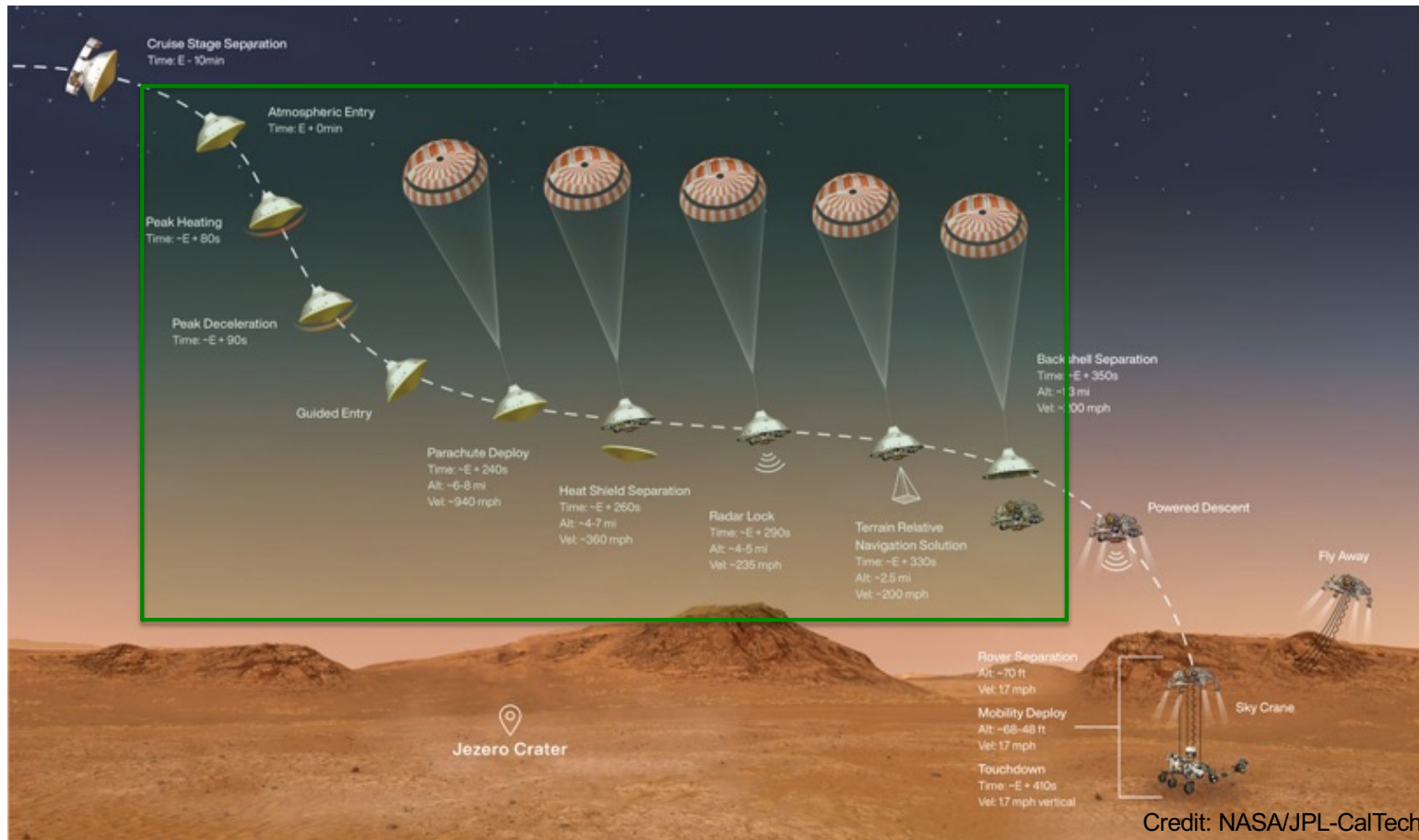


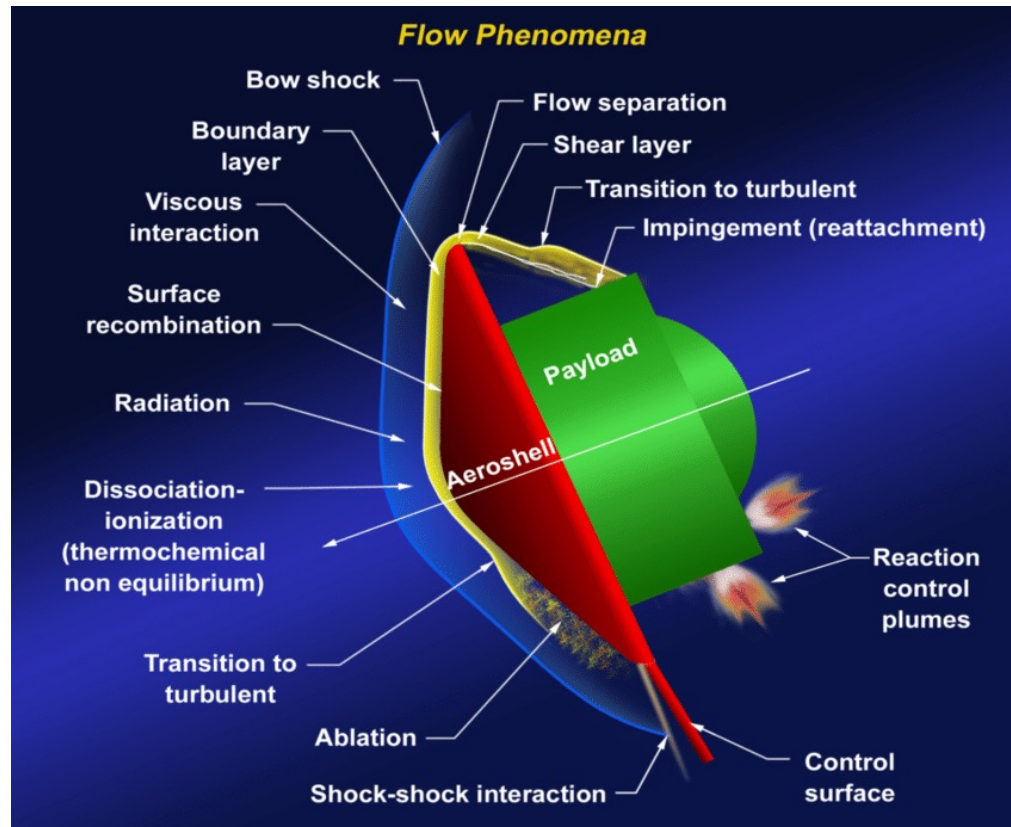
Entry Systems Modeling

Michael Barnhardt, Aaron Brandis, Tom West, Ashley Korzun, Monica Hughes, Michael Wright
EDL Seminar Series | August 04, 2021

Entry, Descent, and Landing



Physics of Entry (Thermal Protection System)



Quantities of Interest:

- Heat flux
 - What material?
- Heat load
 - Bondline temperature → How thick?
- Pressure & shear
 - Static aerodynamics
 - Material stresses
- Vehicle dynamics/control

Examples of Entry Systems



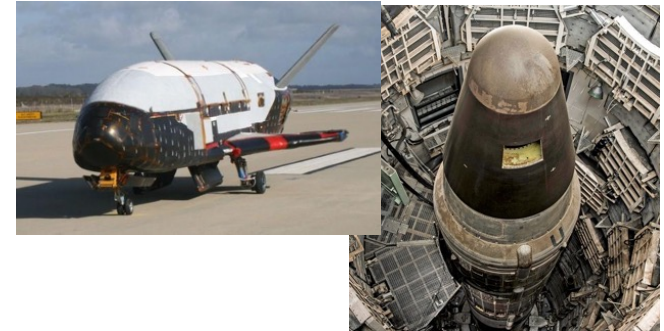
Apollo
First visit to the Moon



Space Shuttle
First re-usable spaceship



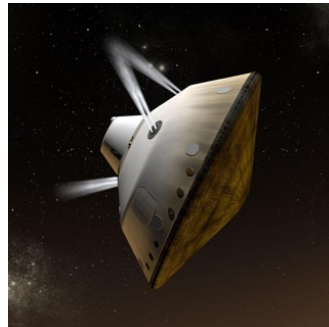
Soyuz
Return from LEO



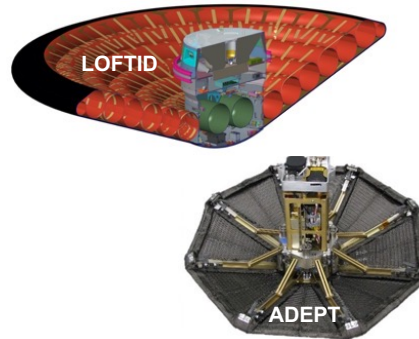
X-37/ICBMs
National Defense



Artemis/Orion
Return to the Moon



Mars 2020
Search for signs of life on Mars



Deployables
Improved packing and performance

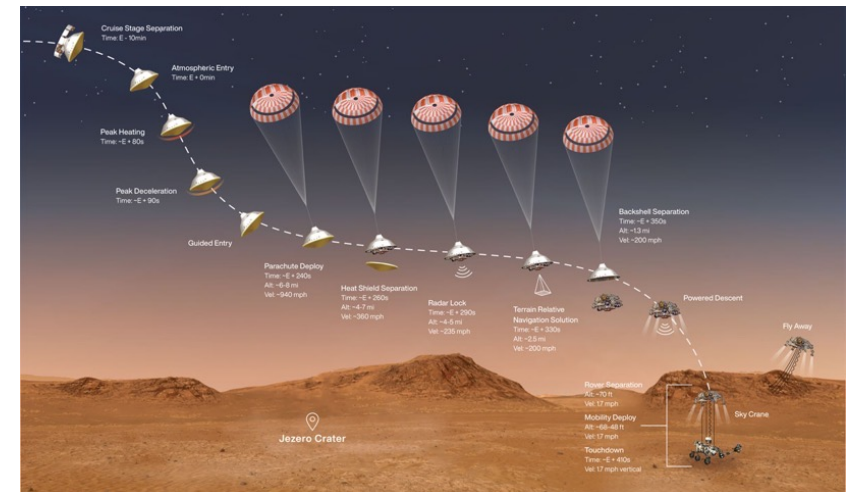


Commercial Space



Modeling Is Critical Path for EDL...

