zoom schlieren capability	(1) Hypersonic aerodynamics, (3) Boundary-layer characterization, 5, (7) RCS Performance and interaction, (8) Retropropulsion performance and interactions, (9) fluid-structures interactions, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development	Flow field diagnostics in region of interactions or shock and density anomalies	Variety of test conditions, including shock interactions and cases with localized phenomenon	Zoom schlieren capability	Hypersonic blowdown and continuous flow tunnels	20" M6, 31" M10, other tunnels with visual access on both sides	AEDC Tunnel 9
8.24	Flow field Density Fluctuations/Velocity in 2+ points							
8.2401	Requirement #1							
8.25	Broadband absorption spectroscopy							
8.2501	Requirement #1							
8.26	Microwave interferometry							
8.2601	Requirement #1							
8.3	**Discrete Sensor Development**							
8.31	Advanced high-frequency pressure/temperature/noise instrumentation							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
8.3101	Requirement #1							
8.32	Shock time of arrival/pressure sensors							
8.3201	Requirement #1							
8.33	Fiber-optic temperature / heat transfer sensors							
8.3301	Requirement #1							
8.34	Development of injection systems for film cooling and BLT control							
8.3401	Requirement #1							
8.35	Miniaturized Spectrometer							
8.3501	Requirement #1							
8.36	Shear stress sensor							
8.3601	Requirement #1							
8.37	Displacement sensor							
8.3701	Requirement #1							
8.38	Strain gages							
8.3801	Requirement #1							
8.4	**Aerodynamic Force & Angle Measurement**							
8.41	Free-flight magnetic suspension							
8.4101	Requirement #1							
8.42	Rapid Development of force & moment balances							
8.4201	Additive manufacturing for force & moment balances	(1) Hypersonic aerodynamics, (2) Supersonic aerodynamics, (6) Propulsion system flow path interactions, (7) RCS Performance and interaction, (8) Retropropulsion performance and interactions, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development, (19) Transonic Aerodynamics	Technique Development	Variety of test conditions	Additive manufacturing for force & moment balances	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C
8.43	High-frequency response balances							

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
8.4301	High Frequency Response Balances	(1) Hypersonic aerodynamics, (2) Supersonic aerodynamics, (6) Propulsion system flow path interactions, (7) RCS Performance and interaction, (8) Retropropulsion performance and interactions, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development, (19) Transonic Aerodynamics	Technique Development	Variety of test conditions	High Frequency Response Balances	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C
8.44	Angle Measurements							
8.4401	Dynamic Angle Measurement	(1) Hypersonic aerodynamics, (2) Supersonic aerodynamics, (6) Propulsion system flow path interactions, (7) RCS Performance and interaction, (8) Retropropulsion performance and interactions, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development, (19) Transonic Aerodynamics	Technique Development	Variety of test conditions	Dynamic Angle Measurement	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C

ID	Customer / Categories / Programs / Objectives	Test Categories	Test Approach	Test Parameters	Measurement Types	Facility Types	Potential NASA Facilities	Potential Non-NASA Facilities
8.4402	Miniaturized Angle Measurement Capabilities	(1) Hypersonic aerodynamics, (2) Supersonic aerodynamics, (6) Propulsion system flow path interactions, (7) RCS Performance and interaction, (8) Retropropulsion performance and interactions, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development, (19) Transonic Aerodynamics	Technique Development	Variety of test conditions	Miniaturized Angle Measurement Capabilities	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C
8.45	Flow Through Balances							
8.4501	Development of flow through balance capabilities	(1) Hypersonic aerodynamics, (2) Supersonic aerodynamics, (6) Propulsion system flow path interactions, (7) RCS Performance and interaction, (8) Retropropulsion performance and interactions, (16) CFD Development and validation, (17) Parametric vehicle screening, (18) Test Technique Development, (19) Transonic Aerodynamics	Technique Development	Variety of test conditions	Development of flow through balance capabilities	Hypersonic Blowdown Tunnels, Hypersonic Continuous Flow Tunnels	20" M6, 31" M10	AEDC Tunnel 9, Tunnel B, Tunnel C

Table 61. Test Requirements for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development.

