Recent Advancements in Modeling and Simulation of Entry Systems at NASA

Michael Barnhardt
NASA Ames Research Center
M/S 230-2
Moffett Field, CA 94035
650-279-7210
Michael.D.Barnhardt@nasa.gov

Aaron Brandis
AMA, Inc.
M/S 230-3
Moffett Field, CA 94035
650-604-0888
Aaron.M.Brandis@nasa.gov

Michael Wright
NASA Ames Research Center
M/S 230-3
Moffett Field, CA 94035
650-604-4210
Michael.J.Wright@nasa.gov

Monica Hughes
NASA Langley Research Center
M/S 489
Hampton, VA 23681
757-864-3942
Monica.F.Hughes@nasa.gov

***Abstract*—This paper describes recent development of modeling and simulation technologies for entry systems in support of NASA's exploration missions. *Mission-tailored* research and development in modeling of entry systems occurs across the Agency (e.g., within the Orion and Mars 2020 Programs), however the aim of this paper is to discuss the broad, *cross-mission* research conducted by NASA's Entry Systems Modeling (ESM) Project, which serves as the Agency's only concerted effort toward advancing entry systems across a range of technical disciplines. Technology development in ESM is organized and prioritized from a system-level perspective, resulting in four broad technical areas of investment: (1) Predictive material modeling, (2) Shock layer kinetics and radiation, (3) Computational and experimental aerosciences, and (4) Guidance, navigation, and control. Investments in thermal protection material modeling are geared toward high-fidelity, predictive models capable of handling complex structures, with an eye toward optimizing design performance and quantifying thermal protection system reliability. New 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 material kinetics, morphology, and other 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, including differential recession of tile gaps. Research and development in the area of shock layer kinetics has focused on air and CO_2-based atmospheres. Capacity and capability of the NASA Ames Electric Arc Shock Tube (EAST) have been expanded in recent years and analysis of resulting data has led to several improvements in kinetic models, while simultaneously reducing uncertainties associated with radiative heat transfer predictions. 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. Aerosciences is a very 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 dynamics; 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. Guidance and control in the context of entry systems has focused on development of methods for multi-axis control (i.e. pitch and yaw, rather than bank angle alone) of spacecraft during entry and descent. With precision landing requirements driven by Mars human exploration goals, recent efforts have yielded 6-DOF models of multi-axis control with propulsive descent of both inflatable and rigid ellipsled-like architectures. Results for both configurations have demonstrated the ability to land within the 50-meter precision requirement demanded by Mars human exploration missions, while also reducing propellant requirements by enabling more efficient control through entry and descent. Ongoing research in GN&C is developing mechanical specifications for the systems and establishing engineering feasibility.**

TABLE OF CONTENTS

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1. INTRODUCTION

NASA's mission to explore the Solar System includes a number of destinations with atmospheres – Mars, Venus, Gas Giants, Ice Giants, Titan and, of course, 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.

Entry Systems Modeling (ESM) [1], a project within NASA's Space Technology Mission Directorate, was formed in 2013. It is the latest in a line of research and development projects at NASA whose purpose is the advancement of low-to-mid TRL technologies for entry systems. There are a number of other NASA projects, from major programs like Orion [2] and Mars 2020 [3] to focused technology development projects like the Heatshield for Extreme Entry Environment Technology (HEEET) [4], which are also engaged in entry systems R&D. ESM, however, is the only project whose mission is to perform fundamental research in entry systems with cross-mission impact.

As the name implies, the current focus of ESM is on modeling and simulation, although in prior years ESM has engaged in development of TPS materials and even flew multiple suborbital and orbital experiments of a SmallSat de-orbit technology called Exo-Brake. The ESM project's portfolio is developed according to needs expressed by a cross-section of NASA stakeholders, including flight and research projects, field centers, and subject matter experts. It is organized and prioritized from a system-level perspective, resulting in four broad technical areas of investment: 1) Predictive material modeling, 2) Shock layer kinetics and radiation, 3) Computational and experimental 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 under development are the Arc Heater Simulator (ARCHeS), a high-fidelity tool for modeling arc jets, and PICA-NuSil, an effort to model the presence of silica coating on the heatshields of Mars Science Laboratory (MSL) and Mars 2020.

The remainder of this paper will highlight recent efforts in each of ESM's core technical areas and the special topics. It is unfortunately beyond the scope of this paper to accurately represent all of the research being conducted. Readers can find further reading material listed in the references and, of course, are encouraged to contact the authors for additional information.

2. PREDICTIVE MATERIALS MODELING

The predictive materials modeling (PMM) technical area develops and validates high-fidelity response models for porous ablative materials, from micro to macroscale. These advancements in material modeling will reduce model uncertainty and enable decreased mass margins and/or improved reliability estimates for future NASA entry missions. At present, analysis and sizing of thermal protection system (TPS) materials for mission design and engineering still rely on material response models largely derivative of 50-year old methodologies. As a consequence, large uncertainties and margins are inherent in the design process, which leads to unnecessarily heavy heat shields, and an inability to quantify the reliability of the resultant space hardware. Over the past five years ESM has developed an entirely 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 loosely 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) [5] 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) [6] performs high-fidelity meso and macroscale modeling, incorporating as much physical detail as possible, in order to establish a benchmark against which we can evaluate the utility of individual modeling components. Finally, knowledge gleaned from the first two activities informs requirements, which may be mission and material dependent, for a robust and efficient engineering tool, Icarus [7].

