Challenges in Qualification of Thermal Protection Systems for Extreme Entry Environments

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Introduction

- This talk is motivated by recent experience with HEEET development and qualification and assessment of its technology readiness

- Unique challenges in qualifying heatshields in extreme environments independent of material choice
  - Extreme environments defined as >1500 W/cm^2 and >1.5 atm for this talk
  - Missions to Venus, Saturn, Ice Giants and Earth reentry
  - Focusing on a subset of challenges for this talk

- Thoughts on how we can tackle these challenges

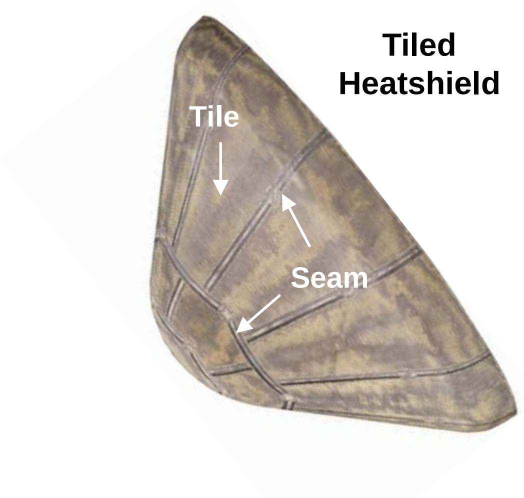
- This talk focuses only on aerothermal loads and qualification
  - Not ground, launch and space environments
  - Not entry structural loads

Aerothermal Qualification of Heatshields

- To qualify a TPS material, we need to demonstrate:
  - The system, including local features such as seams, does not fail at flight-relevant environments
  - Its thermal response must be predictable such that margins exceed uncertainties
    - Computational modelling reduces uncertainties and associated margins

- Requires testing flight-like configurations at scale in flight-relevant environments
  - Flight-relevant environments are achieved by bounding flight parameters (heat flux, pressure, shear, in-depth temperatures) in arcjet tests
  - Test articles large enough to include system features are tested at these bounding conditions

- Measurement quality and analysis fidelity should be sufficient for design tool validation
  - Uncertainties in test data and analysis impact design margins



