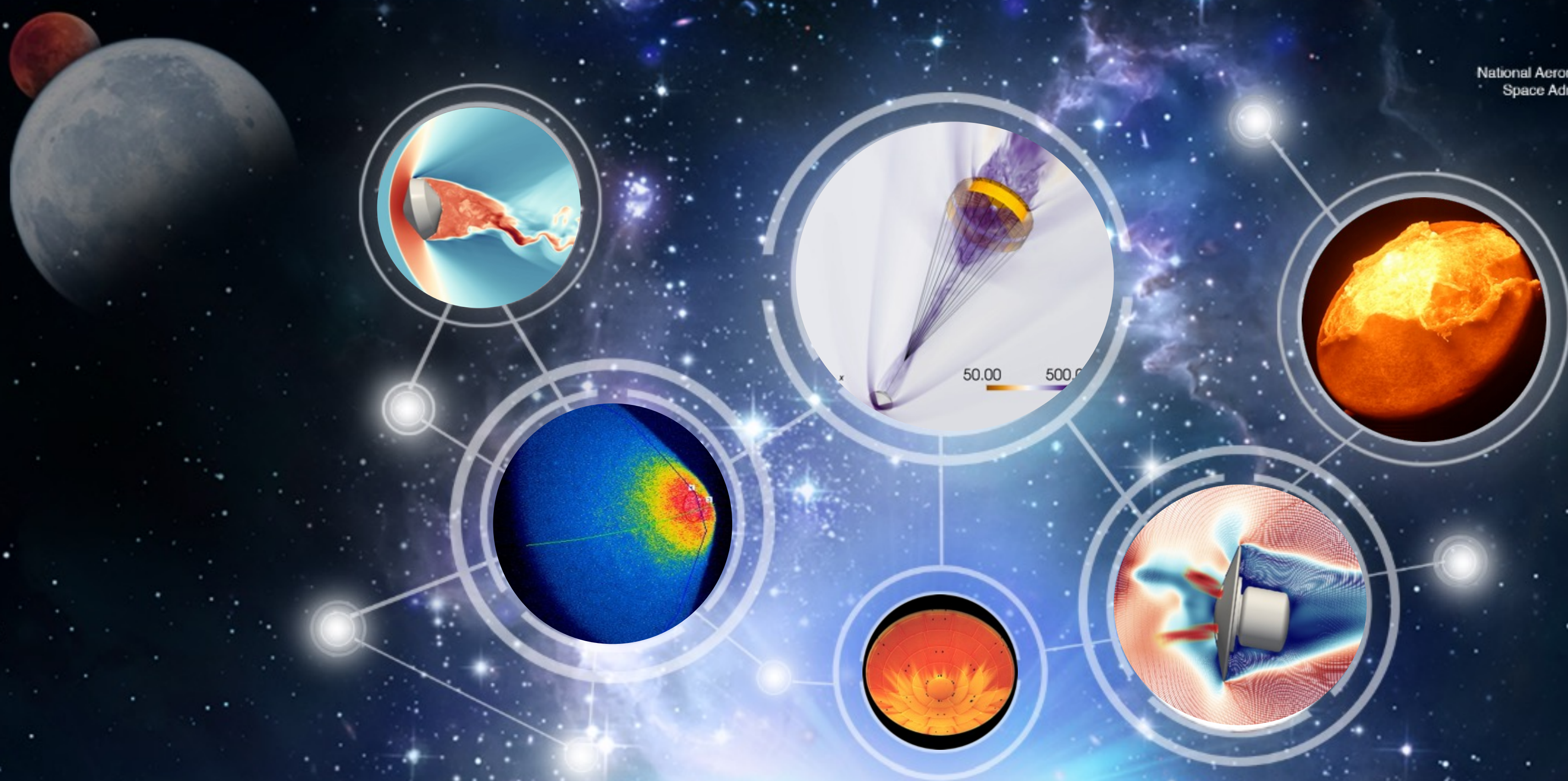
National Aeronautics and Space Administration

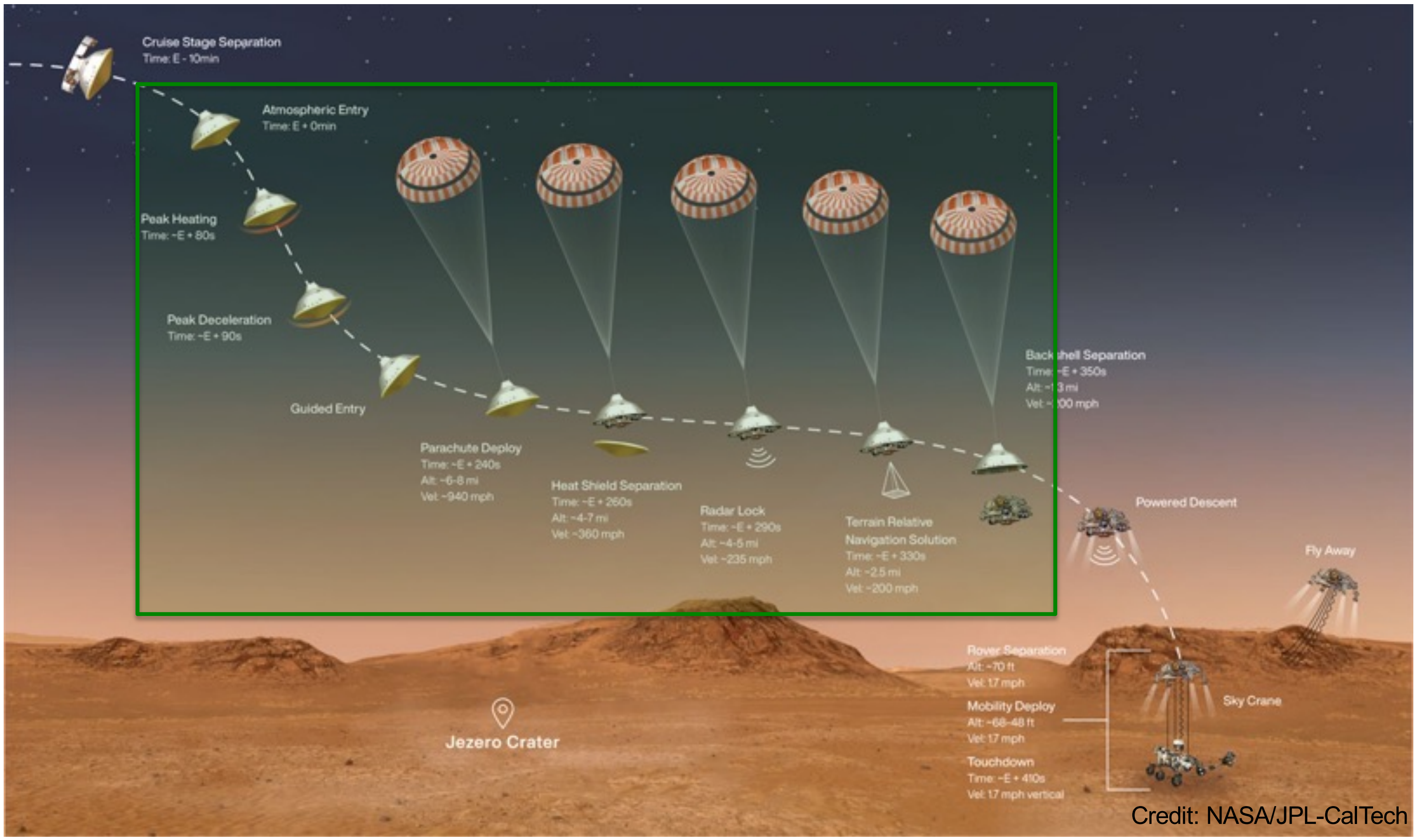


Modeling Entry Systems to Explore Our Solar System

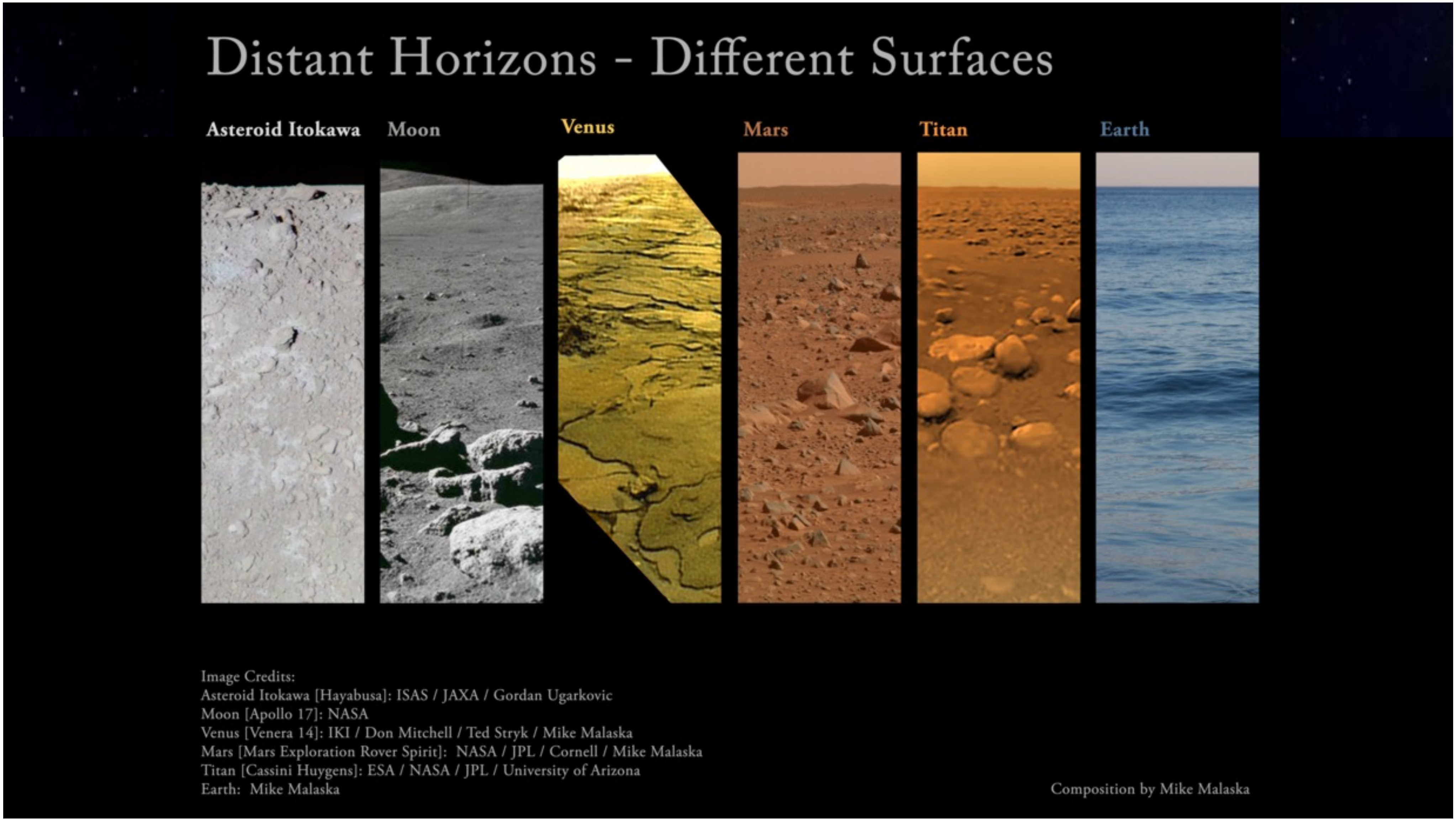
Michael Barnhardt, **Aaron Brandis, Tom West, Monica Hughes, Michael Wright**

