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Fundamental Property Requirements for Thermal and Mechanical Response Analysis of Thermal Protection Materials and Systems

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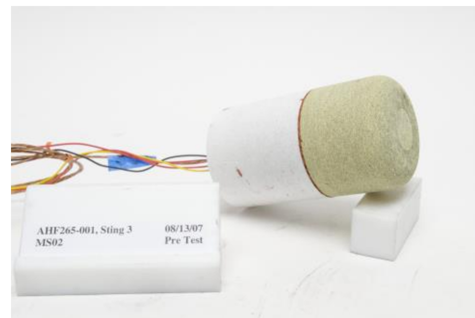
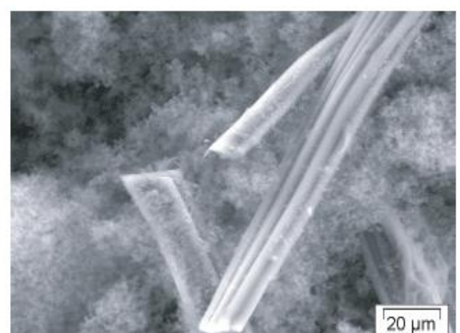
Outline

- **Thermal Protection Systems (TPS)**
  - Design and analysis
  - Characterization of TPS materials
  - Required properties and other information
- **Ablative Materials**
  - Applications
  - Modeling
  - Characterization
- **Computational Materials Modeling**
  - Goals and approaches
- **Summary**





TPS Design & Analysis

- **The design and analysis of thermal protection systems (TPS) for reentry and other hypersonic vehicles are very dependent on a combination of ground-based testing and computational analysis**
  - Flight tests opportunities are rare and very expensive
  - Analyses require high-fidelity material property data to accurately predict performance and validate predictions against test results

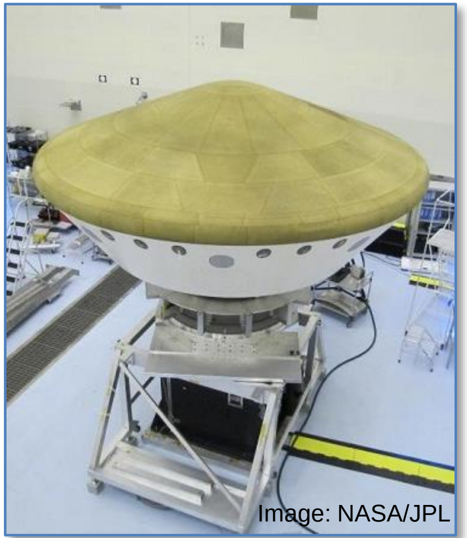
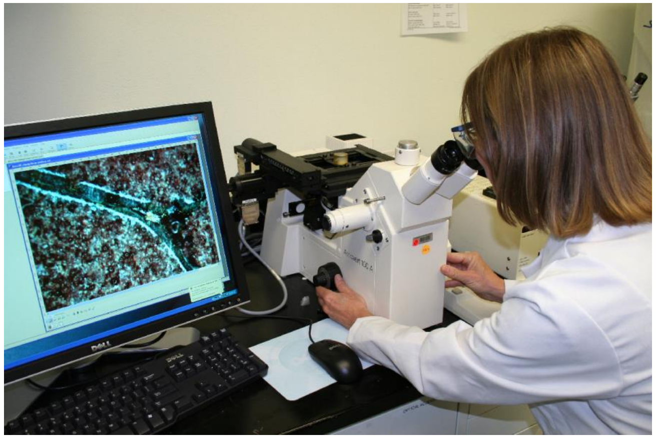


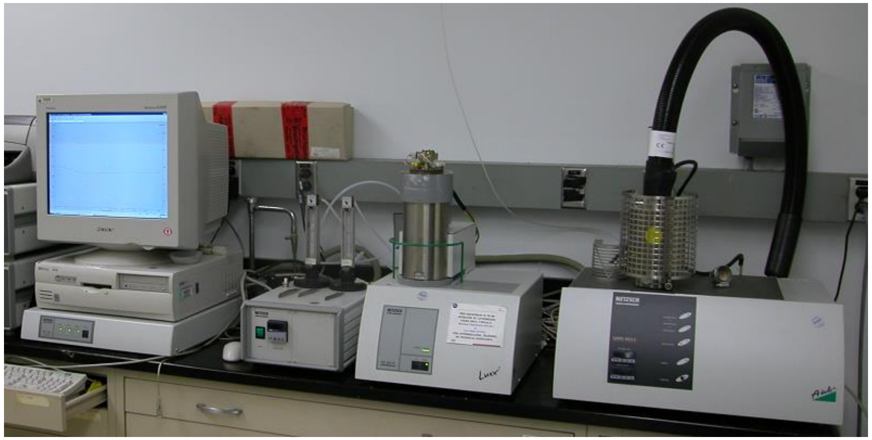
Image: NASA/JPL

- **The design of reentry vehicle TPS is heavily influenced by the material properties, performance allowables, and design margins**
- **Lack of accurate material properties can lead to tighter design allowables and more conservative margins**
  - Often translates into less efficient, heavier, more expensive vehicles
  - It can lead to a design process that does not "close"