Tiled Heatshield

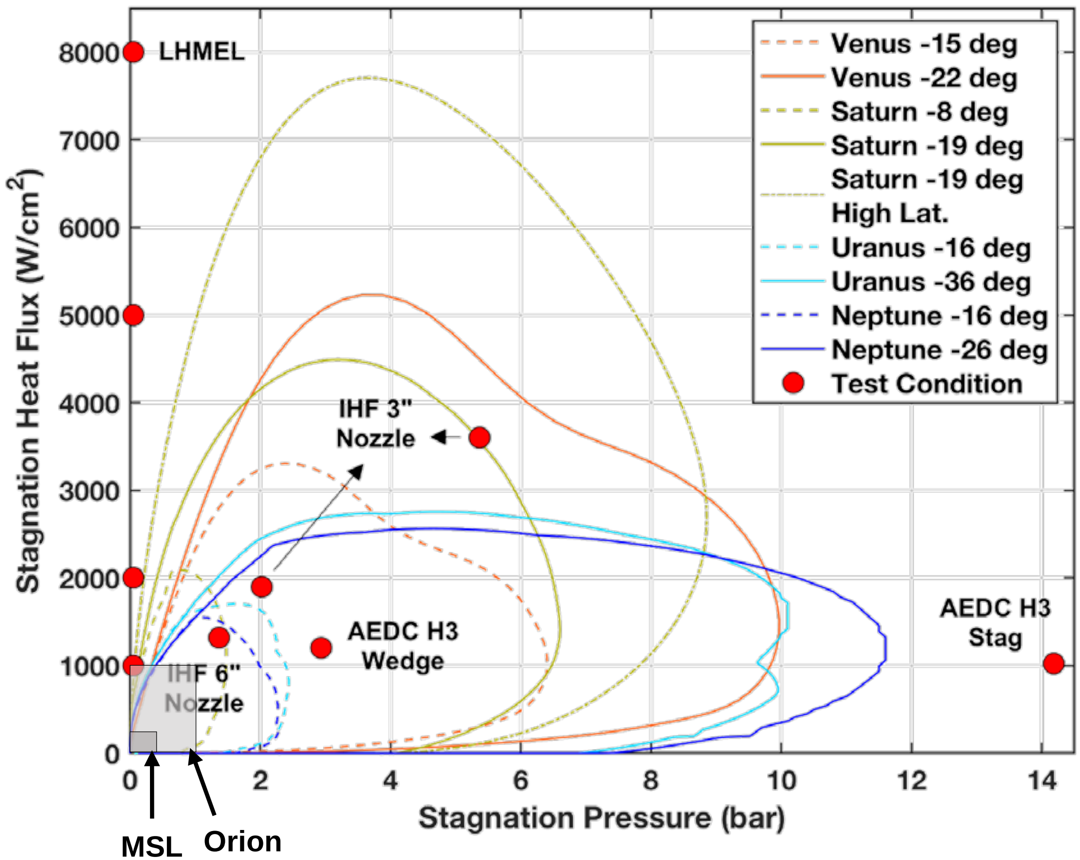
Testing Different Seam Configurations

Flight-Relevant Environments

- Predicted environments for representative entry trajectories cover a wide range of heating conditions
  - Significantly higher environments than recent experience (MSL, Orion)
  - Unmargined stagnation point traces shown here may not be bounding when considering turbulent shoulder environments and margins

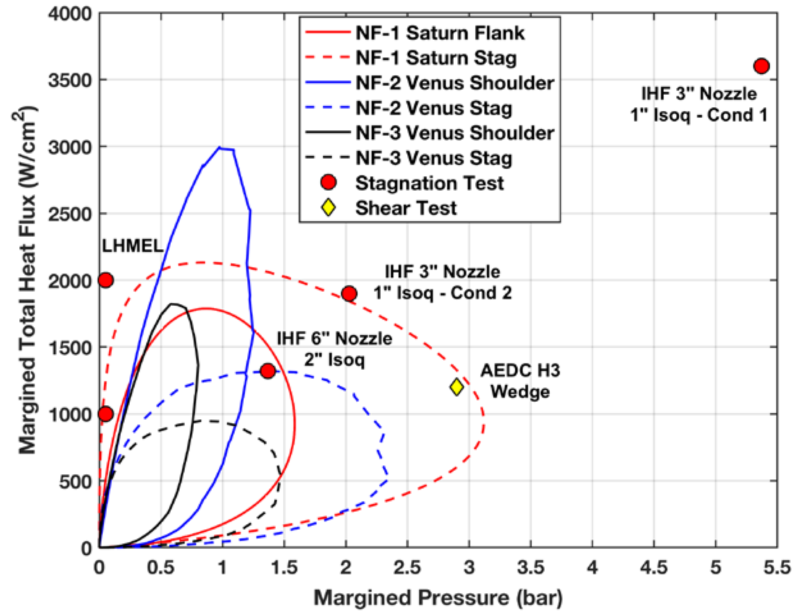
- TPS qualification can only be done by piecewise testing across different facilities
  - Only 1-2 parameters are bounded in each test
  - IHF 3" and 6" for high heat flux/pressure stagnation tests
  - AEDC stagnation for extreme pressure
  - AEDC wedge for shear testing
  - LHMEL for high heat flux testing (no flow)

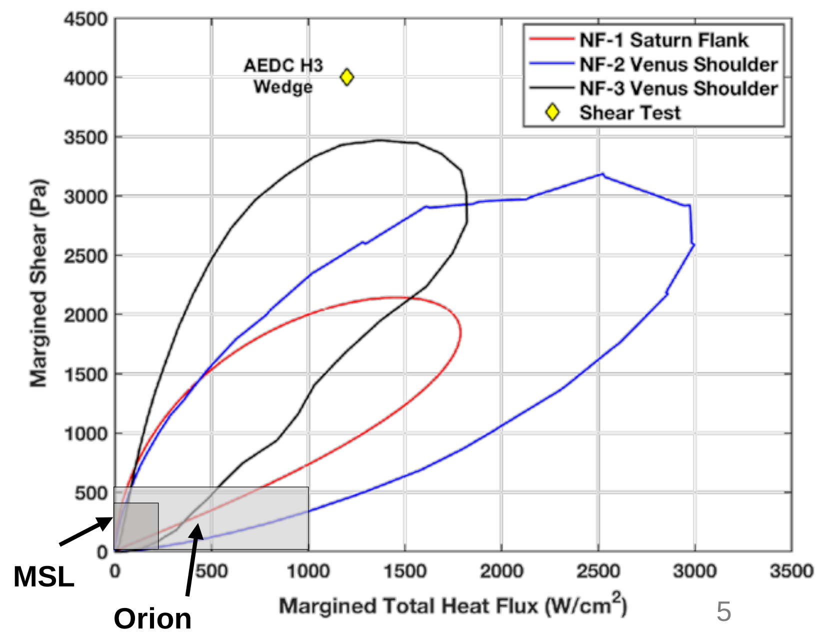
- Conditions for steep and high latitude trajectories are beyond existing facilities



