



TFAWS
MSFC • 2017

Ablative Thermal Protection Systems Fundamentals

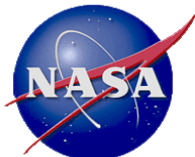
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Overview

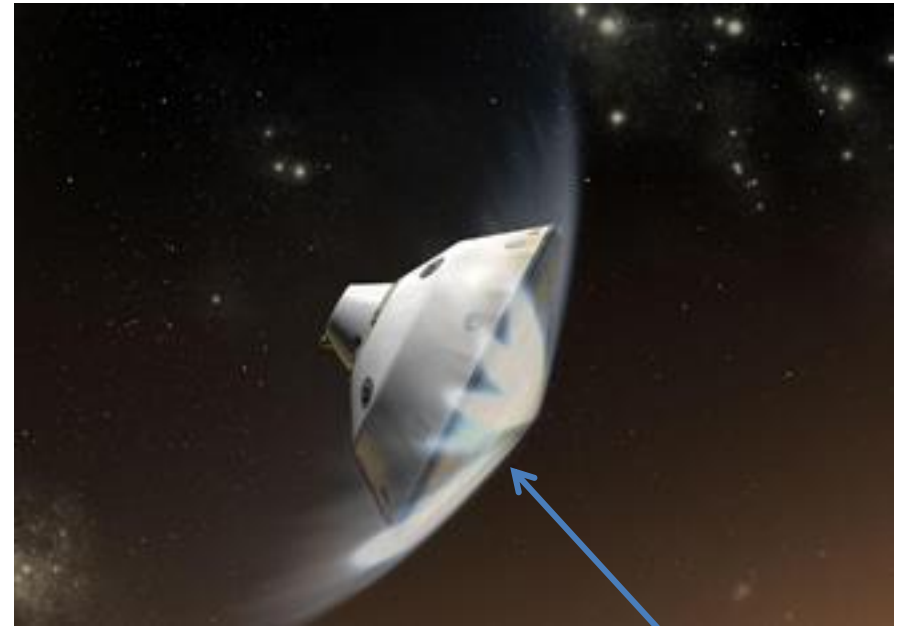
- Thermal protection approaches
- Basics of the ablation process
- Analyzing ablative materials
- Modeling ablative materials
- Sample ground test articles
- Summary



Thermal Protection Approaches



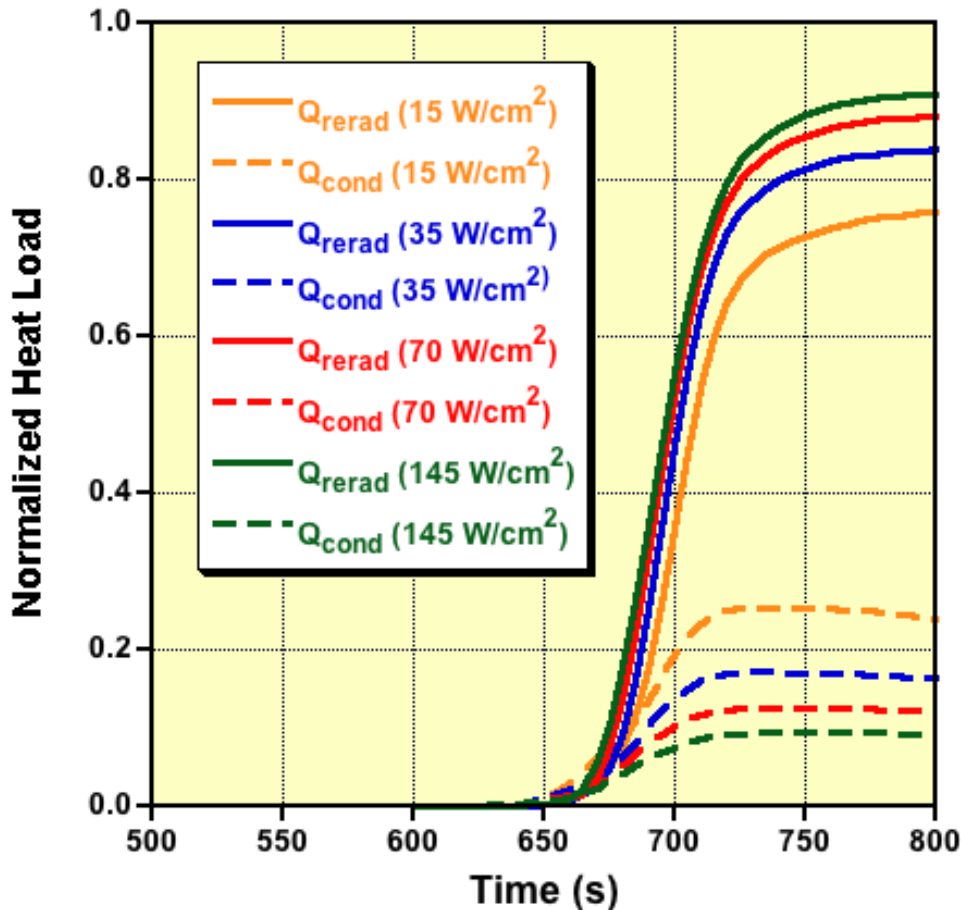
- Low heating environment $< 20 \text{ W/cm}^2$ on belly, 40 W/cm^2 on nose)
- Non-ablating, very low conductivity reusable materials used
- Conduction controlled by coatings to decrease convective heating and increase re-radiation



