New Developments in NASA's Entry Systems Modeling Project

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This paper describes recent developments for modeling entry, descent, and landing (EDL) of spacecraft in support of NASA's exploration missions. Mission-specific research and model development for entry systems occurs across the Agency (e.g., within flight programs like Artemis/Orion and Mars Sample Return), however the aim of this paper is to discuss the research conducted by NASA's Entry Systems Modeling (ESM) Project, which serves as the Agency's only effort dedicated to advancing modeling capabilities that cross-cut multiple technical disciplines, missions and destinations. The ESM portfolio is developed to address the specific needs expressed by a cross-section of NASA stakeholders, including flight and research projects, technical leadership, and subject matter experts. Technology development in ESM is organized and prioritized from a system-level perspective, resulting in four broad technical areas of investment: (1) Thermal Protection System (TPS) material modeling, (2) Shock layer kinetics and radiation, (3) Aerosciences, and (4) Guidance, navigation, and control. In addition to the core technical areas, special topics are rolled into the project portfolio as specific demands arise. Current special topics include TPS Certification by Analysis, improving understanding of woven TPS material performance; Hypersonic Wake Flows, assessing and improving predictions of base flows; and the MEDLI2 Deep Dive, furthering analysis of data obtained during Mars 2020 mission's entry and descent at Mars. Key results from each of these areas are presented in this paper, along with associated references to serve as a roadmap for other EDL researchers to access NASA's publications.

I. Introduction

NASA's mission to explore the Solar System includes a number of destinations with atmospheres – Mars, Venus, Gas Giants, Ice Giants, Titan and, return to Earth. Spacecraft intending to reach the surface of these destinations require entry systems to withstand the extreme environments encountered during hypervelocity flight. There is no single experimental capability that completely replicates flight conditions on the ground and so, since the dawn of the Space Age, engineers have relied on modeling and simulation to inform design decisions. Indeed, as budgets and risk tolerance shrink over time, the dependence on modeling and simulation to fill testing gaps with reliable information has increased proportionally. Crucially, NASA's EDL community has also recognized that mission-specific investments in EDL modeling are insufficient to sustain NASA's capability and meet the ever-evolving requirements of space exploration. This is because missions are narrowly focused on meeting only their own requirements, not the strategic long-term interests of the broader scientific community. Hence it is desirable to form a research group whose scope is explicitly cross-cutting, where products (e.g., simulation tools, models, databases, etc.) are designed to impact multiple missions including those that may only exist as future proposals. In response, Entry Systems Modeling (ESM), a project within NASA's Space Technology Mission Directorate, was formed in 2013 as a development project to advance low-to-mid Technology Readiness Level (TRL) technologies for entry systems. There are four core research areas within ESM, (1) Thermal Protection System (TPS) material modeling, (2) Shock Layer Kinetics and Radiation (SLKR), (3) Aerosciences and (4) Guidance, Navigation and Control (GNC). ESM is structured as a portfolio project where content evolves in response to stakeholder needs. Primary stakeholders are missions (both active and under proposal development), along with technical authorities, subject matter experts, and external parties such as other government agencies and university partners. Research tasks in the portfolio can be generally classified as either "pull" - addressing a concrete

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need identified by a mission - or as “push”, which is typified by low-TRL research with broad impact. All research tasks are prioritized based on measures of potential impact, preferably through rigorous system-scale sensitivity studies when possible, and research with “pull” is prioritized highest.

ESM investments in TPS material modeling are geared toward high-fidelity, predictive models capable of handling complex structures, with the goal of optimizing design performance and quantifying thermal protection system reliability. Computational tools have been developed to characterize material properties and behavior at the microstructural level, and experimental techniques (molecular beam scattering, micro-computed tomography, among others) have been developed to measure parameters needed to inform and validate detailed simulations. Advancements have also been made in macrostructural simulation capability to enable 3-D system-scale calculations of material response with complex topological features. New tools are currently under development to better characterize the performance of woven TPS systems, in particular focusing on quantifying the limits and physical processes that would lead to fracture and failure.

Research and development in the area of shock layer kinetics has largely focused on air and CO_2- based atmospheres, relevant to missions like Artemis/Orion and Mars Sample Return Earth Entry System and Sample Retrieval Lander (MSR-EES-SRL). Most recently, this area has focused on providing validation data for the newly developed off-stagnation-point radiative heating methodology known as shock tube informed bias for both Mars and Titan atmospheres. The diagnostics employed in the NASA Ames Electric Arc Shock Tube (EAST) have expanded in recent years to include absorption spectroscopy measurements, which has been further augmented by university research grants. First-principles calculations of fundamental kinetic, thermodynamic, and transport data, along with state-specific models for non-equilibrium flow regimes, have also yielded new insights and have the potential to vastly improve model fidelity. New reduced order methods for radiative transfer have also opened up possibilities for a significant reduction in the computational cost of 3D radiative heat transfer to the surface of a vehicle.

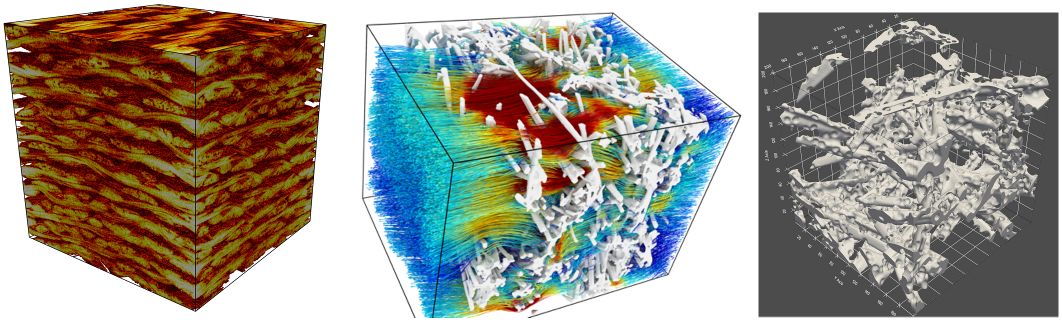
Aerosciences is a broad area of interest in entry systems, yet a number of important challenges are being addressed: Coupled fluid-structure simulations of parachute inflation and dynamics; Experimental and computational studies of vehicle dynamic stability; Multi-phase flow with dust particles to simulate entry environments at Mars during dust storms; Studies of roughness-induced heating augmentation relevant to tiled and woven thermal protection systems; and Advanced numerical methods to optimize computational analyses for desired accuracy versus cost.

Finally, the Guidance, Navigation and Control work under ESM has focused on improving the efficiency and coupling of the POST2 software used extensively at NASA to model flight mechanics of entry systems. Other aspects of GN&C being investigated within ESM currently focus on guidance and aerocapture-relevant algorithm development.

II. TPS Material Modeling

The TPS material modeling technical area develops and validates high-fidelity response models for TPS materials, such as PICA and 3MDCP, as well as TPS coatings, such as NuSil, from the micro to macroscale. These advancements in material modeling aim to reduce model uncertainty and enable decreased mass margins and/or improved reliability assessments. Analysis and sizing of TPS materials for NASA mission design generally relies on material response models largely derivative of 50-year old methodologies, with large uncertainties and margins applied in the design process. This can lead to unnecessarily conservative TPS design margins, and an inability to precisely quantify the reliability of the resultant space hardware. Over the past eight years ESM has developed a new methodology for constructing high-fidelity ablative TPS response models, based on a thorough understanding of the material microstructure and its impact on macrostructural properties of interest. The material modeling technical area is organized around three interconnected levels of modeling. Starting at the microscale, we use micro-computed tomography (micro-CT) in conjunction with the Porous Microstructure Analysis (PuMA) [1] software to characterize the material microstructure: porosity, permeability, thermal conductivity and other quantities of interest to material modeling. Next, the Porous material Analysis Toolbox based on OpenFOAM (PATO) [2] provides a platform to incorporate new physics at the meso and macroscale, as well as a tool to collaborate with our academic and international partners. Finally, there is the tool for TPS mission design and sizing, Icarus [3], which has been built to be a robust and efficient engineering tool, and readily integrated with multi-physics coupled frameworks.

The microscopic simulation element aims to provide fundamental material data for macroscopic simulations and, eventually, to enable microscopic material design and certification of both fibrous and woven TPS [4]. PuMA starts with a microscale material model, either simulated or imported from micro-CT images (see Fig. 1(a)), and computes geometrical, thermal, and structural properties based on the constituent properties. For properties like permeability, which describes the ability of fluid to pass through the medium, PuMA uses a Lagrangian particle-based methods to simulate fluid diffusion. A collaboration with Sandia on their SPARTA [5] code provides a more advanced simulation



(a) Silicon weave.

(b) Simulated flow through a 3-D micro-CT image of FiberForm.