NASA Ames Summer Series | July 14, 2022

Entry, Descent, and Landing



Credit: NASA/JPL-CalTech

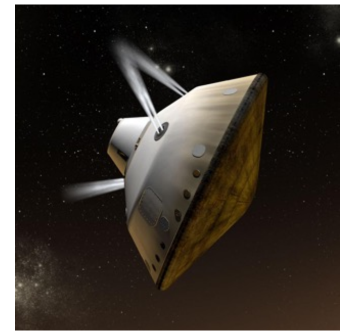

Distant Horizons - Different Surfaces
Asteroid Itokawa
Moon
Venus
Mars
Titan
Earth
Image Credits:
Asteroid Itokawa [Hayabusa]: ISAS / JAXA / Gordan Ugarkovic
Moon [Apollo 17]: NASA
Venus [Venera 14]: IKI / Don Mitchell / Ted Stryk / Mike Malaska
Mars [Mars Exploration Rover Spirit]: NASA / JPL / Cornell / Mike Malaska
Titan [Cassini Huygens]: ESA / NASA / JPL / University of Arizona
Earth: Mike Malaska
Composition by Mike Malaska

Examples of Entry Systems

Apollo
First visit to the Moon

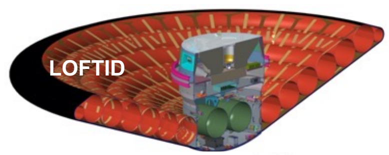
Space Shuttle
First re-usable spacecraft

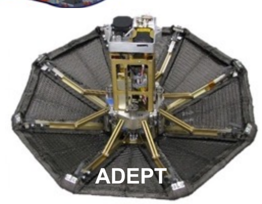
Artemis/Orion
Return to the Moon



Mars 2020
Search for signs of life on Mars

Commercial Space





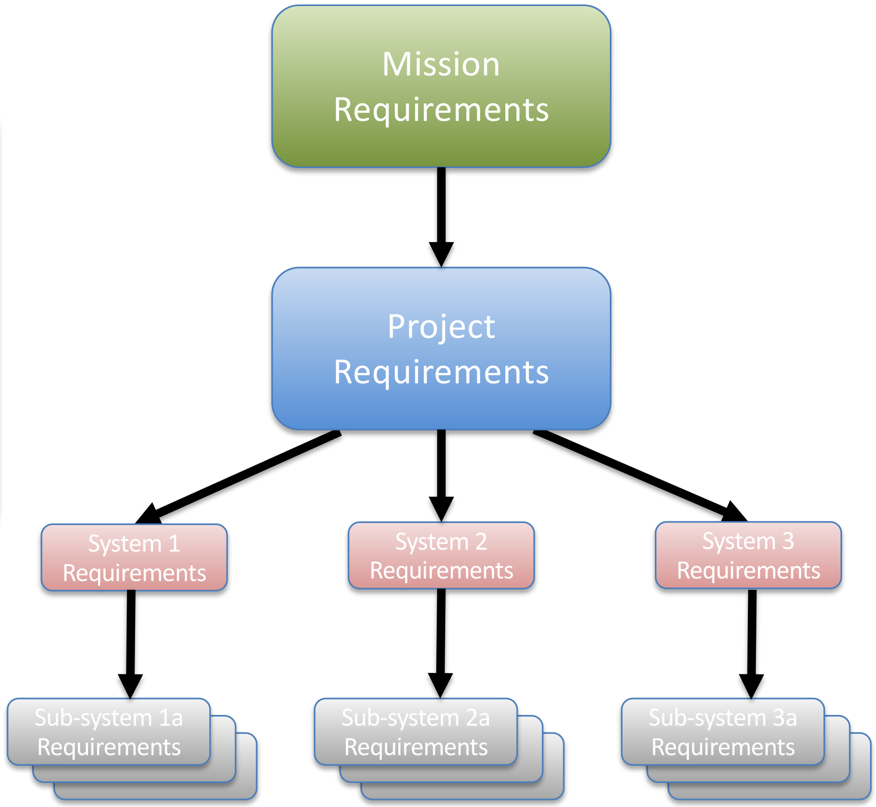
Deployable Systems

National Security

How to Design an Entry System #1:
Define requirements

Some key considerations before you start

- Landing site (lat/long, range, etc.)
- Launch vehicle and payload constraints
  - Mass
  - Thermal
  - Deceleration
- Power
- Reusability
- …



How to Design an Entry System #2:
Select baseline architecture

Your requirements will help guide choice of architecture

Also informed by cost, schedule, and technical risk

- Appeal to heritage is strong – *"If it ain't broke…"*

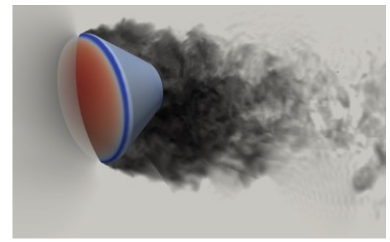
Trade studies are used to guide early decision-making. Key technologies are identified for maturation.

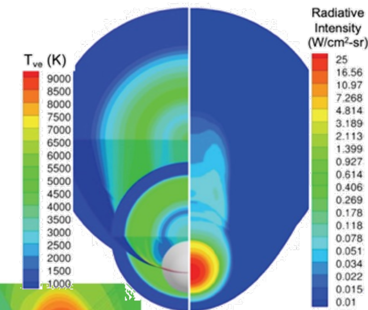
How to Design an Entry System #3:
Estimate the flight environment

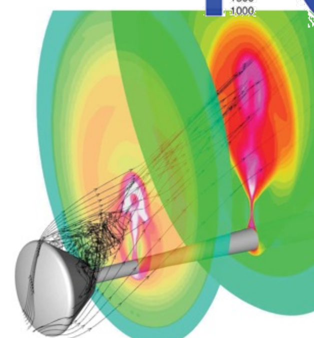
Quantities of Interest
- Heat flux and heat load (material selection and thickness)
- Pressure and shear (aero, material stresses)
- Vehicle dynamics/control (aero)

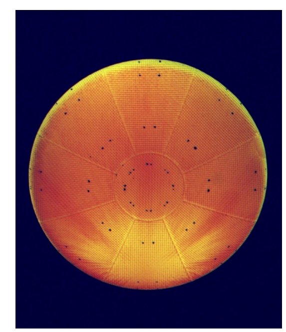
Experiments
- Provide ground truth at *similar* conditions
- Foundations of models
- Validation data to anchor simulations

Simulations
- Help interpret test data
- Fill gaps in test coverage
- Provide ground-to-flight traceability when flight tests are infeasible









How to Design an Entry System #4:
Determine layout and thickness of thermal protection system

Material Selection

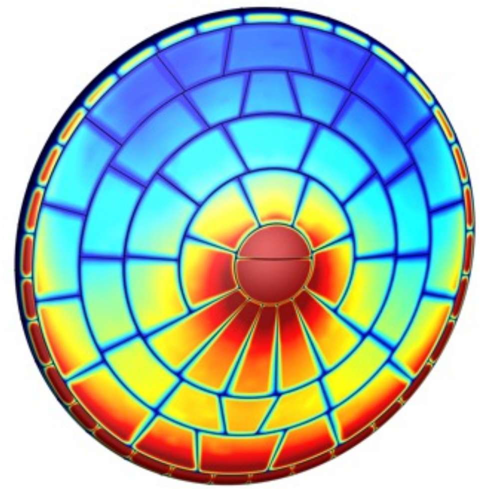
- The heat flux (rate at which the system absorbs energy) and aerodynamic stress dictate material selection
- Insulator or ablator?

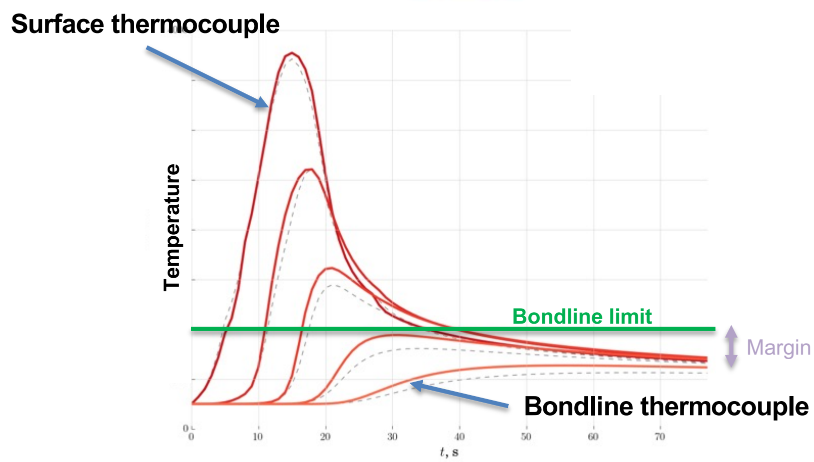
Sizing

- The heat load (total energy absorbed during flight) and material properties dictate overall temperature rise
- Thickness set by not exceeding a bondline thermal constraint

Qualification

- After several design cycles, you must demonstrate that the system will meet performance requirements, including reliability under off-nominal scenarios
  - ➢ Uncertainty Quantification (UQ)





Modeling is Critical Path in Every Mission Phase

- **Trade Studies**
  - Modeling & Simulation (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 and 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

“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; poor extrapolation 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.