- Higher heating environment (as high as 50 kW/cm^2 on Galileo, 220 W/cm^2 on MSL)
- Ablative materials required
- Conduction controlled by including energy loss due to ablation processes

Importance of High Emittance

Surface re-radiation is the most effective TPS energy rejection mechanism and is most efficient as heat flux increases



- For both reusable and ablative TPS, a high emittance surface is desired to promote re-radiation
- As temperature increases, re-radiation increases
- Generally desirable to keep the heat at the surface, so as to increase re-radiation
 - Achieved by using materials with low thermal diffusivity
- Charring ablator example:
 - heat load at 15 W/cm²
 - ~75% re-radiated
 - ~25% conducted
 - heat load at 145 W/cm²
 - ~90% re-radiated
 - ~10% conducted

$$q_{re-rad.} = e_w S T_w^4, \text{ where } e_w = \text{emissivity}$$

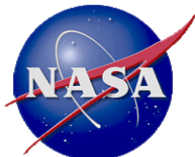


Ablation

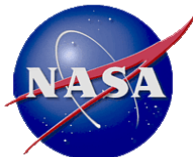
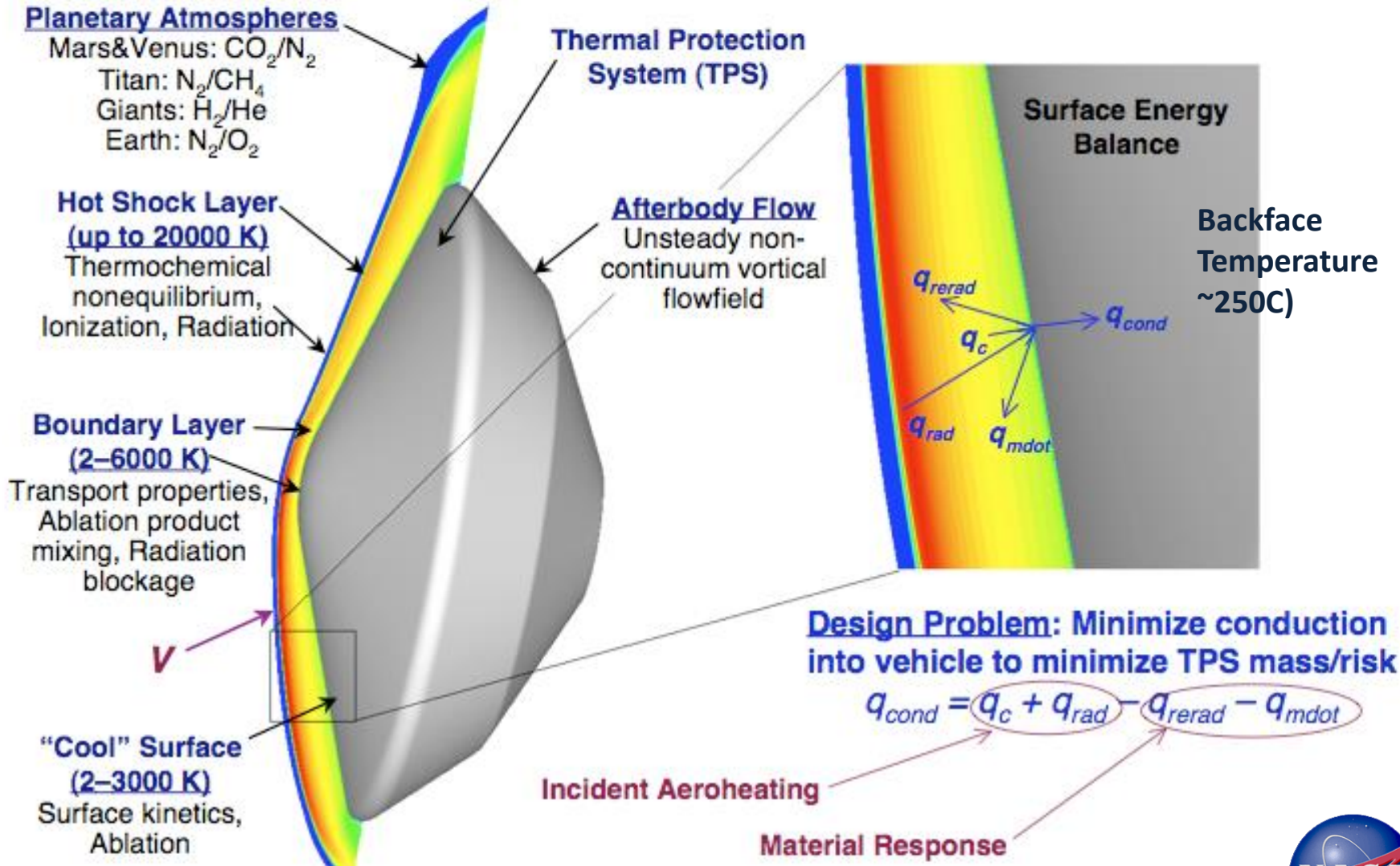
- Ablation is a means of thermal protection based on physicochemical transformations of solid substances by convective or radiation heat flow....Huh?

