National Aeronautics and Space Administration

A Case for High-fidelity Material Response Modeling

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A Brief History of Thermal Protection Material Modeling

AN ANALYSIS OF THE COUPLED CHEMICALLY REACTING
BOUNDARY LAYER AND CHARRING ABLATOR

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Ablation and Thermal Response Program
for Spacecraft Heatshield Analysis

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Abstract

An implicit ablation and thermal response program is presented for simulation of one-dimensional transient thermal energy transpo... materials and structur... surface and decompose... and numerical procedu... Solutions are compare... Aerotherm Charring Ablation Program, an... experiments show that... stable and solves a muc... with the older code. ... applications for therm... heatshields for planetar... Microprobe (Deep Spac... 2001, using advance... developed at NASA A... and discussed.

P = pressure, N/m^2
q_C = conductive heat flux, W/m^2
q_R = radiative heat flux, W/m^2
R = universal gas constant, J/kmol-K

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Overview of the CHarring Ablator Response (*CHAR*) Code

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An overview of the capabilities of the CHarring Ablator Response (CHAR) code is presented. CHAR is a one-, two-, and three-dimensional unstructured continuous Galerkin finite-element heat conduction and ablation solver with both direct and inverse modes. Additionally, CHAR includes a coupled linear thermoelastic solver for determination of internal stresses induced from the temperature field and surface loading. Background on the development process, governing equations, material models, discretization techniques, and numerical methods is provided. Special focus is put on the available boundary conditions including thermochemical ablation and contact interfaces, and example simulations are included. Finally, a discussion of ongoing development efforts is presented.

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Development of a three-dimensional, unstructured material response design tool

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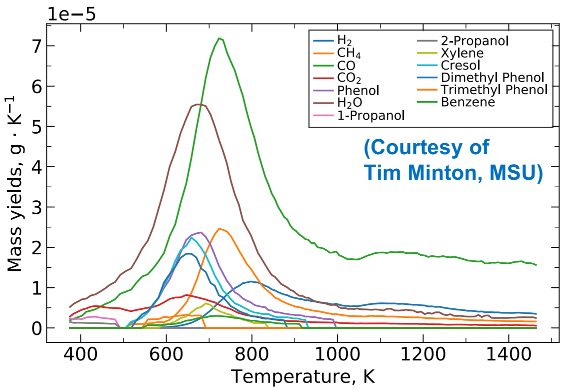
A preliminary verification and validation of a new material response model is presented. This model, Icarus, is intended to serve as a design tool for the thermal protection systems of re-entry vehicles. Currently, the capability of the model is limited to simulating the pyrolysis of a material as a result of the radiative and convective surface heating imposed on the material from the surrounding high enthalpy gas. Since the major focus behind the development of Icarus has been model extensibility, the hope is that additional physics can be quickly added. The extensibility is critical since thermal protection systems are becoming increasing complex, e.g. woven carbon polymers. Additionally, as a three-dimensional, unstructured, finite-volume model, Icarus is capable of modeling complex geometries as well as multi-dimensional physics, which have been shown to be important in some scenarios and are not captured by one-dimensional models. In this paper, the mathematical and numerical formulation is presented followed by a discussion of the software architecture and some preliminary verification and validation studies.

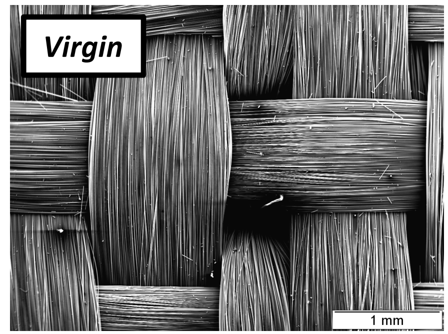
- ***CMA***, 1960s
  - The "original" material response model
- ***FIAT***, 1997
  - Implicit numerics makes CMA model much more robust
- ***CHAR***, ***Icarus***, and many more
  - Three-dimensional, unstructured
  - Parallel computing architecture
  - Pyrolysis gas flow

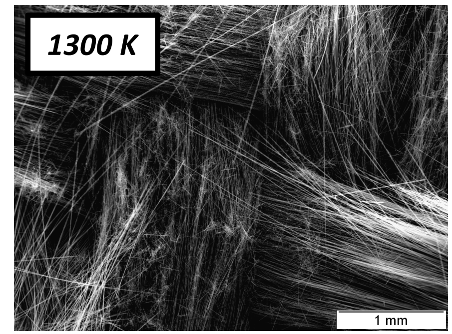
Material response models have been very effective for TPS design for 50+ years

