Predictive Modeling for NASA Entry, Descent and Landing

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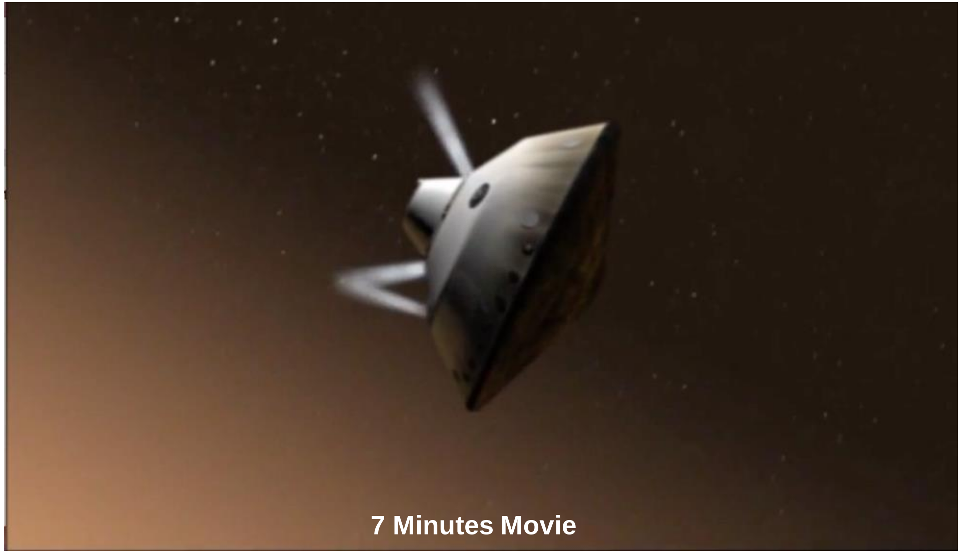
What Is EDL?

- Entry, Descent and Landing is the process by which a spacecraft traverses the atmosphere of a planet, slowing down to the point where safe landing is possible
- Perhaps best defined as the “7 Minutes of Terror”



Modeling is Critical Path for NASA 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.

Entry Systems Modeling: Who We Are

- **ESM is the ONLY Agency project invested in model and tool development for EDL**
  - Focus on delivering *real* changes to current State of the Art in a reasonable time
  - Emphasis on validation across the breadth of the physical models of interest
  - Partner with other NASA projects, building on each other's strengths to ensure timely results
  - Establish creative partnerships with other government agencies, industry, and academia to leverage the best and the brightest with new, innovative, *game changing* ideas

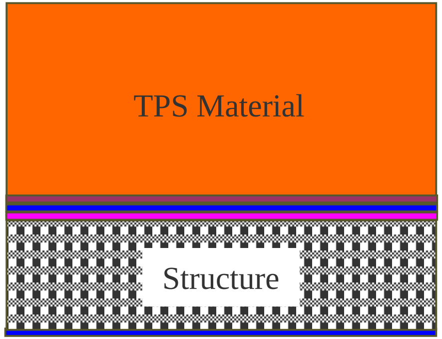
- **Three technical areas with focused research**
  - Aerosciences
  - Thermal Protection Materials
  - Integrated Systems (hardware focused with modeling in a supporting role)

- **ESM is a bridging project**
  - *Collaborate* with academia to ensure that promising ideas are pulled forward and matured
  - Customers range from flight missions to line organizations to other NASA projects
  - Providing fundamental content on a fast-paced delivery schedule

Predictive Materials Modeling

- **Carrying material modeling into the 21st Century and beyond**
  - Accurately modeling the microstructure of the material
  - New codes under development:
    - Pyrolysis Toolkit in Open-Foam (PATO)
    - PuMA
    - Icarus