Microscale Modeling

The microscopic simulation element aims to provide fundamental material data for macroscopic simulations and, eventually, to enable microscopic material design, both fibrous and woven. Figure 1 shows an example of a steady-state flow through a porous material generated by PuMA. PuMA starts with a microscale material model, either simulated or imported from micro-CT images, 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 Lagrangian particle-based methods to simulate fluid diffusion. A more sophisticated module, based on Sandia's SPARTA [8] code, is under development to incorporate the full breadth of fluid transport, in addition to diffusion. To support experimental validation, PuMA and SPARTA have recently added a module for microscopic analysis of molecular beam experiments, as well as a feature to simulate deposition and grading of silica on a material surface. The latter is an important aspect of the PICA-NuSil modeling effort, discussed in Section 6 of this paper, and has potential future applications for studies of other surface coatings.

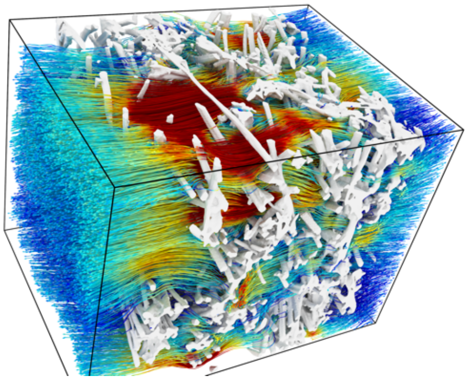

Figure 1. Simulated flow through a 3-D micro-CT image of FiberForm.

Macroscale Modeling

At the macroscale, PATO seeks to implement the highest practical detail for system-scale material response modeling, including detailed descriptions of pyrolysis gas decomposition, finite-rate surface kinetics, and a sophisticated 3-D model framework capable of simulating the effects of non-uniform material properties. Recent efforts have parallelized PATO, enabling 3-D simulations of the entire MSL heatshield including differential recession between tiles and gap filler, as shown in Figure 2 [9]. 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. Research is also underway to couple PATO 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.

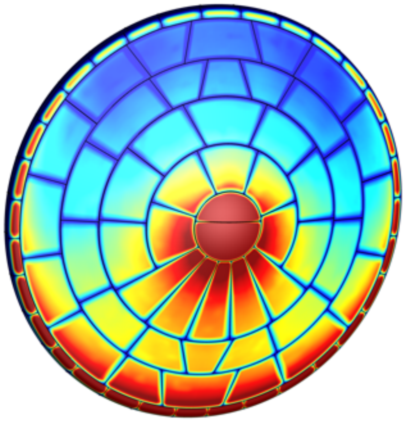

Figure 2. PATO simulation of the tiled MSL heatshield. Contours show surface recession, highlighting the differential recession (fencing) of the gap filler material.

The second objective of macroscopic scale research is to develop an engineering tool for fast and accurate solutions, known as Icarus. Rapid production capability is an important distinction to consider because flight programs typically run tens of thousands of simulations through Monte Carlo uncertainty and dispersion analysis. The detailed PATO simulation shown above takes many hours for a single simulation, in contrast to the typical tool used in Monte Carlo analysis which may take as little as a few seconds to run. One key limitation of the current state of the art, however, is the reliance on 1-D analysis whose accuracy 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. Therefore, recent developments in Icarus have focused on an implicit implementation for solving the governing equations, maximizing parallel-computing scalability, and utilizing an unstructured implementation of the code in order to easily simulate complex geometries. Eventually, Icarus will incorporate a multi-physics capability for cases where the ablation products and boundary layer state are closely coupled, and for coupled thermal stress-strain analysis. One interesting example that turns on a multi-physics capability is the influence of dusty flows present at Mars on the aerothermal environment and TPS erosion. NASA has partnered with DLR, who has a specialized arc jet facility capable of incorporating dust particles, to explore this topic in detail over the next three years.

Experiments and Validation

Underpinning all advances is a need for model input data and validation, and a wide range of experimental data is required. The PMM 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 includes measurements of oxidation of carbon weaves in the flow tube reactor facility at SRI International [11], spallation quantification using a novel particle tracking velocimetry setup at the LaRC HyMETS facility (Figure 3 [12]), in-situ tomography of RTV bonding agent (not yet published), and pyrolysis and molecular beam experiments for calibration of models [13].

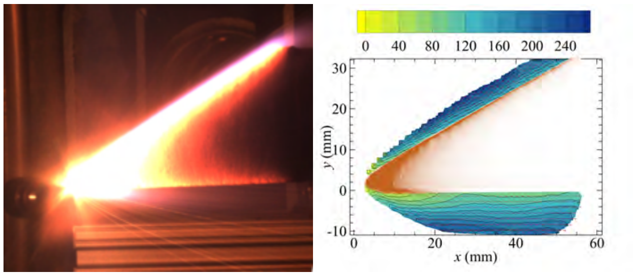

Figure 3. Novel particle tracking techniques can provide useful data for development of spallation models.

3. 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 over the past several years have shown meaningful impact by reducing modeling uncertainties and, hence, applied margins. At the same time, the efforts of the ESM project have uncovered significant contributions from radiation to the backshell which were previously thought to be negligible. Radiative heating now drives backshell heating predictions for Mars (see Figure 4 for a human Mars architecture example), Venus and Titan entry [14] as well as for high-speed Earth entries [15]. 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 data is acquired to either validate model predictions or generate new models. This includes ground testing, primarily using the Electric Arc Shock Tube (EAST). Third, the quantum chemistry and experimental data, along with the improved understanding they provide, are incorporated into NASA's applied radiation models, NEQAIR [16] and HARA [17]. 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 real-world observations.