Characteristics of a High-fidelity Model

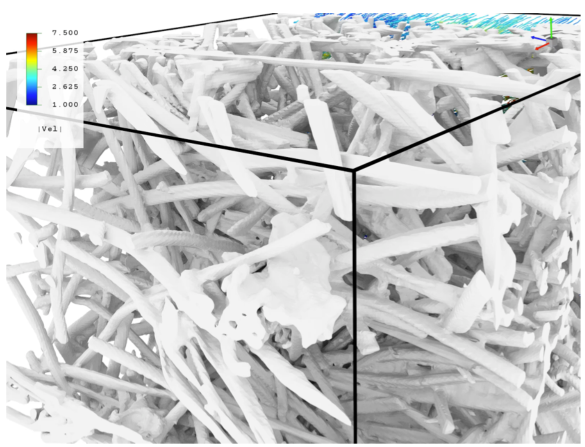
Calibrated fundamental experiments inform physics-based models



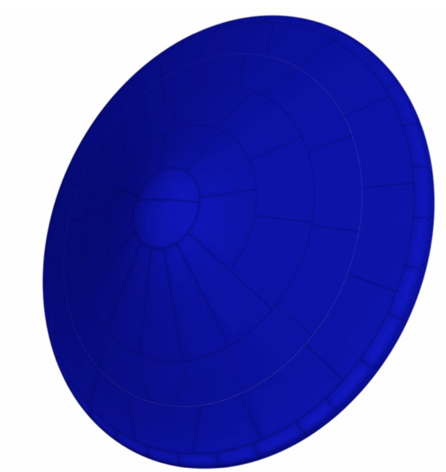




Micro-scale simulations provide material statistics and effective properties



Macro-scale simulations enable analysis of complex, fully-featured systems

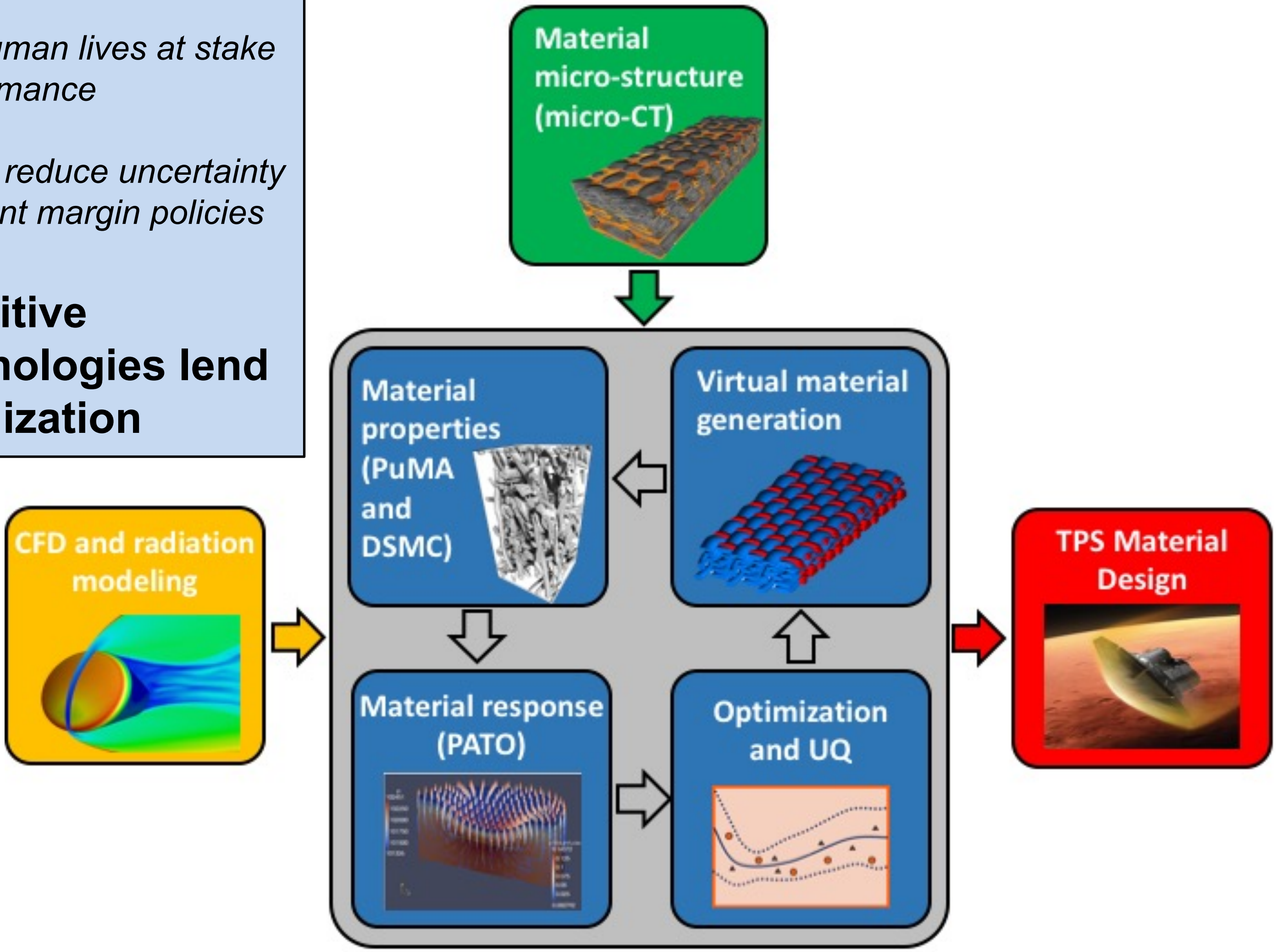


Mission-specific TPS Material Optimization

Missions are becoming less risk-tolerant over time

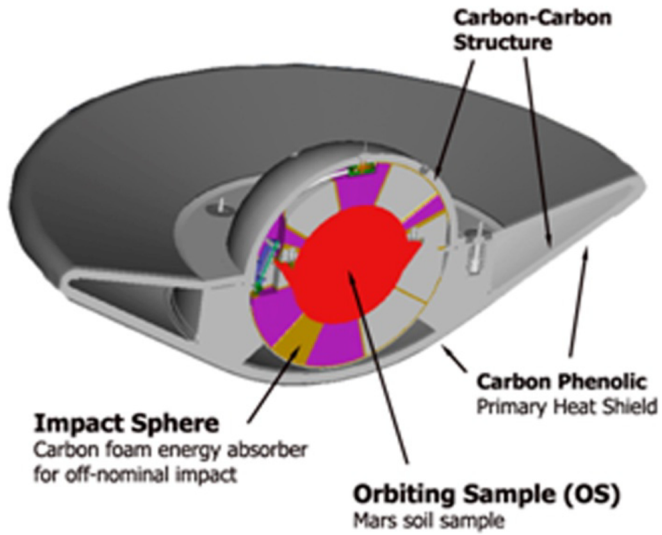
- *Billions of dollars and human lives at stake*
- *Tighter mass and performance requirements*
- *High-fidelity models can reduce uncertainty and support more efficient margin policies*

Woven TPS and additive manufacturing technologies lend themselves to optimization

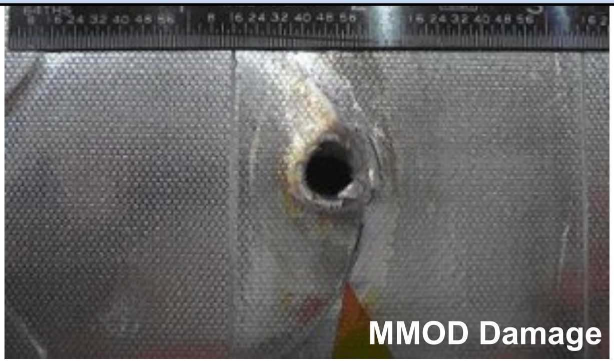


TPS Failure and Reliability Modeling