- ◆ **Flight mechanics** predictions determine landing ellipse; define system performance
- ◆ **Direct Simulation Monte Carlo** analysis used for all aerobraking missions, low ballistic coefficient entries
- ◆ **CFD** predictions define Thermal Protection materials used (aerothermodynamics), aerodynamic performance & stability
- ◆ **Material response** and **thermostructural** analysis defines TPS and structural design



“Can we retire all uncertainties via testing?” – No!

- No ground test can simultaneously reproduce all aspects of the flight environment. A good understanding of the underlying physics is **required** to trace ground test results to flight; extrapolation without a good understanding of the relevant physics can have catastrophic results.
- All NASA EDL missions are reliant on modeling and simulation to predict flight performance of what is typically a single point failure system.

...In Every Mission Phase

◆ Trade Studies

- M&S tools define system performance, establish feasibility, and drive downselects
- Inadequate tools can result in poor decision making at the very beginning of a new mission

◆ Proposal Development

- M&S used to establish viable concepts and demonstrate acceptable risk

◆ Mission Design & Engineering

- M&S is critical path to predict performance, select materials, and design EDL system

◆ Mission Execution

- M&S used to drive course corrections, enable aerobraking, evaluate residual risk

◆ Post-flight Analysis

- M&S used to reconstruct EDL sequence and compare to flight data
- Accurate predictions (as opposed to simply conservative) are required to fully understand system performance

EDL hardware systems and accurate M&S capability are inextricably linked. The fidelity of our M&S capability will drive not only mass and reliability, but directly impact which hardware technologies are selected for maturation.

NASA Has Models in all Major Disciplines... Are We There Yet?

- **Models, particularly in aerosciences and material response, have poorly defined uncertainty levels for many problems (limited validation)**
 - Without well-defined uncertainty levels, it is difficult to assess system risk and to trade risk with other subsystems
 - Result is typically (but not automatically) overdesign
- **Missions get more ambitious with time**
 - Tighter mass and performance requirements
 - More challenging EDL conditions require that models evolve
- **Even re-flights benefit from improvement**
 - Reflights are never truly reflights; changing system performance requires new analysis, introduces new constraints
 - ‘New physics’ still rears its head in the discipline (e.g., CO₂ radiation)
- **Some of the most challenging problems have the “worst” models**
 - Parachute dynamics, separation dynamics, TPS failure modes, backshell radiation...

“Since atmospheric and surface conditions of planetary surfaces are so varied [...] it is virtually impossible to test all aspects of EDL as they would be performed when landing. Consequently, we have to rely on M&S to give us confidence we can choose the right technologies and successfully perform EDL wherever we land. It is critical to develop validated physics-based models for the flight systems and sub-systems – for the TPS, parachutes and proximity operations. We need to fully understand off-nominal scenarios and be able to design fault tolerant systems that will work autonomously.”

-- Pat Beauchamp, Chief Technologist, JPL Engineering & Science Directorate

Focused investment in EDL M&S, *guided by mission challenges*, ensures that NASA is ready to execute the challenging missions of tomorrow

EDL Modeling & Simulation at NASA

Investments span multiple directorates, programs, and projects

- **Human Exploration and Operations**
 - Artemis
 - Commercial Crew Program
- **Science**
 - MSL/MEDLI and Mars 2020/MEDLI2
 - Mars Sample Return
 - Dragonfly
- **Aeronautics Research**
 - Limited overlap with Transformational Tools and Technology (TTT) and Hypersonics Technology Project (HTP)
- **Space Technology**
 - Heatshield for Extreme Entry Environment Technology (HEEET)
 - Adaptable Deployable Entry and Placement Technology (ADEPT)
 - Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)
 - Advanced Supersonic Parachute Inflation Research Experiment (ASPIRE)
 - Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE)
 - Descent Systems Study (DSS)
 - Pterodactyl
 - Entry Systems Modeling (ESM)
 - Space Technology Research Grants (STRG)
- **NASA Engineering and Safety Center**
 - Several focused, short-term activities and grants

EDL Modeling & Simulation at NASA

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Space Technology Mission Directorate Entry Systems Modeling Project

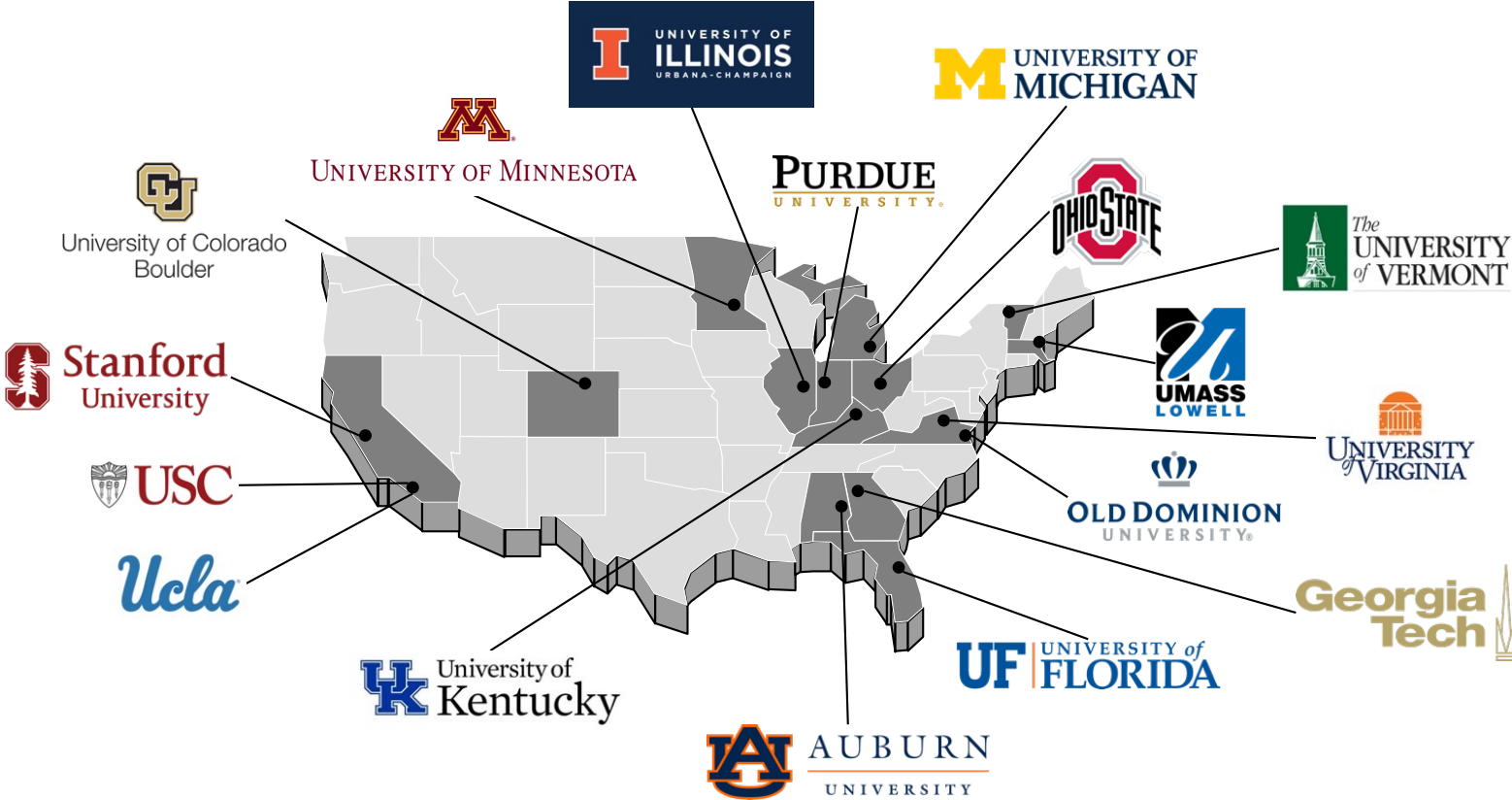
The Entry Systems Modeling Project (ESM) is focused on delivering real advancements to the current SoA that impact NASA missions

- Mid-TRL R&D, with topic areas driven by mission needs
- Mature new capabilities and prepare them for mission infusion
- Establish a “pipeline” to fundamental research via creative partnerships within NASA, OGAs, and academia to leverage the best new and innovative ideas
 - Over 100 academics (students & faculty) involved each year via multiple funding mechanisms
 - Multiple international partnerships supported (DLR, JAXA, U Queensland, VKI, CentraleSupélec, Oxford)

“For complex missions that cannot be fully tested on Earth, we rely on computer models to convince ourselves that the integrated system will work in its intended environment. We have no other way to do this. Detailed subsystem hardware and software testing help us validate that each of these models do a good job of representing reality.”

