NASA SBIR 2021 Phase I Solicitation

Z7.06 Entry, Descent, and Landing (EDL) Terrestrial Testing Technologies

Lead Center: ARC

Participating Center(s): LaRC

Scope Title:

Optical and Laser-Spectroscopic Imaging Techniques for High-Enthalpy Arc-Heated Test Facilities

Scope Description:

Arc-heated high-enthalpy test facilities at NASA's Ames and Langley Research Centers are used for evaluation and certification of high-temperature materials and structures of an entry vehicle's thermal protection system (TPS). Future exploration missions will utilize new ablative TPS materials that release decomposition products into the gas stream ahead of the vehicle, influencing flow-field behavior. Data and observations from materials testing programs using NASA's arc jet facilities are critical for validation of high-fidelity modeling and simulation tools used to design and margin TPS specifications for entry vehicles. However, the complex multiphysics processes that manifest as entry aeroheating of ablative TPSs present formidable challenges for model validation. The available diagnostic techniques for arc jet testing provide little direct evidence of the subject aerothermal and thermophysical processes.

NASA is seeking advanced and new optical and laser-spectroscopic techniques applied to arc jet testing programs. Experimental methods for arc jet facility characterization strive to quantify thermodynamic and gas dynamic properties of the arc jet stream and serve multiple purposes, such as verification of test conditions (facility operations), validation of arc heater and flow-field simulations, and measurement of incident/boundary conditions for material response simulations. Of equal importance are methods that can detect and identify pyrolysis gases and particles injected into the shocked gas region ahead of TPS material test articles, providing needed insight to the complex interactions of the flow field with material response. Experimental methods that measure recession, temperature, and optical properties of the TPS surface enable characterization of surface thermal response phenomenology.

The off-body gas phase diagnostics are to detect and quantify:

- Major species in the arc jet stream (N, O, N_2, NO for air; CO and CO_2 for facilities capable of operating with CO_2 mixtures).
- Ablation species and recombination products in the shock layer (C, CN, CH, H, Ca).
- Spalled particles from test articles penetrating the shock layer.

Also of importance are measurements of velocity and free stream and shock layer temperatures, including vibrational temperature. Planar or line imaging techniques are desired to characterize spatial distributions with 1-mm or smaller resolution at kHz data rates. Burst mode (>100 kHz) imaging approaches that enable correlation of temporal-spatial intermittencies are of particular interest.

The requested surface imaging diagnostics are to measure test-article temperature and spectral emissivity, topology, and recession rate. Hyperspectral techniques are preferred if they enable characterization of multiple surface properties simultaneously while discriminating from shock layer radiation. Spatial resolutions and acquisition rates of <1 mm and >30 Hz, respectively, are desired. Adaptation of standoff surface spectroscopy techniques may hold promise for time-resolved species detection and identification.

Spallation characterization requires measurements of ejected particle size distributions, 2D and 3D trajectories, and velocity distributions. Techniques for both stagnation and shear testing configurations are desired. Imaging spatial resolution and field of view needs to account for particle trajectories that travel upstream and penetrate shock waves. Methods that provide insight to the chemical composition of spalled particles would be particularly valuable. Anticipated particle size and speeds are 1 to 100 µm and 1 to 200 m/s, respectively.

Expected TRL or TRL Range at completion of the Project: 3 to 6
Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Assessment study of potential diagnostic techniques.
Phase II: Prototype instrument demonstration in relevant environment with hardware delivery to NASA.

State of the Art and Critical Gaps:

The requirements for spatially resolved, species-specific measurements of high-temperature-reacting gas properties necessitate the use of optical-spectroscopic methods. The state of the art at NASA’s arc-heated facilities are techniques based on nanosecond-pulsed laser-induced fluorescence (ns-LIF). Pointwise flow property measurement requires approximately 60 to 90 sec per acquisition to recover properties calibrated to engineering units (velocity, temperature, species densities) at one location. The low sensitivity and long standoff distances in arc-heated facilities preclude line or planar imaging. The long acquisition times result in a poor use of expensive testing resources. The ns-LIF approach is not suitable for post-shock and near-surface regions, as the moderate pressures, high temperatures, and strong gas and surface luminosity confound signal interpretation, effectively prohibiting quantitative ablation species detection. Emission spectroscopy techniques for free-stream and shock-layer measurements have been used with success for many years, but these are limited to observation of excited-state populations along integrated lines of sight. Tunable laser absorption spectroscopy can target ground-state or excited-state populations of certain species of interest; however, the low-density/high-temperature test conditions and the short path lengths yield absorbances too low for detection with demonstrated laser absorption techniques.