Schematic of Mars Sample Return Earth Entry Vehicle (MSR-EEV)



- Planetary Protection: 1 in 10^6 reliability requirement for MSR
- Multi-element campaign demands higher reliability for each element in the operational sequence



How do defects, damage, and features in TPS become failures?

Engineering Science Data Return

Avcoat heatshield is instrumented with thermocouples, pressure ports, and radiometers to enable aerothermal environment reconstruction and TPS performance assessment

Aerothermal environment reconstructions are no more accurate than the material response model

- Inverse algorithms employ material response model to reconstruct surface environments from in-depth thermocouple data

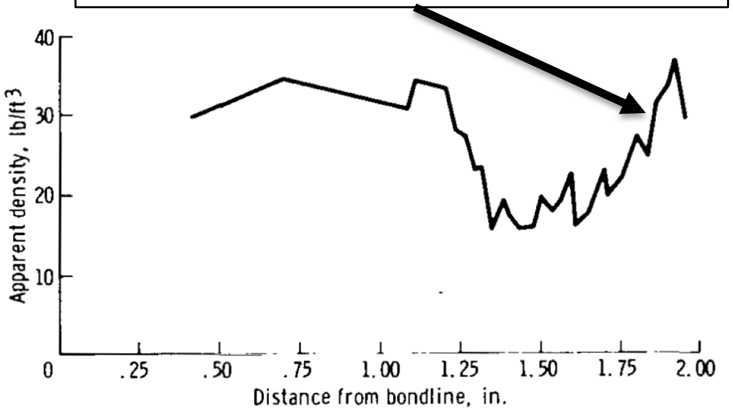
Sufficiently accurate reconstruction requires better models than presently exist. Higher fidelity models should include