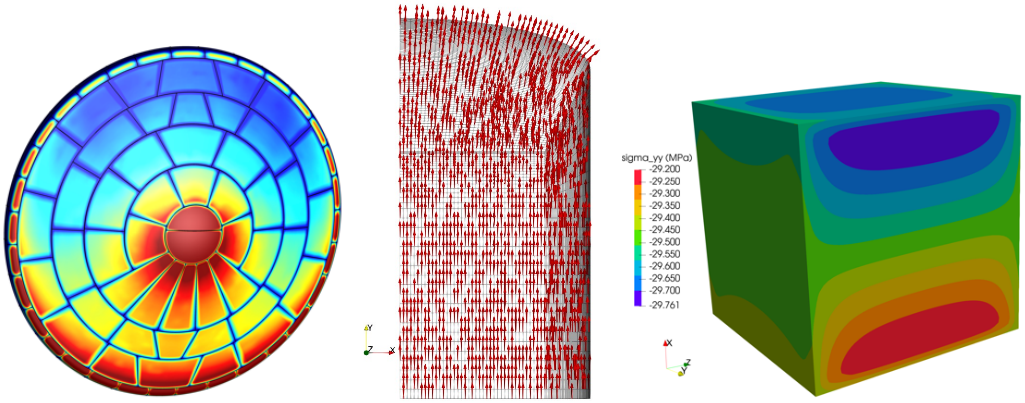
(c) Fiber pitting.

Fig. 1 Applications of PuMA microscale calculations

capability for fluid transport and diffusion within a porous TPS. Figure 1(b) shows an example of a steady-state flow calculated with SPARTA through a porous material reconstructed using PuMA [6]. SPARTA has also been used to analyze the impact on material performance due to pitted fibers as generated by PuMA [7], see Fig. 1(c). To support experimental validation, PuMA and SPARTA have the ability to perform microscopic analysis of molecular beam experiments, as well as features to simulate deposition and grading of silica on a material surface. The latter is an important aspect of the PICA-NuSil modeling effort, where a thin layer of NuSil silicone-based coating is sprayed on the base PICA layer in order to suppress dust generation during manufacturing. The presence of NuSil on the surface has a measurable influence on thermal response and thus impacts NASA's efforts to interpret flight data [8, 9]. The methodology developed for the PICA-NuSil system is expected to have potential future applications for studies of other TPS surface coatings.

At the macroscale, PATO seeks to implement new material response models and capabilities for full flight system scale analysis. A previous example of a flight scale simulation is shown in Fig 2(a) for the entire MSL heatshield including differential recession between tiles and gap filler. This phenomenon is known as fencing and induces local heating augmentations, or even early turbulent transition of the boundary layer, which complicates interpretation of thermocouple flight measurements if not characterized well (characterization being a goal of the Mission Relevant Roughness task discussed in section IV.D). Having a more detailed understanding of RTV intumescence and differential recession will be valuable for interpreting data from both MEDLI and MEDLI2 flight instrumentation suites. PATO has also been coupled with Sandia's uncertainty quantification tool, Dakota [10], in order to identify the most sensitive modeling parameters for MSL, and thereby guide future research efforts. The most influential material modeling parameters identified for material response were the heat capacity and thermal conductivity of the virgin and charred PICA, while for the aerothermal environment the heat transfer coefficient and the recovery enthalpy were most prominent. Recent efforts have focused on the development (Fig. 2(b)) and verification (Fig. 2(c)) of a mechanical erosion (spallation) model [11] as well as a detailed material response model for NuSil coated PICA [8, 9], which will be addressed in more detail in section VI.C on the MEDLI2 Deep Dive task.

The second objective of macroscopic scale research is to develop a modern, applied engineering tool for fast and accurate solutions, known as Icarus, see Fig 3(a) [3, 12]. Two key limitations of the generally applied heritage tools are the reliance on 1-D analysis and limited or no coupling between the flowfield and material response solvers. The accuracy of 1-D analysis is suspect near any sort of complex surface features like windows, compression pads, or even the tight radius of curvature found at the vehicle shoulder [13]. Coupling can be particularly relevant for more extreme entry conditions, as well as for validation with Arc Jet data where the run time heat loads are often stressing compared to flight and can show significant recession and 3-D effects. Therefore, developments in Icarus have focused on utilizing an unstructured and parallelized implementation to simulate complex geometries and perform 3-D sizing [13] as well as coupling with the US3D flow solver through the Ares framework, see example shown in Fig 3(b) [14, 15]. Ares is currently in active development to provide a multi-physics coupling framework to integrate not just flowfield and material response calculations, but also radiative heating and the presence of discrete particles. A few interesting applications that demonstrate the need for a multi-physics coupling capability are the influence that dust particle laden flow at Mars can have on the aerothermal environment and TPS erosion (see Fig 3(c)), thermal response of micro-meteoroid and orbital debris (MMOD) damaged material relevant to the MSR-EES TPS design (see Fig 3(d)) [16], and informing the



(a) PATO simulation of the tiled MSL heatshield. (b) TPS material orientation. (c) Thermal expansion verification in PATO.

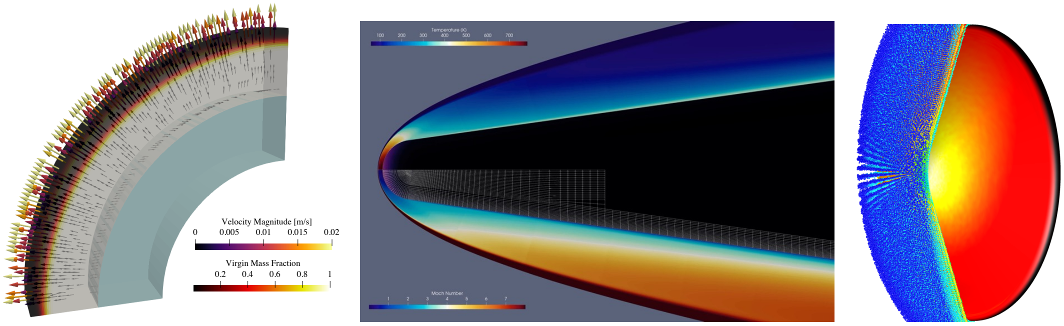
Fig. 2 Applications and mechanical erosion implementation into PATO

design of vehicle shoulder geometries for missions such as Dragonfly and MSR-EES [13].

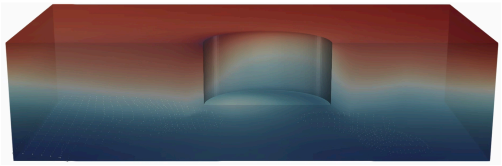
Underpinning all advances is a need for fundamental material model input data and validation datasets. Therefore, a wide range of experimental data is required. The TPS material modeling area's experimental element relies on an array of data sources: thermogravimetric analysis (TGA) and mass spectrometry, micro-CT and SEM imaging, flow tube experiments, plasma torches and arc jets. Examples of some of the data generated are measurements of oxidation of carbon weaves in the flow tube reactor facility at SRI International [17], spallation quantification using a novel particle tracking velocimetry setup at the LaRC HyMETS facility [18], in-situ tomography of RTV bonding agent, pyrolysis and molecular beam experiments for calibration of models [19], and PICA-NuSil testing in HyMets (both tests already performed, and planned for the future). A recent NASA Ames Arc Jet test in collaboration with the University of Kentucky conducted tests to provide data for two science objectives: 1) Spallation particle tracking via video and capturing the spalled particles within a gel, and 2) Pyrolysis gas flow within a test article via a hole in the article sidewall, with temperature gradients monitored and modeled. Experimental objectives of the ESM project continuously evolve to meet demands of its modeling efforts.

III. Shock Layer Kinetics and Radiation

For missions entering planetary atmospheres with large vehicles or high velocity, shock layer radiation has been known to be a significant contributor to vehicle forebody heating. Design margins traditionally carried for radiative heating have been substantial, but efforts in the Shock Layer Kinetics and Radiation (SLKR) task under the ESM project have shown meaningful mission impact by reducing modeling uncertainties and, consequently, reducing applied margins. At the same time, research within SLKR has uncovered significant contributions from radiative heating to the backshell which were previously thought to be negligible. Radiative heating now drives backshell aerothermal environments for Mars, Venus and Titan entries [20] as well as for high-speed Earth entries [21, 22]. The SLKR technical area addresses the task of reducing uncertainty and improving understanding through a three-pronged approach. First, quantum mechanical calculations are used to provide fundamental data and insight into radiation processes. Second, experimental and flight data is acquired to either validate existing model predictions or inform model updates. This includes ground testing, primarily using EAST, instrumented heatshield data, such as obtained with MEDLI2 or Artemis/Orion instrumentation, and observation of missions returning to Earth, such as Hayabusa-2. Third, the quantum chemistry and experimental data, along with the improved understanding they provide, are incorporated into NASA's applied radiation models, NEQAIR [23] and HARA [24]. With this approach, ESM is able to quantify uncertainty for the purpose of informing margin policy and improve modeling practices to better reflect both the underlying physics and flight observations.



(a) Icarus multi-material verification case. (b) Ares coupled material response and flow calculation. (c) Dust particle's impacting a heatshield at Mars.



(d) Icarus simulation of MMOD impacts.

