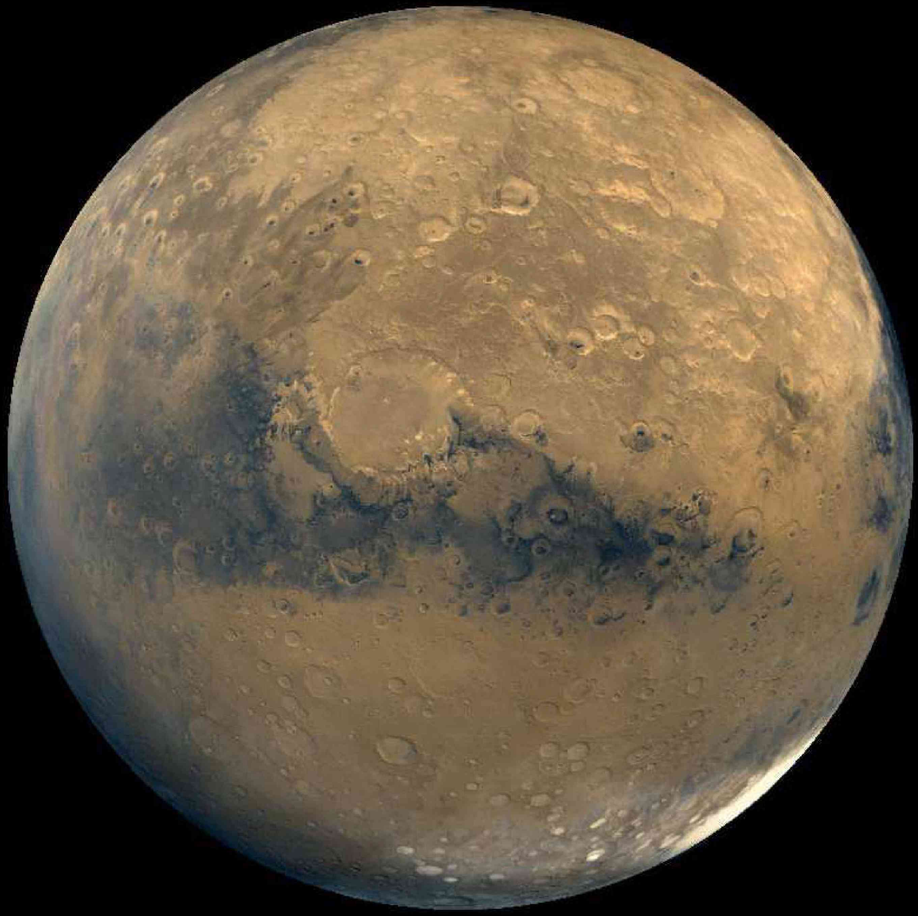
EDL Modeling Challenges for Past & Present Planetary Missions



Michael J. Wright

Project Manager
Entry Systems Modeling

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Modeling is Critical Path for EDL…

- **Flight mechanics predictions determine landing ellipse; define system performance**
- **Direct Simulation Monte Carlo analysis used for 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't we retire all uncertainties via testing? – No!

