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NASA Ames Thermophysics Ground Test Facilities Supporting Future Planetary Atmospheric Entry

By

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ABSTRACT

A review of the current facility capabilities for testing Thermal Protection Systems and quantifying their entry environments at NASA Ames Research Center is presented based on the expected targets of interest to the Planetary Science and Astrobiology communities. While the operational capabilities of these facilities are generally considered sufficient for supporting future missions to targets of interest, expanded ground test capabilities such as larger sample sizes, flight-relevant gas mixtures, dusty environments, and flight-relevant shear/pressure combinations would reduce entry vehicle design uncertainties and applied margins. These reduced uncertainties may translate into reduced entry vehicle masses, increased robustness, and decreased operational risks during entry phases for science missions. Expanded ground test capabilities would also offer the ability to study material failure modes in environments even more representative of flight than are currently achievable. A list of desired future test capabilities is presented. The main recommendation of this paper is the undertaking of a detailed study of the benefits and associated costs of each of these expanded capabilities to determine the best future path.

1. INTRODUCTION

This Decadal Survey white paper, provided by the Entry Systems and Technology Division at NASA Ames Research Center, is a general assessment of the current capabilities of the Ames ground test facilities with respect to Thermal Protection System (TPS) testing and quantification of entry environments for the exploration of planetary targets with atmospheres. These anticipated future targets are Mars (including sample return), primitive bodies (asteroid and comet sample return to Earth), Venus, and the Outer Planets and their moons (including Titan and Enceladus sample return).

2. CURRENT FACILITIES

Aerothermodynamic ground test facilities for studying atmospheric entry phenomena generally fall into one of three categories: impulse facilities, ballistic ranges, and heating facilities [1]. No single ground test facility can simulate all aspects of atmospheric entry, and each of these three categories offers unique access to a different aspect of atmospheric entry.

NASA Ames provides unique and critical facilities in each of these three categories. The Electric Arc Shock Tube (EAST) is the nation's only arc-driven shock tube and provides measurements of shock wave radiation in the supersonic and hypersonic ranges for many different flight-relevant gas mixtures. The Hypervelocity Free Flight Aerodynamic Facility (HFFAF) at the NASA Ames Ballistic Range Complex provides the nation's only ground test environment capable of hypersonic aerodynamics testing, aerodynamics testing at transonic to hypersonic speeds in gases other than air, testing at subatmospheric pressures, and lifting model testing. Finally, the NASA Arc Jet Complex provides large-scale high-heating convective and radiative environments for prospective TPS materials at conditions that cannot be achieved at any other facility in the nation. Without this complex, there would be no way to qualify TPS materials for planetary exploration missions. Maintaining and improving all of these ground test capabilities is vital to supporting missions to the nation's future atmospheric entry targets.

3. STATE-OF-THE-ART AND DESIRED FUTURE CAPABILITIES

Table 1 shows example entry conditions for actual missions or mission concept studies to targets of interest. Since these values have been taken from ongoing mission concept studies and design conditions are constantly being updated, the values in Table 1 are included primarily to give order-of-magnitude comparisons between different trajectories. Current test capabilities of EAST, HFFAF, and the Arc Jet Complex are detailed in [2]. For comparison with Table 1, the Arc Jet Complex can provide cold-wall convective heating rates up to approximately 4000 W/cm^2 and stagnation pressures up to 500 kPa, but these maximum conditions are restricted to a 2.5-cm diameter sample. Simultaneous radiative and convective heating is also available, but only in a wedge configuration. This section addresses which entry conditions can be met with existing ground test capabilities and which will require expanded capabilities.