Fig. 3 Applications of Icarus

A. Quantum Chemistry

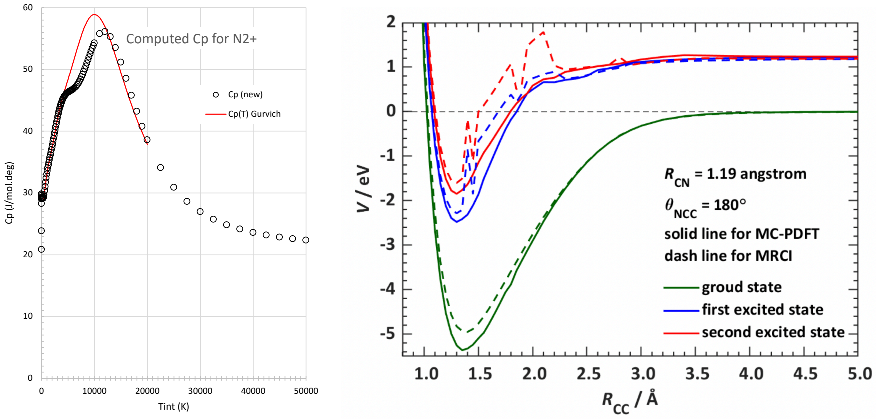
Theoretical quantum chemistry can provide high-fidelity inputs to be used in prediction tools for data that is known to be highly uncertain or where significant discrepancies have been observed with experiments. Furthermore, quantum chemistry can provide data for processes that can't be measured directly. Recent work has focused on understanding the processes that lead to the creation of free electrons during Earth entry as well as examining discrepancies observed with simulations and EAST data for the N_2^+ molecule. Thermodynamic data for N_2^+ has been calculated with *ab initio* techniques for temperatures between 300 K and 50,000 K, which required a database of ro-vibrational levels to be compiled for all electronic states up to the first dissociation limit. The heat capacity, C_p, as plotted in Fig. 4(a), shows significant differences between the new values calculated for C_p and the historical results obtained from Chemical Equilibrium with Applications (CEA) software [25] for temperatures between 5,000 K and 12,000 K.

A focus over the last several years has been the development of a new tool to calculate molecular electronic structure known as the Massively Parallel Electron Correlation (MPEC) code [26, 27]. The motivation for MPEC is to perform calculations beyond the limitations of the heritage tool, Molpro, such as collisions between two CO_2 molecules, while also incorporating support for modern high performance computing architectures in mind. Upcoming quantum chemistry work will focus on providing *ab initio* results to inform discrepancies between EAST measurements and simulations for CN radiative heating, as relevant to Titan entry. The objective is to calculate rates that contribute to CN electronic excitation. Potentials for C_2N, which participates in CN formation via exchange reaction, are shown in Fig. 4(b).

B. SLKR Validation

1. Electric Arc Shock Tube

Experimental data has been obtained for validation of model predictions from both EAST and through collaborations with domestic and international academic partners. The data not only provides benchmarks for model validation, but also can be used to infer reaction rates, flow temperatures, and spectroscopic data. A wide range of conditions and physics relevant to all atmospheres in our solar system have been reported in the literature. Earlier testing focused on matching radiative conditions for lunar return and Mars entries [28, 29], and for simplified compositions, such as pure CO [30], CO_2 and N_2 [23]. The pure CO and CO_2 tests utilized Tunable Diode Laser Absorption Spectroscopy (TDLAS) for the first time in EAST [31]. The combination of TDLAS with emission spectroscopy enables researchers to infer all four temperatures (translational, rotational, vibrational and electronic) as well as ground and excited state number density information from each test. This provides a wealth of data for model validation. The pure N_2 set



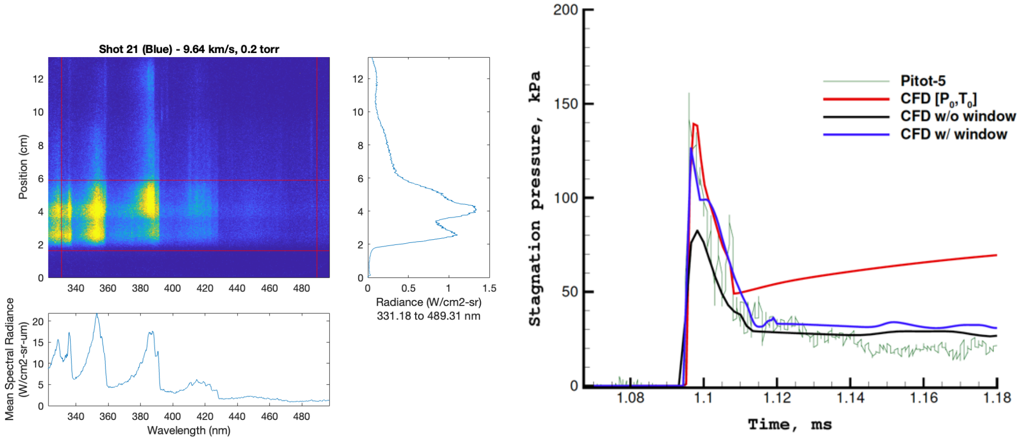
(a) *Ab Initio* thermodynamic properties.

(b) Calculation of C_2N potentials with MPEC.

Fig. 4 Recent quantum chemistry results

provides a benchmark for better understanding of fundamental processes, including dissociation, vibrational relaxation and other nitrogen mechanisms with a simpler chemistry [32]. There have been substantial theoretical efforts to provide *ab initio* data for nitrogen in recent years [33–37] and experiments like the N_2 test, which covered a wide range of conditions with different degrees of non-equilibrium and nitrogen dissociation, provide crucial validation data.

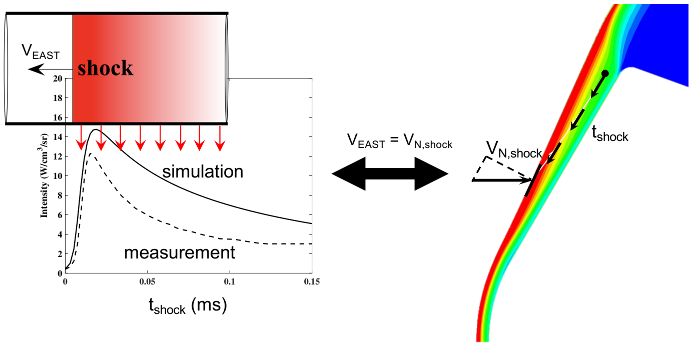
Recent testing has focused on providing validation data for expanding flows (see Fig. 5) and the shock tube informed bias (STIB) methodology developed by Johnston [38] for Titan entry. STIB is a methodology to use EAST measurements, coupled with streamline similarity arguments, as a source of benchmark data representative of the gas conditions that originate behind the oblique shock around the shoulder and into the wake of an entry vehicle, see Fig. 6. STIB thereby enables uncertainty and margin estimates for non-stagnation regions of the vehicle, including in the highly expanded wake. An exploratory test campaign was also conducted using an expansion cone installed at the end of the standard test section to provide data to validate backshell radiative heating, with an example spectra shown in Fig. 5(a). Unlike EAST tests where the test gas is under compression and analogous to a blunt body stagnation line (relatively straight forward to simulate), the expansion cone needs to be simulated with CFD to provide the state of the shocked gas as it expands. An example for a stagnation pressure comparison between Coolfluid CFD and EAST measurements made in the cone is shown in Fig. 5(b). A recent EAST Titan test campaign performed to address known problems with old emission data in N_2/CH_4 mixtures, with the aim of improving simulated flight environments for Dragonfly, the New Frontiers mission to Titan [20]. The recently completed STIB Titan data-set, see Fig. 6(c), will be used to expand the application space of the STIB methodology for Titan and inform the Dragonfly aerothermal margins [39]. Finally, an important new direction in EAST testing is the upcoming installation of the 21" internal diameter Low Density Shock Tube (LDST). The LDST will provide NASA a capability to measure radiative heating at lower density conditions, with the first campaigns focused on providing lower pressure STIB data relevant to both Dragonfly and MEDLI2 reconstruction. All data generated in EAST are published at NASA's open data portal, data.nasa.gov



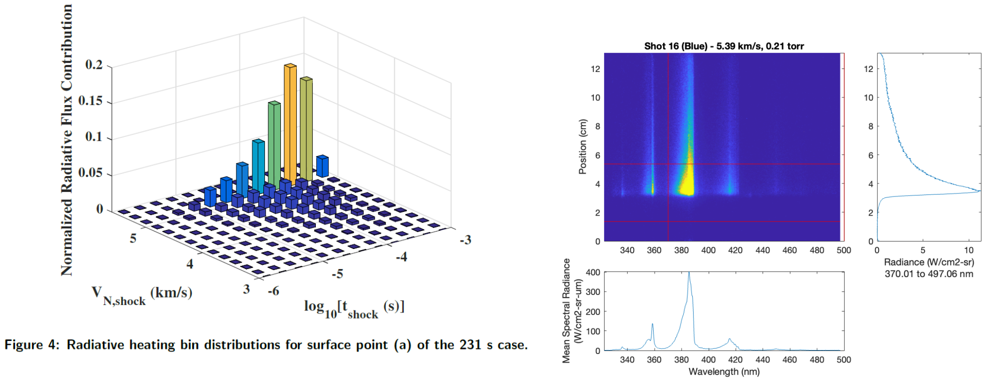
(a) Example of EAST expansion cone testing in Air.

(b) Comparison of simulation and EAST.