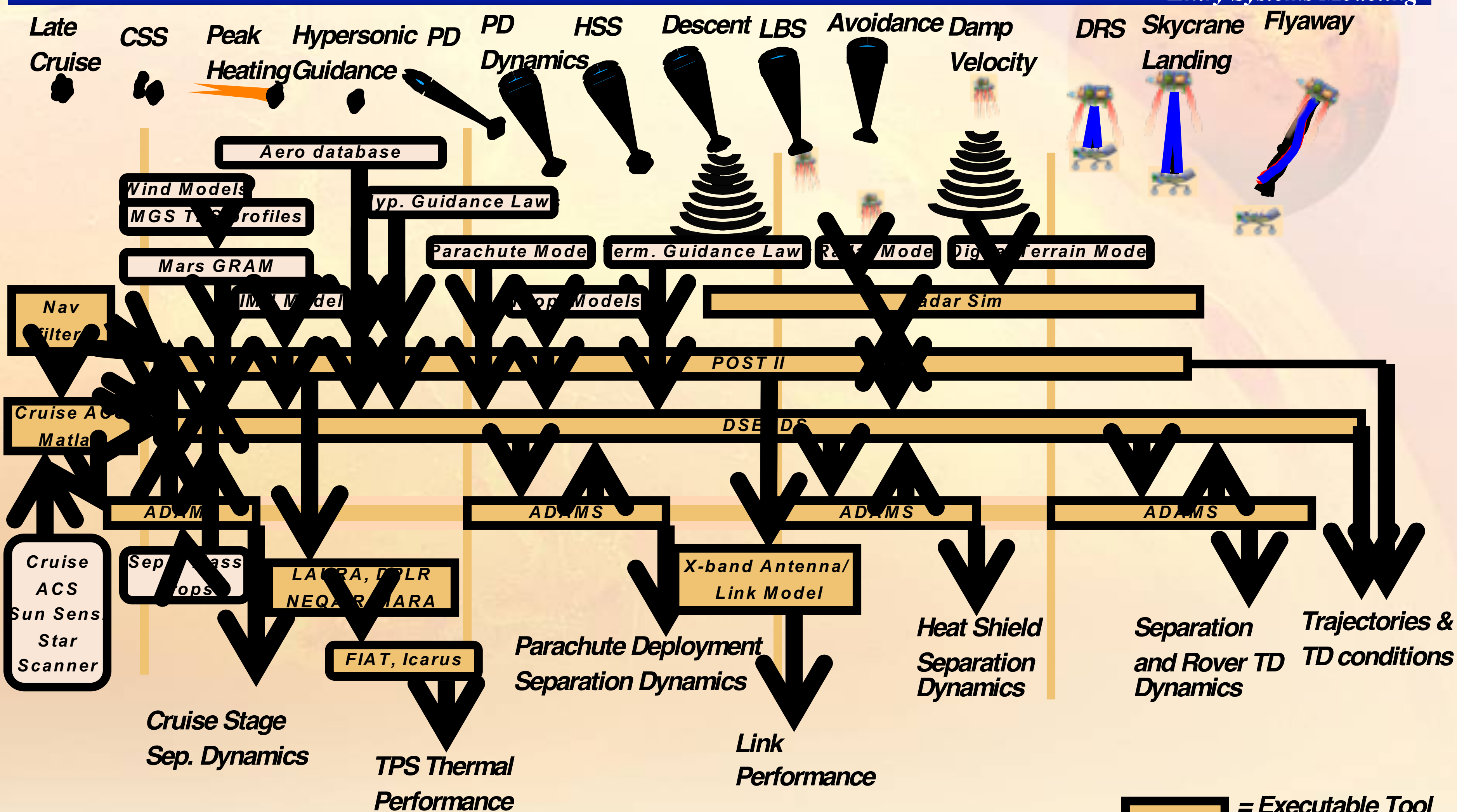
- No ground test can simultaneously reproduce all aspects of the flight environment. A good understanding of the underlying physics is *required* to trace ground test results to flight; extrapolation without a good understanding of the relevant physics can have catastrophic results.
- All NASA EDL missions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

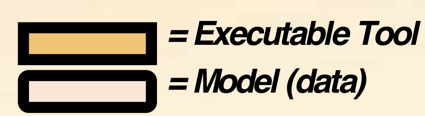
… In Every Mission Phase

- **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 architecture
- **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. For this phase 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 not only drives mass and reliability, but directly impacts WHICH technologies are selected for maturation.

Key EDL Tools & Models (MSL Example)





> *"Validated, integrated EDL simulations are our ONLY way to convince ourselves that EDL will work."*
> *-- Rob Manning (JPL)*