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
8	**Ground Test Technique Development**							
8.1	**Global optical Surface Measurement Techniques**							
8.11	High-temperature phosphor thermography							
8.1101	Phosphor Thermography	NA	NA	4 weeks	NA	NA	updated cameras	Ceramic casting and colloidal/phosphor mixing and spraying for new materials (should be similar to existing materials)
8.1102	High Temperature Phosphor Thermography	NA	NA	4 weeks	NA	NA	NA	New ceramic materials, 3D printed ceramics
8.12	Infrared thermography							
8.1201	Development of Quantitative IR Capability	NA	NA	4 weeks	NA	2 weeks	NA	High Temperature, thermally stable, moderate thermal conductivity materials
8.1202	Development of High-Speed IR Capability	NA	NA	4 weeks	NA	2 weeks	High Speed Data Systems	High Temperature, thermally stable, moderate thermal conductivity materials
8.13	Pressure sensitive paint							
8.1301	Development of Advanced Pressure Sensitive Paints	NA	NA	4 weeks	NA	3 weeks	NA	NA
8.14	Temperature sensitive paint							
8.1401	Development of Advanced Temperature Sensitive Paints	NA	NA	4 weeks	NA	3 weeks	Coating excitation lamps and camera systems to measure temperature changes	material properties for new materials in use, Smooth, uniform coating process
8.2	**Flow Field Optical Diagnostics**							
8.21	Laser-Based Velocimetry							
8.2101	Planar Laser Induced Fluorescence	Long run times, Seeding systems if needed in flow	NA	10 weeks	NA	5 weeks	High Speed Data Systems	Complex internal plumbing for gas seeding
8.2102	Femtosecond Laser Electronic Excitation Tagging	Long run times, Seeding systems if needed in flow	NA	10 weeks	NA	5 weeks	High Speed Data Systems	Complex internal plumbing for gas seeding
8.22	Laser-Based Temperature measurements							
8.2201	Planar Laser Induced Fluorescence	Long run times, Seeding systems if needed in flow	NA	10 weeks	NA	5 weeks	High Speed Data Systems	Complex internal plumbing for gas seeding

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
8.23	3D Flow field Density Measurements							
8.2301	Focusing schlieren capability	optical access for camera systems	NA	4 weeks	NA	NA	Knife-edge, light source, mirrors	N/A
8.2302	Zoom schlieren capability	optical access for camera systems	NA	4 weeks	NA	NA	Knife-edge, light source, mirrors	N/A
8.24	Flow field Density Fluctuations/Velocity in 2+ points							
8.2401	Requirement #1							
8.25	Broadband absorption spectroscopy							
8.2501	Requirement #1							
8.26	Microwave interferometry							
8.2601	Requirement #1							
8.3	**Discrete Sensor Development**							
8.31	Advanced high-frequency pressure/temperature/noise instrumentation							
8.3101	Requirement #1							
8.32	Shock time of arrival/pressure sensors							
8.3201	Requirement #1							
8.33	Fiber-optic temperature / heat transfer sensors							
8.3301	Requirement #1							
8.34	Development of injection systems for film cooling and BLT control							
8.3401	Requirement #1	Longer run times, portable blowing system for testing RCS, retropropulsion, etc.	NA				High speed data systems and high-speed camera systems	complex internal plumbing for gas seeding
8.35	Miniaturized Spectrometer							
8.3501	Requirement #1							
8.36	Shear stress sensor							
8.3601	Requirement #1							
8.37	Displacement sensor							
8.3701	Requirement #1							
8.38	Strain gages							
8.3801	Requirement #1							
8.4	**Aerodynamic Force & Angle Measurement**							