Characterization of TPS

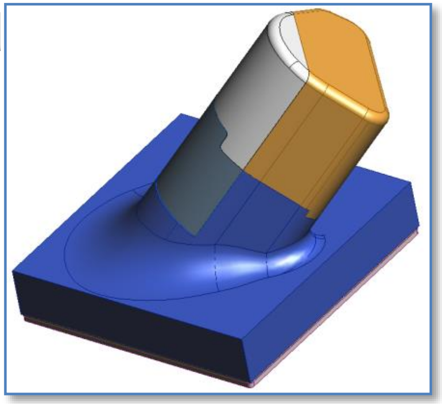
- **Proper characterization of thermal protection materials leads to more efficient and reliable designs**
- **Characterization data allows for:**
  - Evaluation/prediction of system performance through analysis and ground testing
  - Efficient material selection
  - Verification of manufacturing reliability and reproducibility
  - Ability to model the behavior of the material/system reliably
  - More efficient design of system/heatshield
  - Correlation of processing/properties – may lead to improved of materials

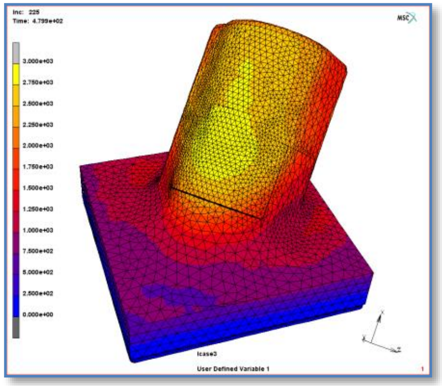


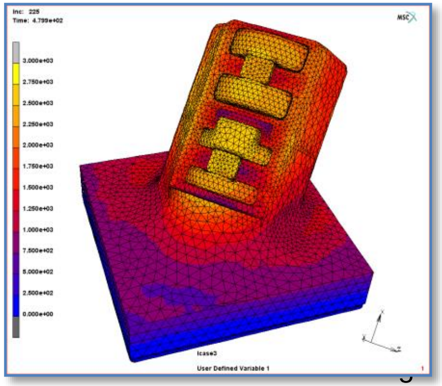


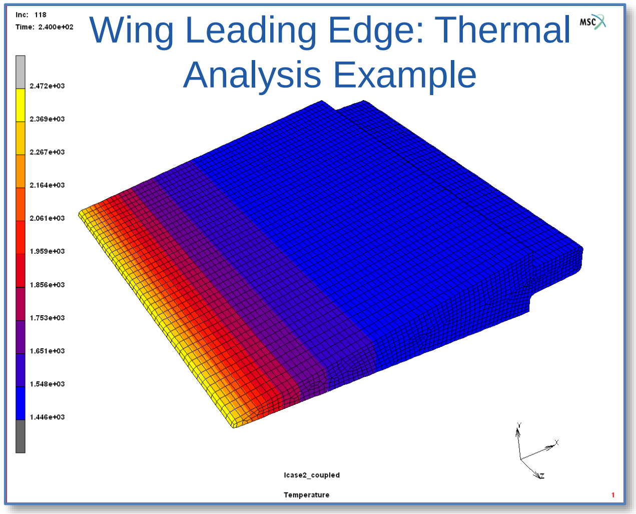
Analyses Methods & Tools

- **Finite element analysis (FEA): thermal and coupled thermal/mechanical**
  - Tools such as MSC.Marc, MSC.Patran
- **Ablative material response**
  - In-house tools, such as Fully Implicit Ablation and Thermal program (FIAT)
- **Computational materials**
  - Tools based on first principles

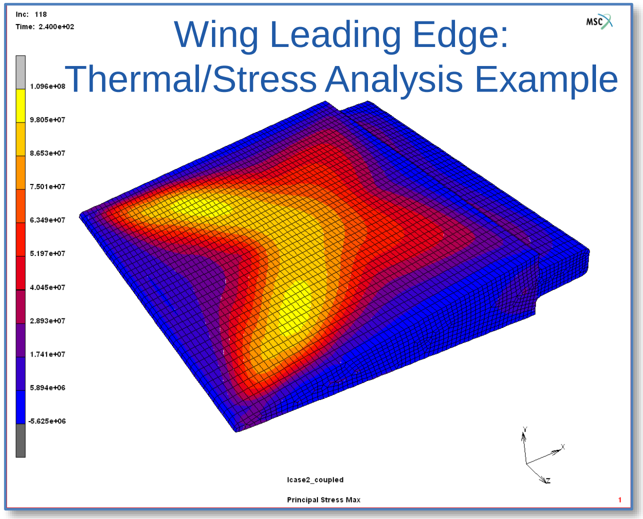








Wing Leading Edge: Thermal Analysis Example



Wing Leading Edge: Thermal/Stress Analysis Example

TPS Material Properties for Design

- **Properties and characterization necessary for proper analysis of TPS materials**

Thermal/Material Response Analysis
Density (virgin/char)
Thermal Conductivity (virgin/char)
Specific Heat (virgin/char)
Emissivity & Solar Absorptivity (virgin/char)
Elemental Composition (virgin/char)
Thermal Gravimetric Analysis
Porosity & Gas Permeability
Heat of Combustion (virgin/char)
Heat of Pyrolysis