What We Do Today…



Simple 1D simulations of homogeneous materials

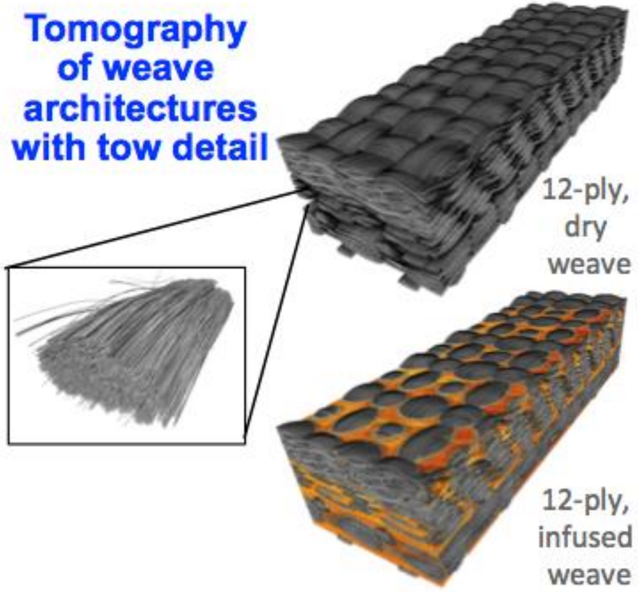
Where we are headed…

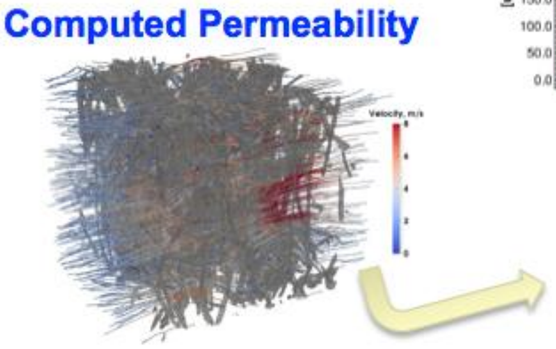
Detailed 3D simulations accounting for microstructure

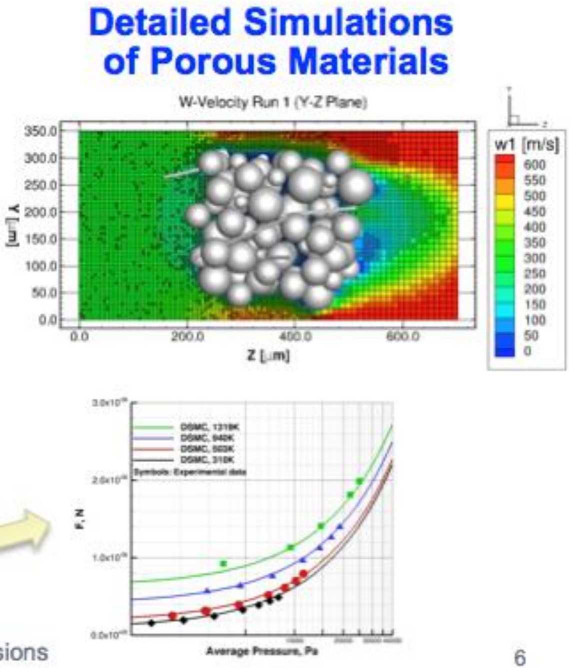
Predictive Materials Modeling

➢ **Current research enables the possibility of computational materials design**

- Computationally intense (supercomputers are required)
- Potentially game changing in the discipline of TPS; new materials currently require millions of dollars and many years to bring to market







Shock Layer Radiation

➢ **Shock layer radiation is the largest remaining uncertainty for heating on entry vehicles**

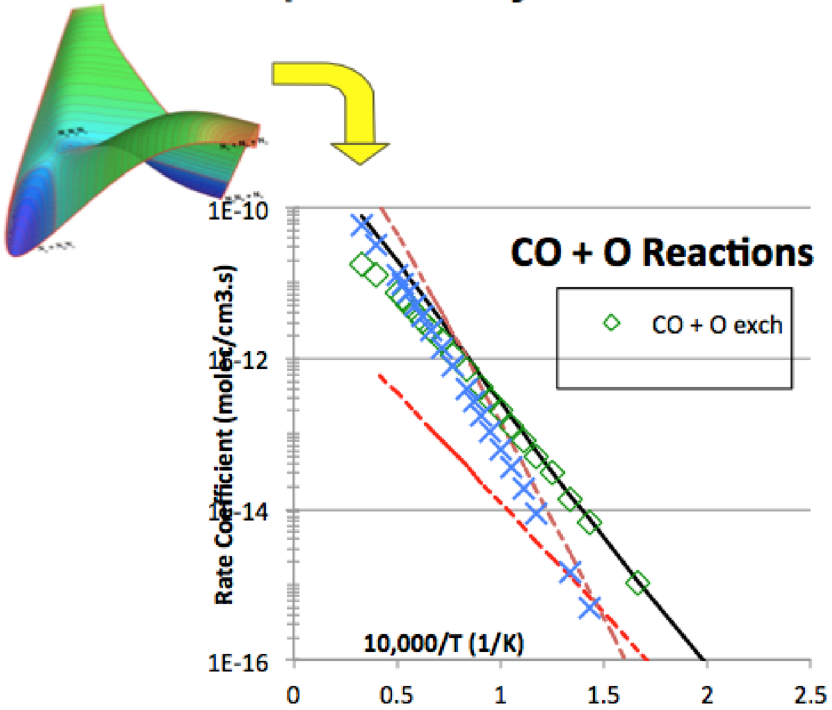
- Complex and highly nonlinear physics
- Models are routinely used to extrapolate to flight conditions – requires basis in actual physics