-- Rob Manning, Mars Program Chief Engineer

Academic Partnerships

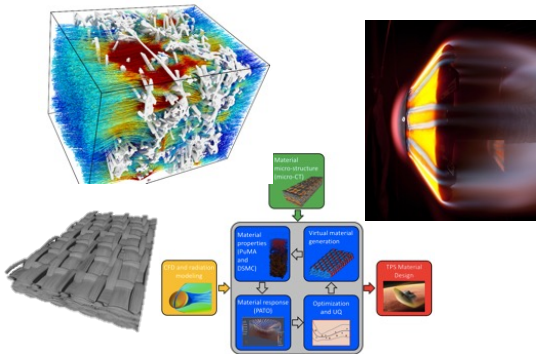


Entry Systems Modeling Project (ESM)

Core Technical Areas

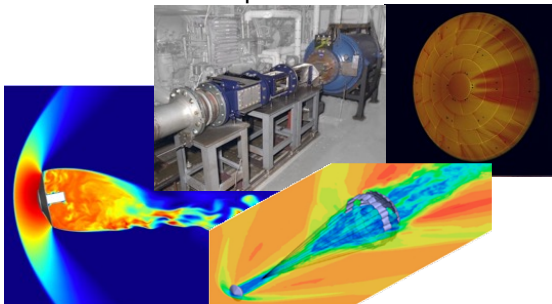
TPS Materials Modeling

Advanced models for PICA, Avcoat and woven TPS; Micro- to engineering-scale analysis tools; Detailed material characterization and model validation



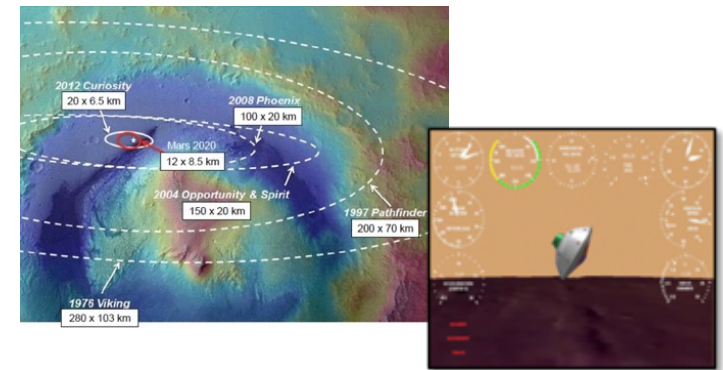
Aerosciences

Parachute dynamics; Free-flight CFD; Magnetic suspension wind tunnels; Experimental validation; Roughness-induced BL transition; Advanced computational methods



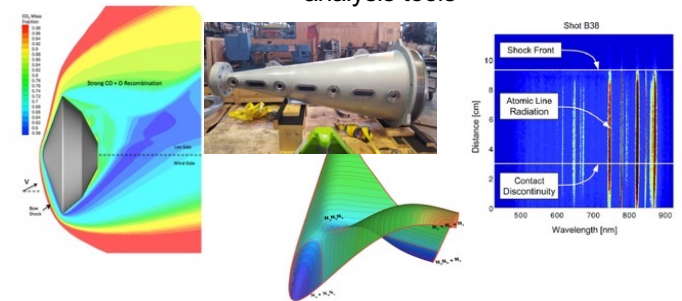
Guidance, Navigation, and Control

GNC methods to enable precision landing of large robotic and human Mars missions



Shock Layer Kinetics and Radiation

Radiation databases and models for destinations of interest across the Solar System; High-fidelity coupled analysis tools



ESM Core Portfolio in FY21

Predictive Materials Modeling (PMM)

- **Multiscale model and tool development**
 - Emphasis on PICA, HEEET, and Avcoat
 - Enhancing thermal models to predict failure
- **Component and system-scale V&V**

Key Products: PuMA, PATO, Icarus

Comp. & Exp. Aerosciences (CEA)

- **Magnetic Suspension Wind Tunnel**
- **Free-flight CFD**
- **Parachute FSI**
- **Mission-relevant roughness**
- **Advanced numerical methods**

Key Products: MSWT, FF-CFD (US3D), eddy, turbulent heating databases

Shock Layer Kinetics & Radiation (SLKR)

- **Experimental and theoretical databases**
 - Primarily Earth and Mars, with capability for other destinations as need arises
 - Developing new flight regimes and diagnostics
- **Uncertainty quantification**

Key Products: EAST; HARA and NEQAIR; chemical and spectral databases

Guidance, Navigation, & Control (GNC)

- **High-performance trajectory modeling**
 - Parallelization of POST2
 - Interoperability
 - POST2-FUN3D coupling for RCS/free-flight simulation

Key Products: HPC version of POST2

ESM Special Topics in FY21

MEDLI2 Deep Dive

- **Comprehensive post-flight analysis**
 - Instrumentation error models
 - High-fidelity aero and radiation analysis
 - High-fidelity material response, including NuSil
 - Integration of sensor and model data

Key Products: **Best-estimate reconstruction of Mars 2020 flight**

Hypersonic Wake Flows

- **Assessment of SoA with existing data**
- **Planning and execution of new tests**
- **Develop improved modeling capability**

Key Products: **Hypersonic aeroheating DBs; UQ**

TPS Certification by Analysis

- **Multiscale TPS failure modeling**
 - Emphasis on HEEET
 - Identify highest-priority failure modes and estimate response under off-nominal conditions

Key Products: **PuMA, NASMAT**

ARChES

- **High-fidelity models of arc-jet plasma**
 - Dynamics of plasma core
 - High-fidelity estimate of upstream BC for test chamber
 - Facility maintenance and future upgrades

Key Products: **ARChES**

PMM

Technology Overview

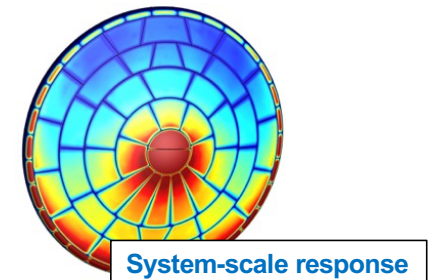
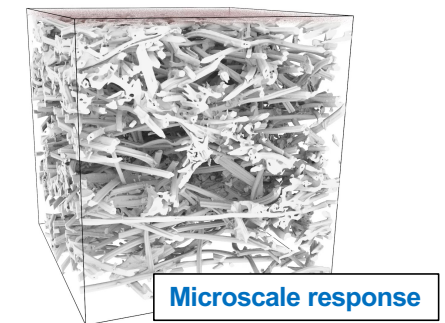
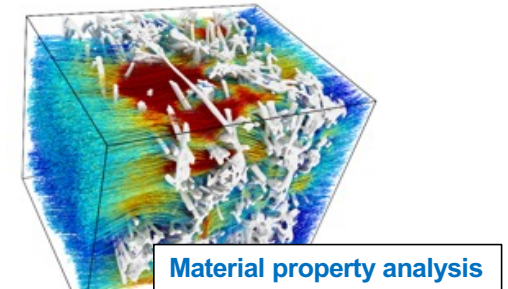


➤ Technology Product Capability

- Span the length scale from microstructural to full aeroshell.
- Extensive validation at the component and system level.
- Develop predictive models of material thermal and thermo-structural behavior that not only power next generation aeroshell design, but also provide the framework for TPS failure mode prediction, reliability modeling, and eventually computational materials design.

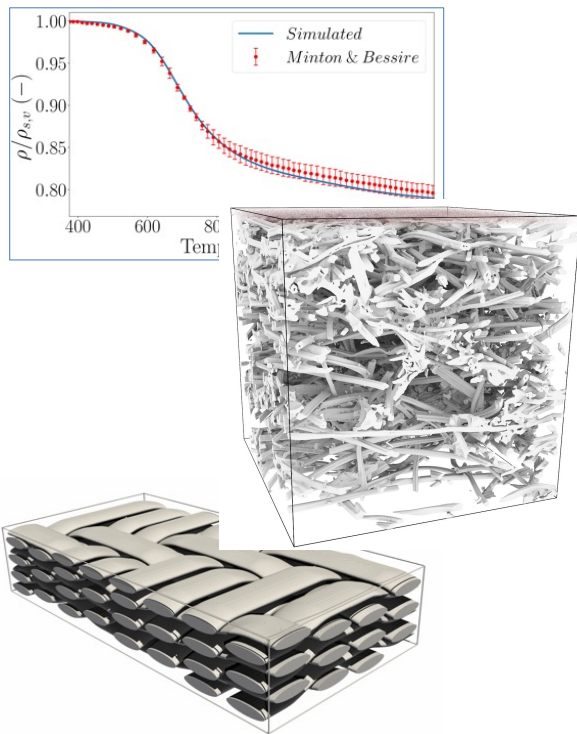
➤ Exploration & Science Impact

- Benefits all NASA missions with an EDL segment
- Save mass and/or improve system reliability. Reduce mission risk.
- Failure modeling will be critical path for high-reliability EDL applications (MSR and humans-to-Mars)
- Computational materials design will dramatically reduce development costs for new materials and will enable mission-tailored multi-functional TPS



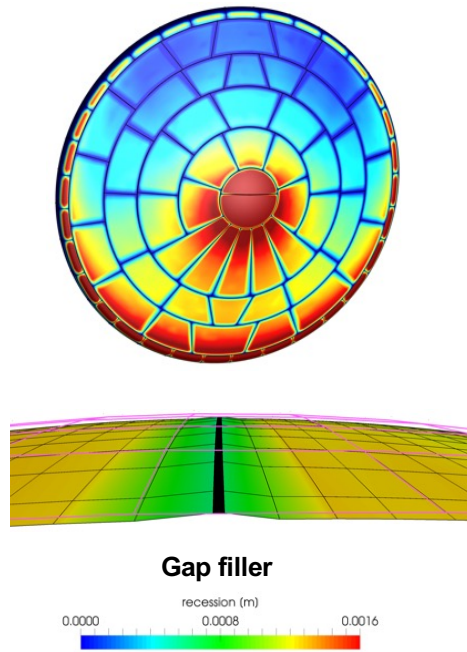
TPS Materials Modeling

Microscale



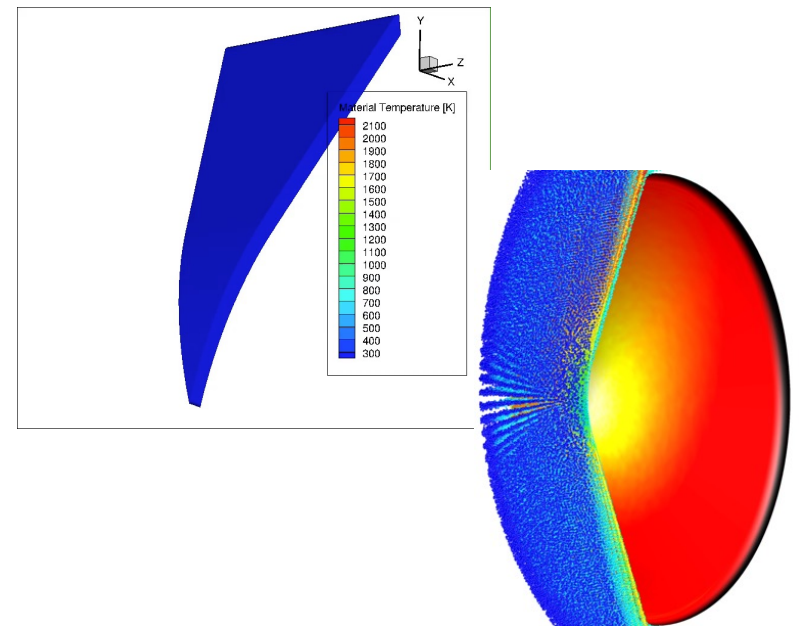
Microscale experiments and analysis for fundamental properties, validation