Table 1: Example Entry Conditions for Targets of Interest

	Mars, MSL	Sample Return, MSR EEV	Venus, Aerobot	Uranus, Ice Giants	Neptune Odyssey	Titan, Dragonfly
Relative entry velocity (km/sec)	5.8	12	10.6	22.5	26.3	7.3
Entry flight path angle	-16.1°	-25°	-8.5°	-30°	-17.8°	-49.7°
Peak margined hot-wall convective heat flux (W/cm^2)	226	3600	4000	2500	5470	143
Peak margined radiative heat flux (W/cm^2)	17	1080	170	not calc-ulated	not calc-ulated	151
Peak stagnation pressure (kPa)	30.4	230	93.3	900	620	22.8
Peak shear (kPa)	0.5	6	3	"large"	4	0.188
Diameter (m)	4.5	1.3	2.8	1.2	1.26	3.75
Entry Mass (kg)	3153	95	1450	321	275	1700
Primary Components of Atmosphere	CO_2, some N_2 and Ar	Air	CO_2, some N_2	H_2, He, some CH_4	H_2, He, some CH_4	N_2, some CH_4
Reference	3	4	5	6	7	8

3.1 Coupling Ground Testing and Modeling through Flow Characterization

As discussed, no single ground test facility can match all flight-relevant entry parameters. Matching just two or three simultaneous parameters is extremely difficult, and in some cases, even matching an individual entry parameter can be difficult. Therefore, a piecewise TPS certification strategy is necessary. Such a strategy requires a close interaction between ground testing and modeling, which is validated by flow characterization measurements in the facilities.

Standard flow diagnostics for NASA arc jet tests include calorimeters and pitot probes inserted directly into the flow. Specialized non-intrusive diagnostics are occasionally employed as well, including emission and absorption spectroscopy, laser-induced fluorescence, and photogrammetric recession. All of these specialized diagnostics aim to quantify flow or sample material characteristics, but most are complicated and require extensive post-processing to produce useful flow or material parameters. Further study would be helpful in identifying improved measurement techniques for key parameters (enthalpy and shear) and which flow parameters might be missing from the existing measurement set that could improve the ability to model arc jet flows and material recession.

The primary diagnostic in the EAST facility is emission spectroscopy. A suite of four spectrometers image the radiation along the axial direction of the tube, providing spectrally and spatially resolved radiance data that are required to model radiative heating magnitudes. These spectrometers can make calibrated spectral measurements from the vacuum ultraviolet (VUV) through the mid-wave infrared (MWIR). The VUV radiation mechanism may comprise over half of the radiative heating magnitude for many entry scenarios. The MWIR radiation is an important factor in CO_2 atmospheres (Mars/Venus) and may dominate the heating on the vehicle backshell. New diagnostic techniques in EAST are being developed to understand specific mechanisms within the flow, the most recent of which is tunable diode laser absorption spectroscopy (TDLAS) to study the evolution of CO_2 and CO dissociation within shock waves representative of Mars and Venus.

In the HFFAF, sixteen shadowgraph imaging stations are used to capture orthogonal pairs of images of a hypervelocity model in flight. These 32 images, combined with the recorded flight time history, can be used to obtain critical aerodynamic parameters, examine flow-field structural details, and observe ablation behavior. Surface roughness testing at the HFFAF provides insight into boundary-layer transition and turbulent heat-transfer augmentation.

3.2 Mars and Titan

The United States entry systems community has successfully landed many entry vehicles on Mars and continues to plan regular missions there [9]. Peak heating is low (100-250 W/cm^2) compared to other planetary destinations due to low atmospheric density and low entry velocities. As such, existing ground test capabilities are generally sufficient to support future robotic missions on the scale of Mars Science Laboratory (MSL) or Mars Sample Return (MSR). Radiation from shock-heated carbon dioxide in simulated Mars atmospheres has been quantified at the EAST facility [10]. The HFFAF has supported the Viking and MSL missions with its capability of testing in carbon dioxide environments.