Artists conception of radiating shock layer during entry

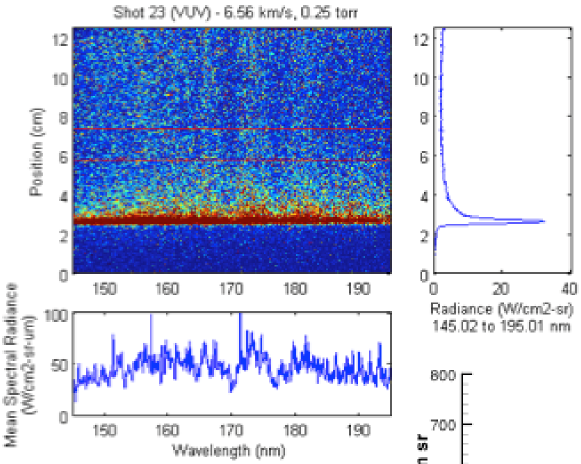
Airborne observation of Stardust Reentry (2006)

Shock Layer Radiation

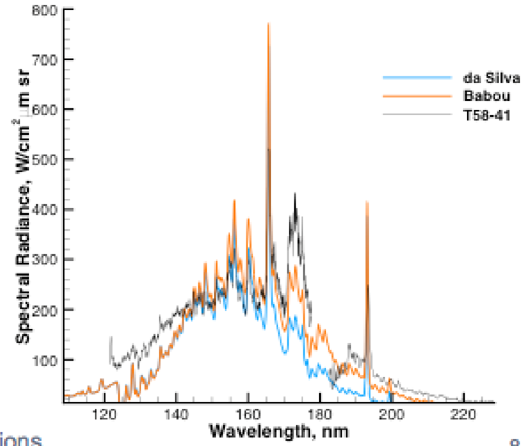
➢ **Quantum mechanics underpins models that are experimentally validated**



Quantum calculations of key reactions for Mars entry



Vacuum ultraviolet radiation: (left) measured in a shock tube, and (below) compared to simulation

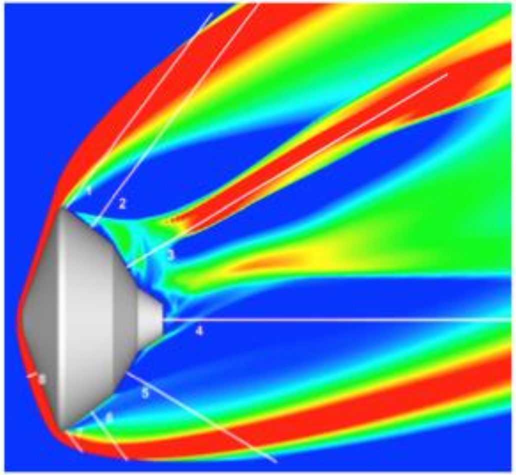


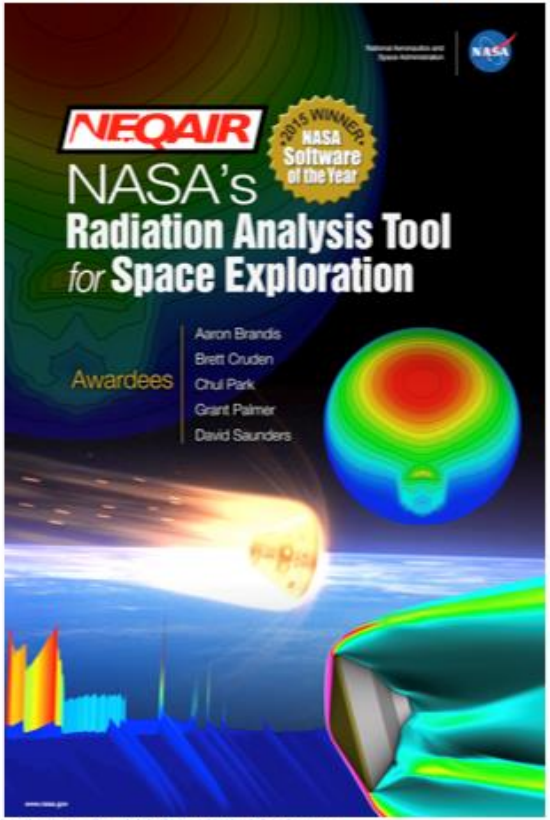
Shock Layer Radiation

➢ **Quantum data feeds high-fidelity computational models that are making a difference**