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., CO_2 radiation)
- **Some of the biggest design drivers 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

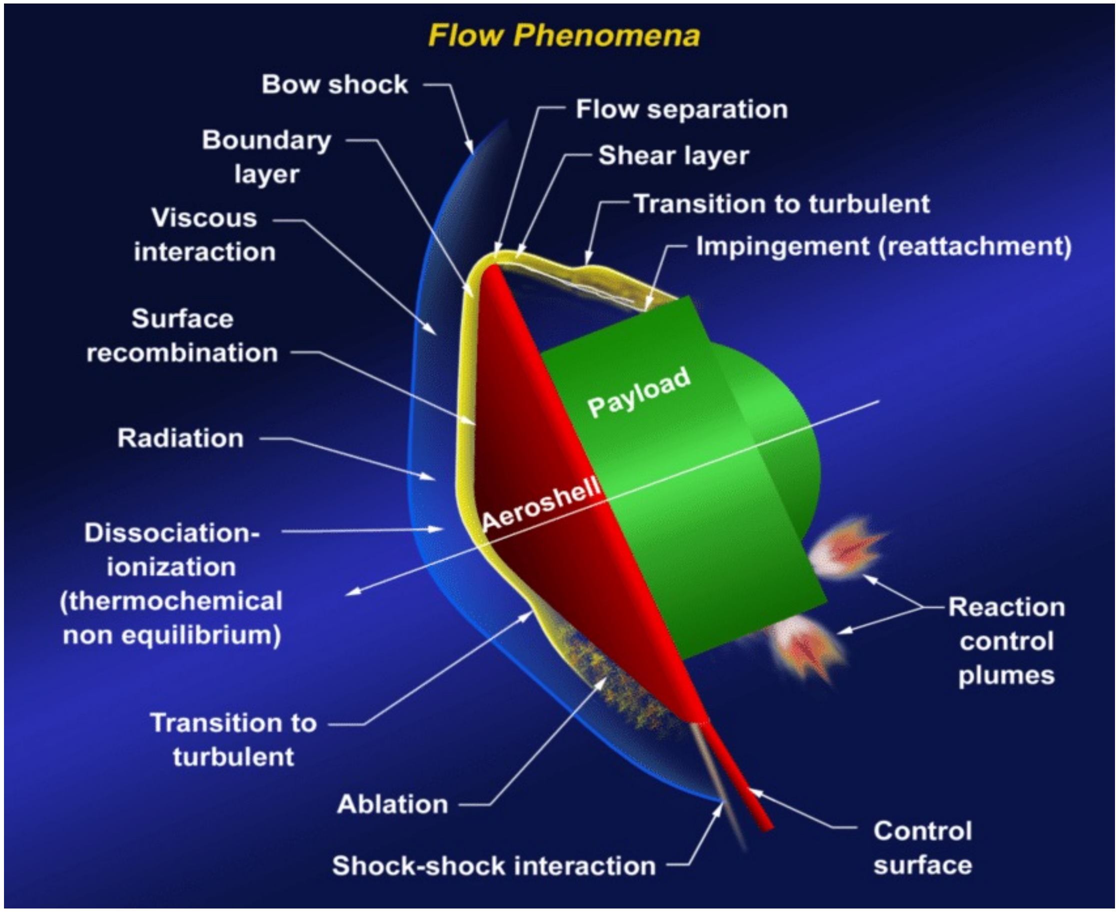
Focused investment in EDL M&S, *guided by mission challenges*, ensures that NASA is ready to execute the challenging missions of tomorrow

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

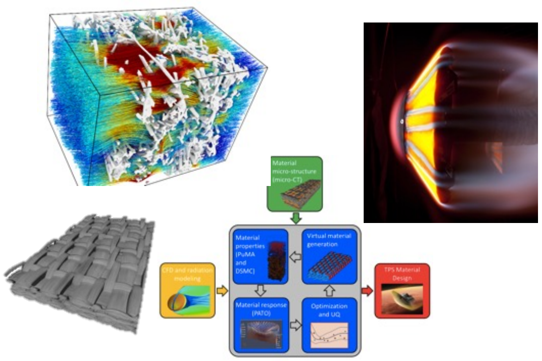
Physics of Entry



Entry Systems Modeling is…

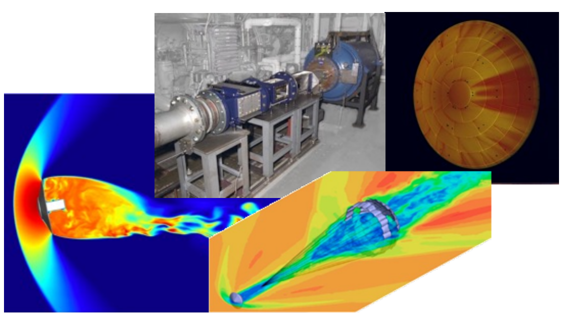
TPS Materials Modeling

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



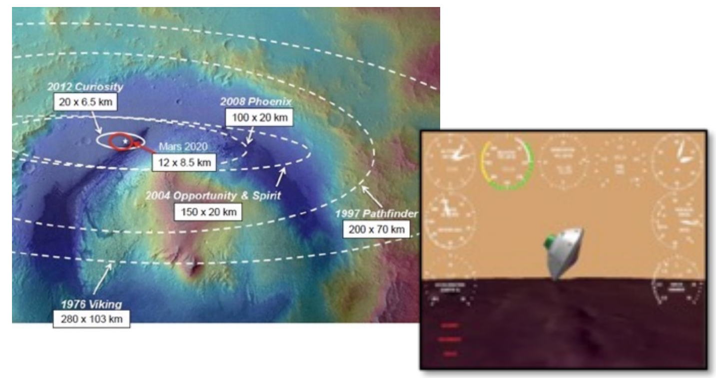
Aerosciences

Parachute dynamics; Entry vehicle dynamics; Transition & turbulence; Experimental validation; Advanced computational methods



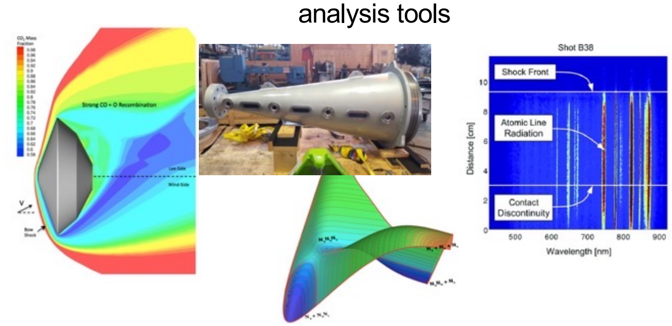
Guidance, Navigation, and Control

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



Shock Layer Kinetics and Radiation

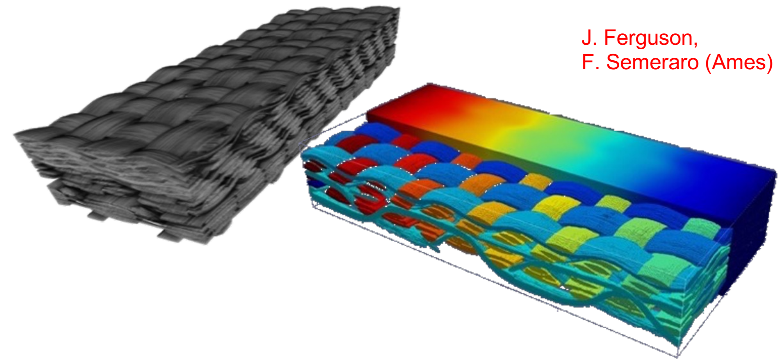
Radiation databases and models for destinations of interest across the Solar System; High-fidelity coupled analysis tools



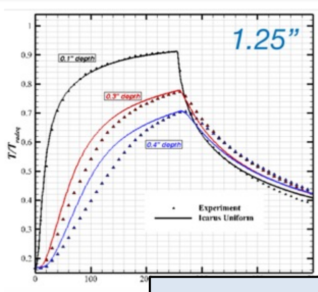
Woven Thermal Protection Materials

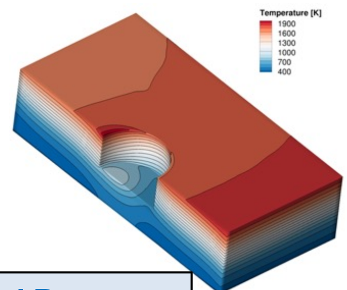
New classes of woven materials, like Heatshield for Extreme Entry Environment Technology (HEEET), are enabling for many missions

Weave Visualization, Generation, and Material Property Estimation



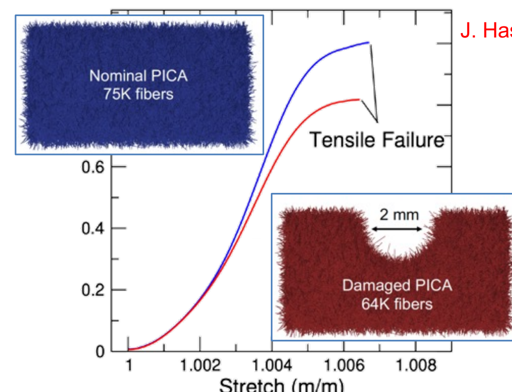
J. Ferguson,
F. Semeraro (Ames)





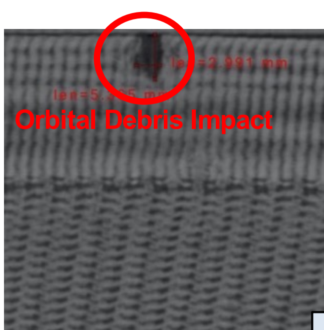
Multi-D Material Response

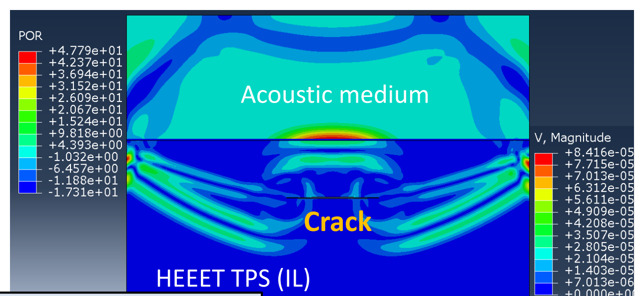
E. Stern,
J. Schulz (Ames)