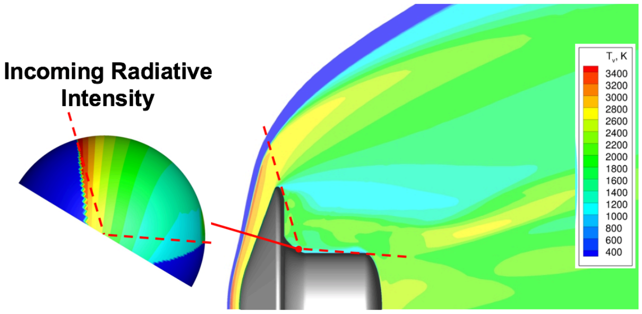

Figure 4. Example demonstrating how significant radiative intensity can be generated by the entry environment and transmitted to a vehicle's backshell.

Theoretical Modeling

Theoretical modeling 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. For example, recent work has focused on understanding discrepancies observed with simulations and EAST data for N_2^+ molecule. Thermodynamic data for N_2^+ has been calculated with *ab initio* techniques for temperatures between 300 K and 50,000 K. This work 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, calculated by ESM is shown in Figure 5. The figure shows significant differences between the new values calculated for C_P and the historical results obtained from Chemical Equilibrium with Applications (CEA) software [18] for temperatures between 5,000 K and 12,000 K. Once the calculations have been double-checked for accuracy, the new data will be fit with polynomials for easy inclusion in CFD codes. Work has also focused on trying to identify ablation species with significant concentration in the boundary layer and potential for absorbing atomic radiation. In order to achieve this goal, thermodynamic functions were computed for ablation products and then searched for low-lying excited electronic states. The efforts concentrated on C_2H, C_2, C_3H, C_3, C_4H, C_4 and C_5. C_4H in particular was found to have a very intense optical transition close to 174 nm wavelength (a strong nitrogen atomic line emission) [19]. Future work will determine if the molecule is effective at blocking atomic nitrogen radiation from reaching the heatshield surface.

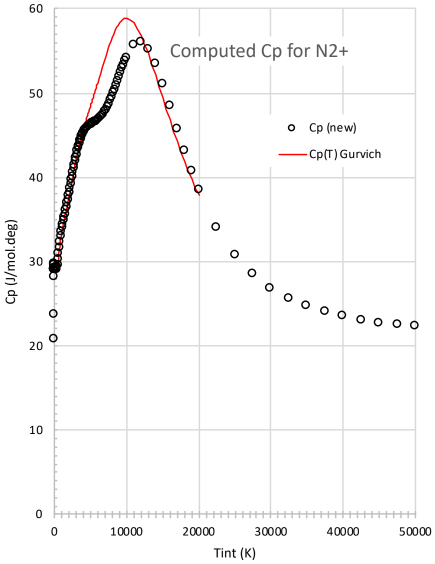

Figure 5. New thermodynamic calculations show significantly more detail than historical data, even at moderate temperatures.

Electric Arc Shock Tube (EAST) & Other Validation

Experimental data has been obtained for validation of model predictions from both the Electric Arc Shock Tube (EAST) as well as 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 relevant physics have been reported in the literature. Earlier testing focused on matching radiative conditions for lunar return and Mars entries [20][21], while the most recent testing has covered pure CO [22], CO_2 and N_2 [23], as well as Titan atmosphere [14]. The pure CO and CO_2 tests utilized Tunable Diode Laser Absorption Spectroscopy (TDLAS) for the first time in EAST [24]. 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 provides a benchmark for better understanding dissociation, vibrational relaxation and other nitrogen mechanisms with a simpler chemistry. Figure 6 shows an example of equilibrium spectra in nitrogen from the experiments. There have been substantial theoretical efforts to provide *ab initio* data for nitrogen in recent years 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. With regard to Titan, very little data is available to characterize radiation in the nitrogen and methane-rich environment, and questions have been raised concerning accuracy of past reported shock tube data for Titan. Therefore, a recent test series in EAST was conducted to generate an expanded set of measurements and to comprehensively examine the old data. The new campaign showed significant discrepancies to previously reported results. The discrepancies were largely thought to be due to small levels of air contamination in the previous tests. The updated EAST Titan database is already being utilized to better inform flight environments for Dragonfly, the proposed New Frontiers mission to Titan currently in Phase A development. An important new direction in EAST testing is to investigate flow through a recently fabricated and installed expansion cone. The idea behind expansion testing is to provide data to validate models for radiation on the backshell of an entry vehicle. Test series relevant to both Earth and Mars entries are planned in 2019 and will be published shortly after completion. All data generated in EAST are published at NASA's Open Data Portal, data.nasa.gov.

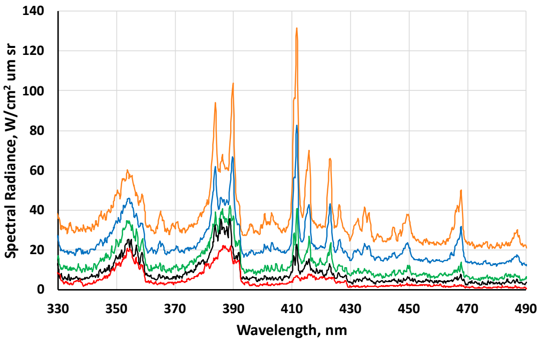

Figure 6. Equilibrium spectra for nitrogen at a number of shock speeds.

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 CO2 conditions analogous to Mars entry [25]. Additional ongoing tests in HET are measuring incident shock Mid-Wave Infra-Red (MWIR) emission in CO_2. CO_2 was also added to the plasma torch at Centrale Supelec [26] 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 [27] and CO_2 [28]. Furthermore, a new Space Act Agreement is currently in the works with Oxford University to collaborate with their new T6 tunnel [29] when it is online. In order to improve understanding of EAST operation, and therefore the data produced by EAST, ESM has a collaboration with the University of Minnesota (UMN) to simulate EAST with the US3D fluid dynamics software [30]. Prior attempts at simulating flow in EAST have been completely unsuccessful. 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) and, as can be seen in Figure 7, this advanced capability has indeed provided a promising solution absent of the numerical instabilities observed in all prior attempts.