- New codes under development:
  - NEQAIR
  - HARA

Shock layer radiation predicted from CFD solution





NASA 2015 Software of the Year – Radiation solver from ESM

"NEQAIR was critical to predict the radiative heating environment…"
Christine Szalai; InSight Aerothermal/TPS Lead

"AFIT has used NEQAIR for classified studies of immediate National Security interest… While the details cannot be expanded upon here, it has proved to be an invaluable asset to the defense of the nation."
Prof. Robert Greendyke; Air Force Institute of Technology

Computational Aerosciences

- **The next frontier for Computational Fluids is dynamic unsteady flows**
  - Computationally intense; solving multiple partial differential equations time accurately for long periods of elapsed time (seconds or minutes of time must be integrated with micro-second time steps)
- **Order of accuracy is important, but computational efficiency is king**
  - Highly efficient parallel scaling on modern computer architectures
  - Algorithms amenable to GPU processing and other cutting edge techniques
- **Two examples follow**
  - Simulation of capsule dynamic stability
  - Parachute fluid-structure interaction

Simulation of Dynamic Stability

Dynamic stability is a concern for all entry vehicles

- Current approach is experimental; costly and prone to large uncertainty
- Lack of physical understanding of phenomenon means all spacecraft must be tested

Challenge: can we do this in the computer?

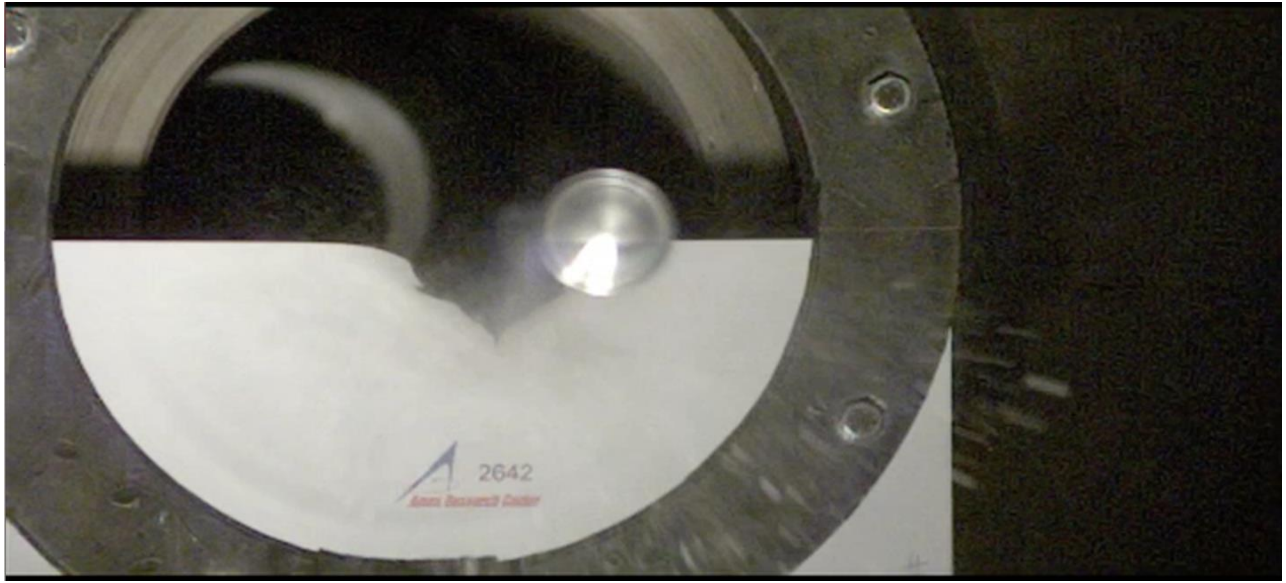
- Potentially large cost savings due to reduced testing requirements
- Improved understanding of underlying physics can open up new avenues in advanced spacecraft design

Genesis Spacecraft tumbling due to dynamic instability after parachute failed to deploy (September 8. 2004)