J. Haskins (Ames)

Material Strength & Failure





Damage Detection

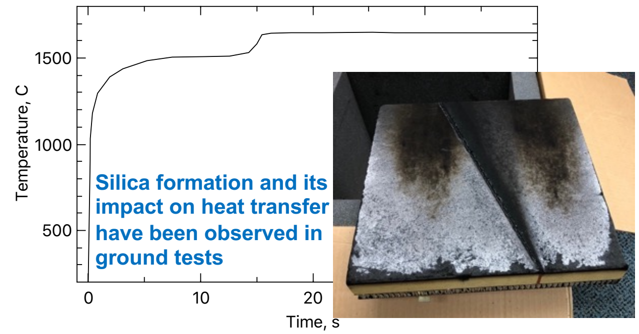
J. Haskins (Ames)

PICA-NuSil

Mars Science Laboratory, Mars 2020, Sample Retrieval Lander

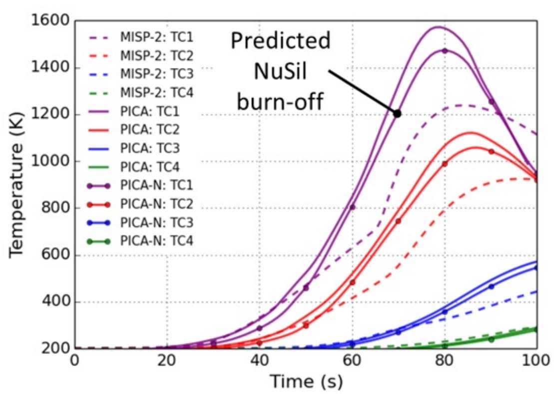
NuSil (silicone) coating on MSL and Mars 2020 significantly impacts our interpretation of flight measurements

- **Models are used to reconstruct the flight environment by inverse analysis of thermocouple data**
- **Silica formation on the vehicle surface can significantly alter thermal response**
- **Modeling ablation of PICA-NuSil system is therefore crucial for post-flight reconstruction**



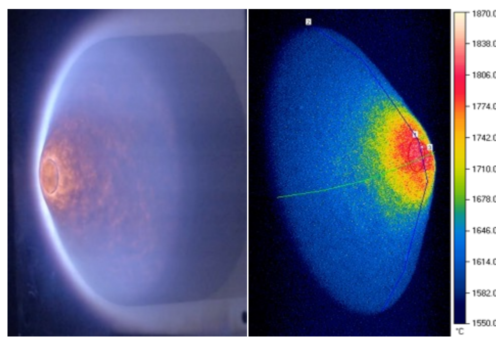
Development of High-fidelity Model

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

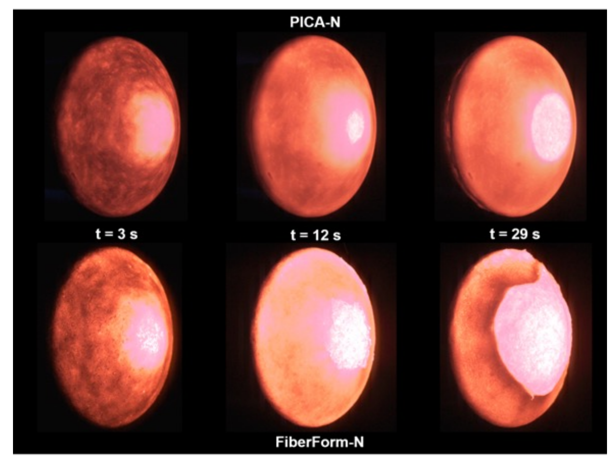


Predictions of MSL/MEDLI

J. Meurisse (Ames)



Ground Test Validation



B. Bessire (Ames)

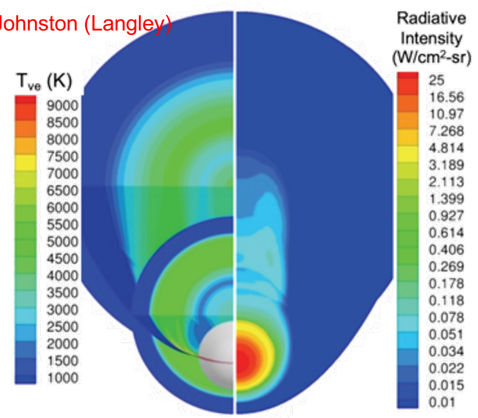
Thermochemistry & Radiation

Flight Validation

Post-flight comparisons to flight instrumentation are extremely important for assessing *true* model uncertainty and design margin

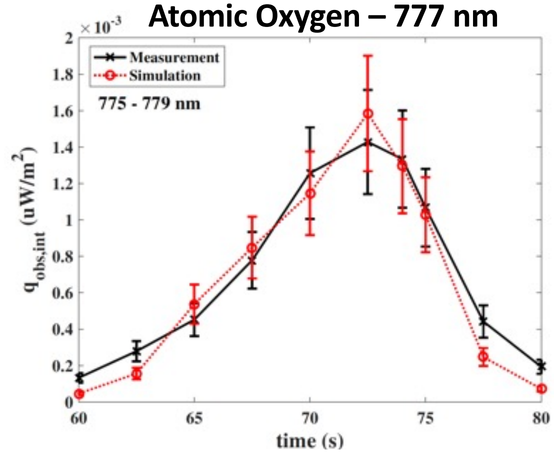
- **Mars Science Laboratory/MEDLI (August 2012)**
- **Schiaparelli entry (October 2016)**
- **Mars 2020/MEDLI2 entry (February 2021)**
- **Hayabusa 2 entry (December 2021)**

C. Johnston (Langley)

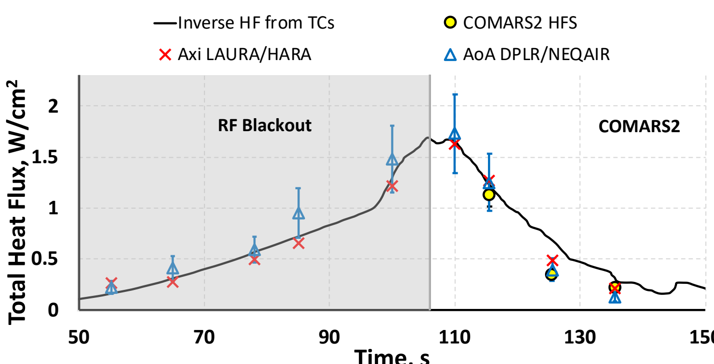


Flowfield around Hayabusa 2

Atomic Oxygen – 777 nm



Excellent agreement for simulations of Hayabusa 2 observation data

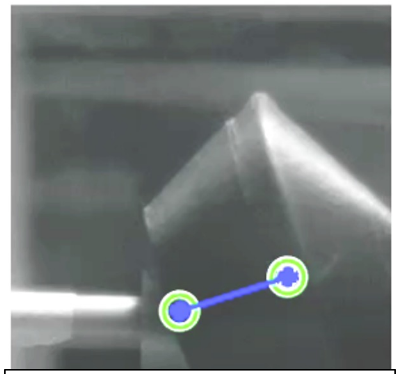


A. Brandis (Ames)

Excellent agreement for simulations of Schiaparelli flight data

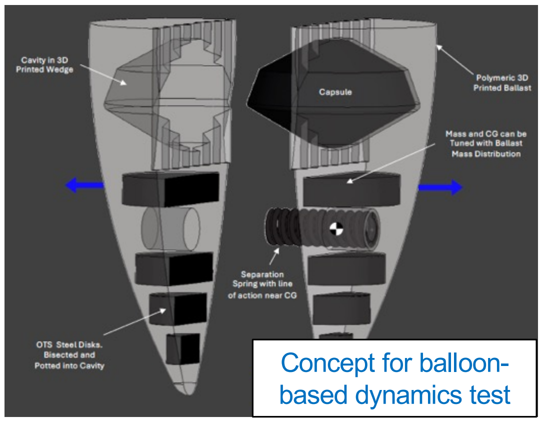
Entry Vehicle Dynamics

New Experimental Techniques



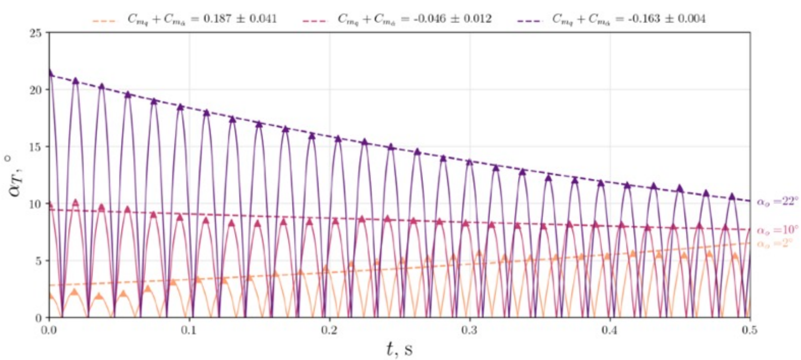
Magnetic Suspension Tunnel

M. Schoenenberger (Langley)

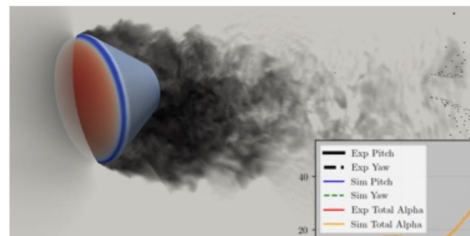


Concept for balloon-based dynamics test

C. Kazemba (Ames)

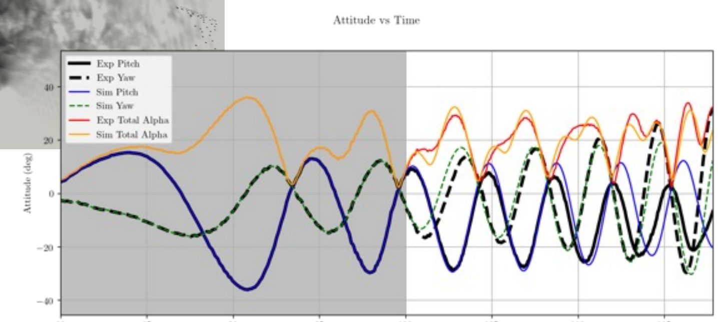


Free-flight CFD



Free-flight CFD of Orion AA-2 flight test

J. Brock (Ames)



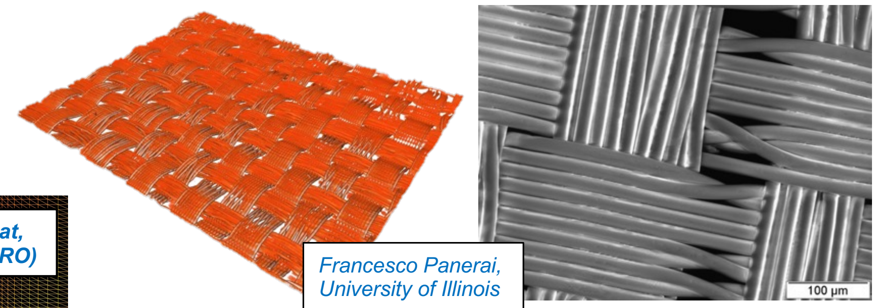
Free flight simulation for the separation of a drag skirt and aeroshell