ID	Customer / Categories / Programs / Objectives	Required Facility Capability	Required Test Points in NASA Facilities	Required Calendar Time in NASA Facilities	Required Test Points in non-NASA Facilities	Required Calendar Time in non-NASA Facilities	Required Instrumentation Capability	Required Test Article Fabrication Capability
8.41	Free-flight magnetic suspension							
8.4101	Requirement #1							
8.42	Rapid Development of force & moment balances							
8.4201	Additive manufacturing for force & moment balances	NA	NA	10 weeks	NA	NA	None	Additive manufacturing and advanced conventional fabrication capabilities. High temperature materials and/or active cooling
8.43	High-frequency response balances							
8.4301	High Frequency Response Balances	NA	NA	10 weeks	NA	NA	High speed data system	High temperature materials and/or active cooling. Integration of piezoelectric sensors
8.44	Angle Measurements							
8.4401	Dynamic Angle Measurement	NA	NA	8 weeks	NA	NA	High speed data system	High temperature materials and/or active cooling
8.4402	Miniaturized Angle Measurement Capabilities	Optical access for video model deformation system	NA	8 weeks	NA	NA	None	High temperature materials and/or active cooling
8.45	Flow Through Balances							
8.4501	Development of flow through balance capabilities	Air systems for the flow through balance	NA	10 weeks	NA	NA	High Pressure measurements	High temperature materials and/or active cooling

Table 62. Gaps List for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development.

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
8	**Ground Test Technique Development**					
8.1	**Global optical Surface Measurement Techniques**					
8.11	High-temperature phosphor thermography					
8.1101	Phosphor Thermography	NA	Facility schedules are full and test time is hard to get. Outside of NASA testing is not an option.	newer, faster cameras, mapping capabilities, 2D and 3D conduction analysis, ability to test multiple orientations in a single run (integration of data). Fused silica ceramic and colloidal (potential replacements but not yet vetted)	3D Ceramic model printing, new high temperature plastics and/or new ceramic materials, ability to fabricate very sharp leading edges. Ability to fabricate small details (steps, gaps, fences, etc.). 3D printing of larger ceramic parts without shrinkage upon firing (helpful, but not required for current fabrication process - useful for ceramic models with very fine features)	Inst-Flow-02, Inst-Heat-01, Inst-Heat-06, Inst-Heat-07, Inst-Heat-10, HTP-03, EDL-01, EDL-09
8.1102	High Temperature Phosphor Thermography	NA	Facility schedules are full and test time is hard to get. Outside of NASA testing is not an option.	newer, faster cameras, mapping capabilities, 2D and 3D conduction analysis, ability to test multiple orientations in a single run (integration of data)	3D Ceramic model printing, new high temperature plastics and/or new ceramic materials	Inst-Flow-02, Inst-Heat-06, Inst-Heat-07, Inst-Heat-10, HTP-03, EDL-01, EDL-09
8.12	Infrared thermography					
8.1201	Development of Quantitative IR Capability	None	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	Windows (MWIR), Cameras	Determination of new materials, Potential to machine material surfaces or 3D printing of materials. Possible material extrusion	Inst-Flow-02, Inst-Heat-01, Inst-Heat-06, Inst-Heat-07, Inst-Heat-09, HTP-03, EDL-01, EDL-09
8.1202	Development of High-Speed IR Capability	none	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	Windows (MWIR), Cameras	Determination of new materials, Potential to machine material surfaces or 3D printing of materials. Possible material extrusion	Inst-Flow-02, Inst-Heat-01, Inst-Heat-06, Inst-Heat-07, Inst-Heat-09, HTP-03, EDL-01, EDL-09
8.13	Pressure sensitive paint					
8.1301	Development of Advanced Pressure Sensitive Paints	NA	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	improved cameras (speed and resolution)	Addition of new materials and understanding of material properties for new materials	Inst-Flow-02, Inst-Heat-07, HTP-03, EDL-01, EDL-09
8.14	Temperature sensitive paint					
8.1401	Development of Advanced Temperature Sensitive Paints	NA	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	improved cameras (speed and resolution)	Addition of new materials and understanding of material properties for new materials, Potential to machine material surfaces or 3D printing of materials. Possible material extrusion	Inst-Flow-02, Inst-Heat-01, Inst-Heat-06, Inst-Heat-07, HTP-03, EDL-01, EDL-09