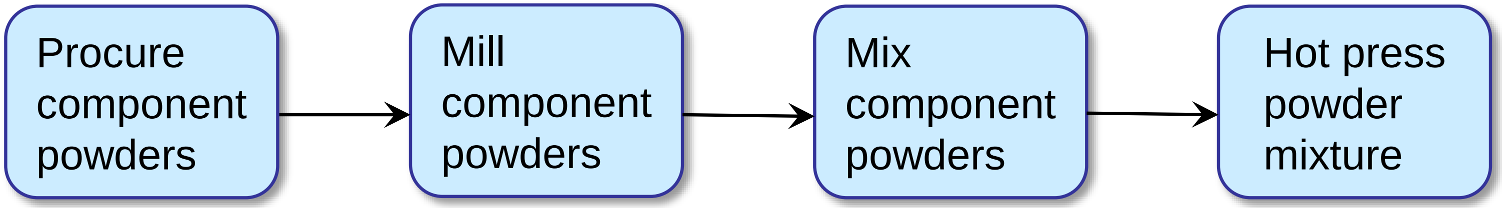
Mechanical Response Analysis
Tensile: strength, modulus, strain to failure
Compressive: strength, modulus, strain to failure
Shear: strength, modulus, strain to failure
Poisson's Ratio
Thermal Expansion (virgin/char)
TPS/Carrier System Tests Tensile strength Shear strength

General Property Requirements

- **In addition to specific material properties, designers and analysts require certain general material information**
- **This information is not directly used in analyses, but is used…**
  - To evaluate analysis results
  - To determine dispersions in design parameters
  - To assess the viability of designs
- **These properties include:**
  - <u>Directionally dependent properties</u>
    - Many real materials exhibit directional dependence of thermal and mechanical properties
  - <u>Property measurement uncertainties</u>
    - Critical to document property measurement techniques and define the nature of the distribution of data
    - Material property uncertainties drive the analysis dispersions and affect the design
    - Tests to measure material properties should be performed under recognized standards, such as ASTM
  - <u>Limitations in material application</u>
    - Manufacturer-derived limitations to material use are valuable data for designers

Material Manufacturing Variability

- **Real-world manufacturing processes have inherent variability**
  - May cause variations in the material properties
  - May lead to issues of reproducibility
- **Necessary to quantify processing variables and define allowable lot-to-lot and in-lot variability of properties**
  - Acceptable density range, or other property values
  - Acceptable flaw and inclusion size
- **TPS materials are unlike other typical aerospace materials, such as metals and composites**
  - Manufactured in relatively small lots and by few vendors
  - Often use proprietary processes
  - May be very sensitive to small variations in processing conditions

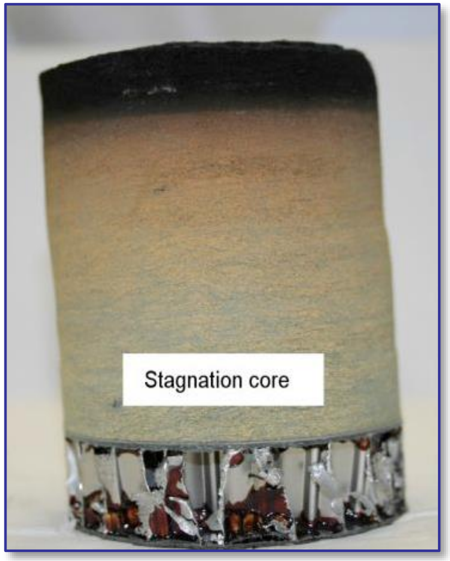


UHTC Processing Example

Focus on Ablative TPS Materials

Ablative TPS Materials

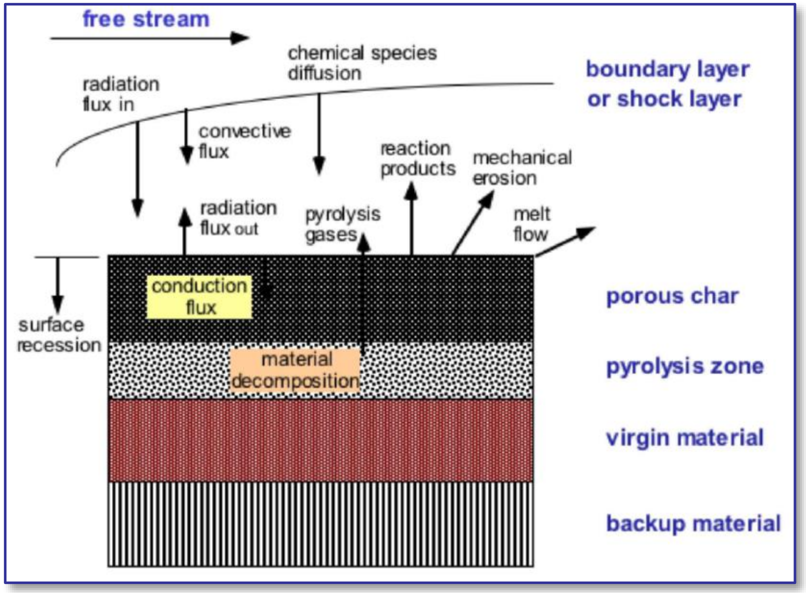
- **Used in high heat flux applications where reusable materials are not appropriate**
  - Material is "consumed" during atmospheric entry heating
  - Decomposition, oxidation, and sublimation of the material area critical aspects of the performance requirements
- **Outgassing of decomposition products aids in the removal of entry heating energy from the material**
  - Gas flow out of the material also attenuations the boundary layer conditions and reduces heat flux to the surface
- **Ablative materials have complex thermal response**
  - Accurate modeling of the material response accuratey is necessary for the design of ablative heatshields
  - Extensive characterization and ground testing is necessary in order to create material response models
- **Material examples:**
  - Phenolic Impregnated Carbon Ablator (PICA) – Stardust, MSL, Dragon
  - AVCOAT – Apollo and Orion