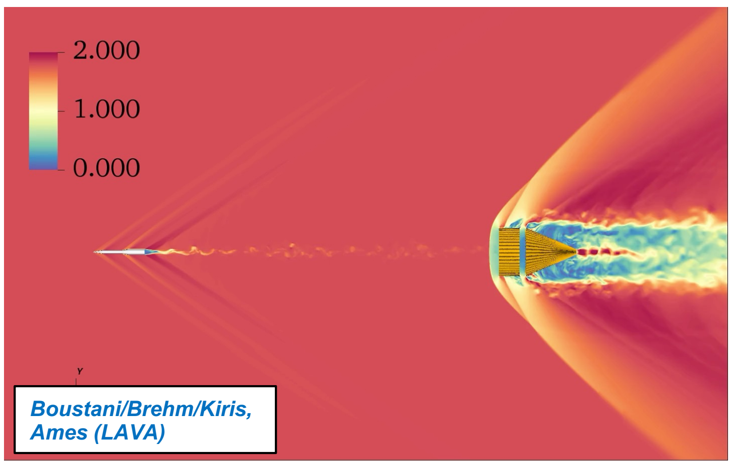
Parachutes for Entry Systems

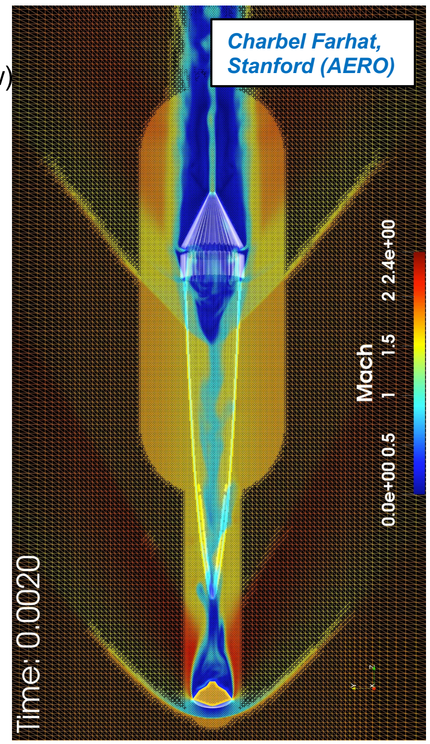
Parachute performance has been a concern of several programs in recent years

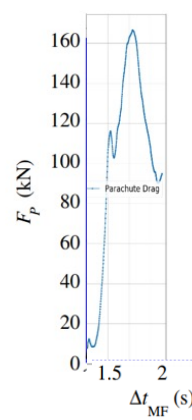
ESM and its partners have pioneered new capabilities

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

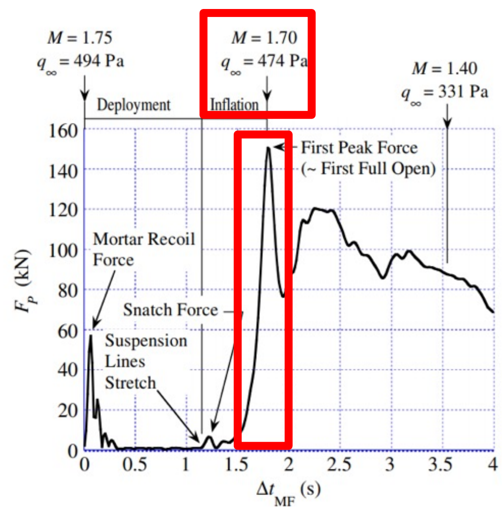








Stanford AERO Code



Test Data

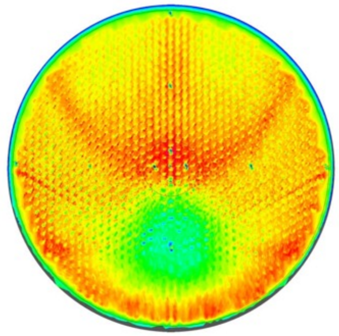
Turbulent/transitional Heating:

Mission-Relevant Roughness

Sand-grain

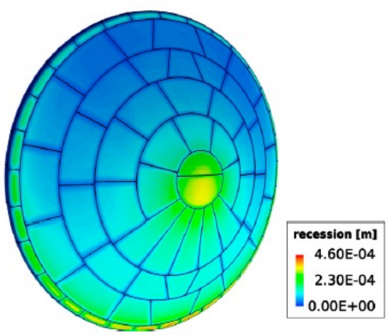
Ablated PICA on Stardust,
Kontinos and Stackpoole
AIAA Paper 2008-1197

Pattern



Honeycomb pattern,
Hollis, AIAA 2020-0121

Discrete

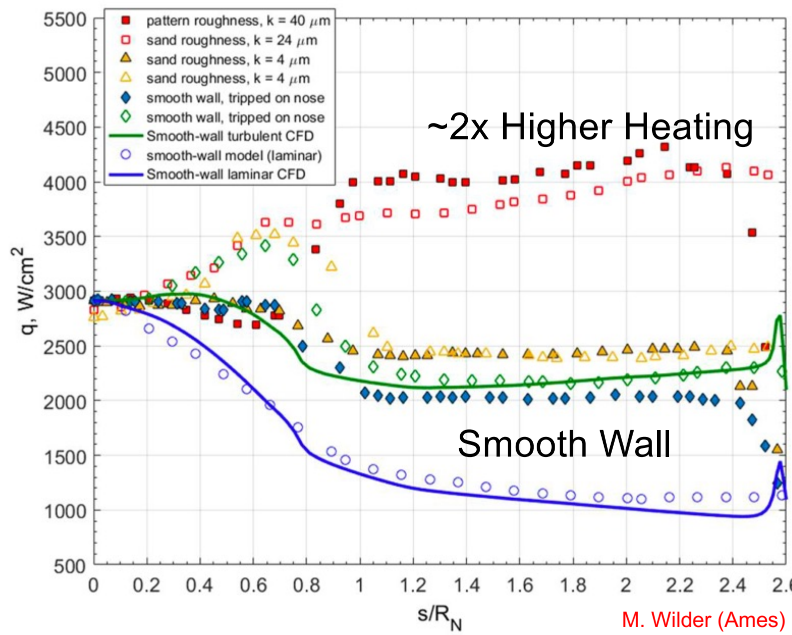


Differential recession on tiled TPS
Meurisse et al., *Aerospace Science and Technology*, 76 (2018)

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

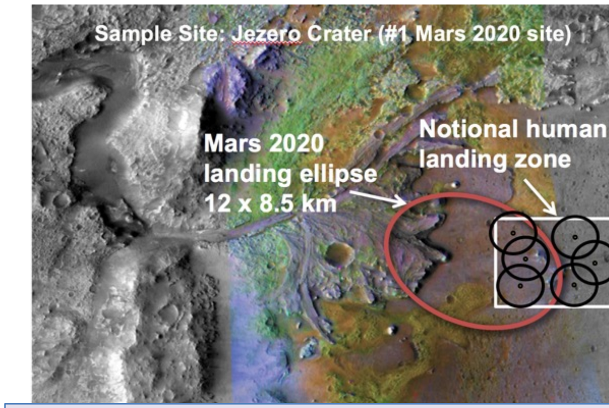


M. Wilder (Ames)

Guidance, Navigation & Control

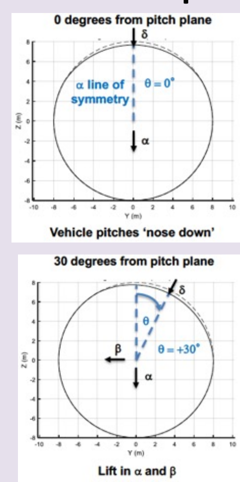
Past work focused on precision landing for human Mars exploration

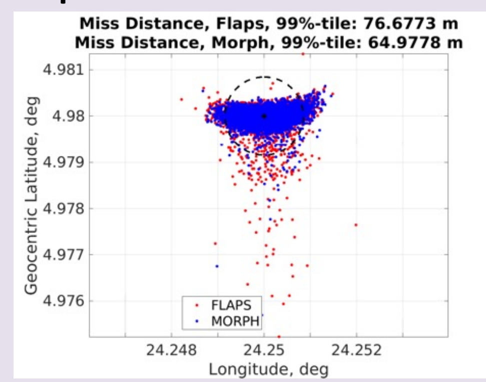
FY22+ emphasis has pivoted to
- Advanced trajectory simulation: POST2 parallelization and interoperability
- SMART guidance
- Aerocapture for Venus SmallSats (and then onto Giant Planets)



Morphing Inflatable Aeroshell

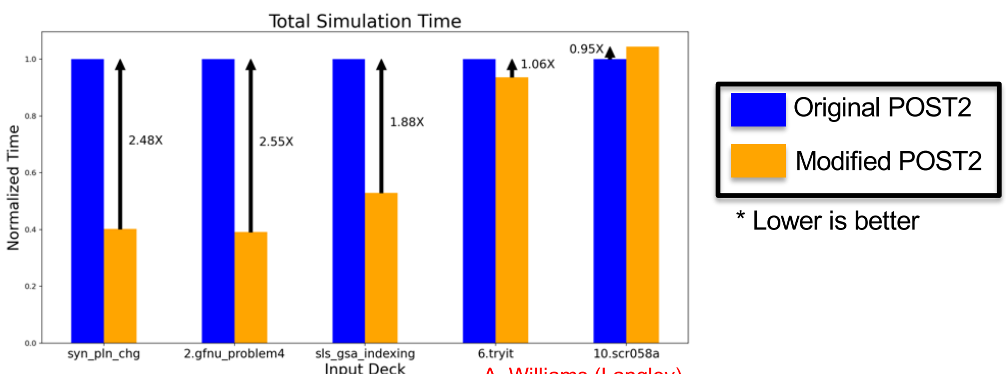
Morphing Shape Performance Results





Preliminary landed footprint in 50 m radius for one instantiation of morphing shape control compared to using flaps.