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
8.2	**Flow Field Optical Diagnostics**					
8.21	Laser-Based Velocimetry					
8.2101	Planar Laser Induced Fluorescence	Longer runs times for blow down tunnels	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	High speed data system	high temperature materials that can be 3D printed to allow for complex internal geometry	Inst-Flow-01, Inst-Flow-02, Inst-Flow-03, Inst-Flow-05, Inst-Flow-06, EDL-07, EDL-09, HTP-07, CFD-03, CFD-08
8.2102	Femtosecond Laser Electronic Excitation Tagging	Longer runs times for blow down tunnels	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	High speed data system	high temperature materials that can be 3D printed to allow for complex internal geometry	Inst-Flow-01, Inst-Flow-02, Inst-Flow-03, Inst-Flow-05, Inst-Flow-06. EDL-07, EDL-09, HTP-07, CFD-03, CFD-08
8.22	Laser-Based Temperature measurements					
8.2201	Planar Laser Induced Fluorescence	Longer runs times for blow down tunnels	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	High speed data system	high temperature materials that can be 3D printed to allow for complex internal geometry	Inst-Flow-01, Inst-Flow-02, Inst-Flow-03, Inst-Flow-05, Inst-Flow-06, EDL-07, EDL-09, HTP-07, CFD-03, CFD-08
8.23	3D Flow field Density Measurements					
8.2301	Focusing schlieren capability	Optical access for camera systems	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	Availability of high-speed cameras	None	Inst-Flow-01, Inst-Flow-08, CFD-08
8.2302	Zoom schlieren capability	Optical access for camera systems	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	Availability of high-speed cameras	none	Inst-Flow-01, Inst-Flow-08, CFD-08
8.24	Flow field Density Fluctuations/Velocity in 2+ points					
8.2401	Requirement #1					Inst-Flow-06
8.25	Broadband absorption spectroscopy					
8.2501	Requirement #1					
8.26	Microwave interferometry					
8.2601	Requirement #1					
8.3	**Discrete Sensor Development**					
8.31	Advanced high-frequency pressure/temperature/noise instrumentation					
8.3101	Requirement #1					Inst-Aero-05, Inst-Flow-01, Inst-Heat-05
8.32	Shock time of arrival/pressure sensors					
8.3201	Requirement #1					Inst-Aero-05, Inst-Heat-05
8.33	Fiber-optic temperature / heat transfer sensors					

ID	Customer / Categories / Programs / Objectives	Facility Capability Gaps	Facility Cost / Capacity Gaps	Facility Instrumentation Gaps	Test Article Fabrication Gaps	# Gap List
8.3301	Requirement #1					Inst-Heat-02, Inst-Heat-05
8.34	Development of injection systems for film cooling and BLT control					
8.3401	Requirement #1			High speed data systems and high-speed cameras		Inst-Flow-03, Inst-Flow-04
8.35	Miniaturized Spectrometer					
8.3501	Requirement #1					Inst-Flow-01, Inst-Heat-02
8.36	Shear stress sensor					
8.3601	Requirement #1					Inst-Flow-02, Inst-Heat-02
8.37	Displacement sensor					
8.3701	Requirement #1					Inst-Heat-02
8.38	Strain gages					
8.3801	Requirement #1					Inst-Heat-02
8.4	**Aerodynamic Force & Angle Measurement**					
8.41	Free-flight magnetic suspension					
8.4101	Requirement #1					
8.42	Rapid Development of force & moment balances					
8.4201	Additive manufacturing for force & moment balances	None	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	None	Additive manufacturing and advanced conventional fabrication capabilities. High temperature materials and/or active cooling	Inst-Aero-03, Inst-Aero-04
8.43	High-frequency response balances					
8.4301	High Frequency Response Balances	None	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	High speed data system	High temperature materials and/or active cooling. Integration of piezoelectric sensors	Inst-Aero-01, Inst-Aero-02, Inst-Aero-03, CFD-07, CFD-10
8.44	Angle Measurements					
8.4401	Dynamic Angle Measurement	None	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	High speed data system	High temperature materials and/or active cooling. Integration of MEMs sensors	Inst-Aero-01, Inst-Aero-02, Inst-Aero-03
8.4402	Miniaturized Angle Measurement Capabilities	Optical access for video model deformation system	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	None	High temperature materials and/or active cooling. Integration of MEMs sensors	Inst-Heat-02
8.45	Flow Through Balances					
8.4501	Development of flow through balance capabilities	Air systems for the flow through balance	Facility schedules are full and test time is hard to get. Cost limitations for outside of NASA testing	High Pressure measurements	High temperature materials and/or active cooling	Inst-Aero-04