Fig. 5 EAST air expansion cone testing (a) experimental data, (b) comparison of stagnation pressure



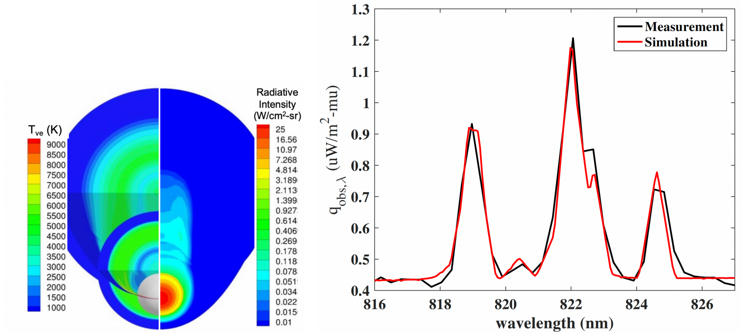
(a) Mapping of shock tube informed bias between flight and EAST.



(b) Shock tube informed bias binning.

(c) EAST CN Violet measurement.

Fig. 6 Shock tube informed bias for Titan entry



(a) Simulated Hayabusa-2 flowfield showing temperature and radiative intensity.

(b) Comparison of atomic Nitrogen lines.

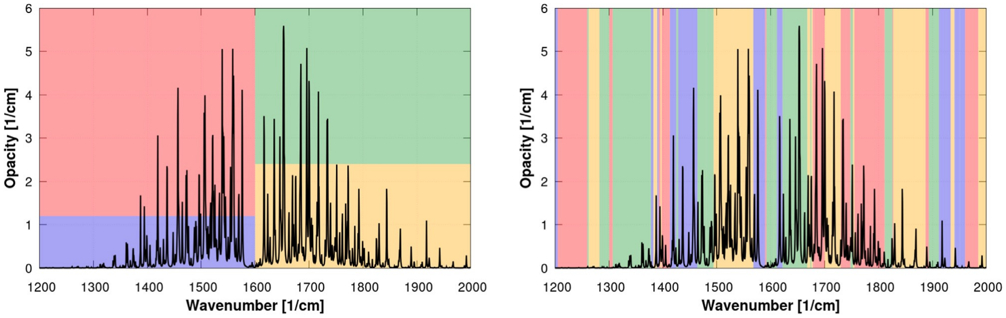
Fig. 7 Simulation of Hayabusa-2 re-entry observation measurements (a) LAURA flowfield and (b) Comparing simulations to flight obervation data

2. Flight Data Validation

The ESM project has previously utilized flight data from both MEDLI, Orion EFT1 and ESA's Schiaparelli probe with great success, combining shock tube tests and modeling to explain discrepancies between measurements and predictions. This approach is continuing with MEDLI2 (as part of the Deep Dive) and planned to continue in future years with regards to Artemis/Orion flights, University small satellites (e.g., SASSI2 at UIUC and HyCube at U. Minn), Dragonfly/DrEAM and any relevant Discovery or New Frontiers entry instrumentation. A recent example of a successful flight data analysis was performed by Johnston [40] who conducted post-flight simulations and analysis of the Hayabusa-2 re-entry observations made by the SCIFLI team, see Fig. 7(a). These simulations included coupled ablation, which accounts for the injection of ablation products into the flowfield, and coupled radiation. To enable the coupled ablation simulations, a best-estimate model was developed for Hayabusa's carbon-phenolic ablator, based on the limited available published information. The comparison between the simulations and measurements focused on two atomic nitrogen lines and two atomic oxygen lines, as well as the CN Violet band system. For the atomic lines, the measurements and simulations agree within 25% over most of the trajectory – an excellent result given the much larger discrepancies observed with previous analysis, see Fig. 7(b). The improved agreement for these Hayabusa 2 comparisons is both the result of improved measurement quality and enhanced flow field/radiation modeling. It is believed that the excellent agreement between Hayabusa-2 measurements and simulations may be leveraged to inform the radiation heating margin for the Mars Sample Return Earth Entry System [40].

3. Academic Partner Facilities

Academic partnerships have been very fruitful in providing second-source data. The Hypervelocity Expansion Tube (HET) at CalTech has performed second-source measurements of aerothermodynamic heating in CO_2 conditions analogous to Mars entry [41]. CO_2 was also added to the plasma torch at Centrale Supelec [42] to produce equilibrium CO 4th Positive spectra. Both of these test campaigns will be valuable for improving NASA models for Mars entry. As a second source of data for expanding flows, tests have been performed in the X2 facility at the University of Queensland in Australia where emission spectroscopy measurements were taken at various heights above a wedge that expanded the incoming flow in both Air [43] and CO_2 [44]. Furthermore, a Space Act Agreement was implemented with Oxford University to collaborate with their T6 tunnel [45], with data produced for Earth, Mars, Titan and Giant Planet entry. In order to improve understanding of the flow state of the EAST test gas, ESM collaborated with the University of Minnesota (UMN) to simulate EAST with the US3D fluid dynamics software [46]. To overcome previously observed limitations, the simulation frame of reference has been modified to follow the shock (rather than using the typical laboratory frame of reference). The capability has indeed provided a promising solution absent of the numerical instabilities observed in all prior attempts. Oxford University has also developed a pseudo-1D tool to calculate the impact a measured shock deceleration profile has on the state of the gas at the test section [47].



(a) Old (left) and new (right) grouping strategy.

Fig. 8 NERO reduced order grouping

C. Applied Modeling

The ESM efforts for applied radiation modeling are focused on improving the evaluation of radiative heating during atmospheric entry. This element incorporates data from quantum chemistry and modeling improvements inferred from experimental data to update various models as needed and is validated with ground and flight data. The two main radiative heating tools used by ESM and the Agency are NEQAIR and HARA.

Taken together, improvements to physical modeling, interpretation, and analysis of experimental data has had significant impact on many flight missions. Analysis of air test data has reduced uncertainty for equilibrium radiation from 250% down to 17% [21]. The updated lower-speed air radiation model with DPLR/NEQAIR improved agreement with EFT-1 flight data, reducing the discrepancy from approximately 90% down to 9%. These efforts have been rolled together to establish a new radiative heating margin policy for Orion [48]. The new policy leverages results, including the equilibrium air uncertainty cited above, to support a total radiation margin for air entries of 41%, a significant reduction from Orion's previous margin. Similar approaches were implemented for Mars and Titan entry, with updates to margin policy for InSight, Mars 2020, MSR and Dragonfly.

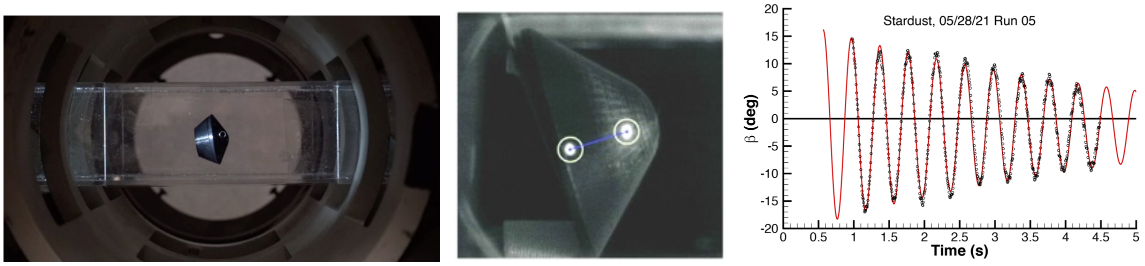
A new reduced order model under development for calculating 3-D radiative transport is known as NERO. NERO uses novel techniques for binning spectra, see Fig. 8, to drastically improve computational efficiency to calculate radiative heating at the vehicle surface [49]. NERO can calculate a full radiative heating on a TPS surface in a matter of minutes, for which a traditional approach would take several hours at discrete surface locations.

IV. Aerosciences

Computational and experimental aerosciences is the broadest technical area in ESM, impacting every phase of flight in several ways. General categories of interest to ESM include aerothermodynamics, aerodynamics, computational methods, and validation via experimental data. A comprehensive treatment of aerosciences is beyond the scope of ESM's resources and so the project has drawn from the NASA Engineering and Safety Center (NESC) Aerosciences Discipline Assessment to provide guidance on key technical challenges. This has shaped the current portfolio to focus on passive flight dynamics of spacecraft (experimental and computational), parachute inflation and descent dynamics, heating augmentation due to tiled and woven material surface roughness, and advanced numerical methods for general accuracy and cost improvements across all computational tools.

A. Magnetic Suspension Wind Tunnel (MSWT)

Passive flight dynamics of spacecraft has historically been important to mission designers because it determines what powered control systems are needed (or if needed at all) to augment stability and when to trigger parachute deployment. Additionally, some mission concepts like MSR-EES rely on unpowered, chute-less designs which, in order to meet planetary protection reliability requirements, will need to have well-characterized terminal descent dynamics in order to ensure that ground impact is within the specified design tolerance. Dragonfly is also a passive entry system utilizing a scaled heritage aeroshell based on Genesis. Genesis became dynamically unstable during its Earth re-entry, so understanding the dynamic stability of the Dragonfly entry is critical. Characterization of passive flight dynamics is typically done through some combination of ballistic range testing and forced or free-to-oscillate wind tunnel testing. The former is limited by a relatively low-fidelity reconstruction of flight, often with only a few observed oscillation



(a) Genesis aeroshell test. (b) Tracking model movement. (c) MSWT Stardust dynamic data.