R. Lugo (Langley)

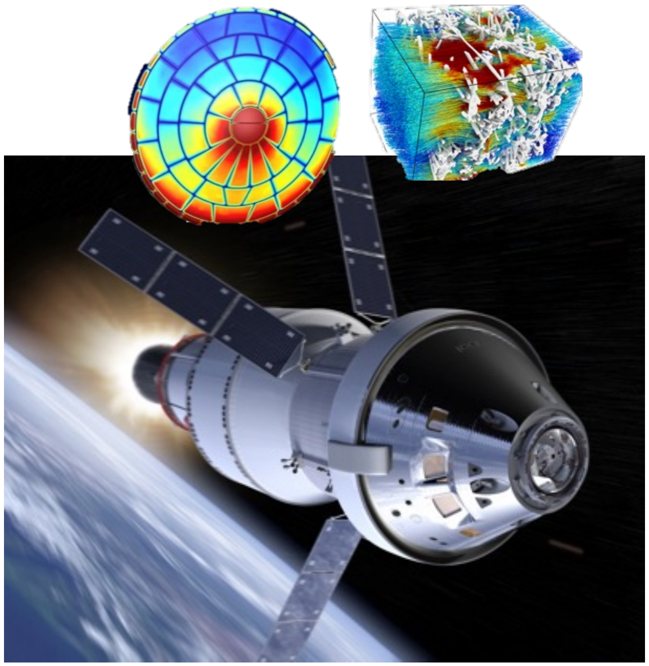


* Lower is better

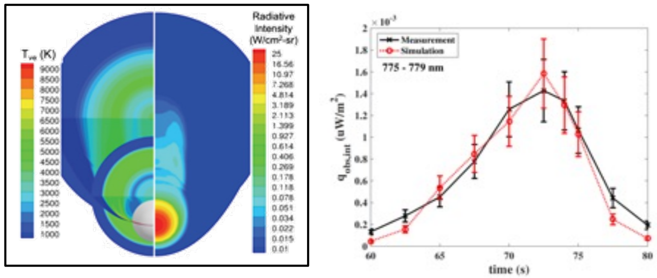
A. Williams (Langley)

Mission Infusion:
Orion

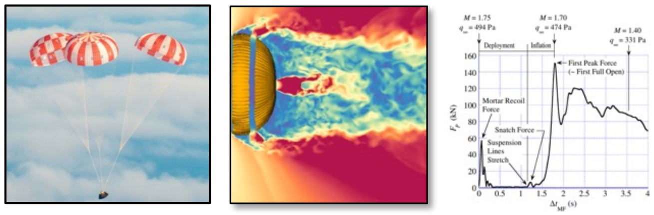
TPS Materials Modeling
High-fidelity models for Avcoat, gap filler, thermal coatings



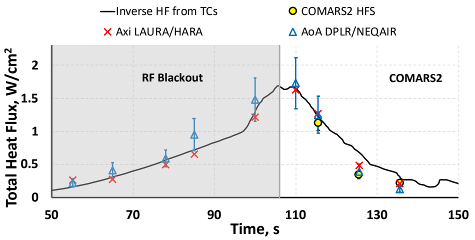
Shock Layer Radiation
Air thermochemistry: uncertainty quantification, margin definition, post-flight analysis, spectrometers Artemis 2-4



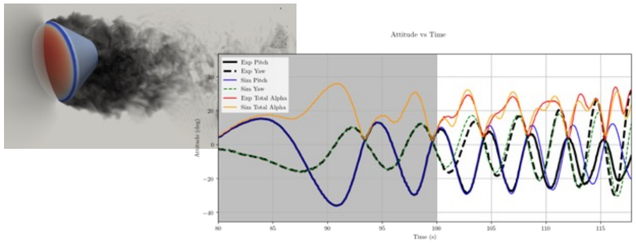
Parachute Modeling
Subsonic descent dynamics of clusters; Validation with Artemis 1



Flight Reconstruction
Tools & processes to quantify uncertainty from flight data, reduce risk of entry system design



Vehicle Aerodynamics
Free-flight simulations of AA-2, Artemis 1; RCS-aero interactions



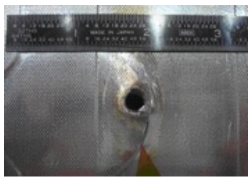
ESM touches on several major aspects of Orion entry system development:
Aero, Aerothermal, TPS, post-flight analysis

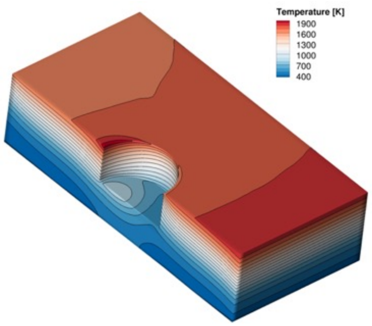
Mission Infusion:

Mars Sample Return / Earth Entry System (EES)

High Fidelity TPS Response Modeling

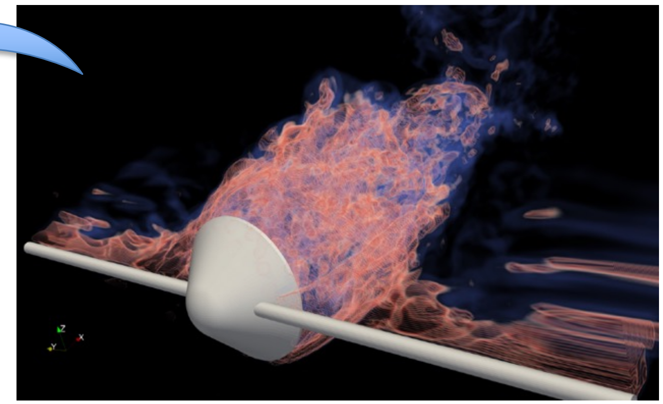
Developing next generation thermal and thermostructural models including failure modes; critical to reliability prediction

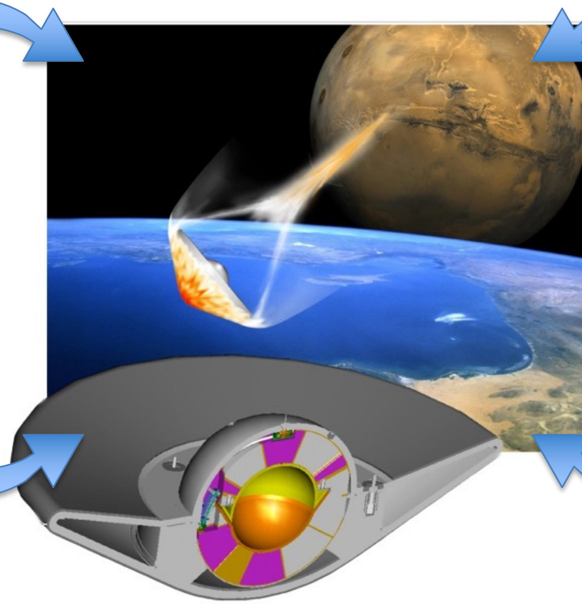




Capsule Dynamic Behavior

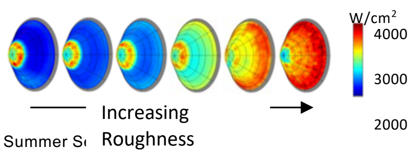
Critical path to modeling chuteless EES performance





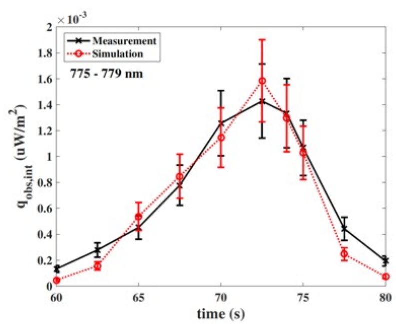
Roughness Heating Augmentation

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



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.



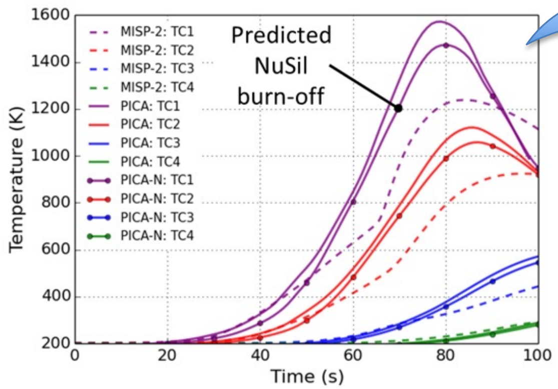
EES is the poster child for advanced modeling. Reliability requirement can only be demonstrated with accurate models.

Mission Infusion:

Mars Sample Return / Sample Retrieval Lander (SRL)

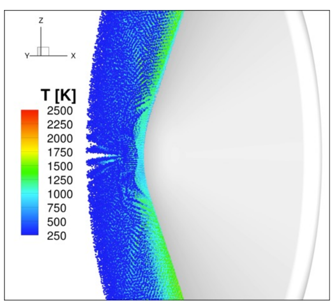
High Fidelity TPS Response Modeling

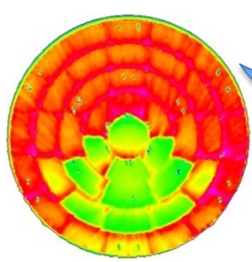
Developing next generation thermal and thermostructural models including failure modes; critical to reliability prediction