Table 63. Gaps Closure and Mitigation Alternatives for Theme: Hypersonic Tools and Methods, Customer: Ground Test Technique Development.

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
8	**Ground Test Technique Development**					
8.1	**Global optical Surface Measurement Techniques**					
8.11	High-temperature phosphor thermography					
8.1101	Phosphor Thermography	Significant gaps in model fabrication needs as well as data reduction capabilities	New suitable ceramic and colloidal are required to maintain critical aeroheating ground testing capability for flight programs	N/A	N/A	N/A
8.1102	High Temperature Phosphor Thermography	Significant gaps in model fabrication needs as well as data reduction capabilities	Potential to impact flight programs (current phosphor coating on cast ceramic models may not have sufficient temperature resolution to observe heating behavior on vehicle configurations in tunnel)	N/A	N/A	N/A
8.12	Infrared thermography					
8.1201	Development of Quantitative IR Capability	Improved materials and material properties as well as the machining of those materials along with the new MWIR window is needed to mature the capability	Potential to impact flight programs (testing where models cannot be phosphor coated for variety of reasons or cast ceramic models are not able to be fabricated with necessary features)	N/A	N/A	N/A
8.1202	Development of High-Speed IR Capability	Improved materials and material properties as well as the machining of those materials along with the new MWIR window is needed to mature the capability. Additionally faster cameras and data systems will be needed	Potential to impact flight programs (testing where models cannot be phosphor coated for variety of reasons or cast ceramic models are not able to be fabricated with necessary features)	N/A	N/A	N/A
8.13	Pressure sensitive paint					
8.1301	Development of Advanced Pressure Sensitive Paints	Improved materials and material properties is needed to mature the capability	Potential to impact flight programs (testing on models where global pressure data is critical)	N/A	N/A	N/A
8.14	Temperature sensitive paint					
8.1401	Development of Advanced Temperature Sensitive Paints	Improved materials and material properties is needed to mature the capability	Potential to impact flight programs (testing where models cannot be phosphor coated for variety of reasons or cast ceramic models are not able to be fabricated with necessary features)		N/A	N/A
8.2	**Flow Field Optical Diagnostics**					
8.21	Laser-Based Velocimetry					