Fig. 9 Magnetic Suspension Wind Tunnel

cycles and, in the case of open-air ranges, limited scaling overlap with the flight regime. Wind tunnel testing, on the other hand, allows for much more detailed observation of dynamic behavior. However, it is naturally constrained to oscillate about a single axis rather than true 3-DOF rotation. The result is that development of aerodynamic models can incur substantial uncertainty, costs, or both.

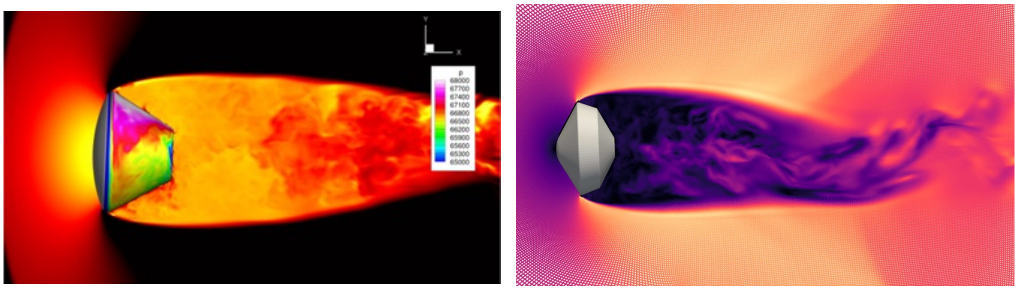
One idea to overcome these limitations is to develop a small-scale capability to magnetically levitate models inside a wind tunnel, thus leveraging the ability to make detailed observations without sting interference. In fact, the magnetic suspension wind tunnel concept is currently in use at JAXA and NASA had previously explored the concept for other applications as far back as the 1960s. ESM has reconstituted that very hardware [50, 51] in order to assess the quality of data that might be generated to provide validation data for computational methods, and to inform development of new aerodynamic models. Figure 9(a) shows a Genesis aeroshell model in the MSWT test section and an image from the camera to track the motion and dynamics of the model during the test is seen in Fig. 9(b). The subsonic capability is now operational and generating 1-DOF pitch oscillation data, an example of which can be seen for Stardust scaled model in Fig. 9(c), with the possibility of extending to supersonic conditions in the future.

B. Free-flight CFD

Free-flight CFD has modified the typically static CFD framework to enable simulated motion of the spacecraft model according to predicted aerodynamic forces and moments [52]. Three primary components are required for accurate free-flight CFD predictions: 1) An efficient mid-to-high resolution CFD solver capable of accurately resolving fine-scale fluid dynamics occurring in the vehicle wake; 2) A robust and efficient moving-mesh capability or overset technique; and 3) A coupled flight mechanics module to compute body movement in response to aerodynamics. Figure 10(a) and 10(b) show instantaneous images of the high resolution flowfield computed by the US3D software during free-flight simulations of the Orion and Dragonfly dynamics respectively. Figure 10(c) shows a comparison of the simulation's predicted dynamics with experimental data from the NASA Ames ballistic range at Mach 3.78 and 2.91. The figure shows that excellent agreement is obtained, when sufficient care is taken to ensure proper spatial and temporal resolution of the flowfield [53]. Future extension of the free-flight CFD capability will explore performance in the subsonic regime (thought to be the most challenging). Exploratory simulations have been performed for powered control via RCS and multi-body dynamics for EDL separation events like heatshield ejection. In order for these calculations to be less reliant on complicated grid construction, an automatic mesh refinement tool has been developed, known as MADAM [54]. Figure 11 shows an example of an initial coarse grid and then a refined grid for an MSR-EES like geometry.

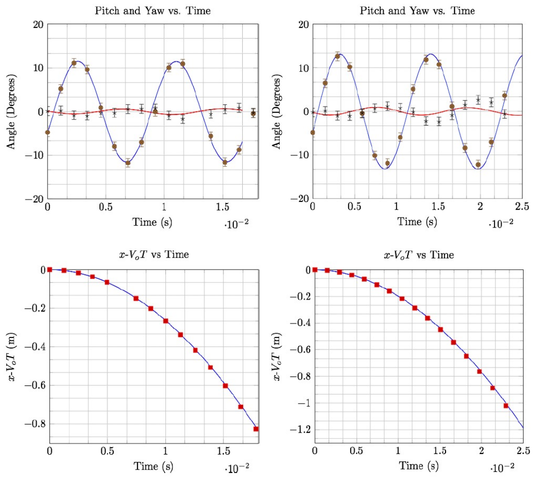
C. Parachute Fluid-Structure Interaction

In recent years, NASA has pursued a better understanding of parachute behavior for EDL systems with great interest. As part of the larger Mars Program, the Low-Density Supersonic Decelerator project attempted to qualify a new ringsail parachute design for larger Mars robotic missions. The two tests resulted in failed parachutes that ripped apart within fractions of a second of deployment [55]. Because the parachutes were designed according to the best empirical/semi-analytical processes available, the failure of the parachutes caused considerable reflection in the technical community. It is thought that failure was due to localized stress concentrations forming during inflation but, without any credibly detailed models to provide guidance, the root cause may never be known definitively. At the same time, NASA's Orion Program was suffering from an anomaly which imparted a pendulum motion to the capsule



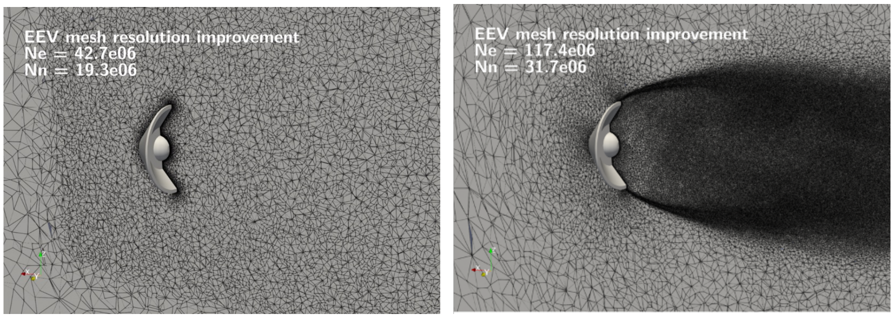
(a) Orion capsule.

(b) Genesis capsule.



(c) ADEPT capsule comparison at Mach: 3.78 (left) and 2.91 (right).

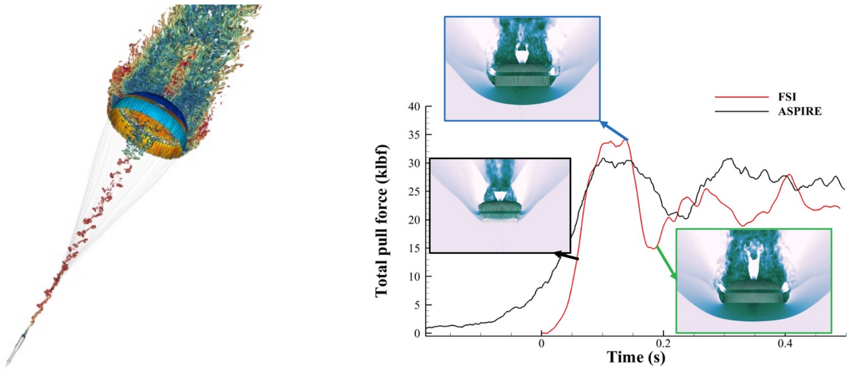
Fig. 10 Dynamic Free Flight CFD



(a) Initial coarse grid.

(b) Automatically refined grid.

Fig. 11 Grid adaption using MADAM



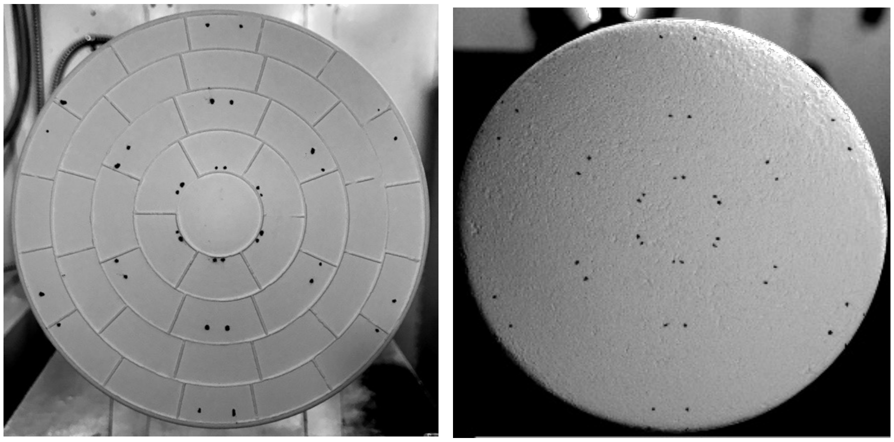
(a) LAVA solution of ASPIRE flight test.

(b) Comparison of LAVA and ASPIRE flight data.