In other words

- Ablation is energy management through material consumption

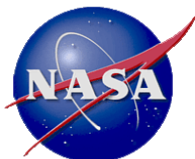


High Energy Heatshield Environments



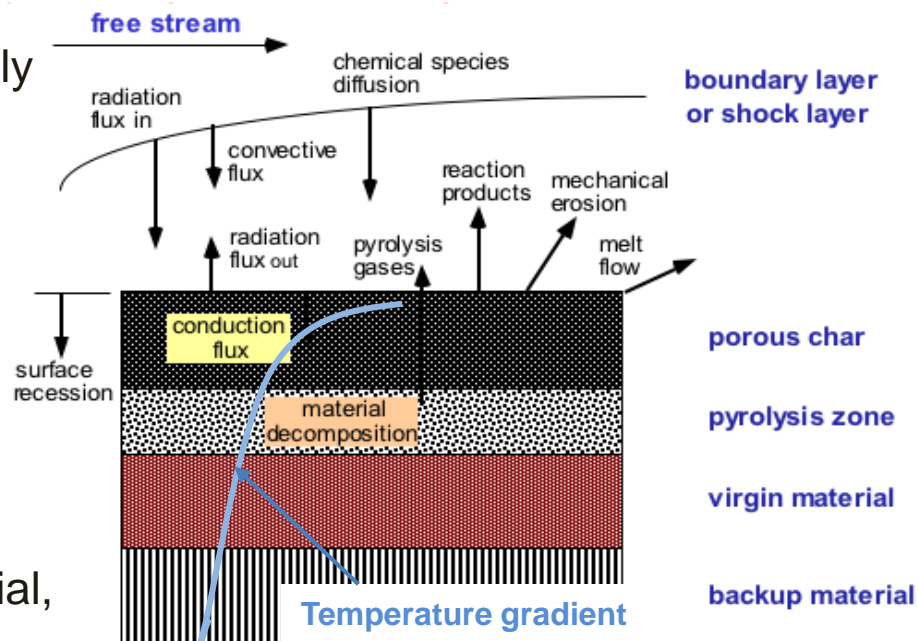
Ablative Materials for Heatshields

- Ablative materials for heatshield design are typically composites
- Composite materials are made from two or more constituent materials with significantly different [physical](#) or [chemical properties](#), that when combined, produce a material with characteristics different from the individual components. The individual components remain separate and distinct within the finished structure.
- Reinforcement materials include carbon, glass, and/or organic polymers that can react with the flowfield gases to oxidize, melt, or sublimate
- Matrix materials are usually polymer resins like phenolic or silicone that react and decompose when heated, losing mass and leaving some carbon behind (charring)



How an Ablator Works

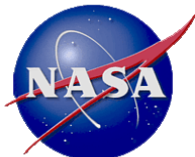
- Hot gases in the boundary layer convectively heat the surface
- Radiant flux from the shock layer heat the surface
- Heat is either re-radiated out or conducted into the surface
- The polymer in the composite begins to decompose (often absorbing energy during decomposition) and pyrolysis gases are formed, carbon remains and a char layer begins to form
- The thermal front moves through the material, causing more decomposition