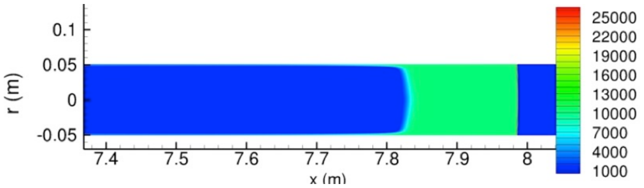

Figure 7. A US3D simulation of flow through EAST facility captures time-dependent flow structure without previously observed numerical instabilities.

Applied Modeling

The ESM efforts for applied radiation modeling are focused on improving the evaluation of radiative heating during entry. This element incorporates data from quantum chemistry to update various models as needed and is validated with experimental and flight data. The two main radiation tools used by ESM and the Agency are NEQAIR and HARA. Recently, both codes have seen significant speed ups (10-30x) due to GPU enhancements and by modifying how the spectral grid is calculated for better efficiency. The multi-band opacity binning model implemented in HARA has been extended to non-Boltzmann molecular radiation [31], further improving the speed of the code. Several updates related to lower-speed Earth entry based on EAST and flight data comparisons have also been incorporated into NEQAIR [21]. Simulations utilizing the LAURA CFD software and HARA have been used to update convective and radiative heating correlations for both Earth [32] and Mars [33] entry. The new correlations offer a significantly larger parameter space of applicability and more accurate results (Figure 8).

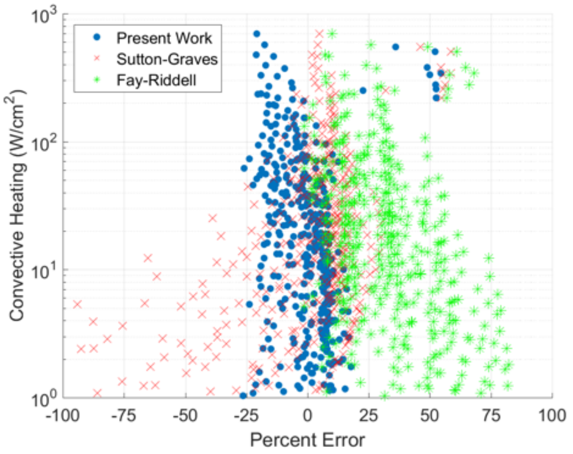

Figure 8. Updated convective heating correlation for Mars entry (blue dots) shows much smaller margins of uncertainty than historical correlations.

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% [34]. 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 [35]. 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 entry, with updates to margin policy for both InSight and Mars 2020.

4. COMPUTATIONAL & EXPERIMENTAL AEROSCIENCES

Computational and experimental aerosciences is the broadest technical area in ESM, impacting every phase of flight in one or more 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 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 surface roughness, and advanced numerical methods for general accuracy and cost improvements across computational tools.

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 to augment stability and when to trigger parachute deployment. Additionally, some mission concepts like Mars Sample Return 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 design tolerance.

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 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 [36], seen in Figure 9, 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. The subsonic capability is now operational and generating 1-DOF pitch oscillation data, an example of which can be seen in Figure 10.

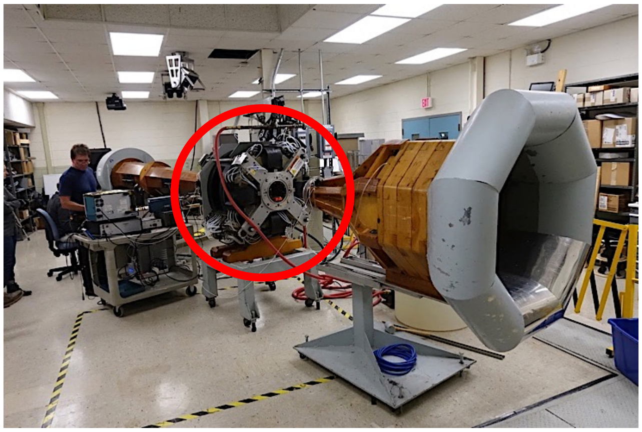

Figure 9. Subsonic wind tunnel with magnetic suspension balance visible in the center test section.

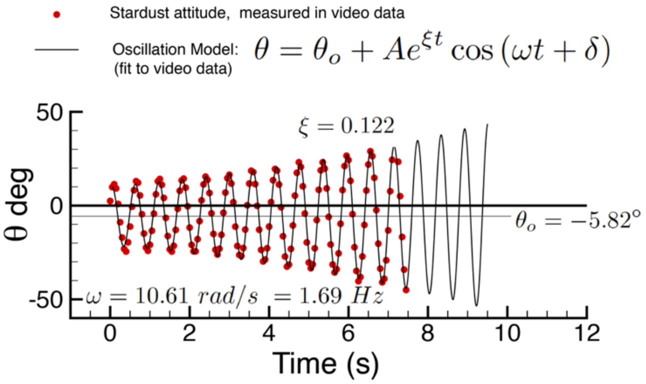

Figure 10. Example 1-DOF pitch oscillation data generated in MSWT for Stardust geometry.