PICA Core from Stardust Heatshield

Ablator Material Properties & Heatshield Design Considerations

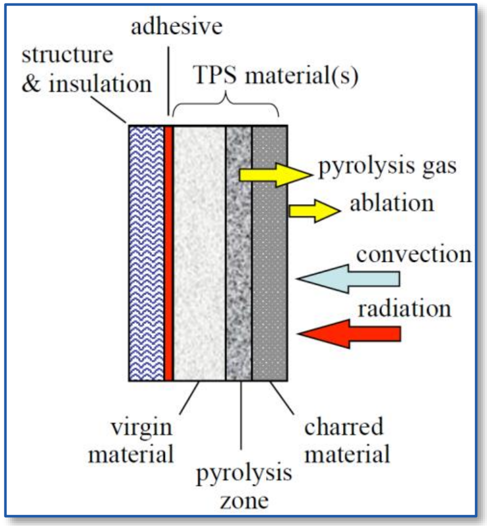
- **Necessary to evaluate:**
  - Both virgin and char thermal and mechanical properties
  - Validate surface recession behavior
  - Decomposition chemistry
- **Evaluating the interconnection between properties**
  - Performance/design tradeoffs
  - Greater density = greater strength, but generally increased thermal conductivity
- **Ablative materials may be tailored for specific applications**
  - Different density ranges
  - Alternate material compositions
    - Substrates
    - Infiltrants

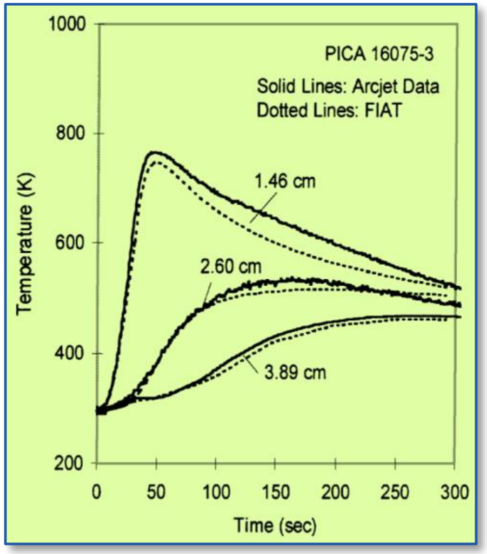


Schematic of Ablative Material Performance

Material Response Modeling

- **Fully Implicit Ablation and Thermal program (FIAT)**
  - 1-D time-accurate solution of thermal diffusion with surface ablation and internal pyrolysis
- **Multilayer material stack**
  - TPS, adhesive, insulation, structure, air gap, etc.
  - Planar, cylindrical, spherical, or "general" geometry
- **Mechanisms modeled**
  - Pyrolysis - internal, thermal decomposition of the solid
  - Ablation - processes that remove mass from the surface
- **Predictions include**
  - Surface recession, char depth, mass loss, in-depth thermal response
  - Iterative option can calculate minimum TPS thickness necessary to maintain structure below a given maximum temperature requirement
- **Use physics- and chemistry-based models with parameters obtained from experiments**





Process for Characterizing Ablators

Determine Material Options

Consider mission environments

Produce flight-like material samples, not lab scale

Evaluate Material's Variability

NDE recommended

Insight into configuration is critical to determine likely challenges

Determine Appropriate Techniques

May depend on material's density and configuration

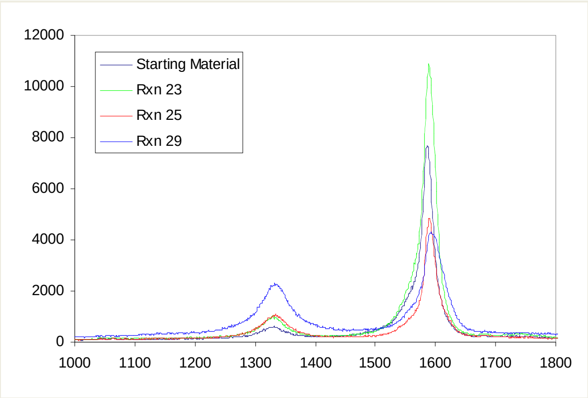
Example: 4-cm honeycomb structure not represented by a 1-cm coupon