The Mars TPS community has shown interest in carbon dioxide arc jet testing. While the chemistry differences between air and carbon dioxide plasma environments are understood well enough for Mars programs to carry out TPS certification testing in air, the impact of CO and atom surface catalycity remains an open question. Currently in the United States, only the small-scale 400 kW Hypersonic Materials Environmental Test System (HyMETS) arc jet has carbon dioxide plasma capability. The Aerodynamic Heating Facility (AHF) 10 MW dual bore arc heater at the NASA Arc Jet Complex ran on carbon dioxide when it was located at NASA Johnson and has undergone integrated systems testing with carbon dioxide since its transfer to NASA Ames, but additional engineering work (on the order of a year) is necessary to bring this arc heater up to fully operational status with carbon dioxide. It is recommended that this work be completed.

Mars is known to have dust storms that can sometimes be quite expansive and the effects of dust on entry systems have not been extensively studied. The recent InSight landing occurred nearly coincident with a dust storm. Because of possible, but poorly understood, augmented recession due to dust, the TPS thickness margin was increased for the InSight heat shield. The L2K facility in Germany and the Simoun facility in France both have capabilities of seeding dust into arc jet flows, and the recent European/Russian EXOMARS mission carried out testing in dust-laden arc jet flows [11]. However, since the closure of the Dust Erosion Tunnel (DET) at the Arnold Engineering Development Complex (AEDC) in the 1990's, the US does not have such a capability. L2K, Simoun, and DET all indicate that a 1-10 MW dusty arc jet is capable of providing useful data on dusty plasmas. A dust-seeded shock tunnel, such as a modified

HYPULSE (decommissioned NASA Langley) or a modified EAST facility, would offer another alternative for studying dusty flows since heating from dust particles has a strong dependence on gas velocity. It is recommended that the United States re-establish the capability of testing in dust-laden flows.

Like Mars, most Titan entries produce low heating conditions compared to other planetary targets and foreseeable entries can be achieved with current ground test facility capabilities. The estimated convective heating is well within the capability of existing arc jet facilities, and the 10 MW and 20 MW arc heaters at the NASA Arc Jet Complex can also run the desired nitrogen environments. However, the Titan TPS community has expressed interest in adding pure nitrogen capability to NASA's 60 MW Interaction Heating Facility (IHF) in order to test much larger models and thus enable the study of discontinuities due to seams, gap filler, or flight instrumentation. This would require an upgrade to the IHF gas supply system. Germany and Italy have the capability of arc jet testing with small amounts of methane in nitrogen flows, and studies there indicate that the small amounts of methane could possibly have a significant effect on surface heating [12]. The United States does not currently have the capability of arc jet testing with methane. This could be added with a modification to the AHF gas supply system and would take a moderate level of engineering effort to ensure system safety.

The HFFAF can support ballistic testing in pure nitrogen environments. Including methane in the Titan gas mixtures for the HFFAF is feasible, but would require some amount of engineering work to assure system safety and implement updated procedures. Shock wave radiation studies in Titan gas mixtures including methane have been carried out in EAST and have identified gaps in the Titan radiative heating models. Additionally, inconsistencies between modern and historical Titan radiative heating data sets warrant further study [13].

3.3 Venus

A Venus entry mission is expected to be of particular interest within the next decade [5, 14] and will encounter relatively high convective heat loads upon entry (see Table 1). The IHF has recently been fitted with a 7.6-cm (3-inch) nozzle that expands its test envelope to include flight-relevant Venus convective heating conditions in stagnation configuration [15, 16]. However, the recommended maximum sample diameter based on 30% blockage in this configuration, 2 cm, is much smaller than the typical 10.2 cm diameter sample. Samples of this size limit the amount of model instrumentation and number of features (e.g. seams and gap fillers) that can be tested. Such a small sample is also much more subject to two-dimensional heating effects, making ground-to-flight traceability arguments more challenging. The ability to test samples at larger scales at similar flight-relevant heating rates is therefore desired. However, meeting such a demand would require a more powerful arc jet than IHF, which would be technically and financially challenging.