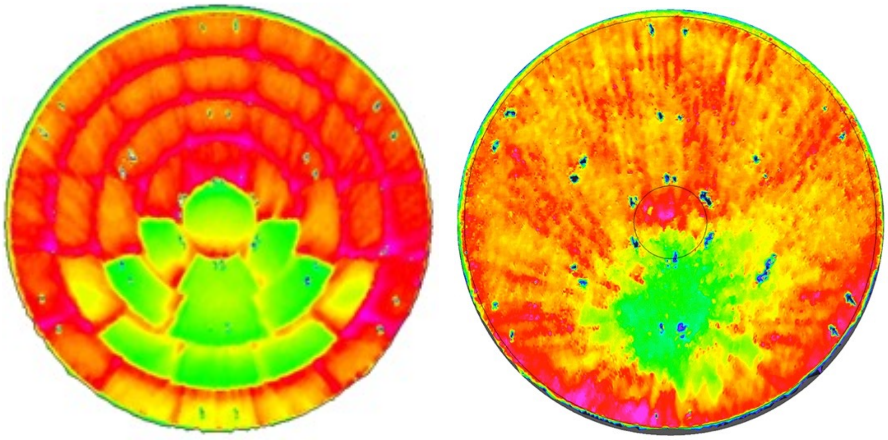
Fig. 12 ASPIRE FSI simulation with LAVA

during descent in a test scenario mimicking a single-canopy failure of the three-canopy system. The swinging motion could result in exceeding ground impact limits and seriously injure astronauts. Thus, ESM has set about developing high-fidelity computational models to separately address the parachute inflation and descent dynamics problems. The supersonic inflation fluid structure interaction problem is being tackled through the LAVA code, with the main focus currently on developing a modeling capability for simulating the ASPIRE flight test. Figure 12(a) shows an example LAVA solution of the ASPIRE flight test, along with a comparison against the total pull force in Fig. 12(b) [56, 57], where good agreement for the maximum force value is seen (within 10%). Further improvements to the model are being implemented, including deceleration of the body in response to parachute drag, more realistic material structural models, and numerical enhancements to increase simulation efficiency.

In a parallel collaboration, parachute modeling, is also under investigation by academic partners at Stanford (Prof. Charbel Farhat) [58] and University of Illinois (Prof. Carlos Pantano-Rubino) via Space Technology research awards. Both groups have advanced capabilities for modeling fluid-structure interactions of fabric, including folding and self-contact. The Stanford group also has a multiscale fabric modeling capability which, when paired with ESM's own micro-CT imaging and micro-/mesoscale mechanical experiments, may provide unique and valuable insights into fabric structural mechanics at the microstructural level.The micro-mechanical experiments are led by Profs. Alireza Amirkhizi (U Mass-Lowell) [59, 60] and Francesco Panerai (U Illinois), also funded through Space Technology research grants. Lastly, in order to address validation of parachute models, Prof. Laura Villafane (U Illinois) is conducting sub-scale wind tunnel tests to parametrically explore the influence of canopy materials and configuration on the resulting dynamic behavior.



(a) Fence gap pattern. (b) Distributed roughness pattern.



(c) Fence gap heating. (d) Distributed roughness heating.

Fig. 13 Thermographic measurements of turbulence transition and heating in the NASA Langley Mach 6 wind tunnel.

D. Mission-relevant Roughness

ESM has characterized the heating augmentation due to distributed roughness patterns analogous to the surface roughness that arises from the ablation of TPS [61–63]. This task has investigated heating augmentation relevant to flight in two important ways. The first is to examine the effects of isolated roughness patterns that arise from tiled heatshield designs, see left images of Fig. 13. The acreage tiles and gap fillers generally recess differentially and thus can create gaps or protrusions that cause local heating augmentation or even premature turbulent transition of the boundary layer. Second, materials like the new class of woven TPS materials like Heatshield for Extreme Entry Environment Technology (HEEET) develop an intrinsic surface roughness due to the wavy nature of the weave, see right images of Fig. 13. Prior to obtaining these datasets, it wasn't clear whether the augmentation due to woven TPS roughness was similar to that predicted for sandgrain roughness. The effects of tiled and woven roughness patterns were examined independently in the ballistic range at NASA Ames Research Center and the Mach 6 wind tunnel at NASA Langley Research Center. The data has immediately provided interesting insight into localized heating augmentation that is relevant to Mars Science Laboratory/Mars 2020, especially post-flight reconstructions of the flight environment derived from MEDLI and MEDLI2 science data. It is also being used to inform aerothermal environments and margin policy for MSR-EES.

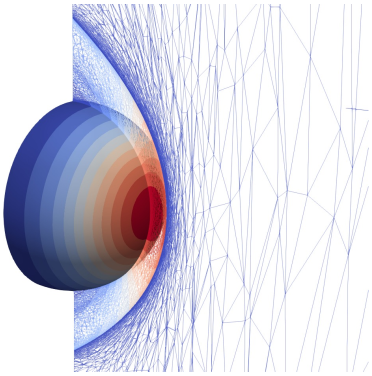


Fig. 14 1 km/s 3D Laminar Flow over a Hemisphere with Hypersolve.

E. Advanced Numerical Methods

Very little fundamental advancement has been made over the last 30 years to the computational methods employed across the aerothermodynamics discipline. Rather, efforts have been focused on developing software functionality for easier analysis, more physically realistic models, and more rigorous validation. Much of the analyst's job remains an artform, and recent advancements in high-performance computing (e.g., GPUs) are largely unexplored in a practical setting. ESM is investing in new techniques that can reduce reliance on expert judgement, introduce more formal assessments of simulation uncertainty, and improve computing output by harnessing petascale systems. While many of these improvements are still years away from being realized, the goal of ESM is to ensure a consistent level of funding is available for broad research and development in order to maximize the chances that breakthroughs can be found. One example currently in development is the Hypersolve code, which uses the *refine* [64, 65] library for both hessian-based and adjoint-based mesh adaptation. The aim is to provide more accurate heat transfer predictions on unstructured grids. Figure 14 shows a HyperSolve solution at 1 km/s 3-D laminar flow over a hemisphere on a fully-tetrahedral mesh, with grid adaption performed with Sketch-to-Solution [65]. The figure shows smooth heating profiles that agree well with established CFD tools, a challenging result with non-shock-aligned grids. Critical next steps for Hypersolve will be to introduce thermochemical non-equilibrium modeling necessary for entry problems and demonstrate accuracy/cost relative to traditional finite volume formulations in wide use. ESM is also interested in the potential of finite element approaches, like Discontinuous Galerkin formulations, which have demonstrated some success in modeling aerothermodynamics problems accurately [66].

V. Guidance, Navigation & Control

Advancement of GN&C techniques for planetary entry has occurred sporadically, slowed by the limited number of flight opportunities and a preference by flight programs to limit risk by adapting legacy approaches to mission-specific requirements. A conservative approach is well-justified without substantially different performance requirements driving a need for new techniques. However, recent and planned missions suggest that an applied research effort in planetary GN&C could be not only beneficial, but even enabling – particularly with regard to high-mass robotic landers and human exploration of the Martian surface. Current landing precision for Moon and Mars is on the order of kilometers, but human missions require 50 m of landing precision. The ESM project made progress towards these goals by developing new guidance and control algorithms to enable precision landing of two candidate architectures for human Mars exploration: A low-L/D concept based on HIAD technology, and a mid-L/D concept based on the CobraMRV ellipsled shape [67]. Current goals for the ESM GN&C task include: optimization of NASA's workhorse trajectory simulation tool, Program to Optimize Simulated Trajectories II (POST2); Development of new guidance and control models; Creation of a "fly-off" system of testing new GNC methods in proven simulation environments. The POST2 development effort focuses on leveraging high-performance computing (HPC) through improved parallelization of the code and interoperability with other tools, such as the interplanetary trajectory code, Copernicus. Figure 15 shows that a speed up of several factors was observed for various applications when run in parallel [68].

Toward the goal of developing new guidance techniques, ESM project is developing the Software for Multi-model Autonomous Real-time Trajectories (SMART). The goal of SMART is to develop an onboard real-time powered descent guidance system that combines machine learning (ML), multifidelity uncertainty quantification (MUQ), and data fusion

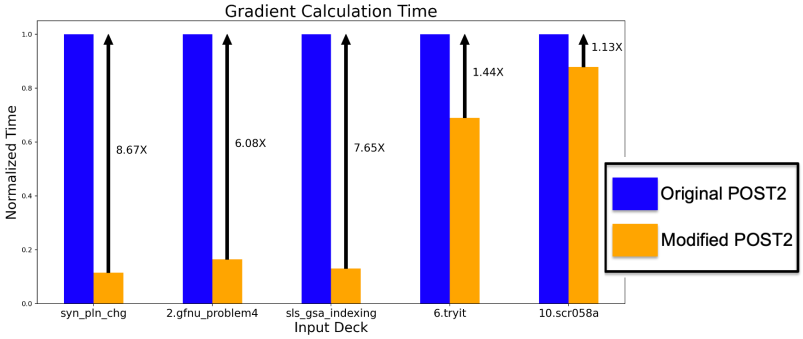


Fig. 15 Improved POST2 computational efficiency.

into a robust trajectory optimization under uncertainty to achieve precision landing.