- The pyrolysis gases, formed deeper in the composite are at a lower temperature than the near surface char, so as they flow through the char, they cool it
- The charred surface reacts (oxidation, sublimation, etc) with the boundary layer and material is removed, causing recession (this may be either exo- or endothermic)
- As the pyrolysis and gases formed at the surface blow into the boundary layer, they thicken it and reduce the convective heating

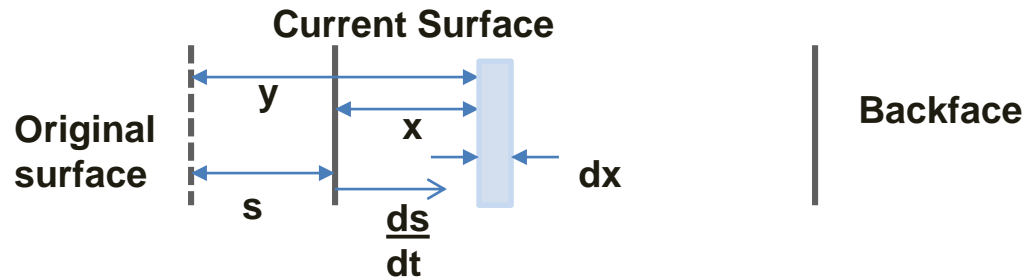
Methods of Surface Removal

- Melting (metals, glass, ceramics, etc.)
 - Heat of fusion (not very significant)
 - $M(s)^* \Leftrightarrow M(l)^*$
- Vaporization (liquid layer from melted metals, glass, ceramics)
 - Heat of vaporization
 - $M(l)^* \Rightarrow M(g)^*$
- Oxidation (graphite, carbon chars, etc.)
 - Exothermic
 - $M(s)^* + O_2(g) \Rightarrow MO_2(g)$
- Sublimation
 - Heat of sublimation (can be significant)
 - $M(s)^* \Rightarrow M(g)$
- Spallation (mechanical material loss)
 - Mass loss with minimal energy accommodation



1-D In-depth Energy Balance

$$\rho c_p \frac{\partial T}{\partial \theta} \Big|_x = \frac{1}{A} \frac{\partial}{\partial x} \left(kA \frac{\partial}{\partial x} \right)_\theta + (h_g - \bar{h}) \frac{\partial \rho}{\partial \theta} \Big|_y + \frac{\dot{m}_g}{A} \frac{\partial h_g}{\partial x} \Big|_\theta + \dot{s} \rho c_p \frac{\partial T}{\partial x} \Big|_\theta$$