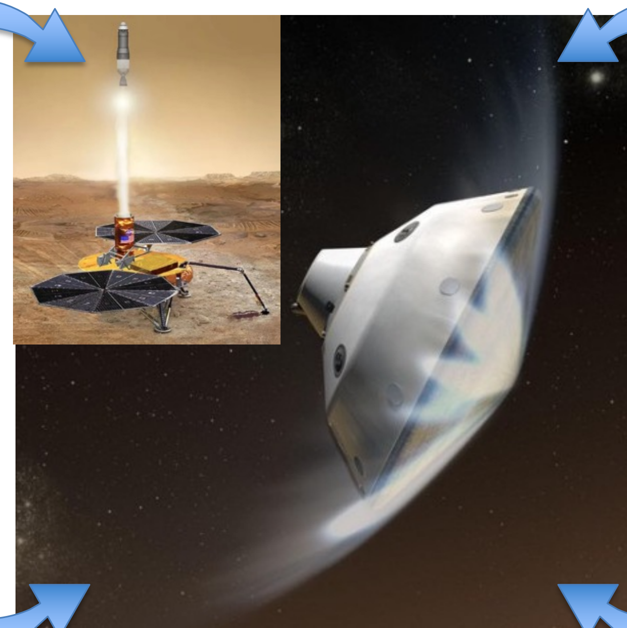


Roughness and Dust Heating Augmentation

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

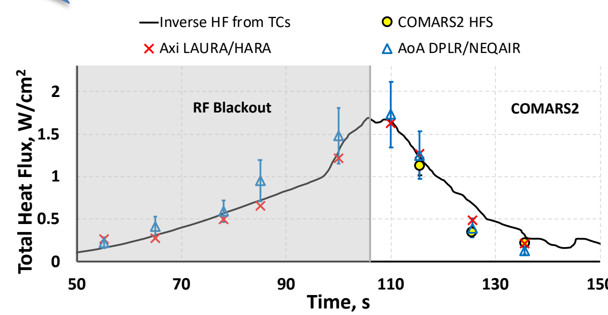






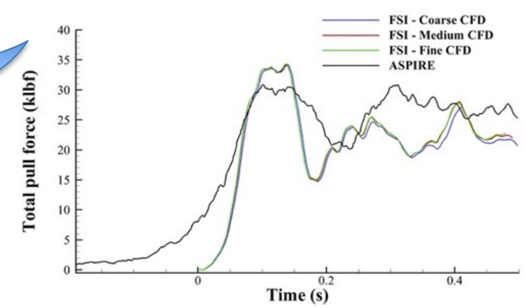
Post-flight Reconstruction

First validation of CO_2 backshell radiation flight data from Schiaparelli. High-fidelity investigation of the Mars 2020/MEDLI2 data



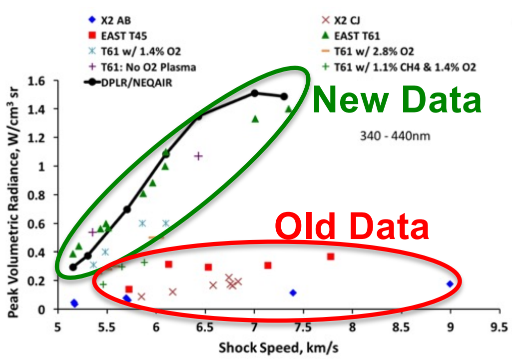
Parachute Modeling

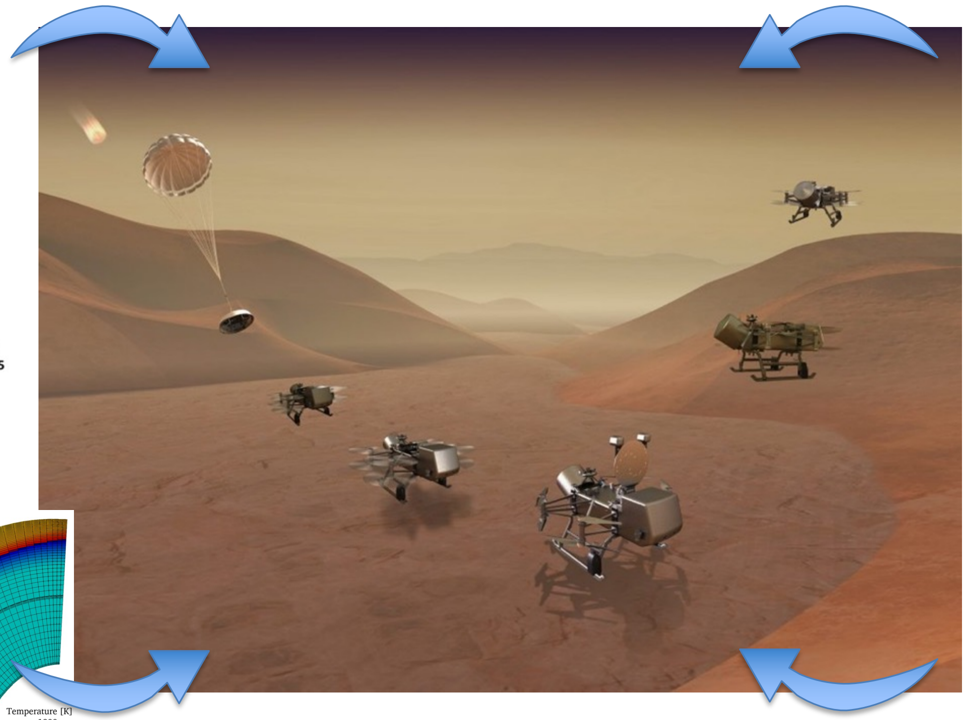
SRL landed mass will exceed previous flights by several metric tons making prior parachute designs unusable. Modeling can guide design trades and qualification of next-gen system.



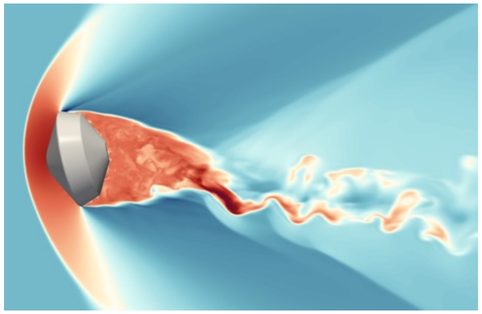
Mission Infusion:
Dragonfly

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

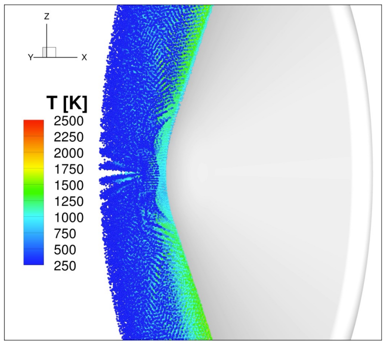




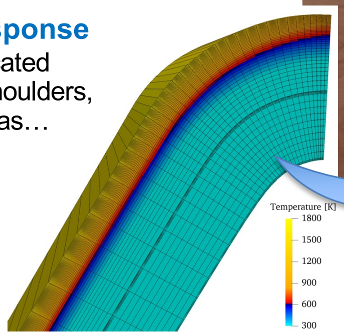
Capsule Dynamic Behavior
Critical path to modeling aerodynamic stability during Dragonfly descent



Dust Erosion
Titan's thick atmosphere contains micron-scale particulates that enhance TPS erosion



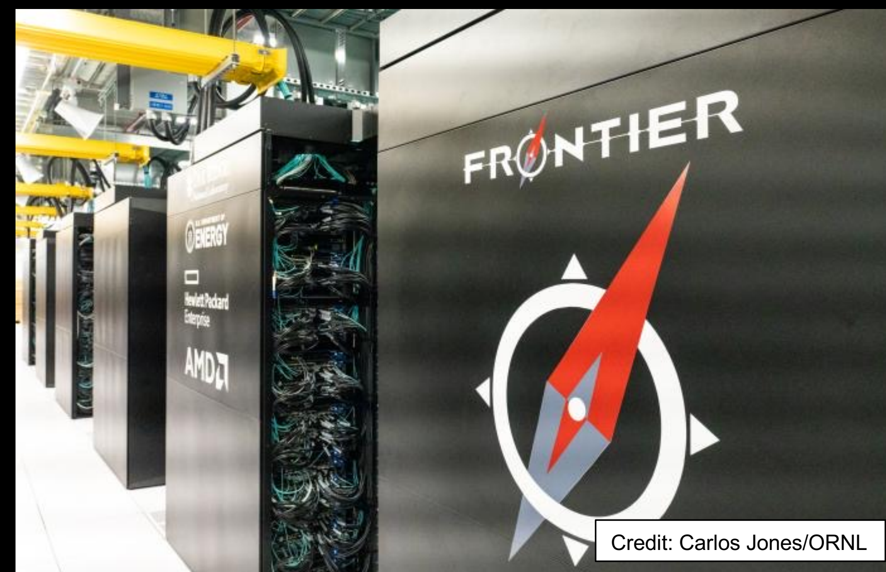
3-D Material Response
3-D design of complicated geometry including shoulders, seals, seams, antennas…



Future Directions:
Peta/Exa-scale Computing

On May 30, Oak Ridge National Laboratory announced their Frontier supercomputer achieved 1.1 exaflops, officially ushering in the era of ‘exascale’ computing


Credit: Eric Nielsen, Ashley Korzun/NASA



Credit: Carlos Jones/ORNL

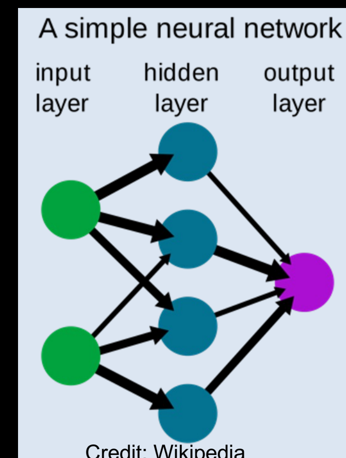
Researchers at NASA are beginning to explore implications of peta/exascale computing in EDL

Many challenges including access, software dev, architecture dependencies, …

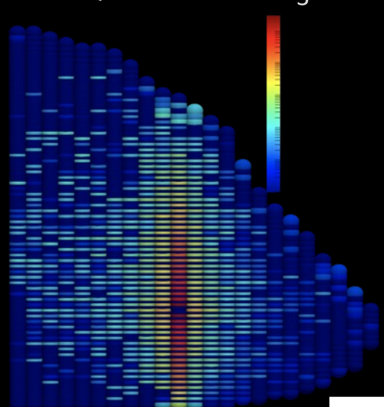
Future Directions:
Data Science/Machine Learning

The proliferation of machine learning platforms presents many opportunities for EDL modeling

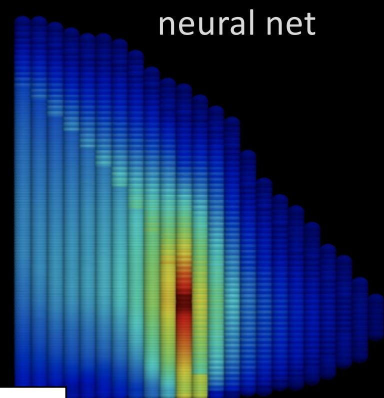
- Massive cost reductions through physics-constrained surrogate models
- Identification of key system characteristics and behavior
- Automation of labor-intensive data reduction and analysis processes



QCT results: N_3



Surrogate Model of N_3 derived from O_3-trained neural net



Credit: Marco Panesi (UIUC)

A transfer learning example: *Sharma et al [1]*

- Train neural network on existing computational chemistry databases for reaction kinetics using characteristic “shape” parameters
- Apply surrogate model, with appropriate scaling of “shape”, to similar systems
- *95% cost reduction with <5% error*

[1] Sharma, M. et al, “Application of DeepONet to model inelastic scattering probabilities in air mixtures,” AIAA Aviation, August 2021.