Ground testing for Venus entries presents the difficult challenge of simultaneously matching high convective heat flux (~4000 W/cm^2), high shear, and moderate pressure conditions (see Table 1). Although missions have ground tested these parameters independently in the past, they are coupled in such a way that testing independently may not capture all of the physical mechanisms taking place when the three conditions are simultaneously present. This cannot currently be achieved in any existing ground test facility. The arc jet facilities at Arnold Engineering Development Complex (AEDC) can achieve high shear conditions that are currently unattainable at the NASA Arc Jet Complex, and projects such as the Heatshield for Extreme Entry Environment Technology (HEEET) have tested at AEDC specifically for high shear conditions. However, due to the high pressures at which the AEDC arc jets operate (>1400 kPa), this is considered over-testing for Venus entries and could result in material failures that would not necessarily occur during flight. The infrastructure at the NASA Arc Jet Complex was designed for operation at low to moderate pressures (100-600 kPa), so it is therefore possible that a facility at the NASA Arc Jet Complex could simultaneously achieve all three of these conditions. However, this would require increasing the flow enthalpy above the current facilities' maximums, and enthalpy in a large facility such as IHF can only be fractionally increased, which likely means that a new arc heater with a smaller working diameter would be necessary. A detailed study of the feasibility and benefits of adding a facility that can reach this combination of entry conditions is recommended.

As with Mars, the ability to carry out arc jet tests in a carbon dioxide environment is a priority for Venus entry missions [15]. This could be achieved with updates to the AHF 10 MW dual bore arc jet as discussed above.

Ballistic testing at the HFFAF can be carried out in flight-relevant gas (CO_2). Radiative heating from the bow shock during a Venus entry is significant enough to warrant further study at the EAST facility as only a small number of tests have been performed to date [17].

3.4 Sample Return

Sample return programs from Lagrange point L1 (Genesis), a comet (Stardust), and an asteroid (OSIRIS-REx) have all successfully tested TPS materials at NASA Ames and such missions are within the capabilities of existing ground test facilities. The radiative heating for sample return missions has been characterized in the EAST facility up to 15.5 km/s [20], but existing gaps in the test data would merit additional study depending upon the expected entry velocity. The question of backshell heating magnitude is not resolved, but future expansion cone testing in EAST is expected to improve models for this.

Work on future sample return missions is underway (Mars Sample Return Earth Entry Vehicle, MSR EEV) and also within existing capabilities (see Table 1), although the mission design space has been purposefully constrained in order to reduce entry conditions such that they fall within the capabilities of the NASA Arc Jet Complex and the AEDC Arc Jet Complex. The new 7.6-cm nozzle at IHF has expanded the ground test support capabilities for high-speed sample return missions. In addition, the IHF arc jet can now support combined radiative and convective heating due to the recent addition of the 200 kW LEAF-Lite laser system, the highest-power continuous wave laser system operating in the United States [18]. However, the sample return community notes that an even higher heat flux capability will enable a larger mission design space (it will be necessary for returns at >13.5 km/s), and desires a modification of the LEAF-Lite system to augment stagnation point heating at IHF. Also, similar to Venus entries, sample return missions will experience high shear conditions (see Table 1) in combination with moderate pressures that are not achievable in any existing US arc jet [19].

3.5 Outer Planets

The EAST facility has been used to characterize the radiation magnitude for entry into H_2/He atmospheres. Radiation is found to be insignificant below ~27 km/s, which is representative for most Uranus trajectories and some Saturn/Neptune trajectories. At higher velocities, the data has identified some modeling gaps. One open question is the impact of small amounts of atmospheric methane on the shock layer characteristics. Though the EAST facility was employed for preliminary studies for Galileo, the radiative heating in a representative Jovian entry has not been measured with the modern instrumentation suite. The HFFAF also ran H_2/He shots in support of Galileo, but not since. Such environments are therefore feasible, but given safety considerations, would take a significant amount of engineering work to accomplish now.