Bounding Heating Parameters

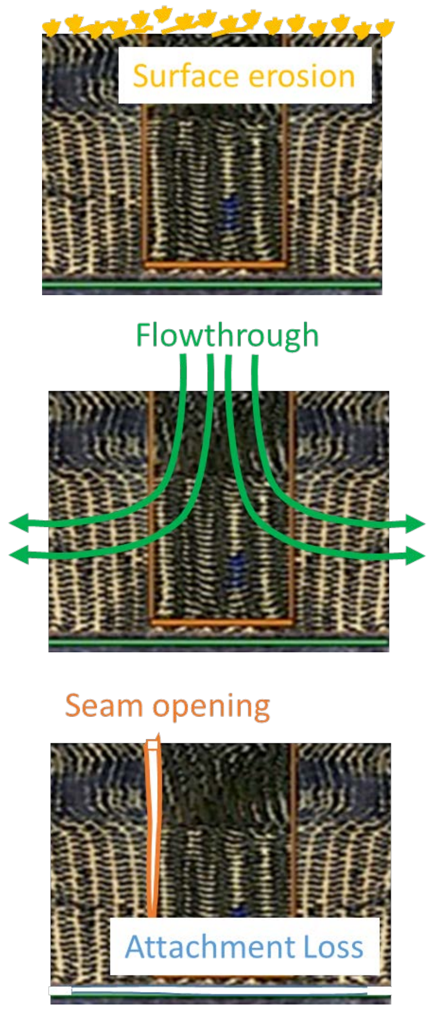
- The need to bound heating parameters drove New Frontiers 4 proposals to shallower trajectories
- Heat flux and pressure are bounded by IHF 3” nozzle test condition
- Shear levels are bounded by AEDC wedge but at lower heat flux
  - Reasonable to assume that the material state is representative at lower flux
  - Residual risk that surface temperature matters for shear-driven failure mode
  - Deemed acceptable by NF proposers
- Future mission designs may be forced to pursue more extreme entries
  - Interplanetary trajectory (entry velocity, FPA, latitude)
  - Mass or manufacturing constraints (weaving thick.)
- Bounding all heating parameters in ground tests is not realistic for these mission applications
  - Mission risk posture dictates what is acceptable for TPS qualification





How to Address This Challenge

- Understanding and predicting failure mechanisms is essential in the absence of facilities that can simulate all relevant flight conditions
  - "Relevant environments" don't necessarily need to be bounding if failure mechanisms and driving parameters are understood
- Requires a combination of modelling and failure testing
  - Categorizing failure mechanisms and identifying the underlying physics (material-specific)
  - Testing to induce failure and validate models
  - Using validated models to identify driving parameters and performance cliffs
- Failure mode modelling is not a simple undertaking
  - Material response that is generally ignored in design (flow inside the material, non-equilibrium surface reactions, mechanical erosion)
  - Coupling thermostructural analysis with flow modelling
  - Better characterization of material composition/structure and properties
- Recent progress in high-fidelity TPS modelling makes failure mode modelling more tractable