Free-flight CFD

Free-flight CFD is the computational counterpart to the experimental MSWT effort. It seeks to modify the typically static CFD framework to enable simulated motion of the spacecraft model according to predicted aerodynamic forces and moments. 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 11 shows an instantaneous image of the high-resolution flowfield computed by US3D software during a free-flight simulation of the Orion spacecraft's transonic dynamics. Figure 12 shows a comparison of the simulation's predicted dynamics with experimental data from a ballistic range. The experimental condition is Mach 1.06. One can see that quite good agreement is obtainable, within 15% of experiment, when sufficient care is taken to ensure proper spatial and temporal resolution of the flowfield. [37]

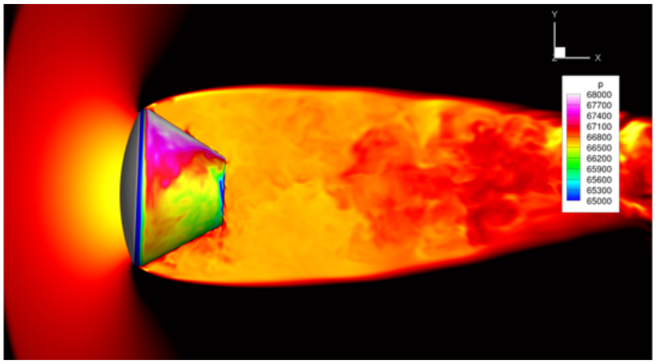

Figure 11. Free-flight simulation using US3D software to analyze transonic dynamics of Orion spacecraft.

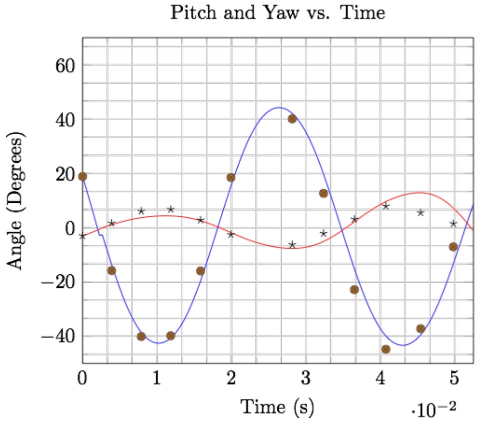

Figure 12. Simulated versus experimental attitude of Orion geometry at Mach 1.06. Lines are computation, symbols are experiment. Blue is pitch and red is yaw orientation.

In addition to US3D, similar capabilities have been demonstrated in other CFD frameworks including OVERFLOW, FUN3D, and CART3D. Future extension of the free-flight CFD capability will explore performance in the subsonic regime (thought to be the most challenging), powered control via RCS, and multi-body dynamics for EDL separation events like heatshield ejection.

Parachute Fluid-Structure Interaction

NASA has pursued with great interest in recent years a better understanding of parachute behavior for EDL systems. In the Mars Program, the Low-Density Supersonic Decelerator project attempted to qualify a new ringsail parachute design for larger Mars robotic missions. The two drop tests that were conducted resulted in failed parachutes that ripped apart within fractions of a second of deployment [38]. 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. At the same time, NASA's Orion Program was suffering from an anomaly which imparted a pendulum motion to the capsule during descent when one of the canopies in the parachute cluster had failed. The swinging motion could result in considerably off-nominal ground impact and serious injury to astronauts.

Thus, ESM has set about developing high-fidelity computational models to separately address the parachute inflation and descent dynamics problems. The descent dynamics are being tackled through an in-house effort using the *eddy* multi-physics CFD software. *eddy* is a high-order, finite element-based code whose goal is to provide benchmark analyses of parachutes for high-risk scenarios where the computational cost is justified. The *eddy* code, example output of which can be seen in Figure 13, is currently capable of modeling dynamics of a rigid canopy [39]. Structural response models for the canopy fabric are under development and will eventually be strongly coupled to the CFD to create a detailed description of the full capsule-canopy system. The code will be validated using drop test data from the Orion Program.

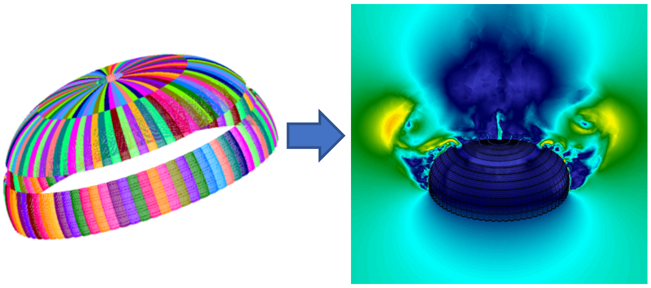

Figure 13. Finite element mesh of DGB parachute feeds high-order simulation of canopy descent dynamics.

Parachute inflation modeling, including dynamic loading of the fabric, is under investigation by academic partners at Stanford (Prof. Charbel Farhat) and University of Illinois (Prof. Carlos Pantano-Rubino) via Space Technology research awards. Both groups have relatively advanced capabilities for modeling fluid-structure interactions of fabric, including folding and self-contact. The Stanford group also has a fabric microstructure modeling capability which, when paired with ESM's own micro-CT imaging and modeling capabilities, may provide unique and valuable insights into fabric structural mechanics at the microstructural level.

Mission-relevant Roughness (MRR)

Previous work by ESM has characterized the heating augmentation due to distributed roughness patterns analogous to the surface roughness that arises from the material ablation process, see for example Reference [40]. The project is now taking that work further in two important ways. The first is to examine the effects of isolated roughness patterns that arise from tiled heatshield designs. 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, the new class of woven TPS materials like HEEET have an intrinsic surface roughness due to the wavy nature of the weave. It is unclear whether the augmentation is the same or similar to that predicted for sandgrain roughness, which is the assumption currently applied during analysis.

The effects of tiled and woven roughness patterns are being examined independently in the ballistic range at NASA Ames Research Center and the Mach 6 wind tunnel at NASA Langley Research Center. In 2018-19, the Mach 6 tests are focused on generating data for the tiled system using global thermophosphor measurements of heating on an idealized heatshield geometry, see Figure 14. The data already qualitatively provide potentially 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 science data.