1. Rate of sensible energy storage
2. Rate of thermal conduction
3. Rate of energy due to the conversion of solid to gas (pyrolysis) at a fixed location
4. Rate of convection due to pyrolysis gases flowing through the material
5. Rate of convection of sensible energy due coordinate system movement (coordinate system is tied to the moving surface)

Decomposition in Ablative Materials

- Typically, we model ablative as matrix (resin) and reinforcement so the density of the solid can be stated as:

$$\rho_s = \Gamma \rho_{resin}(T, \theta) + (1 - \Gamma) \rho_{reinf}(T, \theta)$$

where Γ is the resin volume fraction.

- Goldstein identified that pyrolysis of many resins can be well-represented as two reactions and, therefore, the pyrolysis rate of the composite can be written as:

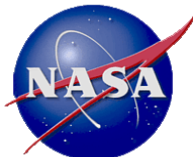
$$\frac{d\rho_s}{d\theta} = \Gamma \left[\frac{d\rho_1}{d\theta} + \frac{d\rho_2}{d\theta} \right] + (1 - \Gamma) \frac{d\rho_{reinf}}{d\theta}$$

where

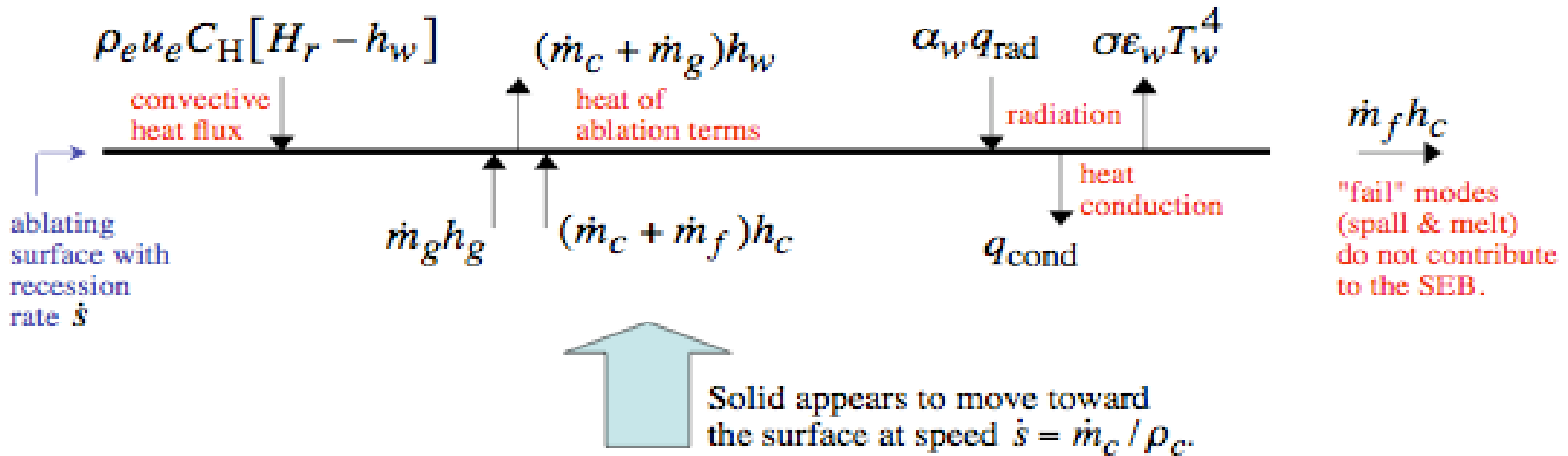
$$\left[\frac{d\rho_i}{d\theta} \right] = -k_{f_i} \rho_{0i} \left(\frac{\rho_i - \rho_{r_i}}{\rho_{0i}} \right)^{n_i}$$

and

$$k_{f_i} = k_{0i} \exp(-E_i / RT)$$



Surface Energy Balance



$$\rho_e u_e C_H (H_r - h_w) - (\dot{m}_c + \dot{m}_g) h_w + \dot{m}_c h_c + \dot{m}_g h_g + \alpha_w q_{rad} - \sigma \epsilon_w T_w^4 - q_{cond} = 0$$

