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Ablative Thermal Protection

An Overview

presented by
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Agenda

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- Why Ablative TPS
- Definitions (ablative vs. reusable TPS)
- Ablative TPS Chronology
  - Strategic reentry systems
  - Solid rocket motor nozzles
  - Space (manned missions and planetary entry probes)
- Ablation Mechanisms
  - Surface
  - Subsurface
- Ablative Materials Testing
  - Environment simulation
  - Thermophysical & thermochemical properties
- Ablative Materials Modeling
- Summary

Why Ablative TPS

- Atmospheric entry probes are designed to slow down from orbital or higher speeds using aerodynamic drag. A consequence of this is the heating encountered by the entry probe.
- A Thermal Protection System(TPS) is required to protect an entry probe from this heating.
- All NASA planetary entry probes (to date) have used ablative TPS
- TPS is a single point-of-failure subsystem, i.e., critical!
- Two classes of TPS:
  - Reusable TPS:
    - No changes in mass, properties
    - Typically limited to *relatively* mild entry environments (e.g., Shuttle < 75 W/cm^2)
  - Ablative TPS:
    - Accommodates high heating rates and heat loads through phase change and mass loss
    - Heritage approach to TPS used for over 40 years in a broad range of applications

Ablative TPS materials

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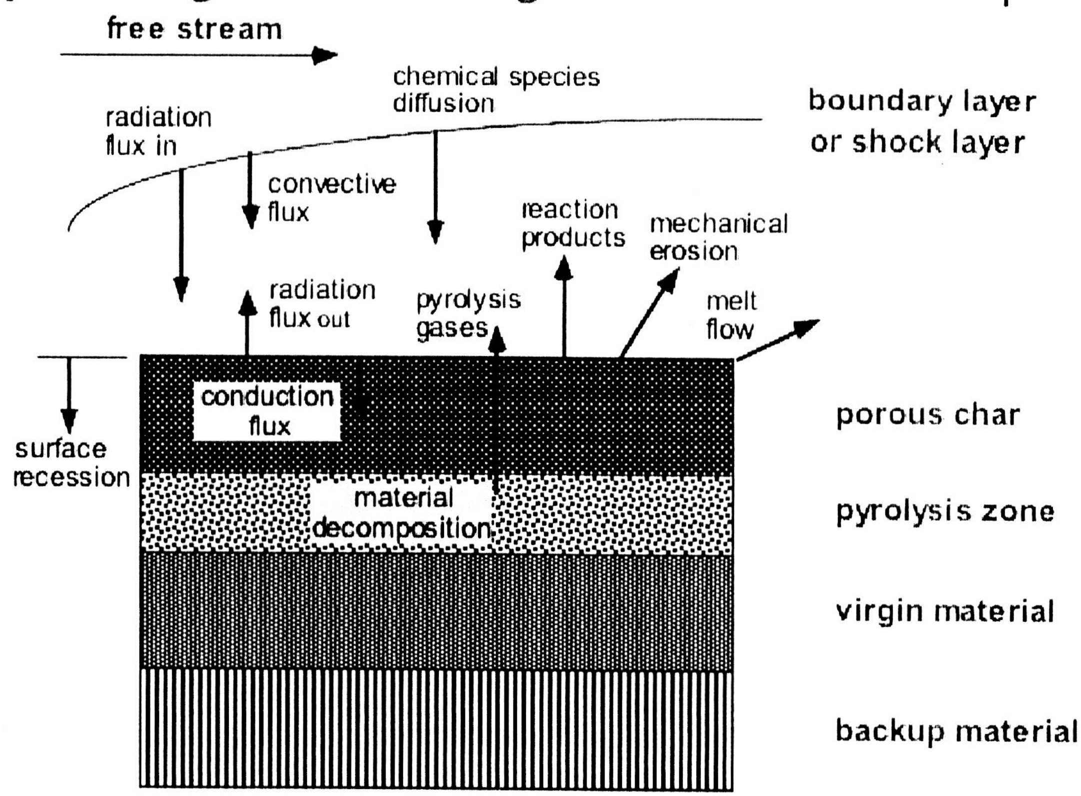
Energy management through material consumption



Ablative TPS Chronology - 1

- Strategic reentry systems
  - 1st ICBM ~ 1958
    - teflon, 2.18 g/cm^3
  - 2nd ICBM ~ 1965
    - silica phenolic, 1.63 g/cm^3
  - MMII ~ 1970
    - Graphite NT, carbon phenolic HS, 1.45 g/cm^3
  - MMIII ~ 1975
    - C-C NT, carbon phenolic HS, 1.45 g/cm^3
  - Peacekeeper ~ 1980
    - C-C NT, carbon phenolic HS, 1.45 g/cm^3