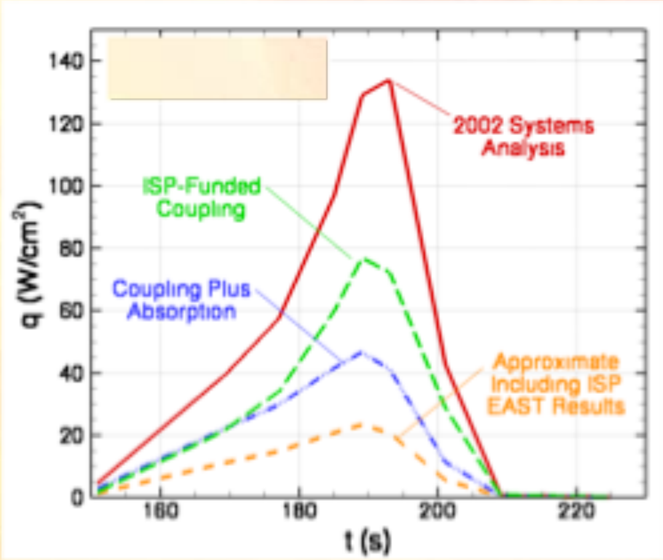
Mission Examples

Huygens Pre-Entry Risk Review

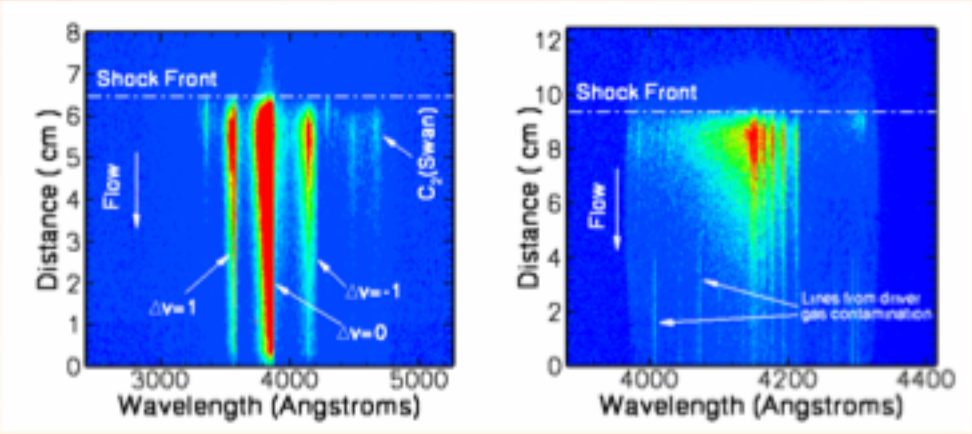
- **Concerns arose with Huygens design prior to planned release in 2004:**
  - TPS exposure to radiation
  - Radiative heating levels
  - Parachute design
- **NASA/ESA team formed to investigate**
  - Made heavy use of then-new models developed via ISP
- **General conclusion was that Huygens was a go for release, and it was obviously successful**
- **However, ISP-era models showed substantial differences from original design**
  - Work since at NASA and UQ have further refined radiation modeling and demonstrated that the contribution of radiative heating is much lower than predicted during design and risk review.

This work was the genesis of today's radiation modeling effort in NASA; the team has defined new heating modes and driven uncertainty levels below convective for some missions