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
8.2101	Planar Laser Induced Fluorescence	Need faster facility data systems and better model fabrication techniques to allow for fabrication of models with complex internal geometries	Potential to impact flight programs that need flow field information including RCS performance, BL interactions, shear layer interactions, etc.	N/A	N/A	N/A
8.2102	Femtosecond Laser Electronic Excitation Tagging	Need faster facility data systems and better model fabrication techniques to allow for fabrication of models with complex internal geometries	Potential to impact flight programs that need flow field information including RCS performance, BL interactions, shear layer interactions, etc.	N/A	N/A	N/A
8.22	Laser-Based Temperature measurements					
8.2201	Planar Laser Induced Fluorescence	Need faster facility data systems and better model fabrication techniques to allow for fabrication of models with complex internal geometries	Potential to impact flight programs that need flow field information including RCS performance, BL interactions, shear layer interactions, etc.	N/A	N/A	N/A
8.23	3D Flow field Density Measurements					
8.2301	Focusing schlieren capability	Need good optical access for facilities as well as easy access to high-speed camera systems	Potential to impact flight programs by providing insight into flow field phenomena due to vehicle configuration that are difficult to visualize with integrated schlieren techniques	N/A	N/A	N/A
8.2302	Zoom schlieren capability	Need good optical access for facilities as well as easy access to high-speed camera systems	Potential to impact flight programs by providing insight into flow field phenomena due to vehicle configuration that are difficult to visualize with integrated schlieren techniques	N/A	N/A	N/A
8.24	Flow field Density Fluctuations/Velocity in 2+ points					
8.2401	Requirement #1			N/A	N/A	N/A
8.25	Broadband absorption spectroscopy					
8.2501	Requirement #1			N/A	N/A	N/A
8.26	Microwave interferometry					
8.2601	Requirement #1			N/A	N/A	N/A
8.3	**Discrete Sensor Development**					
8.31	Advanced high-frequency pressure/temperature/noise instrumentation					
8.3101	Requirement #1			N/A	N/A	N/A
8.32	Shock time of arrival/pressure sensors					
8.3201	Requirement #1			N/A	N/A	N/A

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
8.33	Fiber-optic temperature / heat transfer sensors					
8.3301	Requirement #1			N/A	N/A	N/A
8.34	Development of injection systems for film cooling and BLT control					
8.3401	Requirement #1			N/A	N/A	N/A
8.35	Miniaturized Spectrometer					
8.3501	Requirement #1			N/A	N/A	N/A
8.36	Shear stress sensor					
8.3601	Requirement #1			N/A	N/A	N/A
8.37	Displacement sensor					
8.3701	Requirement #1			N/A	N/A	N/A
8.38	Strain gages					
8.3801	Requirement #1			N/A	N/A	N/A
8.4	**Aerodynamic Force & Angle Measurement**					
8.41	Free-flight magnetic suspension					
8.4101	Requirement #1			N/A	N/A	N/A
8.42	Rapid Development of force & moment balances					
8.4201	Additive manufacturing for force & moment balances	Advanced fabrication capabilities and materials are needed to advance the capability	Enhancement of experimental measurements with potential to impact some flight programs by potential certification with experimental measurements and reduced uncertainty. Improved data and CFD validation	N/A	N/A	N/A
8.43	High-frequency response balances					
8.4301	High Frequency Response Balances	Advanced fabrication capabilities, materials and methods to integrate existing instrumentation are needed to advance the capability	Enhancement of experimental measurements with potential to impact some flight programs by potential certification with experimental measurements and reduced uncertainty. Improved data and CFD validation	N/A	N/A	N/A
8.44	Angle Measurements			N/A		
8.4401	Dynamic Angle Measurement	Advanced fabrication capabilities, materials and methods to integrate existing instrumentation are needed to advance the capability	Enhancement of experimental measurements with potential to impact some flight programs by potential certification with experimental measurements and reduced uncertainty. Improved data and CFD validation	N/A	N/A	N/A

ID	Customer / Categories / Programs / Objectives	Experimental Gaps Summary	Gap Mission Criticality	Gap Closure Alternatives	CFD Capability	CFD Capacity
8.4402	Miniaturized Angle Measurement Capabilities	Advanced fabrication capabilities, materials and methods to integrate existing instrumentation are needed to advance the capability	Enhancement of experimental measurements with potential to impact some flight programs by potential certification with experimental measurements and reduced uncertainty. Improved data and CFD validation	N/A	N/A	N/A
8.45	Flow Through Balances					
8.4501	Development of flow through balance capabilities	Advanced fabrication capabilities and materials are needed to advance the capability	Potential to impact flight programs including EDL missions with RCS or Retropropulsion needs. CFD capabilities are not validated with experimental data	N/A	N/A	N/A