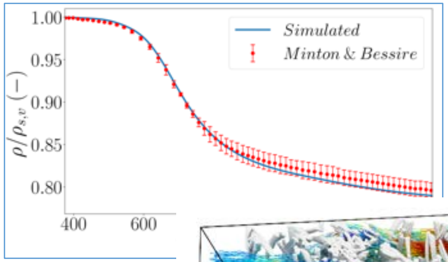


Foundational Blocks of Failure Modelling

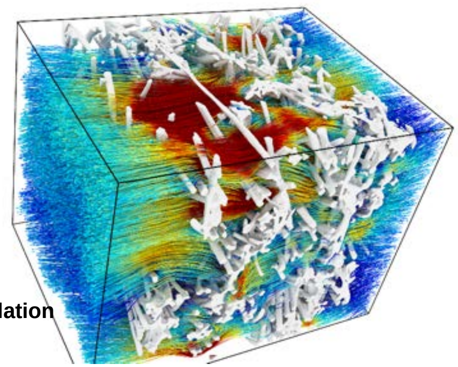
NASA's Entry Systems Modeling Project

Multiscale approach to quantifying stochastic behaviors

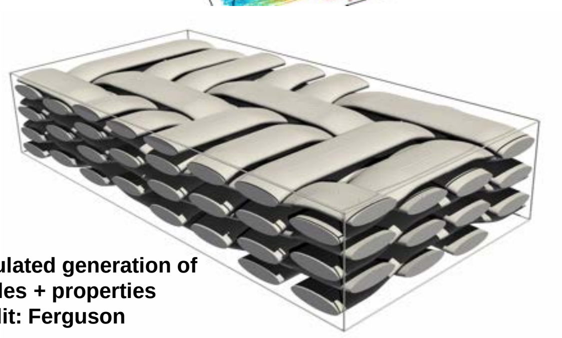
Micro — Meso — Macro



TGA of decomposition products
Credit: Minton

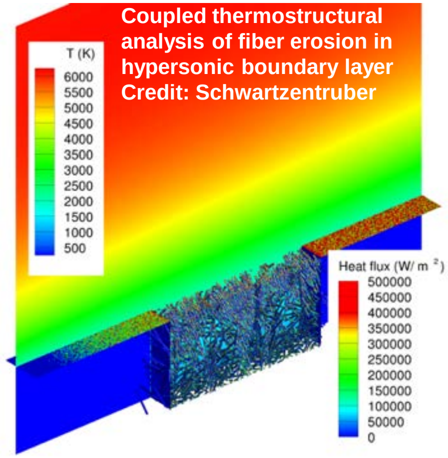


Micro-computed tomography + permeability simulation
Credit: Borner



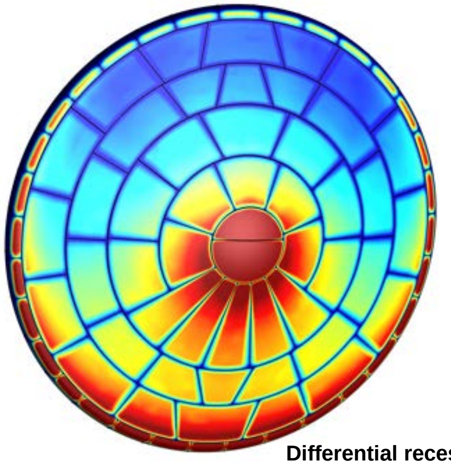
Simulated generation of textiles + properties
Credit: Ferguson

Microscale experiments and analysis for fundamental properties, validation

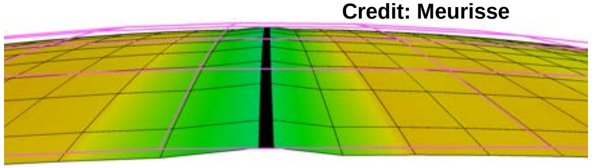


Coupled thermostructural analysis of fiber erosion in hypersonic boundary layer
Credit: Schwartzentruber

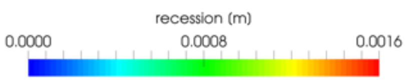
Detailed simulations of features and flaws provide information to inform macroscale models.



Differential recession of tiled heatshield
Credit: Meurisse



Gap filler

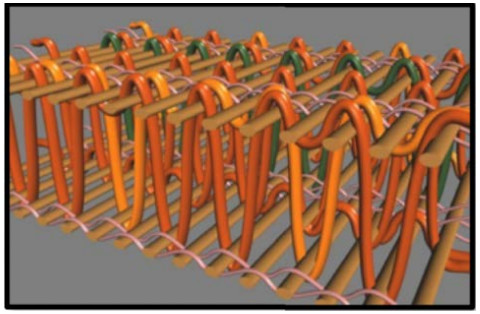


Benchmark simulations of system-scale performance with uncertainty quantification