Finally within the GN&C technical area, there is an effort to create a test platform to develop and compare innovative GN&C algorithms under development for aerocapture missions in multiple simulation frameworks. Aerocapture was chosen to constrain the number of parameters and thereby simplify the process of consistent cross-code comparison. In future years, this activity will look to expand the "fly-off" framework to more complicated phases of flight, such as hypersonic entry and powered descent and landing. The example problem currently considered for this work is the aerocapture of Small Satellites at Venus, which has the potential to serve as a secondary payload on an upcoming Venus mission, or one that has an orbit in the proximity of Venus.

VI. Special Research Topics

In addition to its core portfolio, ESM occasionally receives programmatic authority for relatively short-duration efforts to research specific, high-value topics. ESM is currently embarked on three such research efforts started in 2020: (1) TPS Certification by Analysis, (2) Hypersonic Wake Flows and (3) the MEDLI2 Deep Dive.

A. TPS Certification by Analysis

TPS materials for human missions to the Moon and Mars have stringent reliability criteria. The Orion capsule proposed to take humans to the Moon as part of the Artemis program employs heritage Avcoat tiles as a TPS material. The material itself exhibits a highly temperature-dependent mechanical response and is known to be prone to cracking in its original honeycomb architecture. While such cracking is not expected to result in large-scale failure in typical entry scenarios, the conditions for failure have not been fully understood. An overall limitation of CT-based non-destructive evaluation (NDE) for most ablative TPS materials is that low resolution is necessary for analyzing large articles but poses challenges to the identification of faults. Notably, voids or regions of poor infusion, cracks in gap filler, and porosity in bond-line adhesives are difficult, if not impossible, to resolve with low-resolution CT. The analysis of large-volume CT data is human-mediated, which is tedious, time-consuming, and prone to error. Furthermore, faults that are identified through the NDE process are often certified using qualitative measures without fully considering performance in entry environments.

Borrowing terminology from the evaluation of aerospace structural composites, "certification by analysis" is the use of co-designed experiments and multiscale modeling to evaluate material behavior and mitigate the risk of failure. In this sense, multiscale modeling is employed to both understand what NDE techniques can be used to identify features and faults of interest and to predict material properties and damage evolution given those faults. To this end, a variety of techniques that span the atomic-to-macro scales are employed. TPS certification must consider how structural features and damage couple to the aerothermal environment. While various technical areas of ESM are focused on accurate coupling of the aerothermal environments to materials, there has been limited investigation into how damage evolves within TPS material. Thus, the goal of this new start is to provide a computational framework to accelerate TPS certification for mission-specific entry conditions. TPS Certification by Analysis has three primary objectives [69–71]: (1) Enhanced Feature/Fault Detection, (2) Multiscale Modeling of Properties and Damage, and, (3) Tool Integration and assessment. This effort will focus on woven TPS, namely the HEEET insulation layer (IL) (or 3MDCP) that is the current baseline for MSR-EES, with Fig. 16 showing the different TPS length scales and problem types being investigated within this task.

The enhanced feature and fault detection objective is to perform analyses of low-resolution heatshield CT images and examine various NDE techniques. The first component of this objective is the development and application of tools that automate the analysis of low-resolution heatshield CT images to mitigate the need for human analysis, associated time and potential for error. Automation and evaluation of HEEET IL and 3MDCP for features and faults will be mediated through machine learning analysis of available CT from the HEEET project, namely of the full-scale heatshield entry test unit and subscale model tests performed for MSR-EES. The second component of this objective is to determine shortcomings of CT in resolving faults and provide proof of concept for NDE techniques that will provide enhanced structural metrics. Computational Non-Destructive Evaluation (CNDE) consists of multiphysics simulations of NDE processes on models of weaves with and without defects to obtain expected response signals (e.g., thermal, vibrational). The signals can be analyzed to allow the prediction of the effectiveness of a given NDE technique to resolve specific features. Ideally, the tools and approaches used for both components will provide information on all features and faults of interest to the TPS community, which include weave non-uniformity, cracks in the material, cracks or porosity in boding adhesives, and skipped weaves.

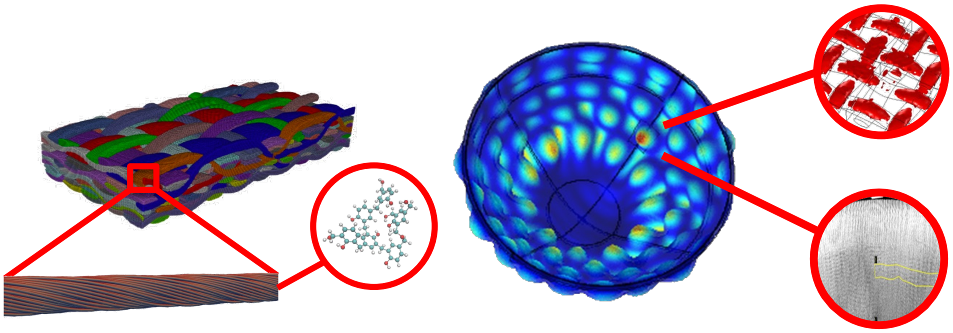
The multiscale modeling of properties and damage objective is to determine the properties of woven TPS material and how damage propagates and changes the failure limits of the material. The first component of this objective focuses on determining the properties of woven TPS material. The focus will be on realistic structures that include the structures identified from NDE, such as features (crimp or non-uniform weaves) and faults/damage (cracks and charring). Atomistic information, in combination with experiments, can be used to inform properties of unit cells of TPS material, referred to as representative volume elements (RVEs). Weave models are enhanced in PuMA, and the direct analysis of micro-CT data using finite element approaches. The RVEs will be constructed to span weave configuration space as noted from the analysis of features and faults from low-resolution CT data of weaves. The second component is modeling how damage propagates and changes the failure limits of the material. Damage is a broad term, but in the context of ablative TPS materials, can be the result of pyrolysis and char formation, impact of MMODs, and growth of native cracks. Adequately addressing both components will require integrating modeling at the molecular, meso, and macro scales. Tools at each scale are available along with a multiscale framework for model integration. The NASMAT multiscale framework [72] can be employed to couple mesoscale information to continuum models that can account for the influence and behavior of materials with large regions of damage, such as those resulting from micrometeoroid or orbital debris impact. This objective is heavily application focused on 3MDCP, though development will be carried out such that tools will be sufficiently flexible to allow future treatment of alternative woven (e.g. ADEPT) and non-woven (e.g. PICA) TPS.

The tool integration and assessment objective is to understand the level of fidelity needed to solve different classes of problems, using tools such as Hydra, LAMMPS [73, 74], PuMA and NASMAT. The first component of this objective is integrating emerging capabilities in machine learning into macroscale codes to provide efficient means to segmenting microtomography scans and providing models for microscale property and damage computations. These toolsets will be assessed in there ability to provide segmented models of TPS for direct use with PuMA and other microstructure-based codes. Depending on the tool performance, new capabilities that leverage physics-based machine learning techniques may be required to segment micro-tomography of more complex 3D weaves like 3MDCP, or significant inherent deviations from expected weave patterns, and damage. The second component is integration of microscale property and damage tools with uncertainty quantification tools like Dakota to determine model sensitivities that require additional refinement to improve accuracy. Interfacing microstructure modeling tools with the uncertainty quantification capabilities will be mediated through the use of Dakota, which will provide uncertainty analyses to determine model sensitivities that will in turn guide efforts to accurate model properties with high-fidelity techniques

(a) Fiber-scale analysis with Hydra.

(b) Yarn generator.

(c) TPS tensile strength prediction.



(d) TPS failure prediction.

(e) TPS feature detection.

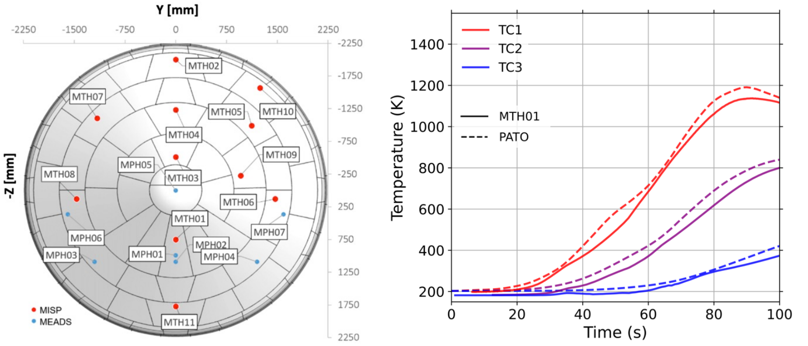
Fig. 16 TPS certification by analysis

B. Hypersonic Wake Flows

Blunt body re-entry vehicles produce highly-separated, unsteady, transitional/turbulent wake flows that affect the backshell/payload heating and vehicle aerodynamics. Future entry system architectures, such as inflatables and large rigid decelerators, will produce more challenging wake flows with tighter accuracy requirements and up until very recently with the successful LOFTID flight test, there has been no legacy data to rely on. Furthermore, accurately predicting a clean wake flow is a necessary precursor to validated models for RCS and retro-propulsion flows. Standard computational approaches for calculating hypersonic wake flows carry large uncertainties for backshell heating predictions, oftentimes exceeding 100%, with the highest aerodynamic uncertainties in the supersonic through transonic range. This activity aims to assess the performance of current aerothermodynamic CFD tools (e.g., US3D, LAURA, and others) through comparisons with archival and new experimental data to better define computational sensitivities and uncertainties. Multiple paths for improvement of current tools and/or development of new simulation tools for wake flow computations will be investigated. These include coupling DSMC to Navier-Stokes simulations for rarefied wake conditions, enhanced grid topology and adaptation schemes, and high-order numerical methods tailored for accurate resolution of unsteady wake flows using petascale computing architectures. Experimentally, multiple wake flow visualization strategies will be explored to assess which approaches provided the highest quality data sets for validation of computational models. These include NO-PLIF, FLEET, and high-speed schlieren. Furthermore, to measure the lower heating rates more accurately on aftbodies, heat transfer measurements will be explored using infrared (IR) thermography and temperature sensitive paint (TSP), which will be compared to the current phosphor thermography techniques. The first experimental campaigns are being conducted in the NASA Langley Mach 10 facility in the fall of 2022, and results are expected to be published later in 2023.