Arc jet testing for Outer Planet (OP) entries is currently the most striking gap in atmospheric ground test facility capabilities, with existing facilities only able to partially achieve relevant aerothermal conditions [21]. Entry conditions for Jupiter, Saturn, Uranus, and Neptune are the harshest in the solar system. The Galileo mission that entered the Jovian atmosphere was supported by a purpose-built H_2/He arc jet at Ames called the Giant Planet Facility (GPF). Since this facility was dismantled in the 1990's, the United States no longer has a H_2/He arc jet capability. The necessity of arc jet testing in a H_2/He environment for future Outer Planets missions is debated. Some argue that a pure N_2 arc jet environment is sufficient for certification of Outer Planet TPS, since both N_2 and H_2/He environments are non-oxidizing [21]. Others suggest that H_2/He TPS testing on at least a small scale is recommended and have proposed a 5 MW H_2/He arc jet to fill this role [6, 22]. Regardless of the debate over the necessity of H_2/He arc jet testing, the community agrees that a pure N_2 flow in IHF is desired [6, 21].

Missions to Saturn, Uranus, and Neptune are currently being studied. Using Neptune as a representative entry, existing arc jets would be pushed to their limits to match the heat fluxes encountered during the most benign of Neptune entry trajectories. However, they cannot simultaneously also match the required high pressures of entry nor can they match heat fluxes for trajectories optimized for telecommunications [6]. As with sample return missions, studies of missions to these planets are restricting design space such that entry conditions fall within test capabilities of the NASA and AEDC Arc Jet Complexes. Thus the Neptune community seeks expanded arc jet capabilities that include simultaneous high-enthalpy and high-pressure testing.

4. RECOMMENDATIONS

The existing NASA Ames atmospheric entry ground test infrastructure is capable of providing ground test environments in support of future missions within certain mission design constraints. However, successfully meeting the science objectives for some targets may demand enhanced or additional capabilities. The desired future capabilities for all targets are summarized in Table 2. Because priority depends inherently upon the mission under consideration and the risk posture of that mission, this list is not prioritized. However, the third and fourth columns give an idea of the relative level of difficulty associated with adding the capability. The fourth column is a very general estimate of complexity since these recommendations can each be achieved in a number of ways.

Table 2: Recommended NASA Ames Ground Test Capability Improvements

Expanded Capability	Target	Facility to be upgraded	Estimated cost and complexity
Dusty arc jet or shock tunnel	Mars	EAST, AHF	Moderate
10 MW CO_2 arc jet	Mars, Venus	AHF 10 MW	Low
Pure N_2 testing in >20 MW arc jet	Titan, Outer Planets	IHF	Moderate
Radiative heating in arc jet, stagnation configuration	Sample Return, Venus, Outer Planets	IHF-LEAF	Moderate
N_2/CH_4 arc jet and ballistic range	Titan	AHF, HFFAF	Low
Simultaneous high heat flux (>3500 W/cm^2), high shear (3-6 kPa), moderate pressures (100-300 kPa)	Venus, Sample Return	-	Moderate

Large-scale (>2cm diameter) high heat flux (>3500 W/cm^2) arc jet	Venus, Outer Planets, Sample Return	-	High
Moderate pressure (>600 kPa) high heat flux (>3500 W/cm^2) H_2/He(/CH_4) arc jet	Outer Planets	-	Moderate
Improved flow characterization (coupled ground testing and modeling)	All	Any, additional diagnostics	Low

Each of these capability improvements would benefit from a concentrated trade study. Some can be completed with modifications to existing facilities, but others will require the consideration of new or different facilities. The authors recommend a detailed study of the value added by each option and its associated cost. Questions to be answered should include: What is the preferred path to establish each of these expanded capabilities? What are the specific technical challenges? What is the risk to a mission if these capabilities are not established?

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