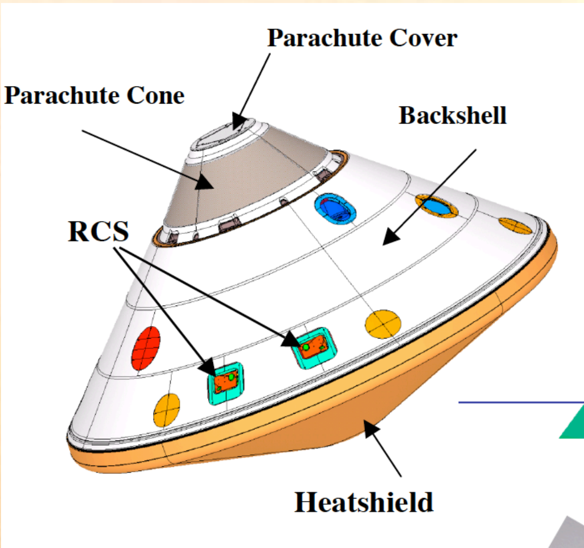
Huygens Radiative Heating Evolution



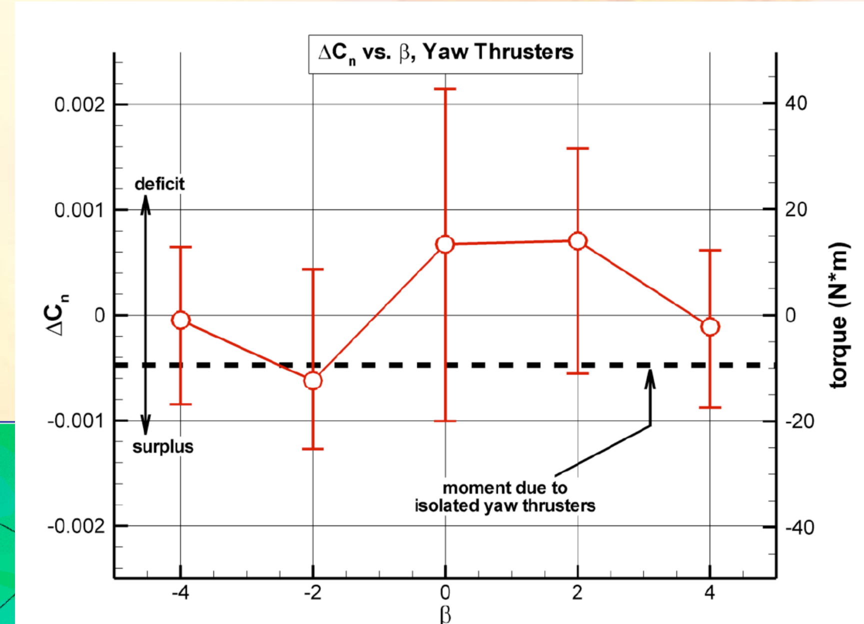
CN Violet (L) and Red (R) Spectra from EAST



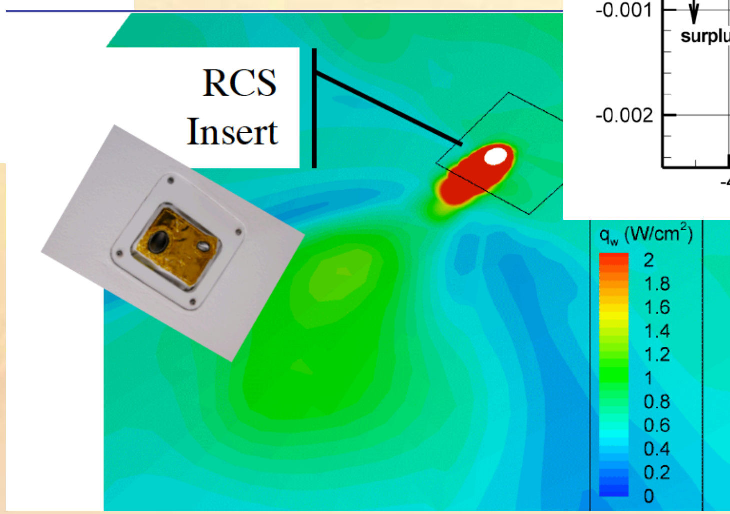
Phoenix: RCS Efficacy



Problem: RCS Undersized for Mission Requirements



Approach: CFD Simulations using best available methods to guide mission response



Result: Two day TIM in July 2007; CFD results had large error bars and often gave conflicting results.

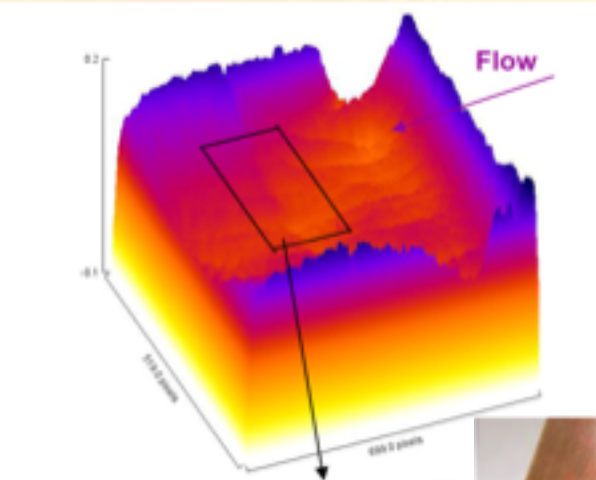
Conclusion: 'deadband' RCS thrusters; enter as a knuckleball.

Advances to the state of the art in wake flow modeling, with and without plumes, is critical to future mission design. Impacts to RCS, SRP and terminal descent.