Ablative TPS Chronology - 2

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- Solid Rocket Motor Nozzles
  - Carbon phenolic/silica phenolic
  - Graphite throat inserts
  - Carbon-carbon throat inserts

NASA's Entry Probe History

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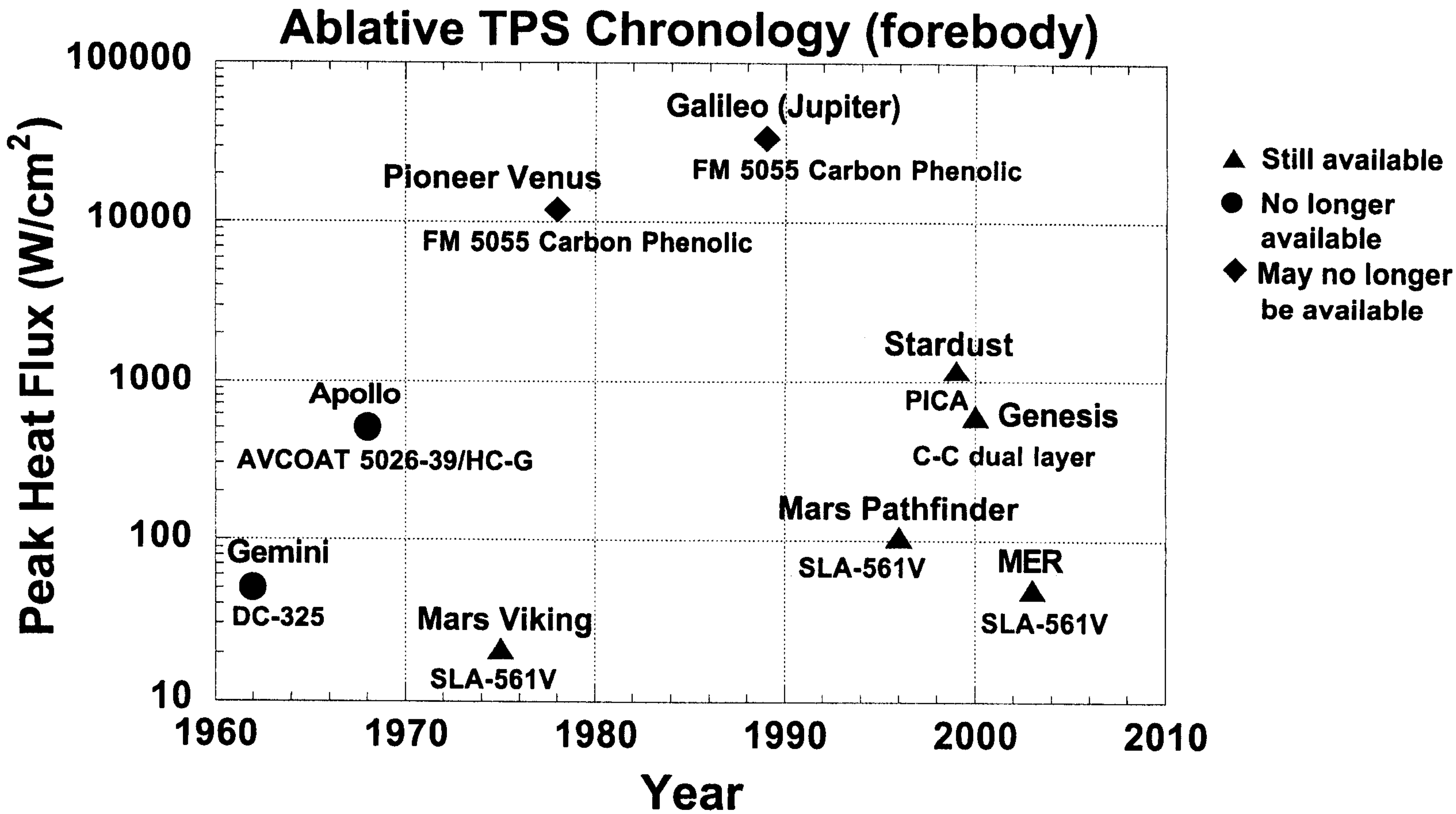
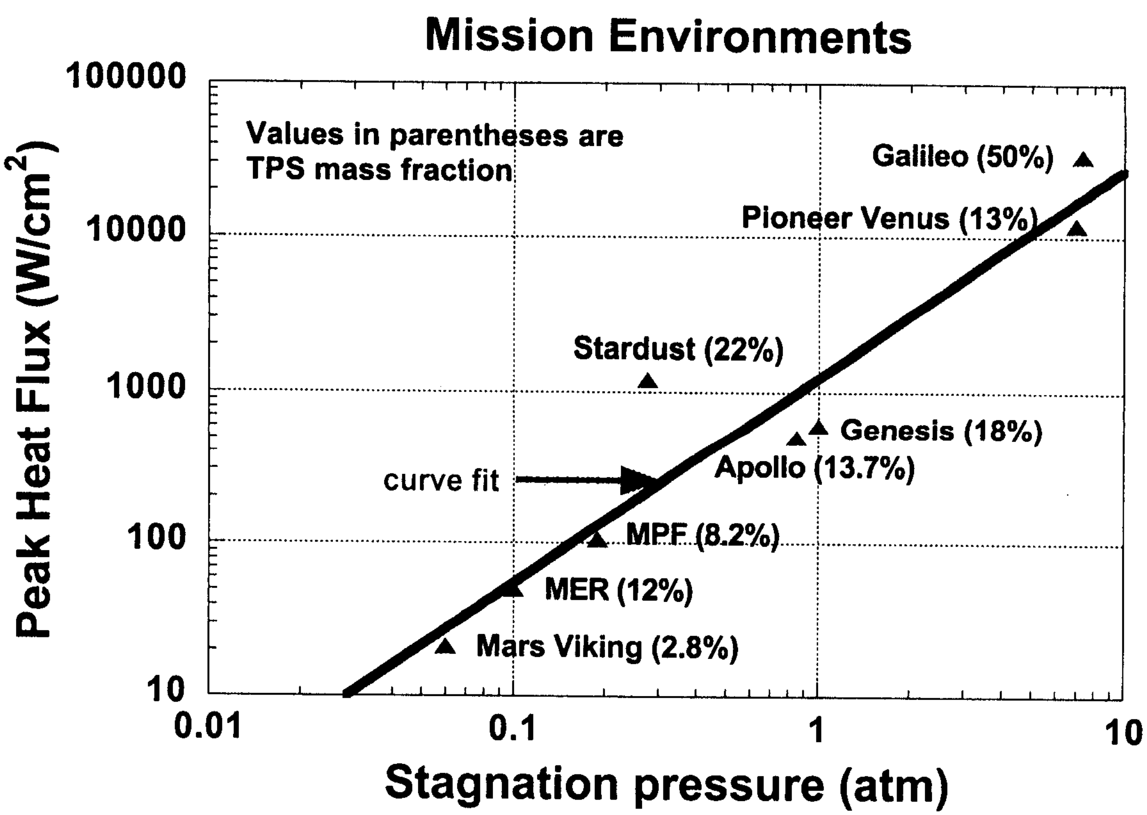