Recent advances in tunable amplified sources pumped by kHz and burst-mode femtosecond-pulse lasers has enabled the development of several nonlinear laser spectroscopy techniques. These new techniques have capabilities that directly address the sensitivity, temporal, and spatial resolution shortcomings identified above.

For spallation diagnostics, both active interrogation/response and passive imaging techniques have potential for characterizing size distributions, trajectories, and velocity distributions. NASA's current capability for observing and quantifying spallation is the use of high-speed gated video, which is limited to situations where particle luminosity can be distinguished from background sources.

Relevance / Science Traceability:

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have ED/EDL (entry and descent or entry, descent, and landing) architectures: Mars Sample Return, high-speed crewed return, high-mass Mars landers, Venus, and gas/ice giant probes. With few exceptions, entry vehicle TPS for these missions will be composed of materials currently under development and without certification heritage in multiple gases. Arc jet testing at conditions relevant for certification will invariably be required for each of these proposed missions. Ground testing at more extreme environments for future missions will challenge existing capabilities. There is a compelling need now to bring research-level diagnostic technologies forward to ensure that facility operations can confidently demonstrate required performance to TPS technology projects.

Conventional instrumentation will continue to be the primary source of facility characterization data. The purposes of the advanced techniques are to provide validating evidence for the conventional instrumentation, reveal error and bias in interpretation of heat flux measurements, and ultimately reduce uncertainty in facility performance data provided to test programs.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. The first-line project is the Space Technology Mission Directorate's Entry Systems Modeling Project.

References:

1. Entry Systems Modeling Project: https://gameon.nasa.gov/projects/entry-systems-modeling-esm/
2. O. Chazot, "Experimental Studies on Hypersonic Stagnation Point Chemical Environment," RTO-EN-AVT-142, Experiment, Modeling and Simulation of Gas-Surface Interactions for Reactive Flows in Hypersonic Flights, pp. 13-1 to 13-32.
3. A. Gülhan, "Heat Flux Measurements in High Enthalpy Flows," RTO EN-8, Measurement Techniques for High Enthalpy and Plasma Flows, April 2000.
4. J. Grinstead, et al., "Consolidated laser-induced fluorescence diagnostic systems for the NASA Ames arc jet facilities," AIAA 2016-4159.
5. S. Bailey, et al., "Experimental analysis of spallation particle trajectories in an arc-jet environment," Experimental Thermal and Fluid Science v. 93, pp. 319-325 (2018).
6. D.A. Codron, "Emission Spectroscopy Characterization of Thermal Protection System Materials in Arc-Heated Flows," AIAA 2014-2112.
7. J.A. Inman, et al., "Nitric Oxide PLIF Measurements in the Hypersonic Materials Environmental Test System (HYMETS)," AIAA Journal Vol. 51, No. 10, pp. 2365-2379, October 2013.
8. D.J. Bamford, et al., "Characterization of the H1 Arc Heater Facility by Laser-Induced Fluorescence," AIAA 2013-0035.
9. P. Danehy, et al., "Quantitative Spectral Radiance Measurements in the HYMETS Arc Jet," AIAA 2012-0856.
10. M. Winter, et al., "Non-Equilibrium Analysis of Emission Spectroscopy Data Taken in the Freestream of the NASA IHF Arc Jet Facility," AIAA 2015-2963.

Scope Title:

Advanced Instrumentation for NASA's Shock Tube and Ballistic Range Facilities

Scope Description:

NASA Ames Research Center operates two specialized-use impulse test facilities for aerodynamic and aerothermodynamic research investigations that support atmospheric entry systems modeling and validation. The Electric Arc Shock Tube (EAST) facility replicates shocked gas environments encountered by entry vehicles transiting planetary atmospheres at hypersonic velocities. EAST creates these environments through calibrated gas mixtures of target atmospheres (Earth, Venus, Mars, Titan, gas giants, etc.) and prescribed preshock pressures and shock speeds. Radiative heating of both fore- and after-body surfaces of an entry vehicle can influence, and in some cases dominate, the design requirements for thermal protection systems. Spectroscopic instrumentation is used to characterize the absolute radiance and gas kinetics behind a traveling shock wave. The Hypervelocity Free Flight Aerodynamic Facility (HFFAF), an enclosed aeroballistic range, is used for the study of dynamically similar supersonic and hypersonic aerodynamics, transition to turbulence, and laminar and turbulent convective heat transfer. Optical imaging instrumentation is used to characterize aerodynamic forces and moments of scaled models launched through the range. Thermographic and spectral imaging instrumentation is used to characterize spatially resolved heating rates to scaled models.