POC: Doug Adams (JPL/APL) / Mark Schoenenberger (LaRC)

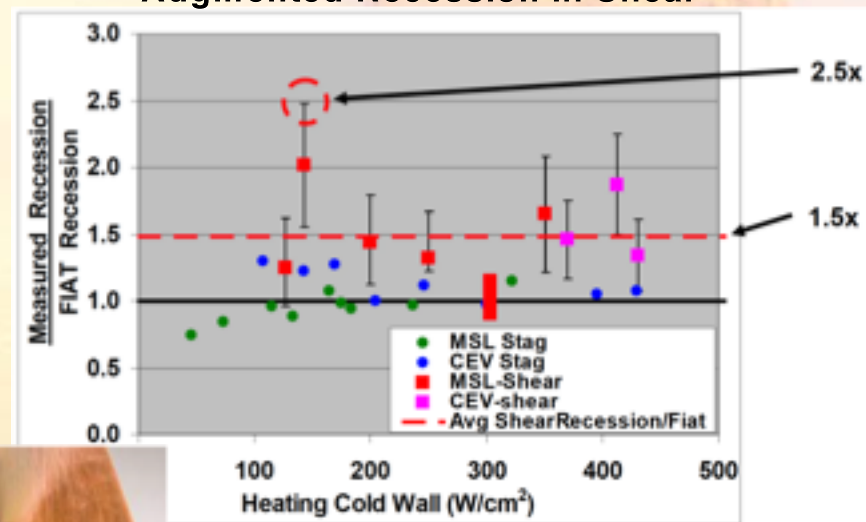
MSL PICA Heatshield

PICA Roughness

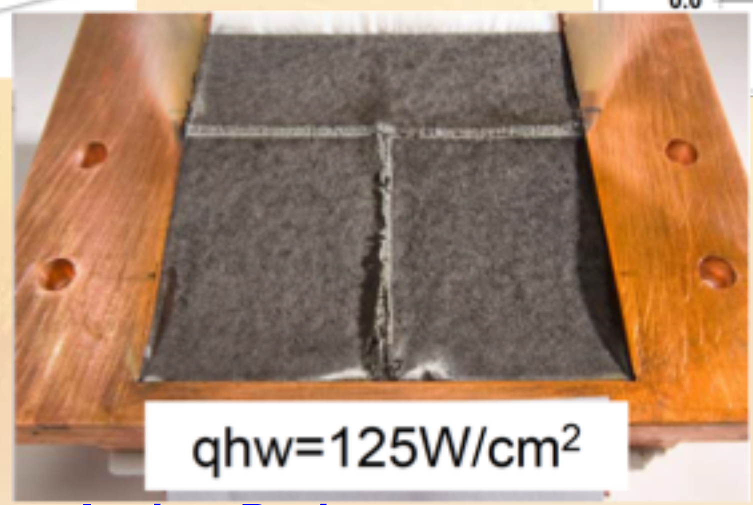


***Problem*: Prove that the PICA concept would work as it was being built**

Augmented Recession in Shear



Gap Filler Protrusion



***Approach*: CFD and material response simulations along with arc jet testing to bound performance risks**

***Result*: Intensive effort resulted in Program confidence that heatshield was adequate.**

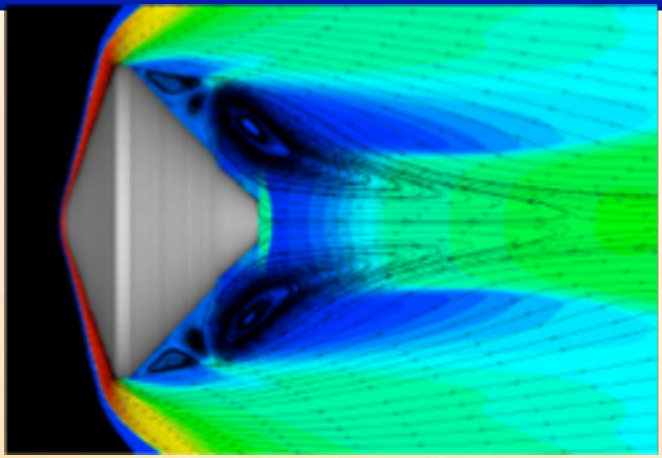
***Conclusion*: several modeling deficiencies resulted in large liens against design that would have been a serious problem with tighter margins**