Benchmark Modeling



Benchmark simulations with PATO software to aid model development and quantify uncertainty

Engineering Applications



Rapid 3-D simulations of TPS and substructure using Icarus, a parallel, scalable software

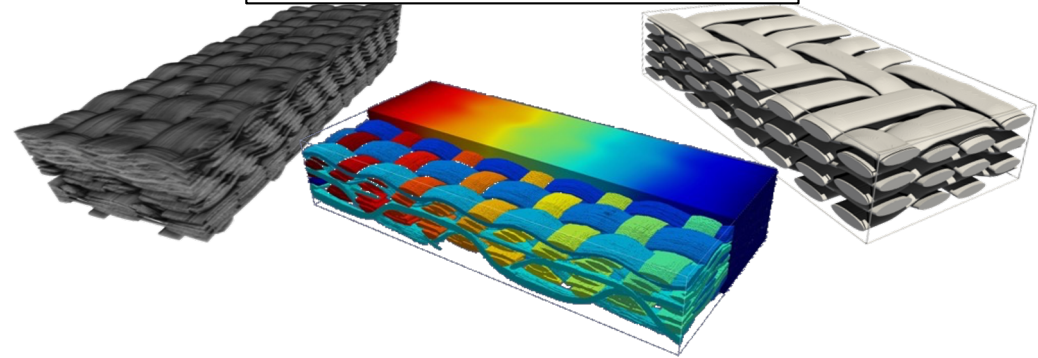
Modeling dust particle impacts for Mars entry

Woven Thermal Protection Materials

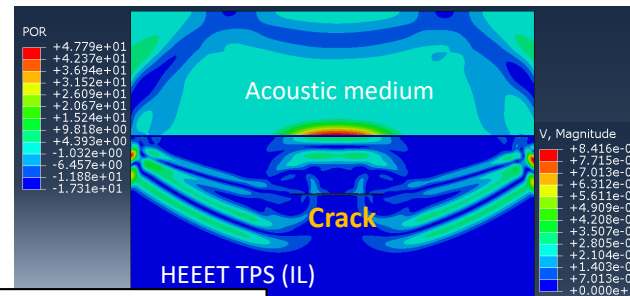
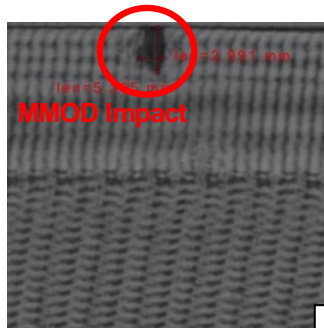
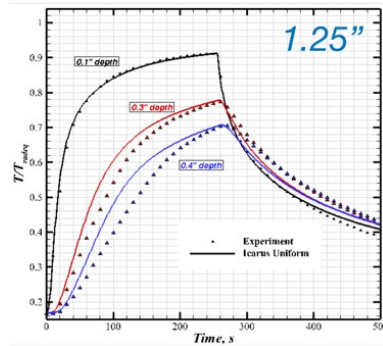
New classes of woven materials, like Heatshield for Extreme Entry Environment Technology (HEEET), are enabling for many of SMD's missions



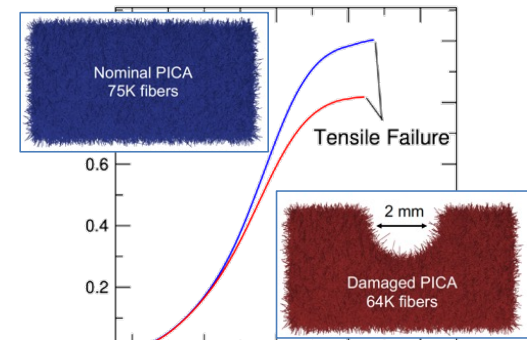
Weave Visualization, Generation, and Material Property Estimation



Multi-D material response



Damage Detection



Material Strength & Failure

PICA-NuSil

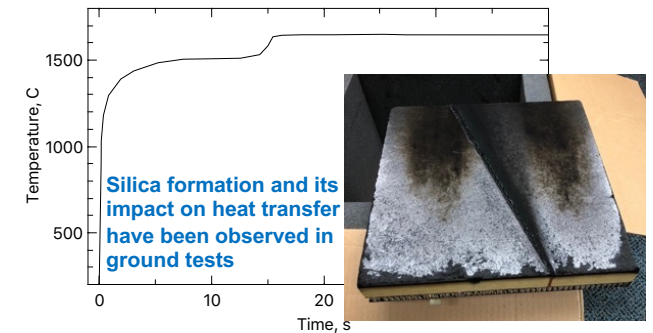
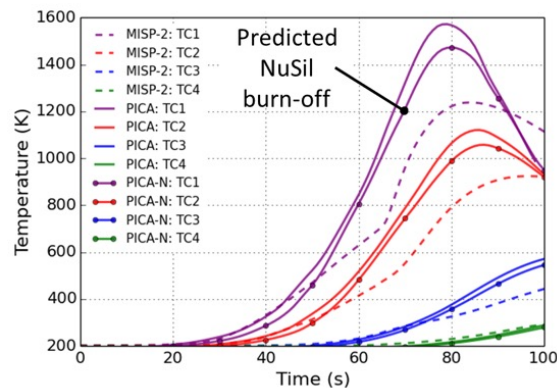
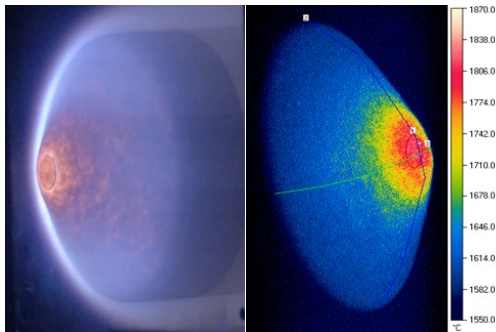
Mars Science Laboratory and Mars 2020

NuSil (silicone) coating on MSL and Mars 2020 significantly impacts our interpretation of flight measurements

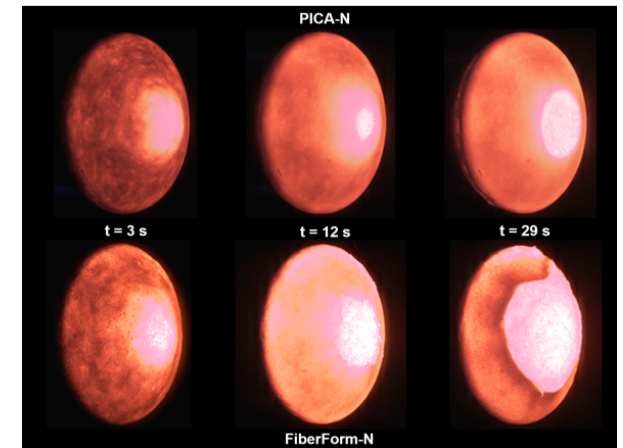
- Silica coating acts as an oxidation barrier
- It could also impair the transport of pyrolysis gas into boundary layer
- Modeling ablation of PICA-NuSil system is crucial for post-flight reconstruction

Development of High-fidelity Model

- PICA-NuSil material properties data
- Finite-rate gas/surface interaction data
- Building out micro- and macro-scale simulation capabilities



Ground Test Validation



SLKR Technology Overview

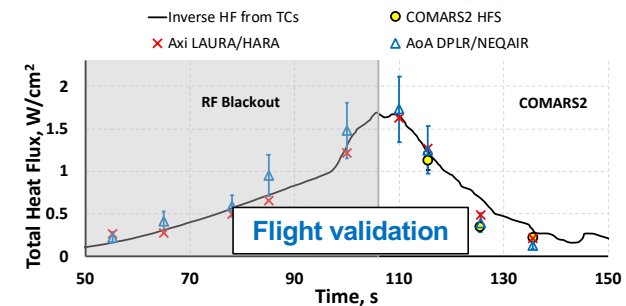
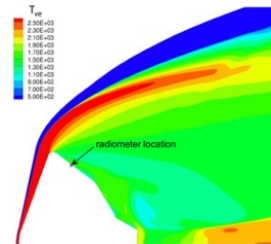
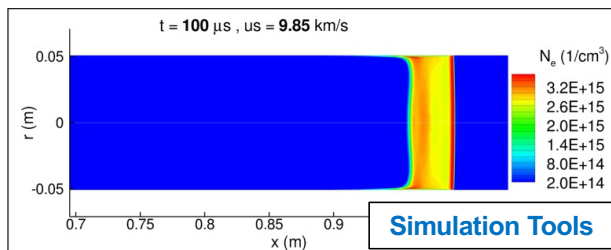
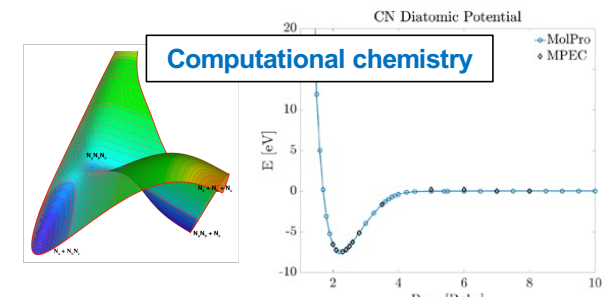


➤ Technology Product Capability

- Experimental facilities and computational capabilities used to develop and validate new models and databases for NASA atmospheric entry missions.
- Fundamental quantum mechanical simulations that underpin physics.
- Emerging new models incorporated into Agency workhorse radiation codes.