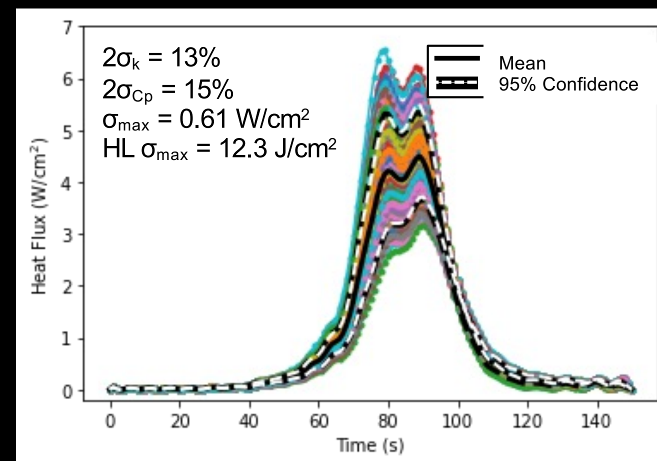
Future Directions: Uncertainty Quantification

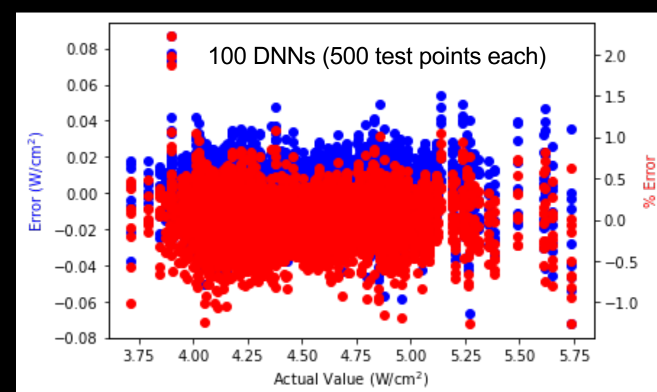
UQ is usually simplified to a small number of direct comparisons to experiments combined with a heap of engineering judgement.
How can we make the process more rigorous and precise?

Advances in UQ methods and machine learning point the way

An example: *Alpert et al [1]*

- Determine parametric sensitivities of thermal model in flight data reconstruction for Mars 2020
- Standard Monte Carlo approach estimated to take ~291 days per sensor
- Trained neural nets produced same analysis *10,000x faster*





> Incorporating UQ directly into the EDL analysis pipeline will reduce unnecessary margin and help engineers identify highest value targets for model improvement

[1] Alpert, H. et al, "Variance decomposition of MEDLI2 reconstructed heating using neural networks," 2nd International FAR Conference, June 2022.

Closing Thoughts

- ➢ **EDL modeling & simulation is a true "cradle-to-grave" technology need**

- ➢ **M&S advancement has a significant payoff in terms of risk quantification/reduction, and reductions in system mass and development cost**
  – Today's missions 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 for the next generation of missions**
  – ESM is filling this role with a focus on aerosciences, materials modeling and GN&C

Research is critical to maintaining a healthy pipeline of ideas, capability, and talent

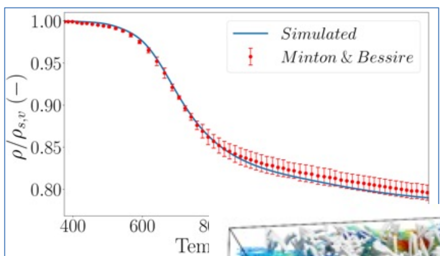
Thank you for your time!

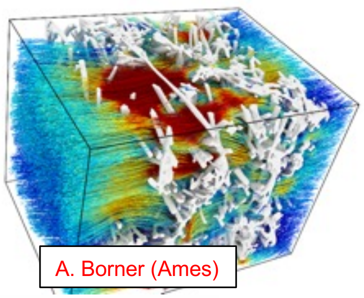
Questions?

BACKUP

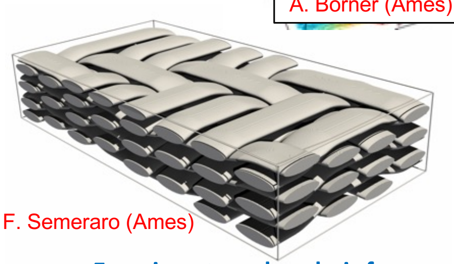
TPS Materials Modeling

Microscale





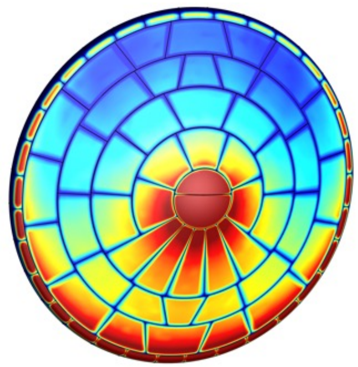
A. Borner (Ames)



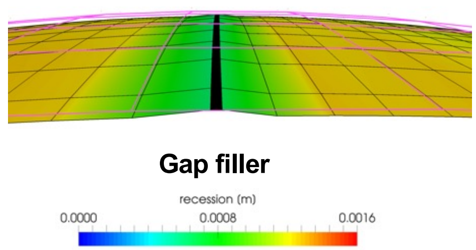
F. Semeraro (Ames)

Experiments and analysis for fundamental properties, validation

Benchmark Modeling

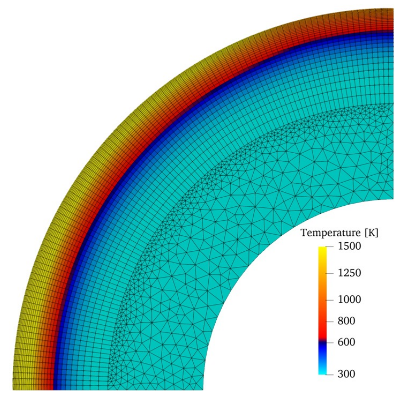


J. Meurisse (Ames)

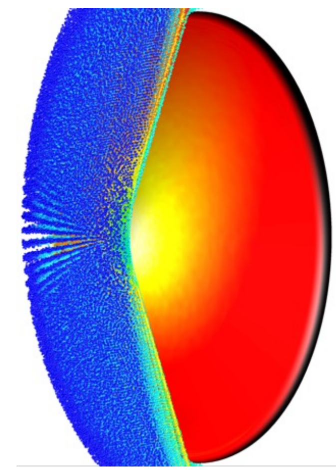


Benchmark simulations with PATO software to aid model development and quantify uncertainty

Engineering Applications



J. Schulz (Ames)



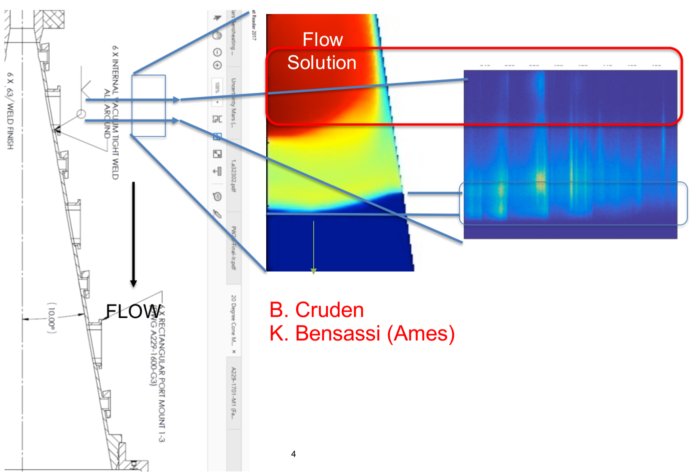
A. Sahai (Ames)

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

Modeling dust particle erosion for Mars entry

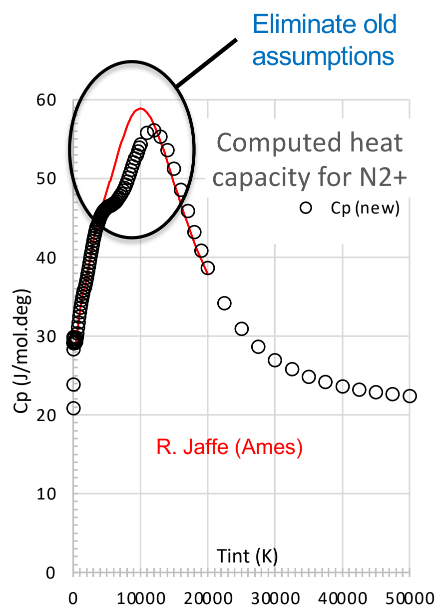
Shock Layer Kinetics and Radiation

Experiments



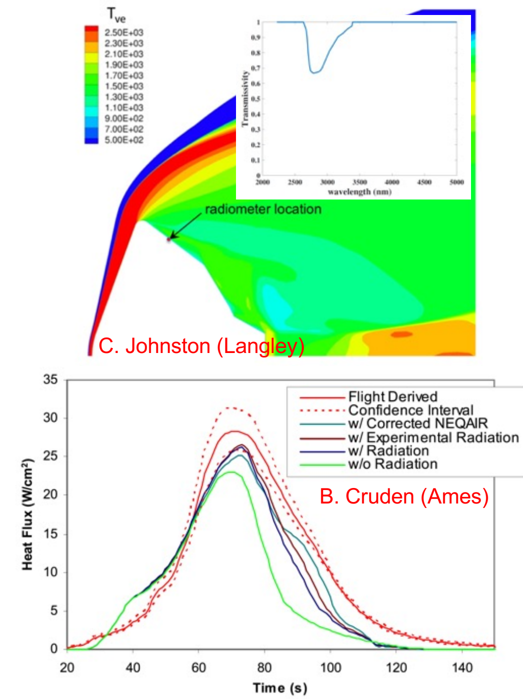
Simulation and experimental data for expanding flow in EAST expansion cone

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 transmissivity on MEDLI2 radiometer window
Bottom: Flight data from MSL strongly suggests CO_2 radiation as a significant contributor to vehicle heating