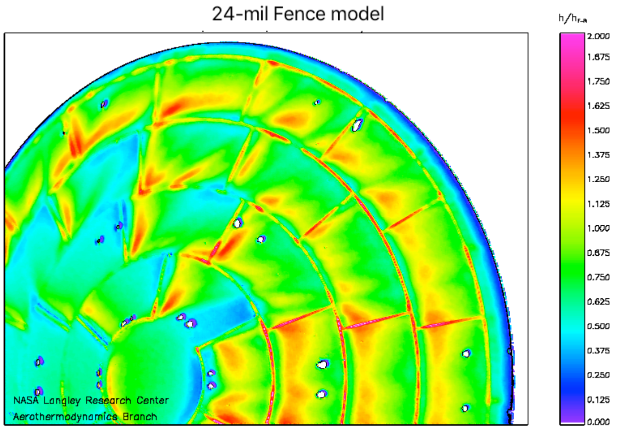

Figure 14. Phosphor thermography image from Langley Mach 6 measurement of heating augmentation due to tiled roughness.

First-year testing in the Ames ballistic range is focused on the woven system. The ballistic range uses laser-etched models to accurately reproduce scaled weave patterns on the model surface, and infrared thermography provides heating estimates from a series of camera stations along the range. Figure 15 shows a detail scan of the laser-etched model surface. Analysis of data is currently underway and ESM expects results from both sets of experiments will be published beginning in 2019.

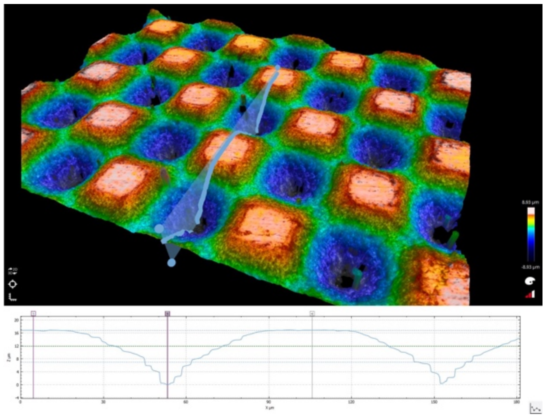

Figure 15. Detailed scan of laser-etched weave pattern on the surface of ballistic range model.

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. ESM is attempting to counter this trend by investing in new techniques that can reduce reliance on expert judgement, introduce more formal assessments of simulation uncertainty, and improve computing output by harnessing exascale 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 specific area of interest is so-called “high-order” methods. The Discontinuous Galerkin (DG) approach, in particular, has been widely investigated by the academic community with promising results, albeit primarily in the low-speed (sub-hypersonic) regime. The ESM project has brought together three independent efforts to explore application of DG methods to aerothermodynamics problems of interest. The high-order nature of DG makes it particularly amenable to solving the long-standing problem of capturing shockwaves on unaligned grids, on which the current state of the art produces significantly inaccurate heating environments. Figure 16 shows the remarkable insensitivity of a DG method to a completely irregular underlying mesh, whereas the traditional finite volume method produces noticeably poor results [41].

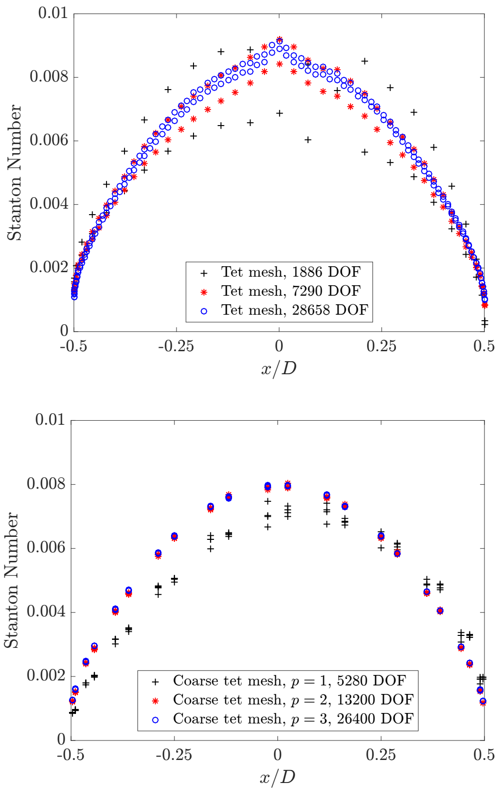

Figure 16. Predicted heating over cylinder using traditional finite volume method (top) and DG method (bottom). The DG method accurately resolves surface heating with 13,000 degrees of freedom, whereas the finite volume method remains unconverged with 28,000 DOF.

Another useful feature of DG methods is that they can easily achieve arbitrary order (that is, rate of error convergence toward zero) by simply varying the polynomial order of the underlying solution reconstruction. The reconstruction also has the property of being local, meaning that it does not depend on data beyond its nearest neighbors, a very important property for efficient implementation on exascale computing architectures. Taken together, these features make DG methods an intriguing candidate for application to some of NASA’s most difficult fluid dynamics problems, including the parachute system mentioned previously, and modeling of other highly unsteady flows like RCS-afterbody interactions and supersonic retropropulsion.

5. GUIDANCE, NAVIGATION & CONTROL

Guidance, Navigation, and Control (GNC) is a new topic of investigation for ESM begun in 2018. It is motivated by the realization, through NASA’s human Mars architecture studies, that insufficient guidance and control models were available to assess architecture performance against requirements. Chief among the performance requirements is landing precision: Candidate architectures must be able to land within 50 meters of intended destination. This is a 100-fold increase in precision over the state of the art embodied by Mars Science Laboratory and Mars 2020. The primary architectures under consideration are the low ballistic coefficient deployable decelerators (inflatable and mechanical) and the so-called mid-L/D shape, examples of which can be seen in Figure 17.