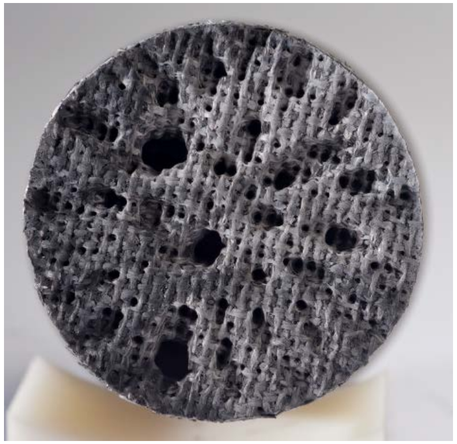
From Foundational Research to Design Tools

- Competed missions don't have the resources to advance modelling from foundational stages
- A concerted effort is needed to bridge the gap and mature current research toward design tools
  - Integrate foundational blocks for application to a specific problem
  - Start with problems with reduced complexity
  - Focus on one material type
- 3D-woven materials (ex. HEEET) are good candidates
  - Simple constituents (carbon and phenolic)
  - Well-defined woven structure that can be modeled computationally
  - Weaves can be altered to develop materials more susceptible to failures
- Use available data from past arcjet tests and design tests to generate data for model validation
  - Testing different weaves (tow size, weaving density) to identify key parameters

Developing Weaves Susceptible to Relevant Failure Modes Under Testable Environments



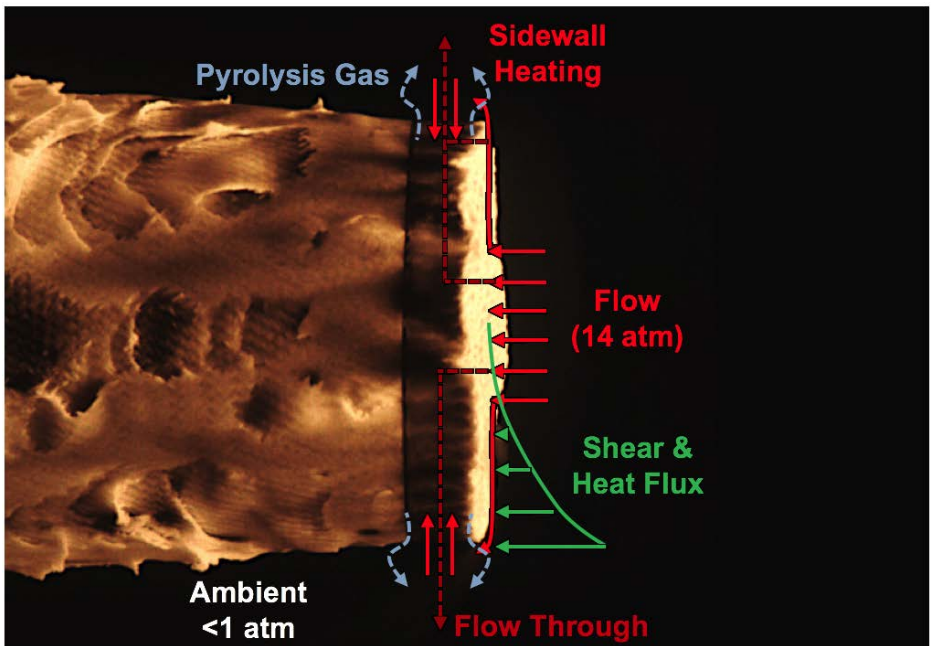
Tunneling Observed in Very Low-density Un-infused Weave



Candidate Problem for Failure Modelling

- AEDC stagnation test is an excellent problem for failure modelling
- Recession measurements 4-5 times higher than predictions for both HEEET and carbon phenolic
  - Potentially due to non-flight-like boundary conditions (extreme pressure gradients near the shoulder causing flow through)
- Explaining augmented recession can remove the current pressure limit on HEEET and inform a better model design for future tests

Non-flight-like Boundary Conditions in AEDC Stagnation Test



Conclusions

- Certain design choices make it easier to bound flight environments in ground facilities
  - Flying shallower trajectories
  - Eliminating seams in woven systems by developing a larger loom
- Yet, not all relevant heating parameters can be bounded in ground facilities
- Understanding and modeling failure modes using higher-fidelity tools will be critical in reducing residual risk
  - May allow for extrapolation beyond ground testing
  - Design better tests and explain unexpected response due to non-flight-like test configuration
- A concerted effort initially tackling problems with reduced complexity is needed to mature foundational research to tools that can be readily used by competed missions
  - Candidate problems with existing test data are available
  - Testing aimed at inducing failure modes is needed

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