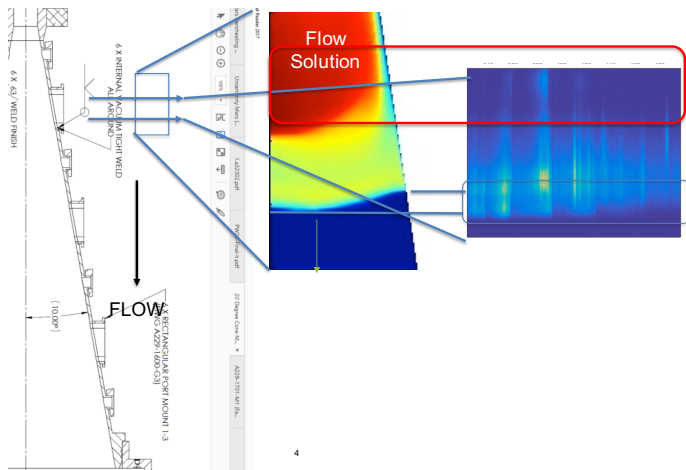
➤ Exploration & Science Impact

- Benefits all NASA missions with an EDL segment
- Radiative heating is a substantial aeroheating contributor and the largest uncertainty for many missions
 - As recently as MSL the community was unaware of its contributions for many applications (25% of heatshield heating and 50% of backshell heating for MSL)
 - Informed by ESM research, MEDLI2 added a radiometer to measure CO₂ radiation.



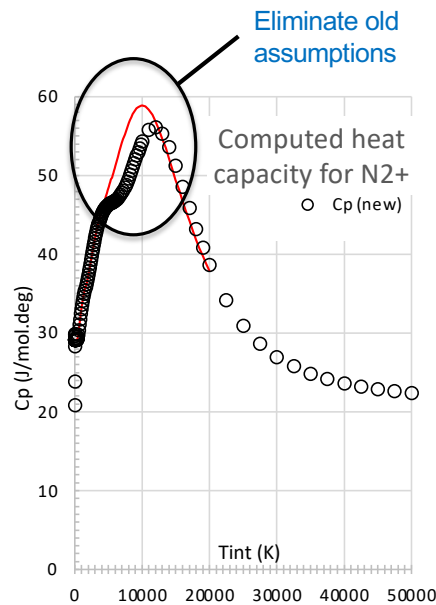
Shock Layer Kinetics and Radiation

Experiments



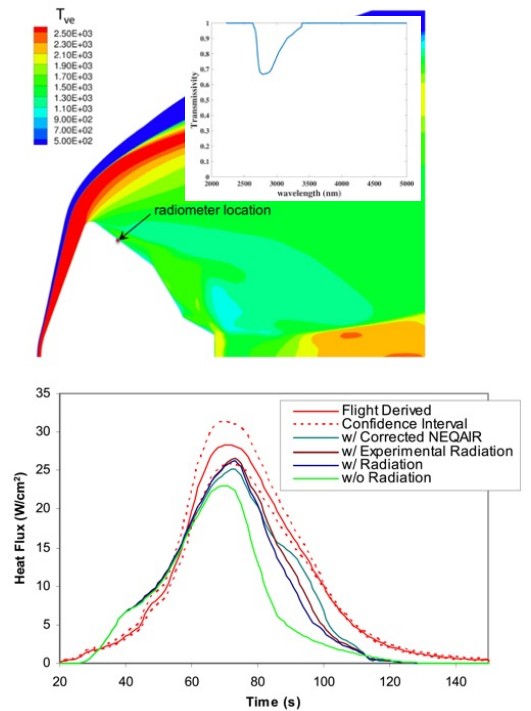
Simulation and experimental data for expanding flow in EAST expansion cone

Computational Chemistry



Many CFD model parameters are inaccessible experimentally. Advancements in computational chemistry enable us to determine parameters with high precision.

Applications



Top: Evaluating impact of deposition products reducing transmissibility on MEDLI2 radiometer window
Bottom: Flight data from MSL strongly suggests CO_2 radiation as a significant contributor to vehicle heating

CEA Technology Overview

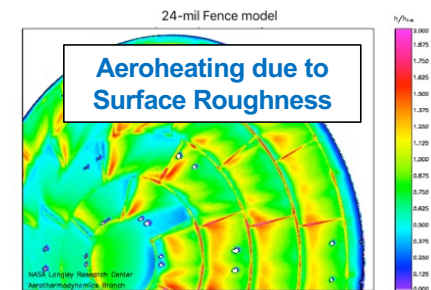
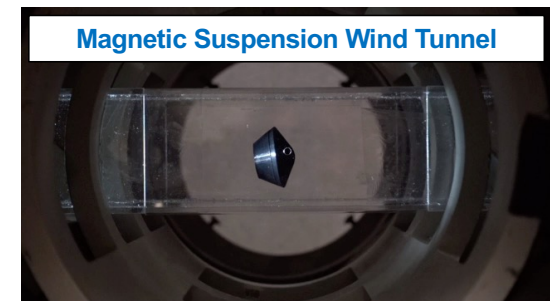
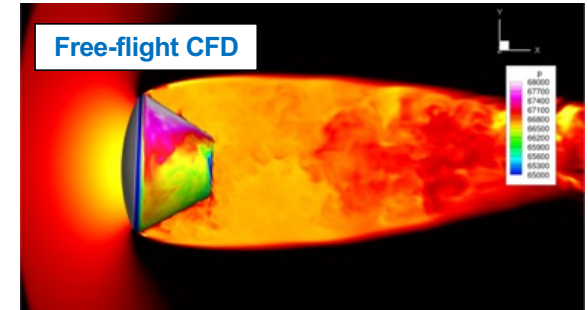
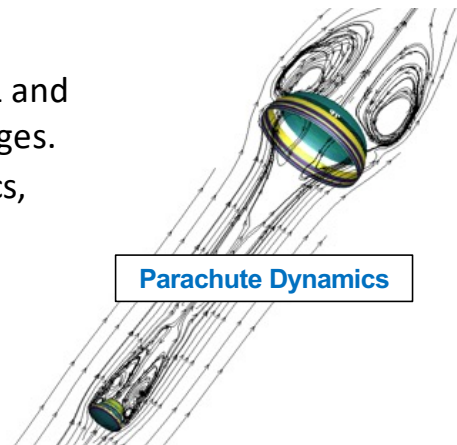


➤ Technology Product Capability

- Fundamental improvements to the tools for aerodynamics & thermal simulation.
- Accurate prediction of unsteady flows with application to modeling base flow dynamics, vehicle dynamic stability, and parachute dynamics.
- Generating mission-relevant databases & correlations to better understand & account for the influence of roughness on aeroheating and flow transition.
- Capability enhancements to support fluid flow and rocket plume interactions.

➤ Exploration & Science Impact

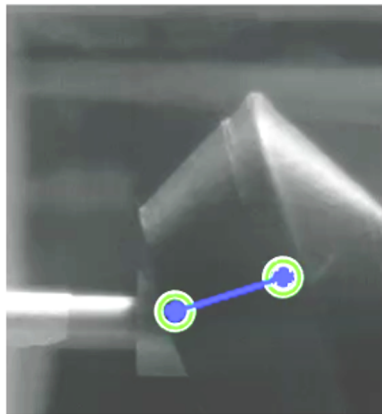
- Benefits all NASA missions with an EDL segment.
- Aerosciences modeling impacts all phases of EDL and encompass some of the largest technical challenges.
 - Vehicle dynamics/separation, parachute dynamics, aeroheating, RCS interaction



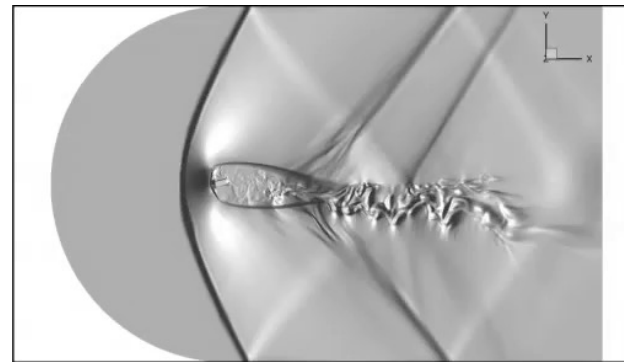
Computational & Experimental Aerosciences

Entry Vehicle Dynamics

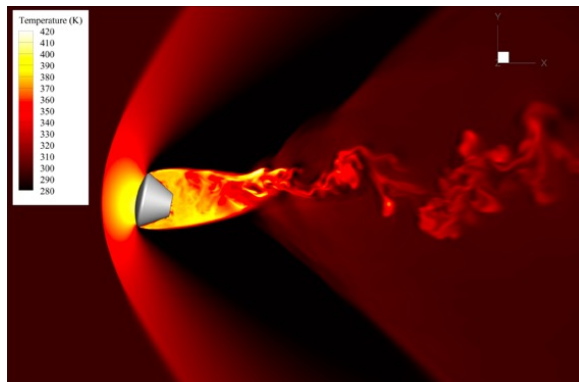
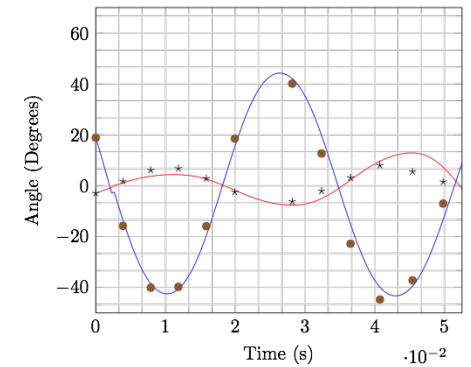
Magnetic Suspension Wind Tunnel



Free-flight CFD



Pitch and Yaw vs. Time

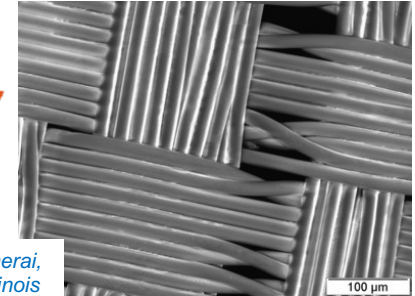
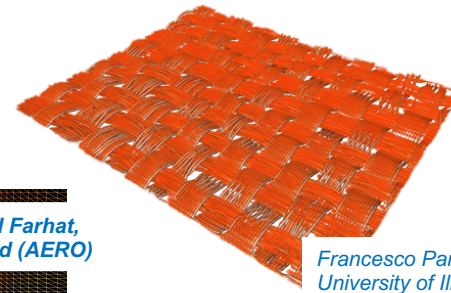