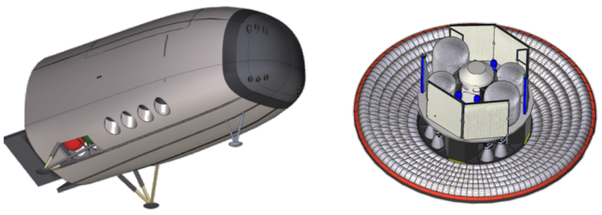

Figure 17. Example mid-L/D (left) and deployable (right) architectures.

ESM is just one part of a GNC research ecosystem, which includes NASA’s architecture teams, the Descent Systems Study, the SPLICE navigation project, and the Pterodactyl study of GNC for a mechanically-deployed ADEPT architecture. ESM’s role is to provide entry guidance and control models as part of a larger end-to-end simulation domain. To that end, ESM is focused on three primary objectives in 2018-19: 1) Building 6-DOF guidance and control simulations for deployable and mid-L/D configurations; 2) Demonstrating mechanical feasibility of control systems within architecture constraints; and 3) Demonstrating impact of real-time flight data on guidance performance. For the deployable configuration, we are particularly interested in exploring multi-axis control schemes (independent pitch and yaw control, rather than bank angle alone) and have identified control schemes based on flaps, morphing aeroshells, and moveable center-of-gravity mechanisms for more detailed study.

The first objective has been met in 2018 for the mid-L/D configuration and the deployable configuration with flaps [42][43]. Figure 18 shows Monte Carlo results of flight simulations for both configurations, demonstrating the ability to achieve the required 50-meter landing accuracy.

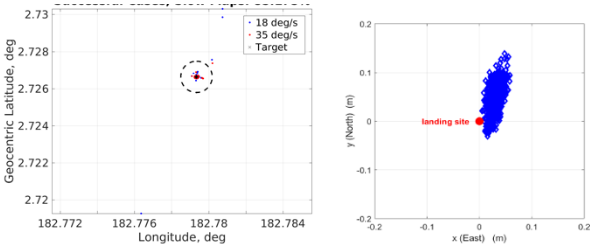

Figure 18. Projected landing results from Monte Carlo flight simulations of deployable (left) and mid-L/D (right) configurations, demonstrating the ability of both to meet precision landing requirement.

Further development of the morphing aeroshell and moveable CG concepts will be completed in FY19, along with the mechanical feasibility assessments. The use of real-time measurements of the flight environment to augment guidance is also currently in progress and expected to be published in the summer of 2019.

6. SPECIAL TOPICS

The preceding core technical areas represent the continuing focus of EDL modeling and simulation work within ESM. Specific activities within the core technical areas are expected to change year to year as some are completed and new ideas are rolled into the portfolio. In addition to the core technical areas, the ESM project pursues a number of temporary, focused research activities. Two of these are detailed below.

Arc Heater Simulator (ARCHeS)

NASA's arc jet facilities produce indispensable data on thermal protection material performance. Nevertheless, the output of the facilities has provided limited value for tool validation because the freestream conditions are not well characterized. In addition, there has been talk for many years of the need to upgrade facility performance which would entail significant design work. In both cases, having a high-quality model of the facility's core component – the arc column – would be very beneficial, yet such a model does not exist. The current state of the art is no more than the original simplified, 1-D models from 30+ years ago, which grossly oversimplify or ignore the complex, dynamic magnetohydrodynamic phenomena that occur in an arc column.

The Arc Heater Simulator (ARCHeS) is a high-fidelity tool for the simulation of arc plasmas built on the open-source CFD framework of OpenFOAM. The baseline OpenFOAM framework is time-accurate and capable of resolving unsteady environment of an arc column. On top of this, ARCHeS couples magnetohydrodynamic equations describing the interaction between plasma fluid and induced electromagnetic fields. Three-dimensional radiative transport is included to properly account for energy transfer through the column. Boundary conditions mimic the effect of electrical ballast in the electrodes that helps to control arc attachment.

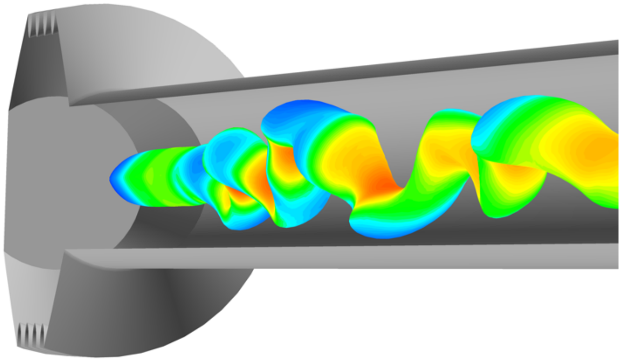

Figure 19. Sample ARCHeS output showing instantaneous iso-contour of arc current colored by magnetic field intensity. ARCHeS can help operators understand arc instability and its effect on performance.

Figure 19 shows a visual example of the output produced by ARCHeS [44]. The flow is unsteady and demonstrates the natural instability that rises in the flow through the arc column. This kind of information can provide valuable insight to arc jet designers and operators about the true operating performance. For example, simulations clearly show the dependence of arc attachment at electrodes, which drives their degradation over time, on the column's unstable dynamics. Placed within an optimization framework like Sandia's Dakota software could drive new designs which minimize the wear and tear on facility components. Future work will pursue this end.