Simulation of Dynamic Stability

➢ **Today's State of the Art**

Entry model fired down NASA Ames ballistic range

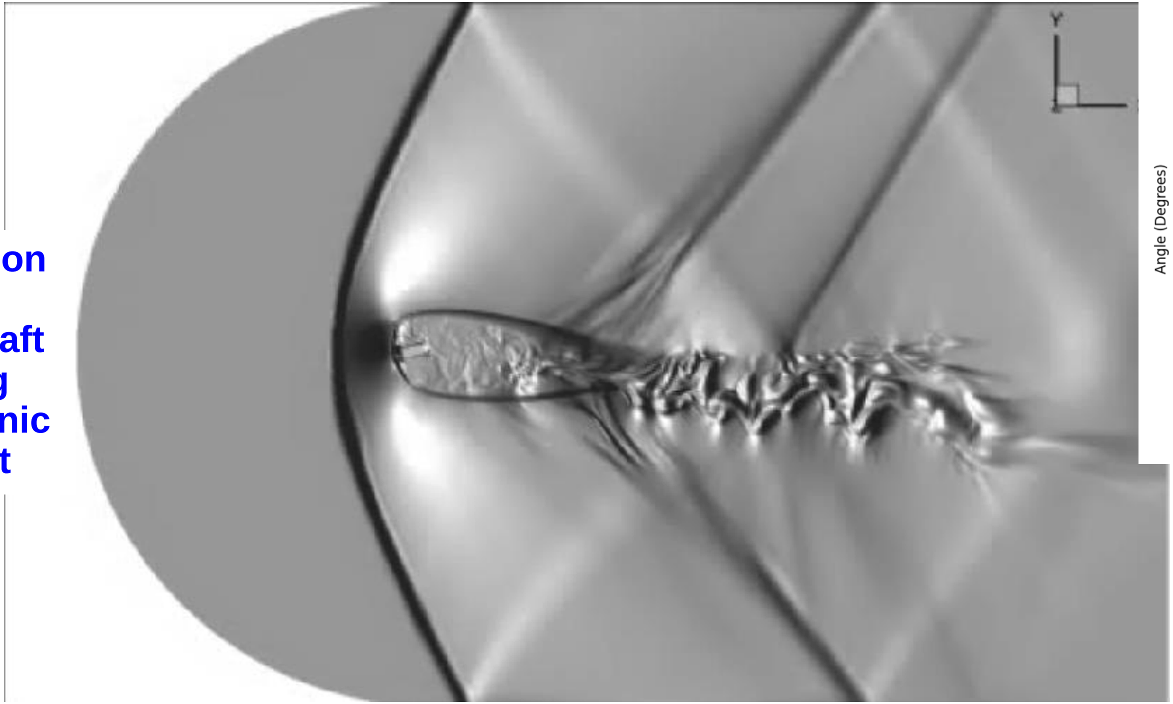


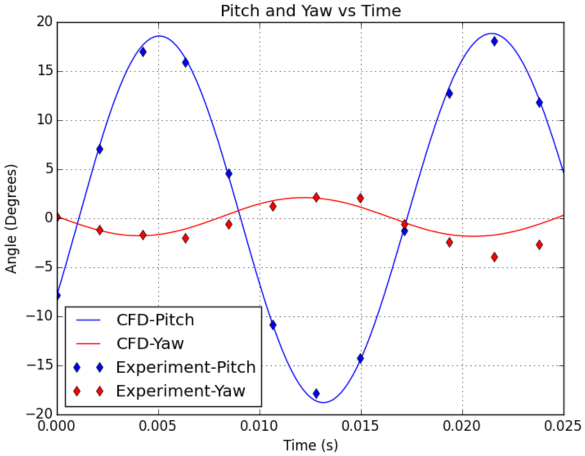
Stability inferred from 16 still images

Simulation of Dynamic Stability

- **Tomorrow's Reality?**

Simulation of spacecraft during supersonic decent





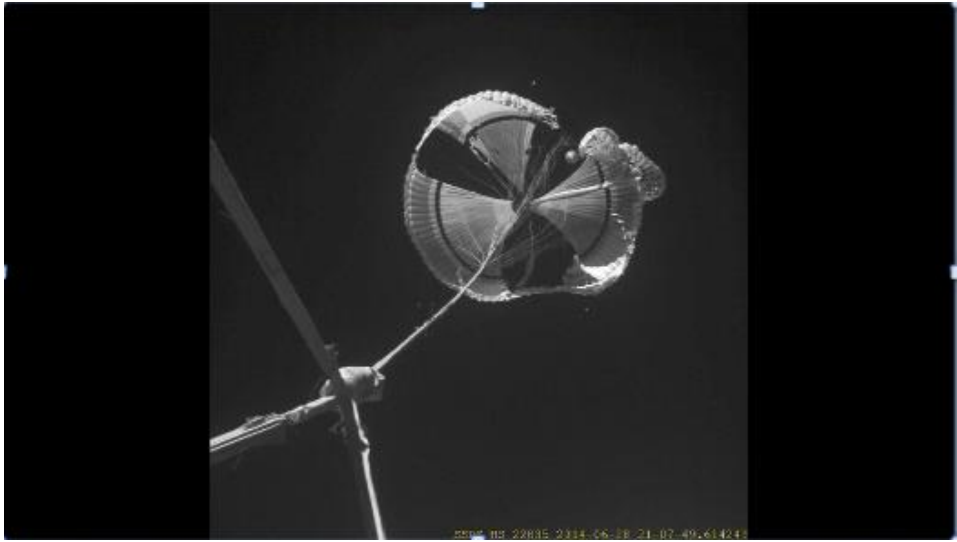
Comparison of simulation to experiment

Parachute Fluid Structure Interaction

➢ **Parachute inflation and dynamic descent is one of the least understood problems in EDL**