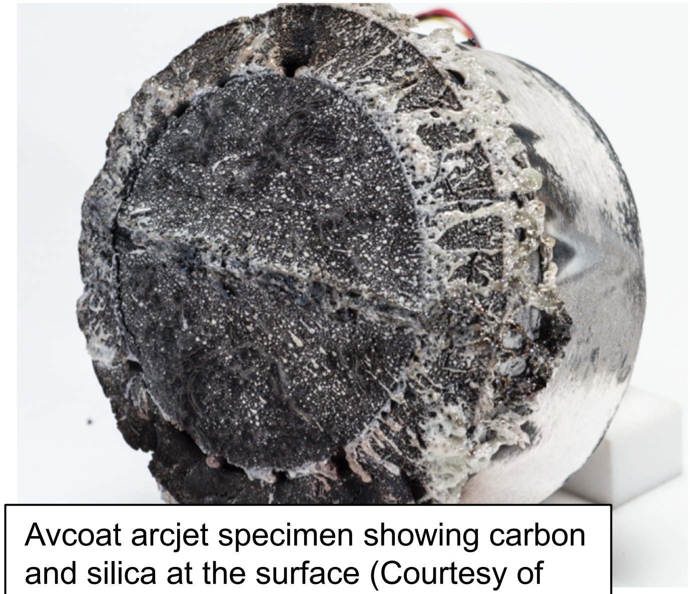
1. In-depth condensation models for carbon and water
2. Kinetic gas-surface interaction models with multiple condensed species (silica and carbon)
3. More accurate high temperature material properties
4. Effects of surface coatings such as paint, pore sealer, and tape
5. Multi-dimensional modeling of thermal interference effects
6. Uncertainty quantification on final environment reconstruction

Realizable mission impacts

- Mass margin reduction
- Increased downrange
- Higher entry velocities
- Greater range of entry flight path angles

Apollo post-flight density profile. Increased density near surface indicates presence of condensed carbon (NASA TN D-5969)



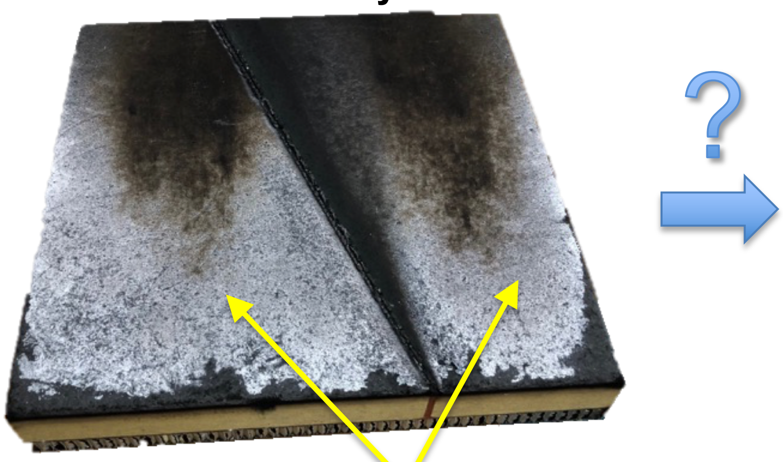


Avcoat arcjet specimen showing carbon and silica at the surface (Courtesy of Alunni and Gökçen, AIAA 2016-3534)

Engineering Science and Data Return

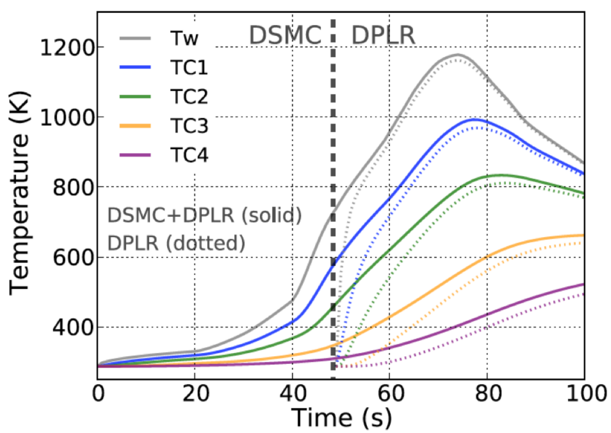
- The MSL heatshield, including the MEDLI plugs, were coated with a silicone-based coating called NuSil CV-1144-0 (RTV Silicone Protective Oxygen Overcoat).
- The MEDLI2 plugs will also be coated with NuSil, impeding MEDLI2's ability to achieve its Level 1 requirement for aeroheating reconstruction.
- NuSil fundamentally changes the surface material properties of the PICA material and therefore the material thermal response.
- A validated high-fidelity PICA-N response model can enable MEDLI2 to meet its requirement, while also increasing our understanding of original MEDLI data

PICA-NuSil System



Silica surface coating

Flight Reconstruction



(Borner et al, IPPW 2018)

NASA Vision 2040 Report

NASA CR 2018-219771

Questions?