Parachutes for Entry Systems

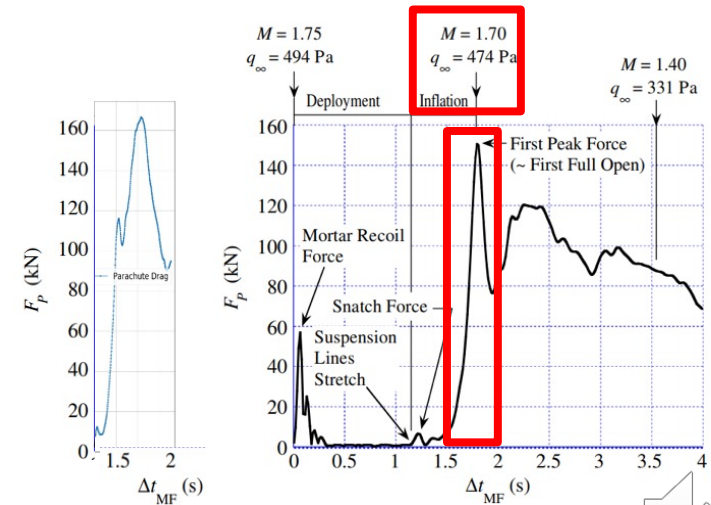
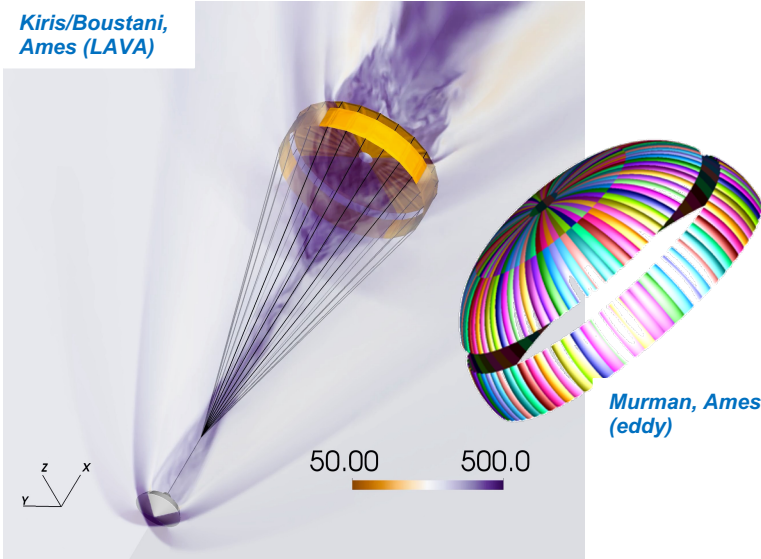
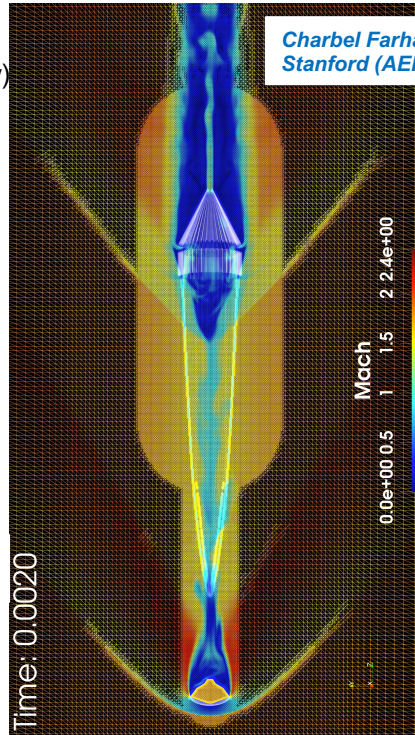
Parachute performance has been a concern of several programs in recent years

ESM and its partners have pioneered new capabilities

- Microscale fabric structure and degradation (Mars InSight)
- Off-nominal descent dynamics (Artemis and Commercial Crew)
- Inflation stress and failure (Mars 2020 and Commercial Crew)



Francesco Panerai,
University of Illinois



Stanford
AERO Code

Test Data

Computational & Experimental Aerosciences

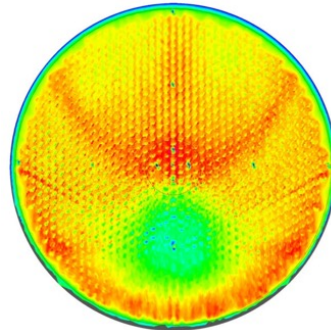
Mission Relevant Roughness

Sand-grain



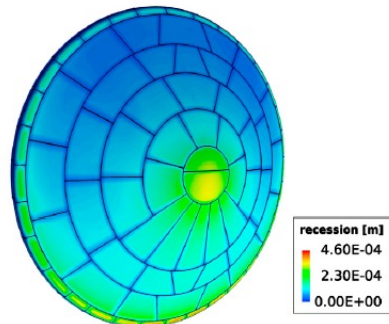
Ablated PICA on Stardust, Kontinos and Stackpole
AIAA Paper 2008-1197

Pattern



Honeycomb pattern,
Hollis, AIAA 2020-0121

Discrete



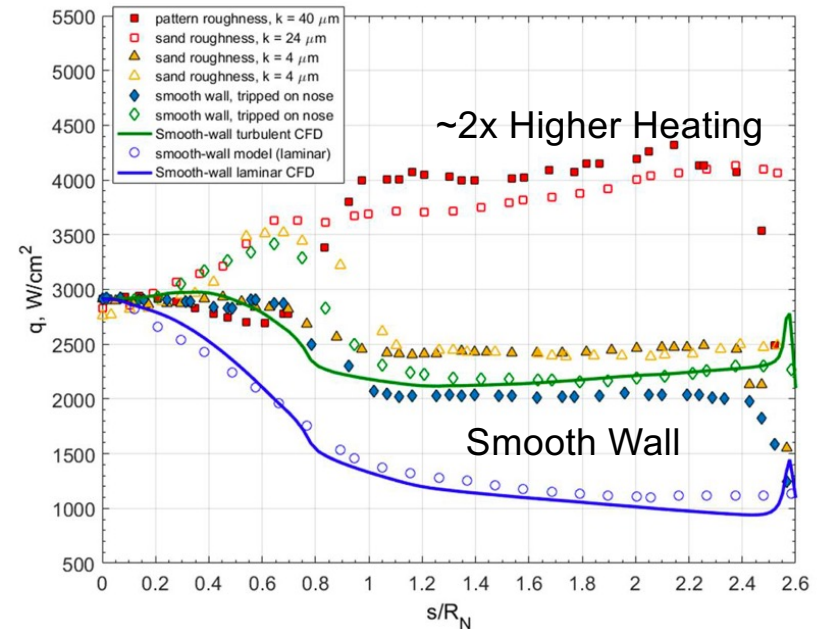
Differential recession on tiled TPS
Meurisse et al., *Aerospace Science and Technology*, 76 (2018)

Woven Pattern



Close-up of the HEEET ETU
<https://www.nasa.gov/centers/ames/thermal-protection-materials/tps-materials-development/woven.html>

Example Heating Augmentation due to Surface Roughness



GNC

Technology Overview

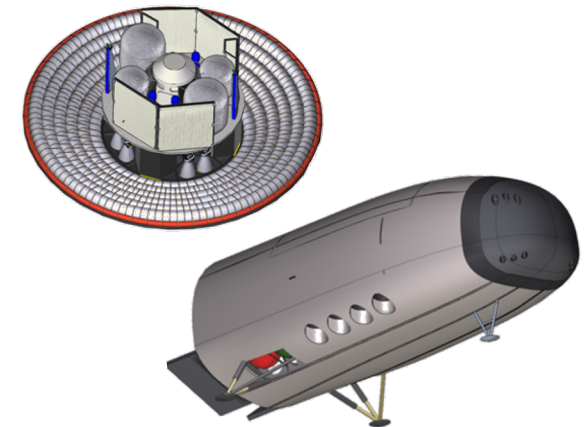
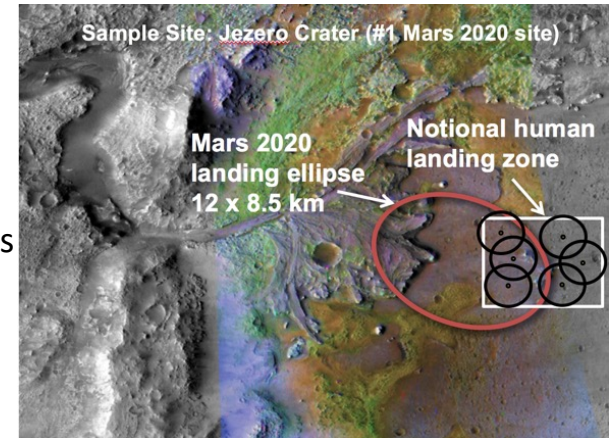


➤ Technology Product Capability

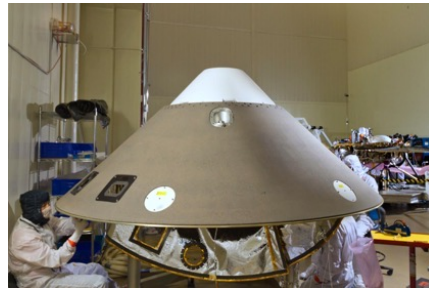
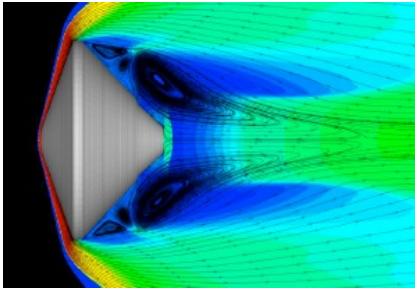
- ESM focus on entry GNC and end-to-end vehicle performance simulation; collaborate closely with SPLICE, DSS for descent and landing technologies
- Improved entry guidance algorithms, controllers, and advanced modeling and simulation functionality that will enable accurate placement of high-mass payloads
- State-of-the-art simulation framework for interoperability with external applications and physical models, including utilization of emerging HPC

➤ Exploration & Science Impact

- Enabling for precision landing of multiple high-mass missions, including humans on Mars, as well as use of heritage shapes for high-priority science solar system destinations, such as Venus and the Ice Giants
- Direct infusion path for Lunar descent and landing GNC
- Increase landed payload and/or site access, optimize propellant usage