- Current approach is experimental; costly and prone to large uncertainty
- Lack of physical understanding of phenomena means all parachutes must be tested (sound familiar?)

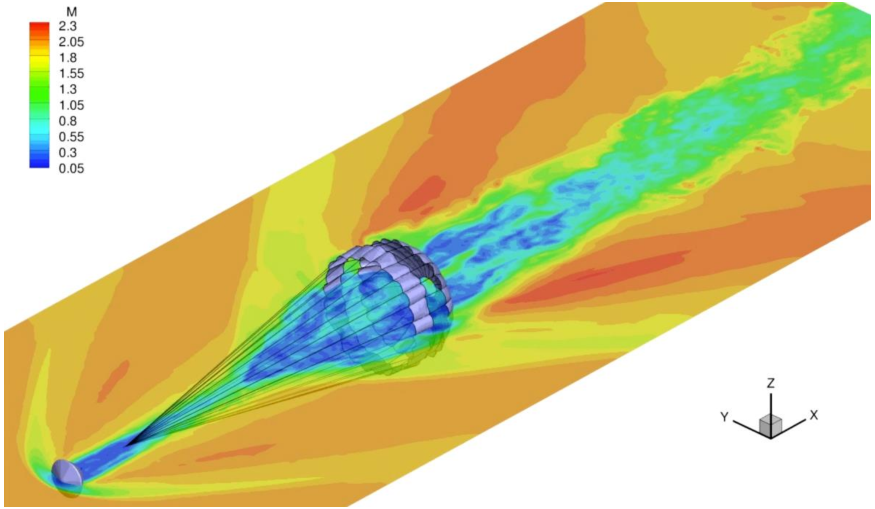
MPCV Orion: Pendulum motion when one chute fails



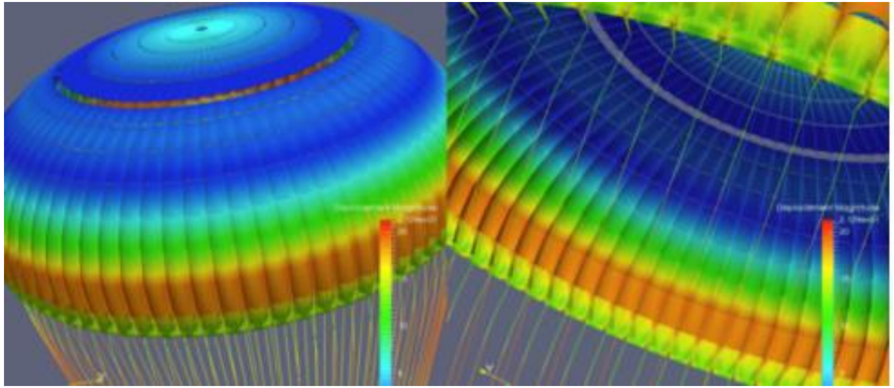
Failure of proposed new Mars Parachute design

Parachute Fluid Structure Interaction

- **A look to the future**
  - Replace/supplement expensive tests with accurate simulation
  - Better inform design by understanding underlying physical drivers