C. MEDLI2 Deep Dive

In February of 2021, Mars 2020 descended into the Martian atmosphere instrumented with the Mars Entry Decent and Landing Instrument 2 (MEDLI2) package [75]. MEDLI2 consisted of multiple sensors on both the forebody and afterbody of the vehicle that measured in-depth TPS temperatures, surface pressures, heat flux, and backshell radiation.



(a) MEDLI2 heatshield sensor layout.

(b) PATO simulations of MEDLI2 MTH01 TCs with PICA-NuSil model.

Fig. 17 PICA-NuSil development to maximise MEDLI2 science (a) MEDLI2 TC layout (b) PATO with NuSil model compared to MTH01

Post-flight, the MEDLI2 team had the budget to analyze the data up until the end of Fiscal Year 21, when the project officially ended. Thus, the primary objective of the MEDLI2 Deep Dive is to further investigate the data to develop and validate tools for future Mars missions, and provide a more thorough understanding of the measurements. The task will utilize high-fidelity analyses of TPS in-depth temperatures, pressure, and radiative heat flux in conjunction with new data fusion techniques. Furthermore, many of the lessons learned under this task are expected to benefit all future EDL missions. The deep dive task will aim to identify deficiencies in current design best practices, establish and/or reduce uncertainty levels for key mission drivers, and establish a new standard for post-flight EDL data analysis.

MEDLI2 is considerably more complex than MEDLI, with instrumentation on the backshell for the first time and several new sensor types (heat flux gauges, supersonic pressure transducers, and radiometers). This motivates further development of NASA's EDL post-flight analysis pipeline beyond what was previously established for the first MEDLI flight. At a high level, key Deep Dive tasks include: evaluation of MEDLI2 Flight Data with advanced ESM tools, extended aerodynamic and atmospheric reconstruction, sensor fusion of measurements made by co-located sensors, detailed aeroheating investigations including impacts of NuSil coating and RTV swelling in tile gaps, as well as additional STIB testing in EAST. With the large investments made by NASA in the MEDLI2 system and the sparsity of flight data sets, it is vital to leverage the MEDLI2 data to the fullest extent possible for model validation and further model development.

Figure 17 shows an example of the developed PICA-NuSil model implemented in PATO as compared to the MEDLI2 thermocouple flight data [8, 9], where good agreement is observed for the location close to the stagnation point. This model has been developed to better interpret MEDLI Integrated Sensor Plugs (MISP) data, as well as for use in TPS design of future missions using a PICA-NuSil heatshield. A test campaign in the Ames AHF arcjet using NuSil coated PICA coupons was also conducted to provide validation data for the model (see Fig. 18), with a Langley HyMETS arc jet test planned for the future. The results from the AHF arcjet indicated that with the heat fluxes experienced by Mars 2020 , it is likely that the NuSil coating did not fully ablate away during entry. Along with the development of the PICA-NuSil model, one of the most significant efforts conducted under the Deep Dive thus far has been to synthesize the co-located backshell measurements, that either directly or indirectly measured heat flux. At nearly the same location on the backshell, there was a thermal couple plug, a radiometer and a total heat flux gauge. An inverse analysis using a Kalman filter was conducted by Karlgaard et al. [76] to provide additional insights into the measured data. The analysis was even able to infer the reduction in radiometer signal due to deposition of material on the window, and showed consistency with ground based arc jet experimental results. In concert with this activity, a STIB test was conducted in EAST, see Fig. 19, to better understand the radiative heat flux measurements. As radiative heat flux dominates the backshell environment, and with good agreement shown against the total heat flux gauge measurements, it has been deduced that there is good agreement with simulations for the radiative heat flux, although questions remain with regards to the convective heat flux. This good agreement with total heat flux is consistent with the analysis of the COMARS total heat flux measurements [77, 78], which suggests that the aerothermal environments for this class of mission to Mars are well characterized.

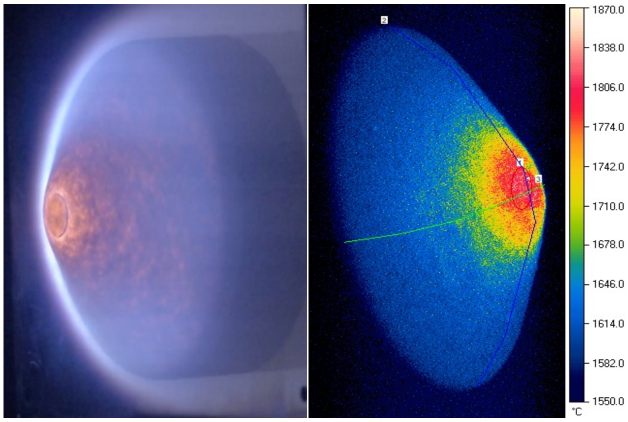
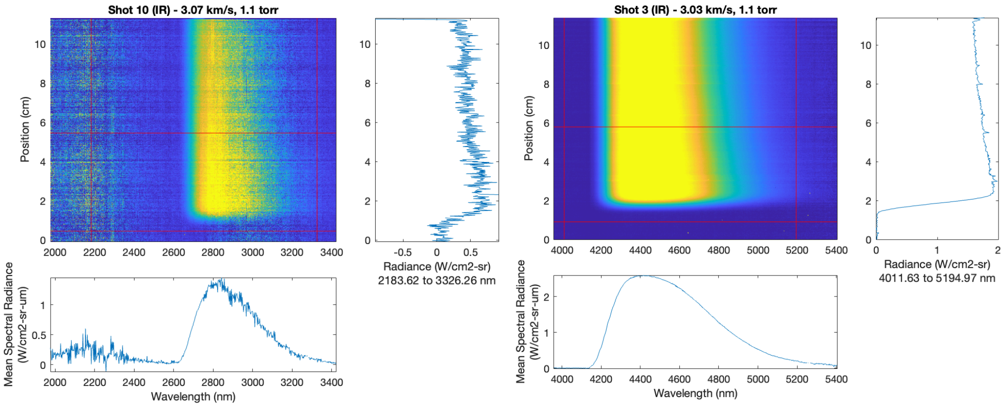


Fig. 18 PICA NuSil AHF arc jet test highlighting the measured surface temperature.



(a) 2.7 μm band.

(b) 4.3 μm band.

Fig. 19 EAST STIB measurements for MEDLI2 reconstruction

VII. Summary

NASA is invested in research and development toward improving and developing next-generation EDL systems. The Entry Systems Modeling Project – in collaboration with many other projects, government organizations, and universities – plays a key role in advancing cross-cutting modeling and simulation capabilities for the breadth of EDL missions, present and future. This paper provides a survey of the recent history of modeling and simulation research in ESM. The project is organized around four core technical areas: TPS materials modeling; Shock layer kinetics and radiation; Aerosciences; and Guidance, navigation, and control. In addition to the core technical areas, ESM has research efforts in TPS certification by analysis, Hypersonic Wake Flows and a Deep Dive into the Mars 2020 / MEDLI2 data. Numerous improvements in each of these technical areas have been made over the years that have had tangible impacts on NASA's technology development and flight missions, highlighting the important role that research and development plays in meeting practical Agency goals. The efforts have been documented across hundreds of journal articles, posters, and conference presentations. Only a fraction of them are referenced here, and the reader is encouraged to contact the authors for more detailed information on areas of specific interest referenced herein.

Acknowledgments

The Entry Systems Modeling Project is part of the Game Changing Development Program within NASA's Space Technology Mission Directorate. A significant portion of ESM's funding comes via partnership with the Planetary Science Division of the Science Mission Directorate. Support from both organizations is gratefully acknowledged. In addition to the core supporting institutions, the work of ESM is greatly augmented through numerous partnerships and collaborations within NASA and with external organizations spanning the U.S. and abroad. Within NASA, the ESM Project is thankful for the support of leadership at Ames, Langley, Johnson and Glenn Centers. Several programs and projects have provided real or in-kind support over the years: Orion, Mars 2020, InSight, OSIRIS-REx, Mars Sample Return, MEDLI-2, Low-Density Supersonic Decelerator, HEEET, and ADEPT. The Space Technology Research Grants office, in particular, has been crucial for funding numerous early-stage academic research programs which act as vital feeders for ESM's research. Largely through their efforts, ESM has built strong ties to a number of university programs spread across the country. Looking abroad, ESM has or is in the process of developing Space Act Agreements with: The German Aerospace Center (DLR), JAXA, University of Queensland, Ecole Supelec, and Oxford University.

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