NASA is seeking innovative imaging and spectroscopic measurement techniques for these two facilities. New electro-optic products and methods will enable measurement of quantities unattainable with current capabilities as well as improve current practices.

Expected TRL or TRL Range at completion of the Project: 3 to 6
Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Assessment study of potential diagnostic techniques or technology upgrades.
Phase II: Prototype instrument demonstration in relevant environment (preferably with hardware delivery to NASA).

State of the Art and Critical Gaps:

The EAST facility’s instrumentation acquires data for shocked gas phenomenology and facility performance characterization. Measurements of radiance, absorbance, electron density, and temperature are used for validation of comprehensive radiation transport simulations of planetary atmospheres. Those measurements are primarily acquired using calibrated optical-spectroscopic instruments with sufficient temporal and/or spatial resolution to correlate observed magnitudes with localized, spectrally resolved absolute radiant fluxes or columnar property densities (including electron densities). Ancillary instrumentation is used to measure shock arrival times and transient pressures at the tube wall to establish shock speeds adjacent to the science instruments.

Measurement techniques that correlate observables to atomic and molecular state populations and radiance magnitudes enable validation of radiance models. Emission spectroscopy techniques, which capture the transient characteristics of excited atomic and molecular state populations, have reached a high degree of maturity and performance.

However, post-shock electron and ground-state or other dark-state population dynamics also influence shock radiance. Measurement of these states rely on more complicated absorption, induced fluorescence, or scattering (spontaneous and coherent) techniques. The lack of light sources and/or detectors with suitable spectral and temporal characteristics, or the challenges of implementation in impulse facilities, have limited the opportunities for such measurements. Techniques that enable measurement of these states would greatly expand opportunities for radiation transport model validation, particularly for conditions in which self-absorption would influence emission spectroscopy measurements. Specific quantities of interest are rotational/translation and vibrational temperatures, electron temperatures, and ground-state population densities of N_2, N_2+, N, O, CO, CN, H_2, H.

Spatiotemporal resolution is necessary to discern nonequilibrium relaxation processes behind a traveling shock wave and is the key requirement for EAST diagnostics. Field imaging at a single instant in time, or time-resolved imaging of a single point in space, must have resolutions equivalent to >1 mm and >1 μs to capture these relaxation processes.

For the HFFAF, shadowgraph and schlieren photography are used to provide time-resolved imagery for aerodynamic force and moment analyses of scaled flight vehicles in free flight. A high-speed shutter (40-ns duration) and a spark-gap light source enable images to be captured without motion blur or image fogging from shocked gas radiance enveloping a test model. The shuttering system relies on Kerr cells filled with benzonitrile and a 35 kV pulse-shaping and switching network. Advances are sought for the eventual replacement of the 32 heritage light source/shutter systems with components that offer equal or greater performance as well as improved safety and reliability.

Relevance / Science Traceability:

Several potential future missions outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses have ED/EDL (entry and descent or entry, descent, and landing) architectures: Mars sample return, high-speed crewed return, high-mass Mars landers, and Venus and gas/ice giant probes. Entry vehicles to these destinations will encounter radiative heating to varying degrees. Radiative heating of a vehicle's backshell has been recognized as a significant concern, so ensuring a full range of diagnostic techniques for expanding flows has become a high priority for the EDL community.

Characterizing the aerodynamic stability of emerging deployable drag devices for entry vehicles is also of high importance for future high-mass lander missions. The HFFAF will be a key ground-test facility for acquiring crucial free-flight aerodynamic data for study and simulation validation.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. Technology development projects supporting these programs are potential beneficiaries of new instrumentation for the EAST and HFFAF.

References:

1. Entry Systems Modeling Project: https://gameon.nasa.gov/projects/entry-systems-modeling-esm/
2. ADEPT (Adaptable Deployable Entry and Placement Technology) Project: https://gcd.larc.nasa.gov/projects-2/deployable-aeroshell-concepts-and-flexible-tps/
3. Many journal papers, conference proceedings, and technical reports describing the NASA Ames EAST and HFFAF test facilities and research are available in the open literature.