Large Eddy simulation of parachute descent



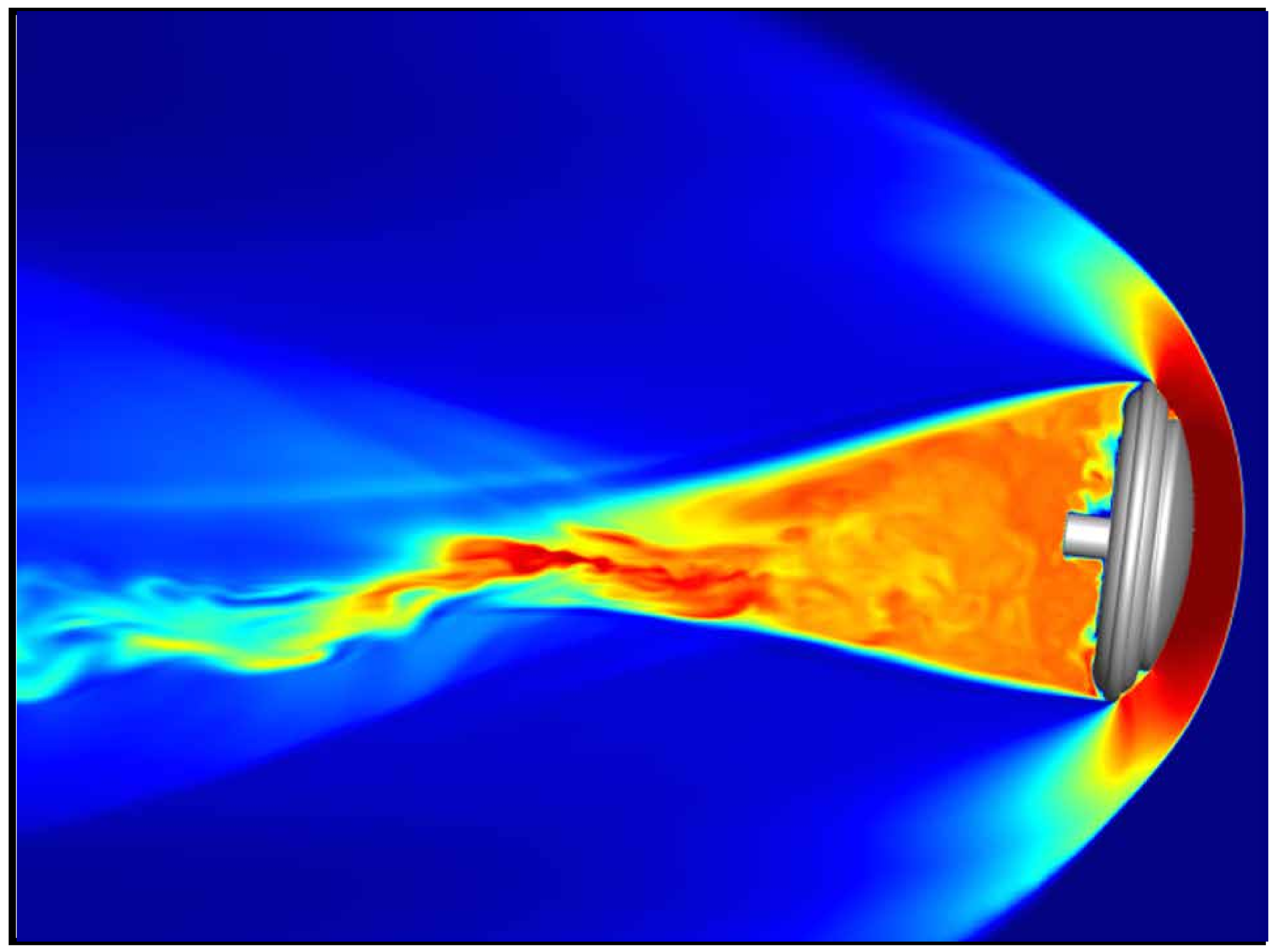
Cable/Membrane Structural Solver – SUNY Buffalo

Aren’t We Done Yet?