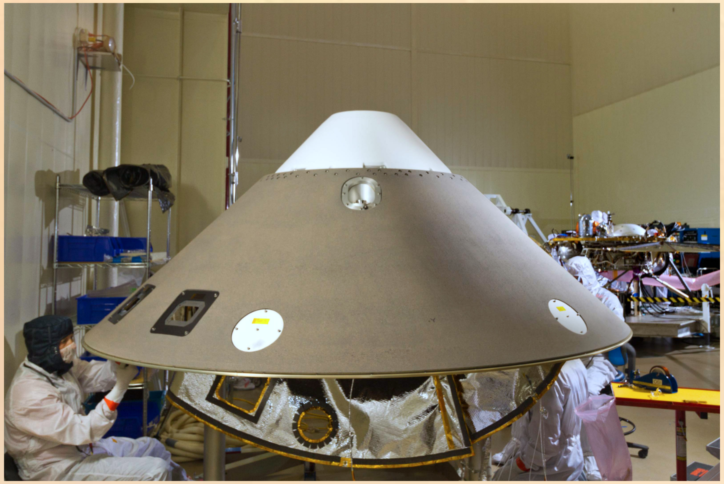
***Key Liens Against Design*:**

- Roughness heating augmentation
- Erosion in shear
- Gap filler induced heating
- Turbulent heating uncertainty

POC: Adam Steltzner (JPL); MSL EDL Segment Lead

InSight CO_2 Aftbody Radiation Implications





InSight Backshell Assembly

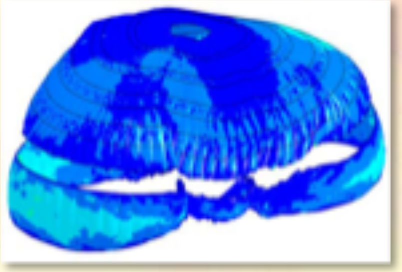
"New" Physics still rears its head in EDL

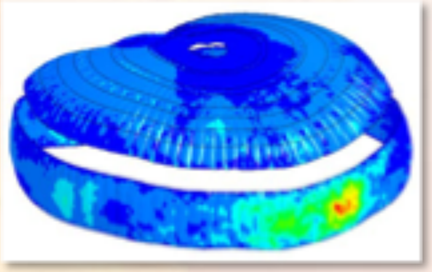
- InSight, a Discovery Class mission, relies on a nearly build-to-print Phoenix aeroshell in order to keep costs down
- Late in the design cycle it was discovered that aftbody radiation, previously neglected for all past Mars missions, may be significant **(discovery based on ESM Research)**
- A significant increase in total heat load, due to the addition of radiation, could lead to hardware design changes (thicker TPS) that could have cost, schedule, and system-level impacts
- Worked with Subject Matter Experts from ESM to quantify the expected radiative heating; resulted in a nearly 50% increase in total heat load on the parachute lid
- Very large uncertainties in radiative heating analysis; a **167%** uncertainty factor was utilized
- Significant analytical effort was required to demonstrate adequate thermal margin for build-to-print aftbody TPS thickness with the incorporation of aftbody radiation
- A better understanding of aftbody radiation and a reduction in modeling uncertainties could mitigate the need for potential TPS design changes for future "build-to-print" missions (**work is underway in ESM**)

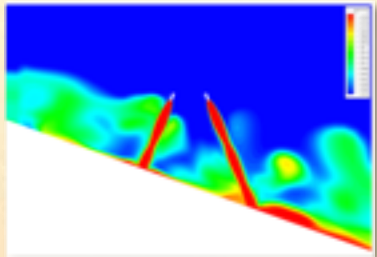
POC: Christine Szalai (JPL)
InSight EDL Systems Engineer & Aerothermal Working Group Lead