PICA-NuSil Modeling

With Mars Science Laboratory's successful landing in 2012, the EDL community gained a unique set of flight data returned from the MEDLI flight instrumentation [45]. Mars 2020 will fly a second suite of instrumentation, known as MEDLI-2. During the course of MEDLI-2's design and qualification, it was discovered that the heatshield of MSL was not bare TPS material but was, in fact, coated with a silica-based product called NuSil. The presence of silica on the heatshield surface is expected to have some impact on the local thermal properties and therefore has a first-order impact on reconstruction of the flight environment using inverse analysis techniques. As a result of this discovery, the Space Technology Mission Directorate and Mars 2020 directed

ESM to develop a high-fidelity model of the PICA-NuSil system in order to meet the accuracy requirement for reconstruction of the heatshield surface environment.

The approach to developing a PICA-NuSil model will follow that outlined under the Predictive Materials Modeling area. Techniques like thermogravimetric analysis and mass spectrometry will be used to characterize decomposition of pure NuSil and NuSil blended with PICA. Molecular beam experiments will measure reaction products at the surface when exposed to oxygen. Heated flow tube experiments will measure permeability of PICA-NuSil as it decomposes. Along with the standard aspects of model development, there are two new features unique to PICA-NuSil. First is the addition of a graded material model that can capture the gradual transition in material properties between pure NuSil at the very surface to pure PICA in depth. Figure 20 shows a micro-CT scan of a NuSil-coated PICA sample which visualizes the transition.

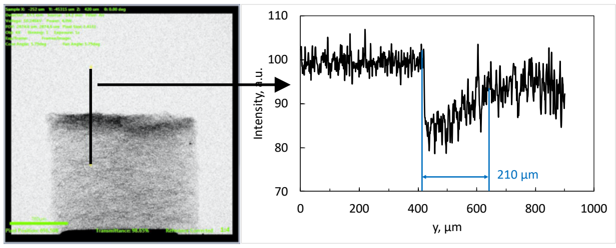

Figure 20. Micro-CT scan of a NuSil-coated PICA sample. The plot on the right shows measured signal intensity, showing the transition from high-density, pure NuSil at the surface to the comparably lower density PICA substrate.

Second is the need for a melt model to capture the formation and transport of liquid silica on the surface. Prior test samples of MSL materials, shown in Figure 21, make the presence of glassy silica residue readily apparent:

Figure 21. Post-test panel of MSL-era PICA coated with NuSil shows persistent glassy silica residue.

Further testing will be conducted to guide model development and validation. Small-scale, inexpensive models will be tested in the HyMETS arc jet at NASA Langley to provide basic information on PICA-NuSil response across a range of conditions. Testing in HyMETS will also enable a parametric study of the influence of coating thickness on response – available documents on the coating process used for MSL do not spell out a clear specification for the amount of NuSil applied. More detailed validation data will come from the NASA Ames arc jets using larger segmented SPRITE [46] models in order to simultaneously measure response of bare PICA and PICA-NuSil. Results from these comparisons will establish whether the models are capable of meeting MEDLI-2's accuracy requirements.

7. 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: Predictive materials modeling; Shock layer kinetics and radiation; Computational and experimental aerosciences; and Guidance, navigation, and control. In addition to the core technical areas, ESM has research efforts in arc jet modeling (ARCHeS) and PICA-NuSil modeling. 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. We hope the reader is left with an appreciation for the potential for modeling and simulation to deliver timely and useful results within a modest budget. The efforts have been documented across hundreds of journal articles, posters, and conference presentations. Only a fraction of them are discussed here, though the reader is encouraged to follow the trail of references that begins at the end of this paper and contact the authors for much more detailed information.

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, and Johnson 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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BIOGRAPHY

Michael Barnhardt *is a member of the Aerothermodynamics Branch at NASA Ames Research Center, specializing in aerothermodynamics and EDL technology. He has been with the organization for 10 years since graduating from the University of Minnesota with a Ph.D. in Aerospace Engineering. Dr. Barnhardt began his NASA career as a CFD analyst and software developer for the DPLR code, and has led many modeling and simulation research efforts during that time. He subsequently collaborated with the University of Minnesota to jointly develop a version of the US3D software for use at NASA. In 2013, he joined the Entry Systems Modeling Project for which he currently serves as Principal Investigator.*

Aaron Brandis *received his undergraduate Bachelor of Engineering (Mechanical and Space) in 2003 and his PhD from the University of Queensland and Ecole Central Paris, France in 2009. Dr. Brandis is a senior research scientist employed by AMA Inc in the Aerothermodynamics Branch at NASA Ames. He is currently the Deputy PI for the Entry Systems Modeling Project and PM/PI for NEQAIR, Co-PI for the Electric Arc Shock Tube, and Aerothermal and ESI lead for Dragonfly New Frontiers mission proposal.*

Michael Wright *has worked at NASA Ames Research Center for twenty years, specializing in Entry, Descent and Landing technologies, aerothermodynamics, and thermal protection systems. He is the primary developer of the aerothermodynamics code "DPLR", 2007 NASA software of the year, and has supported EDL for many flight missions,* *including Orion, MSL, Stardust, Phoenix, and Huygens. Michael is currently the Project Manager for the Entry Systems Modeling Project, and serves concurrent roles as the deputy lead for the Agency EDL Strategic Capabilities Leadership Team and the EDL Assembly lead for the proposed Dragonfly New Frontiers mission to Titan.*

Monica Hughes *has worked at NASA Langley Research Center for 25 years, working on several technologies in Aeronautics, Exploration, and Space Technology. For the last 10 years, she has been working in the Entry, Descent, and Landing field, concentrating on inflatable reentry vehicle technology before shifting focus to entry systems. Monica is currently the Deputy Project Manager for the Entry Systems Modeling Project, and serves a concurrent role as the acting assistant branch head of the Atmospheric Flight and Entry Systems Branch at NASA Langley.*