In over 40 years, NASA entry probes have only employed a few ablative TPS materials. Half of these materials are (or are about to be) no longer available.

Broad Range of Entry Environments



NASA entry probes have successfully survived entry environments ranging from the very mild (Mars Viking ~25 W/cm^2 and 0.05 atm.) to the extreme (Galileo ~30,000W/cm^2 and 7 atm.)

TPS Mass Fraction

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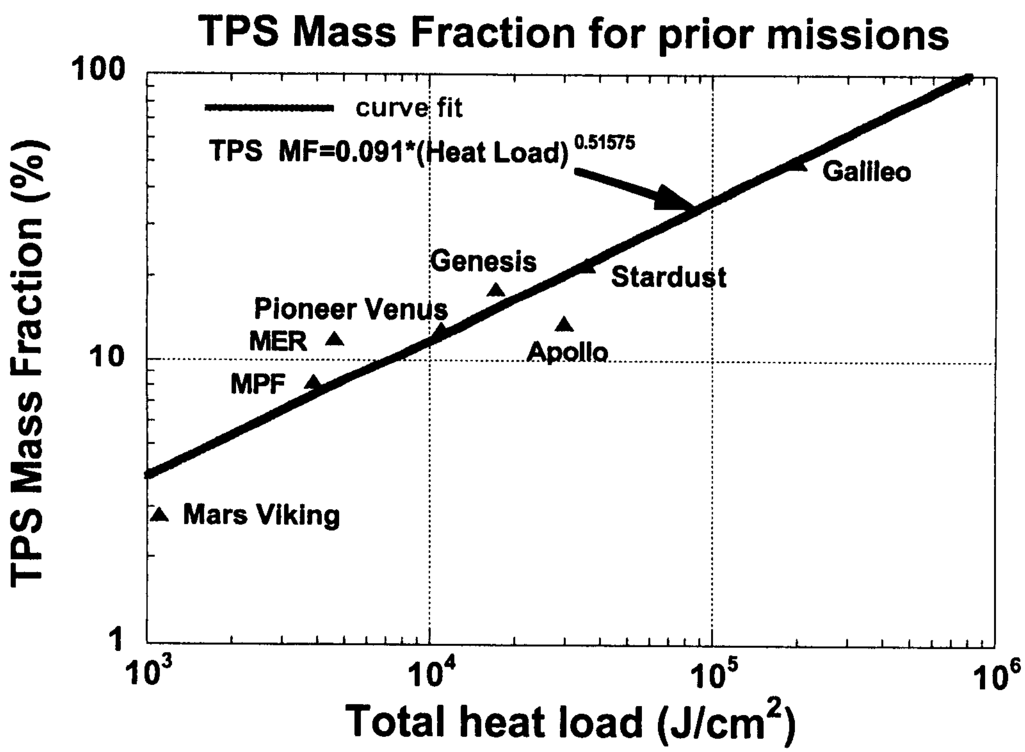