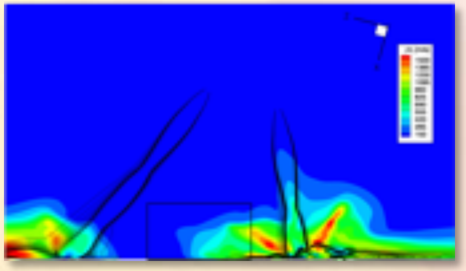
Mars 2020 Key EDL M&S Challenges

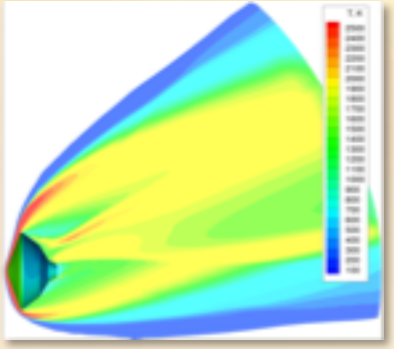
- **Mars 2020 faces several technical challenges where state of the art modeling and simulation capabilities fall short**
  - Predicting parachute inflation behavior and quantifying stresses during the inflation process ***remain beyond our modeling ability***
  - Interactions between engine plumes and terrain continue to be ***notoriously difficult to accurately represent in simulation***
  - Radiative heating was thought to be negligible during design; now known to contribute ~25% to heatshield and ~50% to afterbody heat load
  - Quantifying aftbody aerothermal heating and its impact on TPS margins continues ***to require close scrutiny and large error bars***
- **These technical challenges require some combination of overdesign, large margins or uncertainties, and acceptance of residual risk**









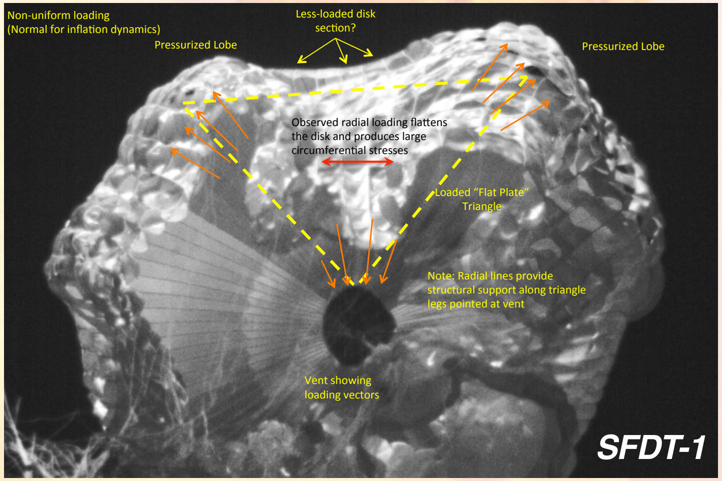


POC: Allen Chen (JPL)
Mars 2020 Cruise & EDL Lead

Improvements in EDL modeling and simulation capabilities could lead to significant risk reduction and cost savings

LDSD/ASPIRE:
Soft Good Performance and FSI

- **Aeroheating of soft-goods on supersonic inflatable decelerators not adequately explained by models**
- **No predictive capability exists for inflation or descent performance**
  - *Total reliance on full-scale flight testing for chute design; limited knowledge from failures*
  - ***ESM is partnering with STRG & JPL to develop simulation capability***



Modeling will play a critical role in infusion of inflatable technologies into a Mars mission

"Performance improvements in mass, drag, stability, etc., could be enabled without having to perform full-scale, at-condition testing, an activity that because of its expense occurs every several decades. Perhaps the most important benefit of improved FSI capabilities is in the area of risk-reduction to development programs and agency flight projects."

--Ian Clark (JPL); LDSD Principal Investigator

NASA Has Models in All Major Disciplines, However…

- **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

> *"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***

- **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 system performance requires new analysis, introduces 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