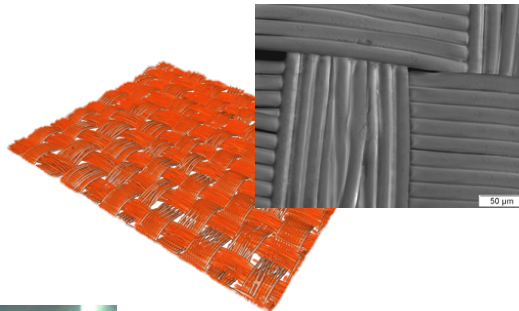


Mission Infusion: Mars InSight



ESM effort [...] allowed the utilization of reduced radiative heating uncertainties, which was key in demonstrating adequate TPS margin for the 2018 trajectory

– Christine Szalai, InSight EDL Systems Engineer



Backshell Radiation from CO₂

- Late in the InSight design cycle it was discovered that aftbody radiation, neglected for all previous Mars missions, may be significant (**discovery based on ESM Research**)
- **ESM Subject Matter Experts quantified the expected radiative heating and demonstrated adequate thermal margin** for the build-to-print aftbody TPS thickness

Descent Parachute Strength

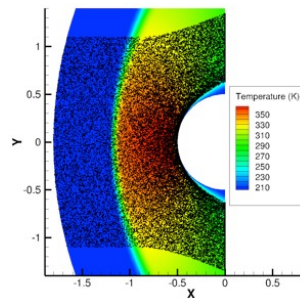
- InSight observed strength reduction in parachute fabrics after subjection to Dry Heat Microbial Reduction (DHMR).
- **ESM provided imaging (SEM, Micro-CT) of several parachute fabric lots to support InSight parachute qualification.** New bi-axial tension testing techniques developed for future applications.

Aeromechanical Erosion from Martian Dust

- InSight carried TPS performance risk resulting from possible aeromechanical erosion due to entry during a Martian dust storm. **ESM leads collaboration with DLR to improve dusty flow models and provide first uncertainty quantification.**
- Post-flight reconstruction is also looking at shape change due to dust erosion as a possible explanation for observed anomalous flight behavior.



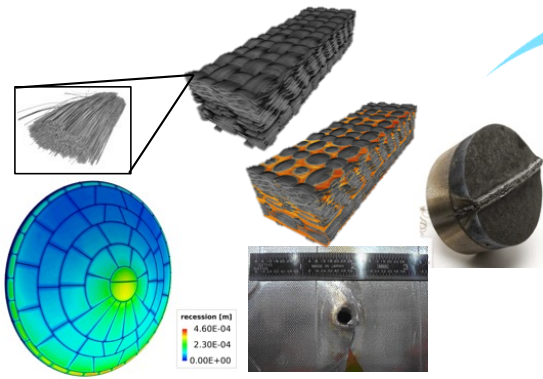
Dust erosion tests in DLR L2K tunnel provide fundamental data for model construction and validation.



Mission Infusion: Mars Sample Return / Earth Entry Vehicle (EEV)

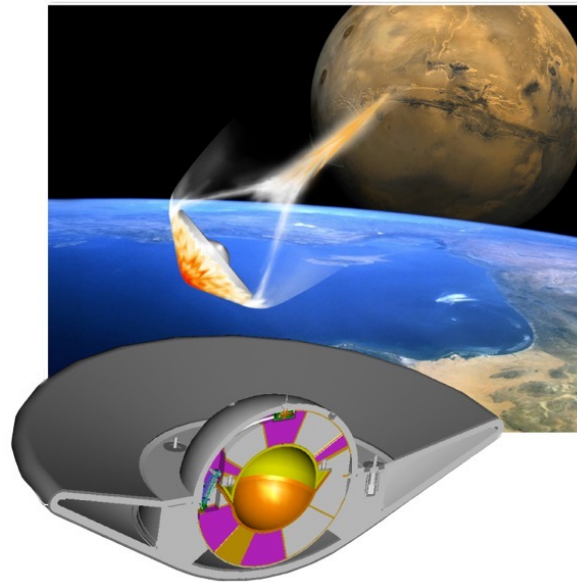
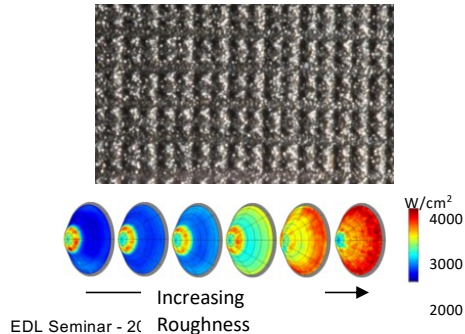
High Fidelity TPS Response Modeling

Developing next generation thermal and thermostructural models including failure modes; critical to reliability prediction



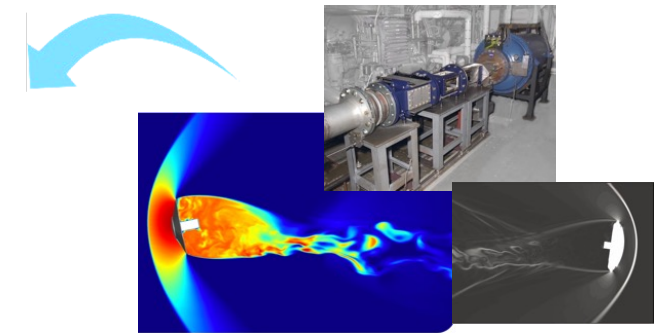
Roughness Heating Augmentation

Developing geometry-specific augmentation models; critical to woven TPS risk



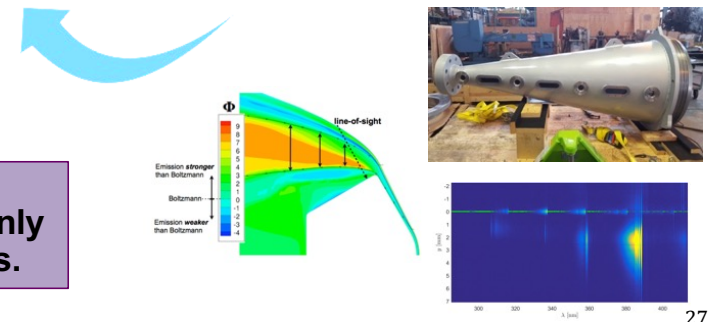
Capsule Dynamic Behavior

Critical path to modeling chuteless EEV performance



High Speed Air Radiation

First of their kind databases for backshell and high velocity radiation. Further work will reduce uncertainty by an order of magnitude.



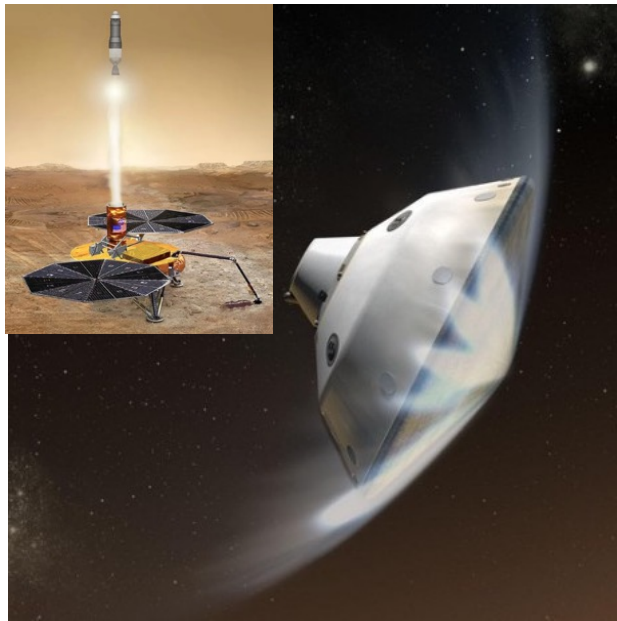
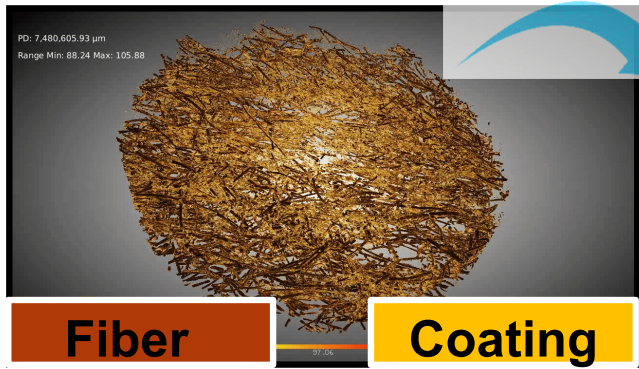
EEV is the poster child for advanced modeling. Reliability requirement can only be demonstrated with accurate models.

Mission Infusion:

Mars Sample Return / Sample Return Lander (SRL)

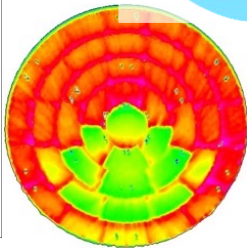
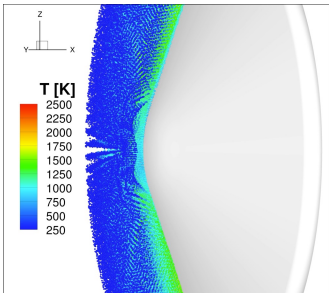
High Fidelity TPS Response Modeling

Developing next generation thermal and thermostructural models including failure modes; critical to reliability prediction



Roughness and Dust Heating Augmentation

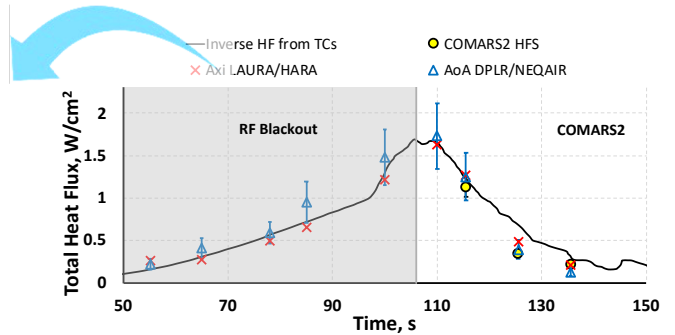
Developing tiled TPS heating augmentation models; as well as convective heating increases due to dust particle impacts



SRL design benefits from ESM advancements enabling more accurate representation of risk.