Determine Quantity and Sampling Scheme

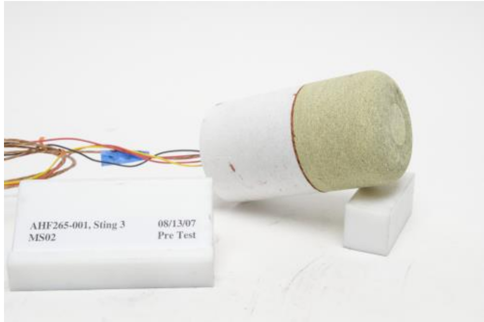
Influenced by material variability & project scope

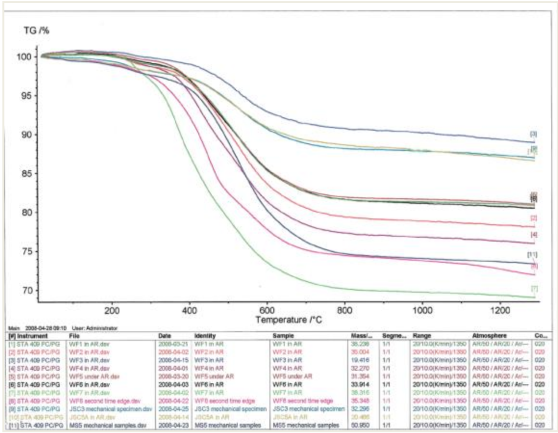
Execute Testing & Evaluate Data

Characterization of Ablative Materials

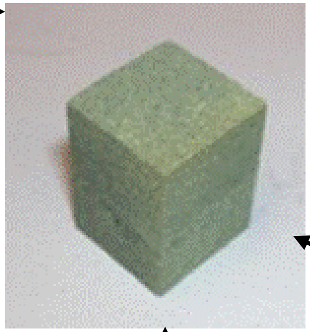


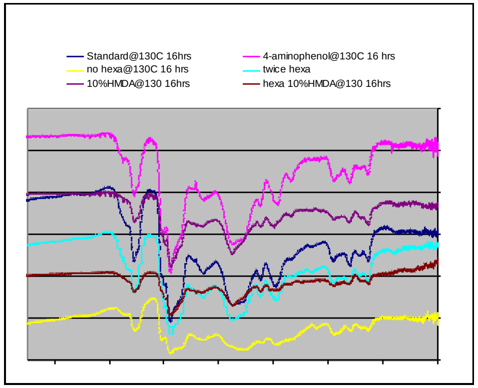
Raman — atomic



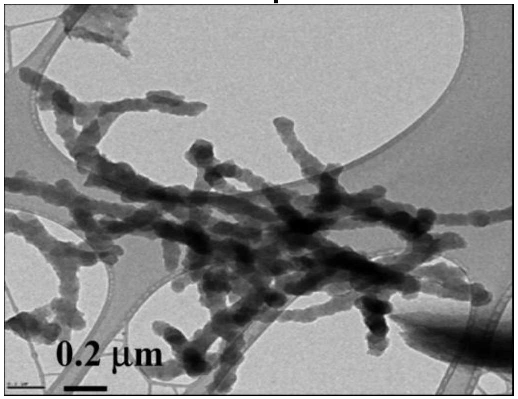


Thermogravimetric analysis — thermal stability

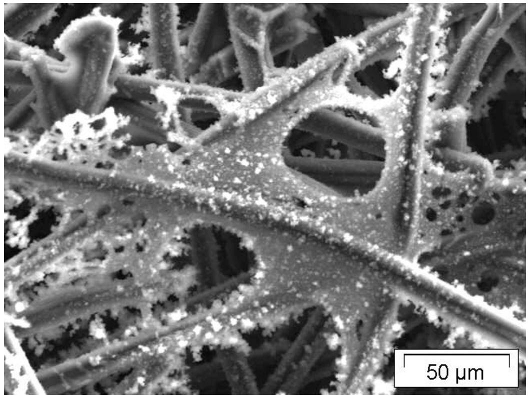




Infrared — molecular



TEM — nanoscopic



SEM — morphology

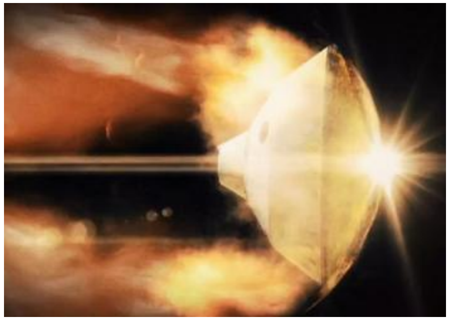
Direct Measurement of Ablative Material Performance

- **Direct measurements of ablative material performance can be gathered in two ways**
  - Ground tests, such are arc-jet testing at the NASA Ames Arc-jet complex
  - Instrumented flight tests