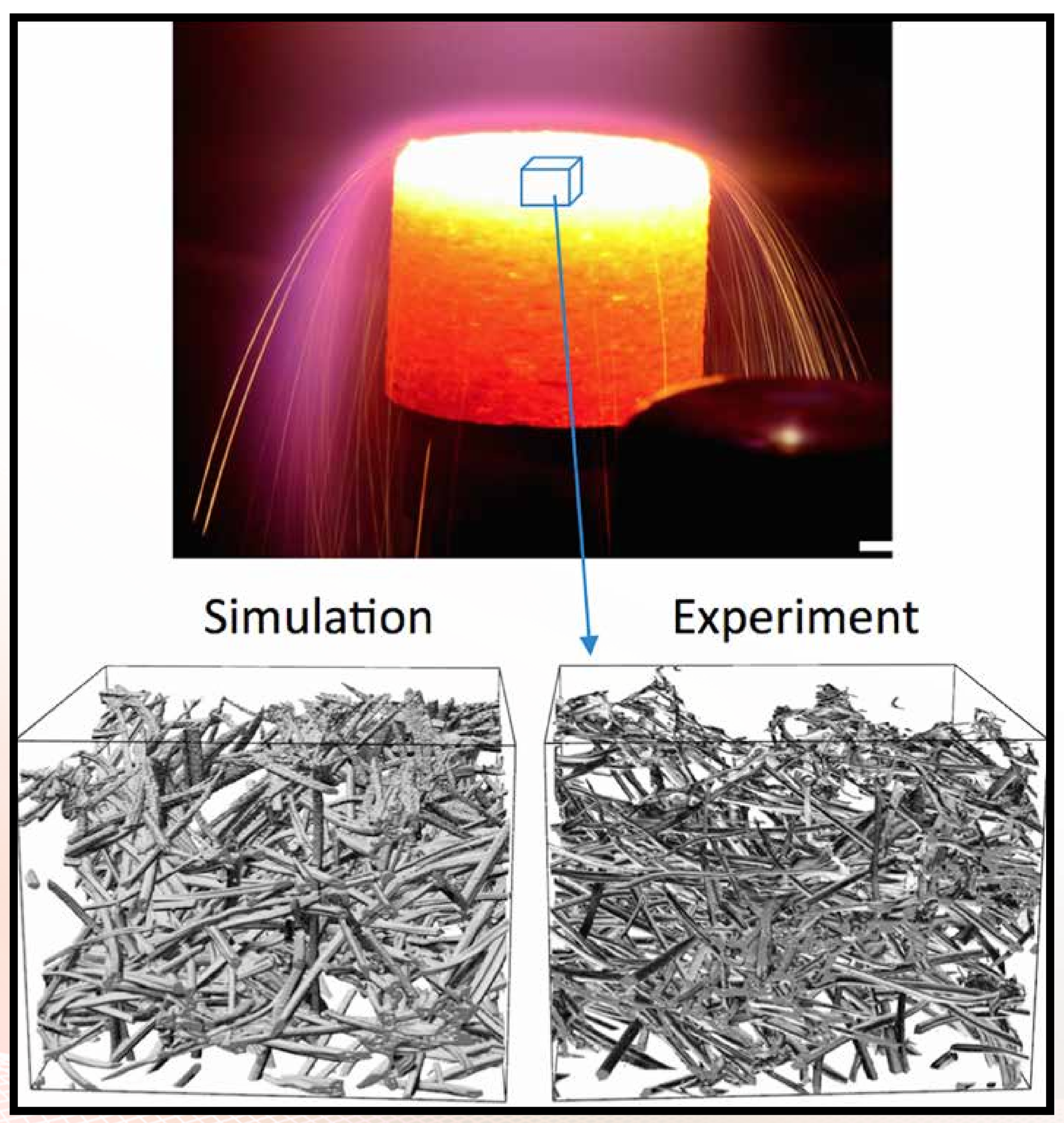
- **Models, particularly in aerosciences and material response, have largely undefined uncertainty levels for many problems (limited validation)**
  - Without well defined uncertainty levels, it is difficult to assess system risk and to trade risk with other subsystems
    - Result is typically (but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

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

Predictive Modeling for NASA Entry, Descent, and Landing Missions



Desktop ballistic range: A visualization of the temperature around a free-flying model tested in the NASA Ames Ballistic Range. The model is allowed to rotate freely according to predicted aerodynamic moments. Observed and simulated flight dynamics are compared in order to validate the computational model. *Joe Brock, NASA/Ames*



Top: Photo of a NASA-developed thermal protection system material during a high-temperature arc jet test. Bottom: Micro-tomography images of the material post-test. The right image was taken at the Advanced Light Source facility at Lawrence Berkeley National Laboratory. The left image is the result of a high-fidelity simulation. Francesco *Panerai, Joseph Ferguson, NASA/Ames*

NASA's Entry Systems Modeling (ESM) Project team is engaged in maturing fundamental research for developing revolutionary computational models in aerosciences and materials for entry, descent, and landing (EDL) technologies. Examples include:

- First-of-their-kind predictive models for shock layer radiation, anchored by detailed quantum mechanics simulations. ESM models have already proved critical for the Osiris-Rex, InSight, and Orion missions.
- Accurate models for thermal protection system (TPS) response during entry. Such a capability is enabling to the end goal of a computational design engine for engineered materials, such as 3D woven materials for the TPS.
- First-ever demonstration that the dynamic behavior of an entry capsule can be predicted via high-fidelity, unsteady computational fluid dynamics analysis.
- High-fidelity simulations of supersonic parachute inflation and descent via coupled fluid-structure interaction. The end goal is a predictive capability for parachute inflation loads and dynamics.

EDL modeling and simulation (M&S) is a critical path capability used in every NASA mission phase to: define mission concepts, select appropriate architectures, design EDL systems and quantify margin and risk, ensure correct system operation, and analyze data returned from the entry system. Since it is impossible to fully test EDL concepts on the ground prior to use, accurate M&S capabilities are required to extrapolate ground test results to expected flight performance. The complexity of these high-fidelity tools requires the use of the agency's largest supercomputers to provide timely data for mission planners.

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