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

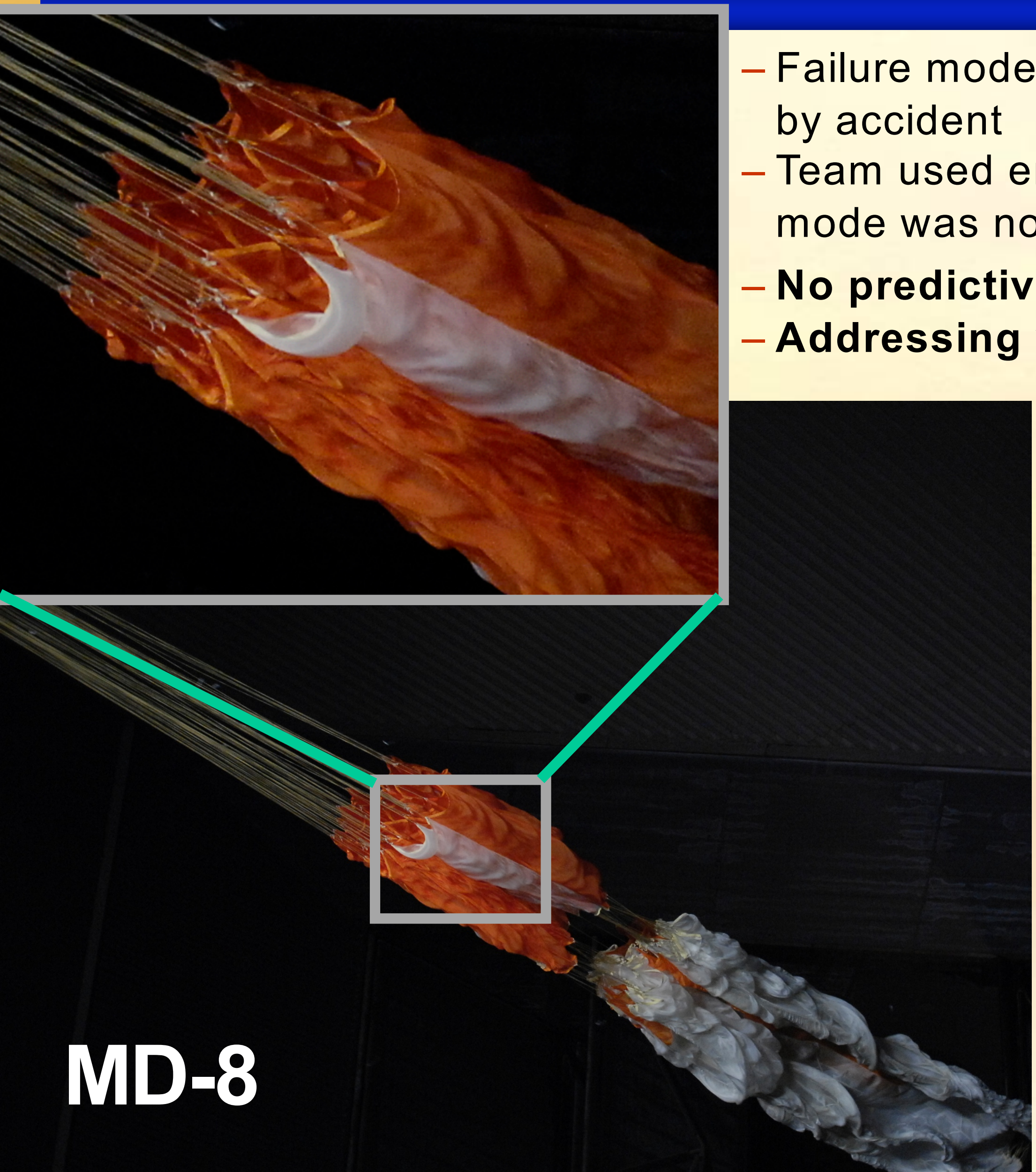
Backup

In a Nutshell

- ***EDL M&S is critical path from the day a mission is envisioned until the day the spacecraft lands on the surface (or aerobrakes into orbit)***
  - Early simulations define what is possible, and determine which technologies require maturation prior to use (TRL 6 by PDR)
  - High fidelity physics models design EDL system architecture and elements
  - A POST team member had a seat at mission control for MSL landing; supercomputers were working late into the night prior to entry to check landing ellipse predictions with latest data
- ***Full mission sims are built in multidisciplinary tools (e.g. POST2)***
- ***However, each and every input to POST2 is based on detailed validated simulation data***
  - A massive effort to design and implement a model validation effort using real physical test of subsystems in earth environments.
  - The validity of the POST2 results are only as good as the quality of the input data (GIGO)

MSL: Parachute NFAC Failures

- Failure mode completely unpredicted; discovered by accident
- Team used engineering analysis to argue that mode was not flight relevant and flew this chute
- **No predictive model exists**
- **Addressing via University grants, flight testing**



POC: Eric Slimko (JPL)