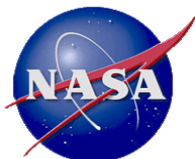
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|---|---|
| <ol style="list-style-type: none"> 1. Convective heat flux 2. Energy of the gases leaving the surface 3. Energy of the solid entering the surface from below | <ol style="list-style-type: none"> 4. Energy of the pyrolysis gases entering the surface from below 5. Radiant heat flux in 6. Reradiated radiant flux 7. Conduction into the material from the surface |
|---|---|

Developing Models for Ablative Materials

- A *high-fidelity* model of an ablative TPS material will *accurately** predict:
 - Surface recession
 - Surface temperature
 - Bondline temperature
 - Char thickness/char depth
 - In-depth temperatures
- Mathematical models of material thermal/ ablation performance are used for:
 - TPS design
 - Materials trade studies
 - TPS mass estimates for systems analysis studies
 - etc.

* $\pm 10\%$ on temperature; $\pm 20\%$ on surface recession and char thickness



Why Do We Need High Fidelity Models?

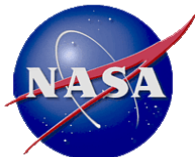
- Typically, TPS design sizes the material thickness to limit bondline temperature to a predefined maximum (adhesive limit)
- If bondline temperature is the design criterion, why isn't a model that accurately predicts maximum bondline temperature adequate?
 - The flight environment cannot be accurately simulated in ground test \Rightarrow requirement to use mathematical models for ground-flight connectivity
 - Maximum bondline temperature is of limited value unless *time* of max bondline temperature is predicted accurately (flight events)
- Mathematical models that adequately represent materials physics and chemistry can be extrapolated to flight with some confidence
 - Performance assessment at conditions beyond range of ground tests
 - Basis for assessment of design margin requirements



Approach to Model Development - 1

Thermochemical Properties:

1. Conduct TGA (thermogravimetric) experiments (inert gas, low temperature rise rates) Residual mass fraction defines *char yield*. Data fits provide decomposition kinetic constants.
2. Conduct DSC experiments (inert gas, low temperature rise rates). Data provides heat of reaction for pyrolysis reactions as function of temperature.
3. Measure elemental composition of virgin material
4. Measure heat of combustion of virgin material and derive heat of formation (unless known)
5. Measure or derive elemental composition of char from known constituents and char yield data
6. Derive heat of formation of char from known constituents and existing data
7. Derive elemental composition of pyrolysis gases. Develop model(s) for pyrolysis gas enthalpy using combination of thermochemical equilibrium calculations and measured heat of pyrolysis data.

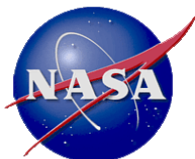


Approach to Model Development - 2

Thermophysical properties:

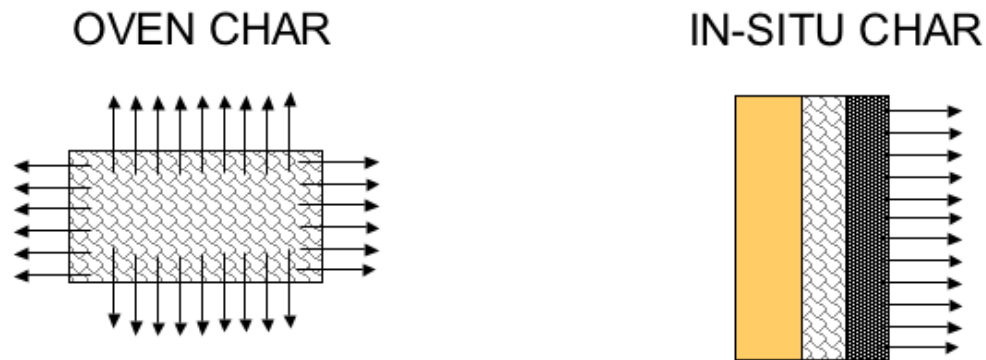
1. Measure specific heat of virgin material as function of temperature.
2. Measure thermal conductivity of virgin material as function of temperature (and orientation, if appropriate).
3. Derive specific heat of char from known (or derived) composition using method of mixtures.
4. Measure optical properties of virgin material
5. Derive optical properties of char from known composition and properties of similar materials (or determine experimentally)
6. Measure thermal conductivity of char as function of temperature (and orientation, if appropriate).