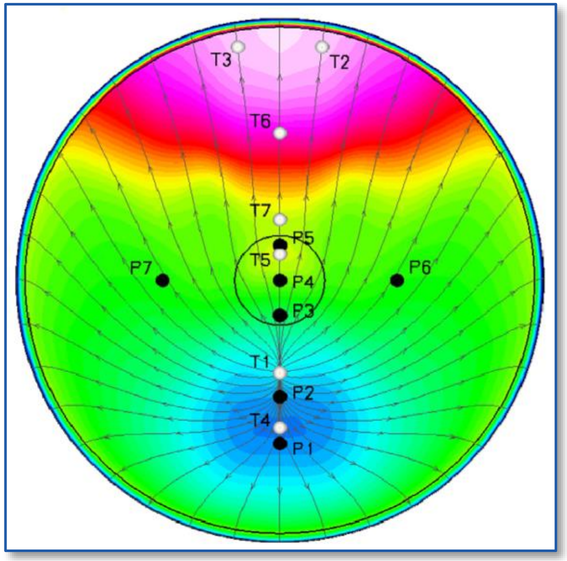
- **Arc-jet testing is somewhat expensive, but readily available**
  - Can reproduce most, but not all, of the actual atmospheric entry conditions in a single test
  - A range of arc-jet tests can bound the possible flight conditions, allowing for the creation of material response models that can accurately predict flight performance
- **Flight testing of ablative TPS materials is rare and very expensive**
  - MSL PICA heatshield was instrumented and data sent back to Earth
  - Some vehicle heatshields are recovered – Apollo, Stardust, SpaceX Dragon, X-37b
- **Measured data include:**
  - Total surface recession, estimated recession rates, and mass loss
  - Char depth
  - Transient thermal response (thermocouples imbedded in depth)

Importance of Flight Instrumentation

- **All atmospheric entries are essentially "experiments" from which we should gather data**



- **Data used to validate both material response and aerothermal (CFD) models**
  – Better models mean margins can be reduced and science payload increased
- **MSL PICA heatshield was instrumented with the Mars Entry Descent Landing Instrumentation (MEDLI) package**

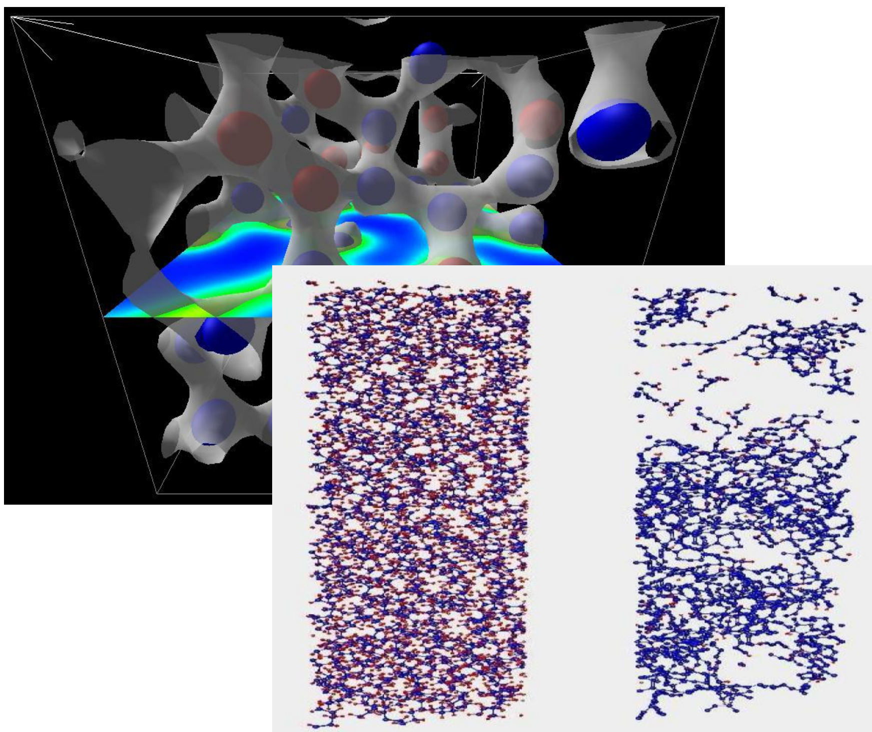


  – MEDLI instrumentation suite successfully measured temperature, pressure, and recession of the vehicle's primary heatshield
  – Seven (7) pressure ports, seven (7) thermocouple plugs with recession sensors
- **TPS flight instrumentation is often not originally included in the vehicle design**
  – Instrumentation must "buy its way" onto the vehicle – mission benefit
  – Must not negatively impact the primary mission

