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

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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.