Assertion: the thermal conductivity of the char cannot be measured in standard lab facilities!



Approach to Model Development - 3

- Traditional practice has been to bake the material in an oven and measure the thermal properties of the resulting “char.”
- Studies conducted under the Apollo heat shield program (and re-validated in other programs) demonstrated that the cellular structure of “oven chars” was different than the cellular structure of chars formed in ground test or flight.



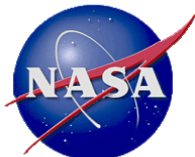
- Given that finding, why would one expect the thermal conductivity of oven chars to be representative of actual material properties?

Approach to Model Development - 4

1. Assemble all measured/derived thermophysical and thermochemical properties (with exception of char thermal conductivity)
2. Conduct ground tests over range of conditions of interest
3. Instrument each ground test material sample with multiple in-depth thermocouples (ensuring data capture over full range of anticipated temperatures)
4. Derive the “char thermal conductivity” $[k_c = f(T, p)]$ through **iterative correlation** of the in-depth thermocouple data

WARNING: The char thermal conductivity derived in this manner should not be treated as a material property as it compensates for the uncertainties in all of the other properties/parameters in the material thermal model.

This approach has been used successfully for many materials and TPS applications for over 40 years and repeatedly validated with flight data.



Examples of Instrumented Ground Test Articles

- Arc jet test samples



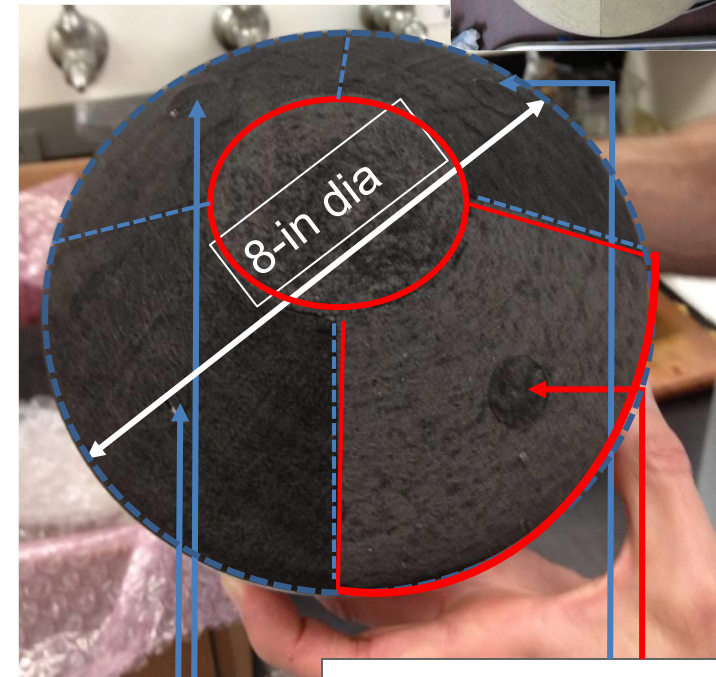
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Standard PICA

New “Small Probe” configuration



Standard PICA
Conformal PICA



Summary

- You have gotten a introductory look at ablative materials
 - What they are
 - How they work
 - How to analyze them
 - How to model them
- I encourage you to dig deeper to learn more about ablative TPS and how to design with them

Any Questions?