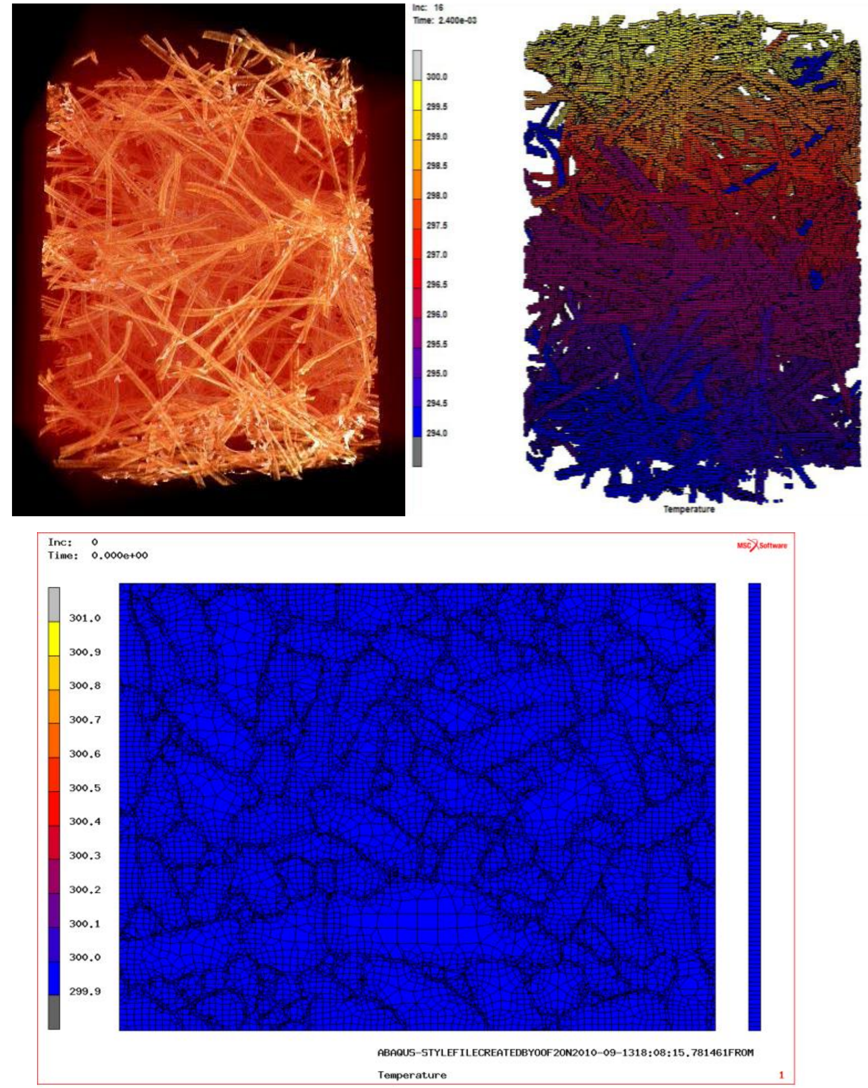
Focus on Computational Materials Modeling

Multiscale Computational Materials

- **Computational materials modeling uses a multiscale approach to help new ablative materials with mission specific properties**



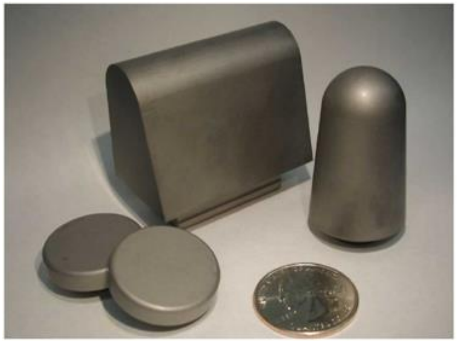
Atomic scale



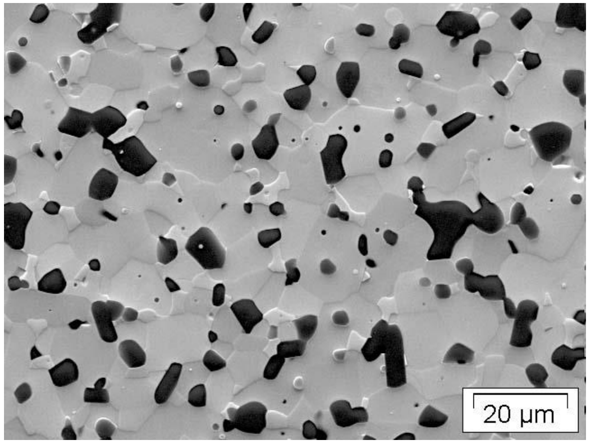
Microstructure scale

Computational Materials Modeling: UHTC Example

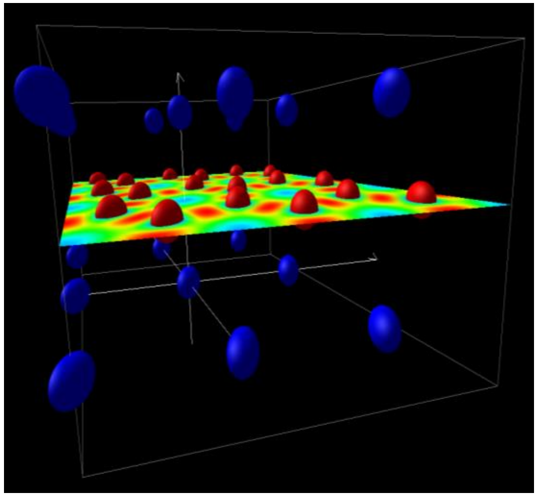
- **Goals**
  - Reduce materials development time
  - Optimize material properties/tailor materials
  - Guide processing of materials
  - Develop design approaches
- **Approach**
  - Develop models integrated across various length scales
  - Correlate models with experiment whenever possible