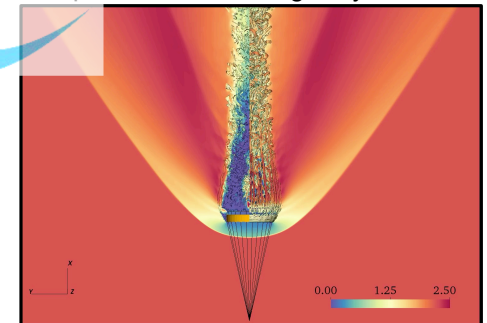
Post-flight Reconstruction

First validation of CO₂ backshell radiation flight data from Schiaparelli. High-fidelity investigation of the Mars 2020/MEDLI2 data



Parachute Modeling

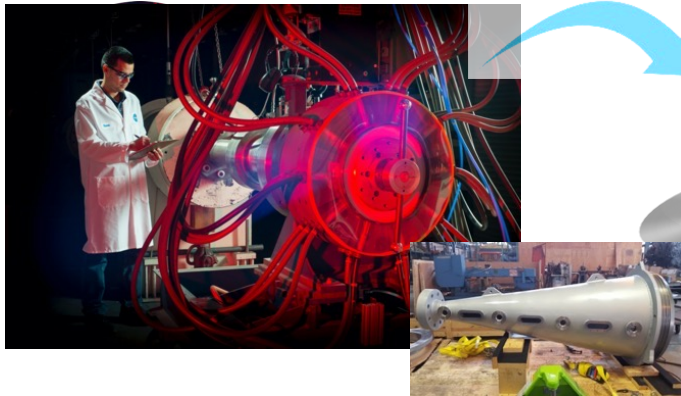
SRL landed mass will exceed previous flights by several metric tons making prior parachute designs unusable. Modeling can guide design trades and qualification of next-gen system.



Mission Infusion: Dragonfly

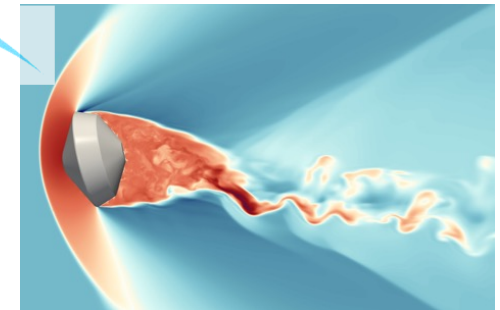
Radiative Heating

The benchmark experimental data for Titan entry (N_2/CH_4), along with model development and uncertainty quantification



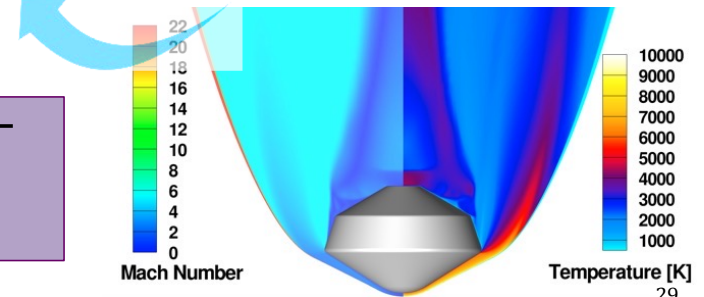
Capsule Dynamic Behavior

Critical path to modeling aerodynamic stability during Dragonfly descent



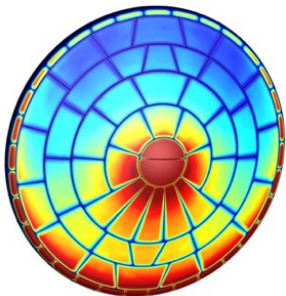
Aerothermal Margins

Innovative methods for experimental comparison, quantum chemistry feed into robust physics-based margin policy



3-D Material Response

3-D design of complicated geometry including shoulders, seals, seams, antennas...



Dragonfly is a mission of many firsts – ESM improves chance of success by retiring risk through analysis and validation with benchmark data.

Closing Thoughts

- ***EDL modeling & simulation is a true “cradle-to-grave” technology need***
- ***Improvements will have a significant payoff in terms of risk quantification/reduction, and reductions in system mass and development cost***
 - Today’s missions clearly highlight both strengths and weaknesses of the SoA
 - Advances may enable a new generation of ambitious science missions
- ***A mix of ground-based testing and theoretical model development, guided by sensitivity/uncertainty analysis, is the best way to advance SoA to be ready for the next generation of missions***
 - ESM is filling this role with a focus on aerosciences, materials modeling and GN&C
- ***University research is critical to maintaining a healthy pipeline of ideas and talent***



Questions?

Orion & Mars 2020 Margin Policies

Radiative Heating

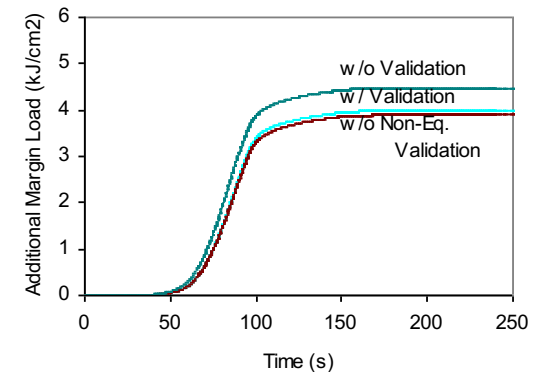
- ESM and other projects have done a tremendous amount of work generating data for validation of aerothermodynamic models
- ESM developed a rigorous uncertainty model for radiative heating, quantifying individual contributions from variety of phenomena and applying Bayesian statistics

“Development of a Radiative Heating Margin Policy for Lunar Return Missions”

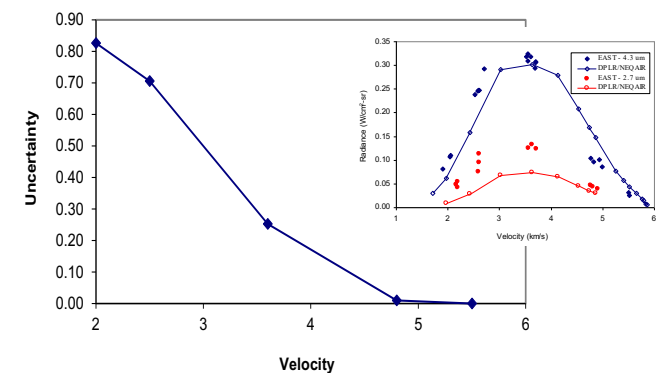
Brett Cruden, Aaron Brandis, Christopher Johnston
Journal of Thermophysics and Heat Transfer, 2018

- The process was applied to Orion and Mars 2020 radiative environments to update their margin policies
 - Orion margin decreased from 53% to 42%
 - Mars 2020
 - Forebody margin decreased from 50% to 36%
 - Aftbody margin decreased from 67% to 47%
 - Negative margins were eliminated, preventing re-design

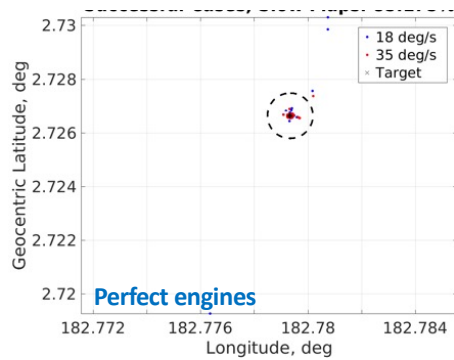
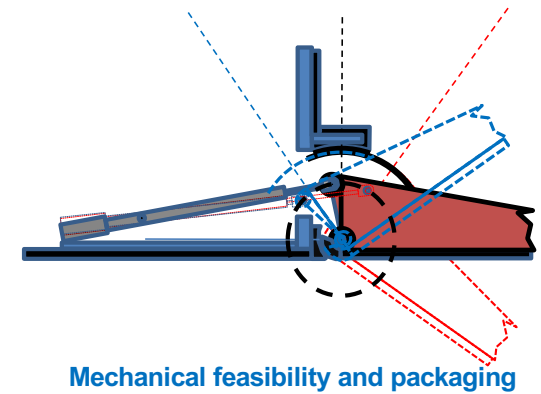
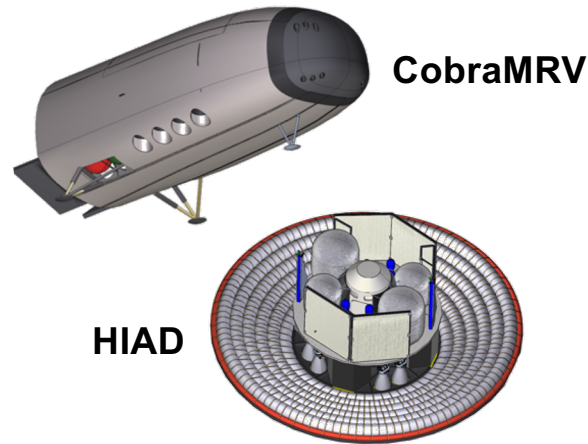
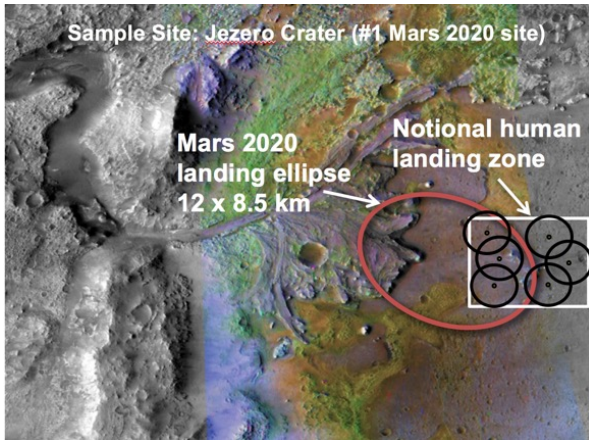
Margined heat load over direct lunar entry trajectory



Radiance uncertainty vs. velocity during Mars entry



Guidance, Navigation & Control



Landing Precision of HIAD w/Flaps