Examples of UHTC Components



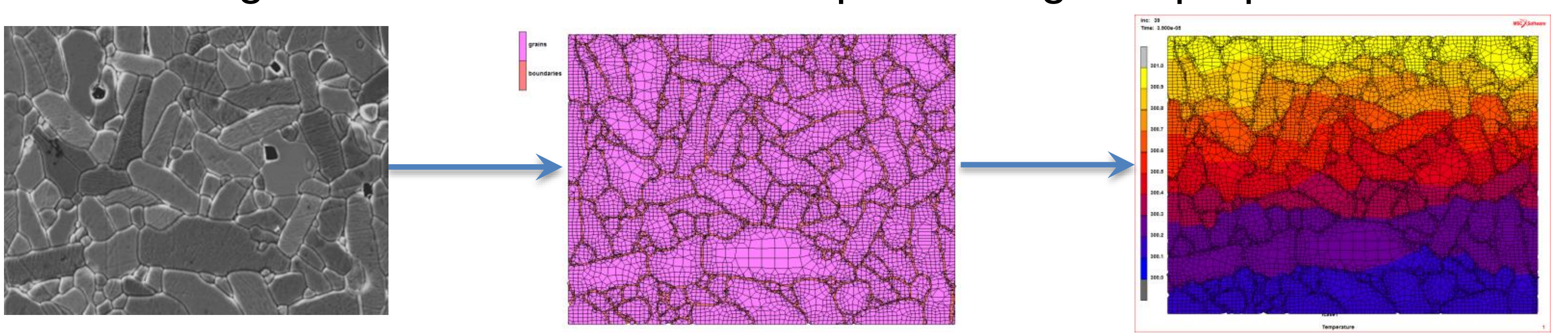
Micrograph of UHTC Material



Computational 3D structure with Boron and Zirconium planes

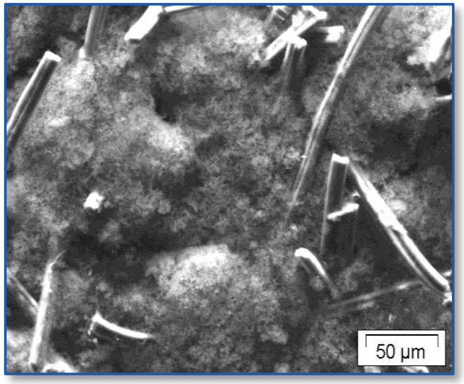
Modeling UHTCs – What's Next?

- **Accomplishments**
  - Ab initio calculations of lattice structure, bonding characteristics, elastic constants, phonon spectra and thermal properties of ZrB2 and HfB2
  - Ab initio calculations of formation and migration energies for simple defects (vacancies)
  - Development of interatomic potentials for ZrB2 and HfB2 for atomistic simulations
- **Opportunities**
  - Ab initio calculations of simple/ideal grain boundary structures with and without chemical impurities
  - No UHTC atomistic simulations exist in the literature. New potentials mean the field is wide open!
  - FEA modeling of microstructure to relate processing and properties

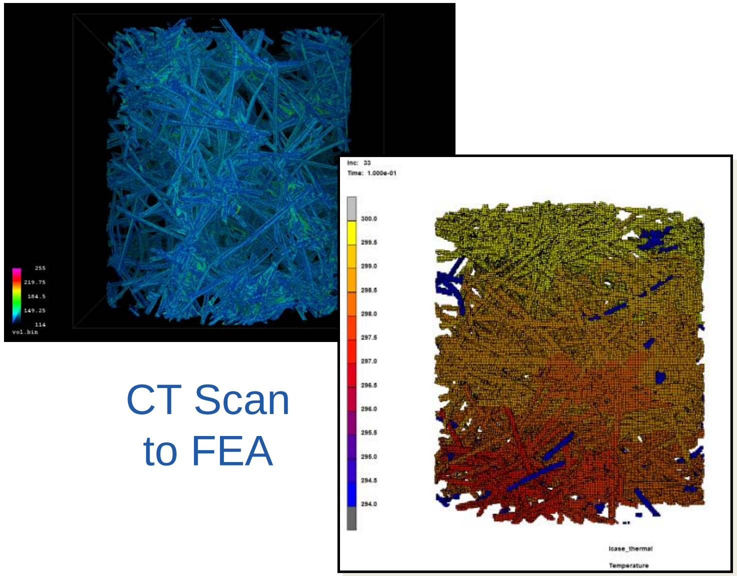


Computational Materials Modeling: Ablators Example

- **Intrinsically multi-scale materials with multiple decomposition phenomena**
- **Pyrolysis chemistry (ab initio)**
  - Pyrolysis simulation is very challenging, no current solution
- **Phenolic networks (atomistic)**
  - Virtual mechanical and thermal testing
  - Phenolic network design parameters
    - Linkage Sites
    - Cross-linking
- **Microstructure Modeling (continuum)**
  - X-ray CT images gives 3D micron scale, realistic microstructure
  - FEA models for thermal/mechanical analysis



PICA - carbon fiber/phenolic matrix



CT Scan to FEA

Final Comments

- **Thermal protection system design for spacecraft relies on clear understanding of material properties**
  - Designers need to know the material limits
  - Analysts need accurate thermal, mechanical, and physical properties in order to predict material behavior
- **TPS needs to fit the application – vehicle location, environment**
  - Reusable materials: ceramic tiles, UHTCs
  - Ablative single-use materials: PICA, AVCOAT
- **Critical to characterize materials and archive data**
  - For selecting appropriate material
  - To ensure material demonstrates desired behavior
  - To have materials ready for new missions
- **Need to gain full data value from flights/experiments with appropriate instrumentation**
- **Heritage materials may not always be heritage**

Goal of all TPS is reliable and efficient performance!

Acknowledgements

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  - Y.K. Chen
- **Computational Materials Modeling:**
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  - Charles W. Bauschlicher

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