- TPS material selection requires an assessment of the entry environment and trade between ablation and insulation performance
- Pioneer-Venus with 13% TPS mass fraction is an excellent example of TPS optimization for a very demanding mission
  - High heat fluxes
  - High pressures
  - Relatively modest total heat load
  - Carbon phenolic (not a very good insulator but an excellent ablator) was a good choice.

The TPS mass fraction for an entry probe is a strong function of the total integrated heat load (e.g., ≈ 50% for Galileo) and the TPS material optimal performance characteristics.

Material Performance Limits

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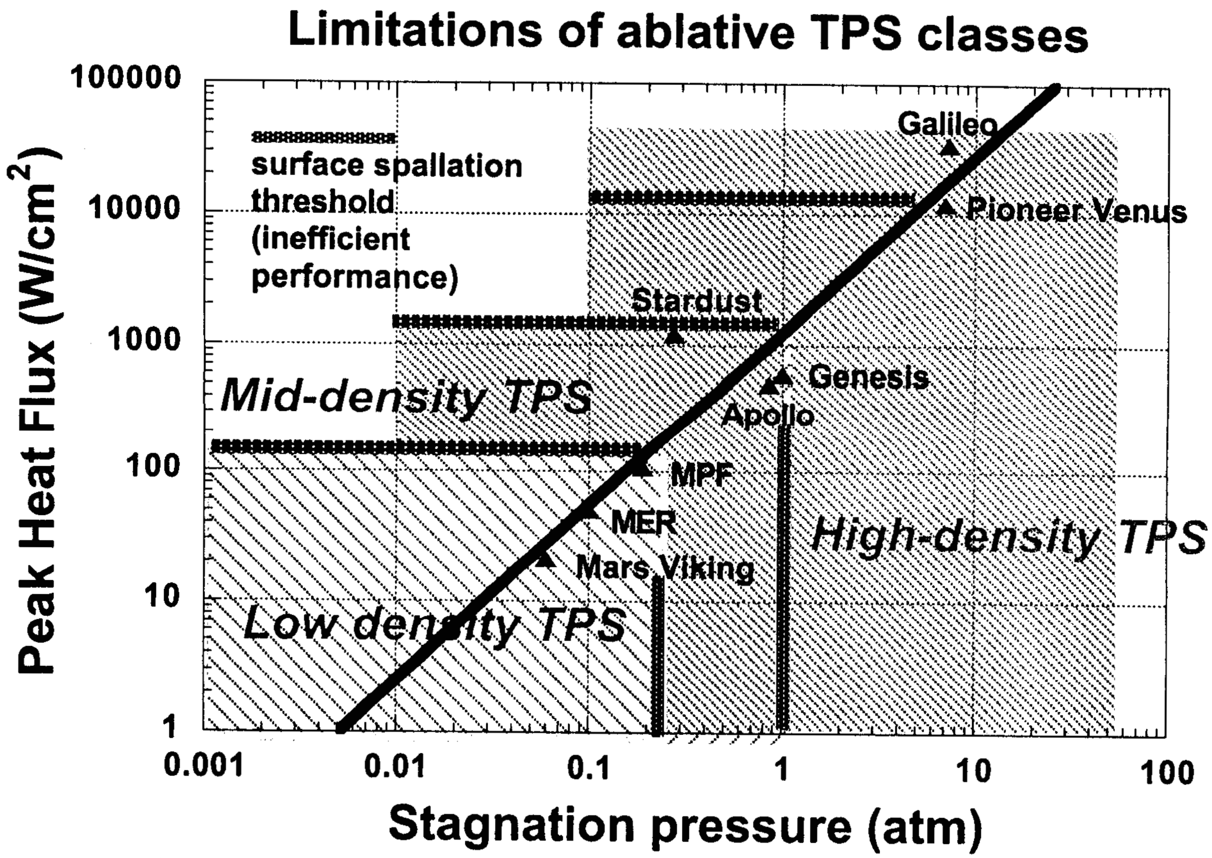

Optimal performance regime is balanced between ablative and insulation efficiency. When material is used outside of optimal zone, inefficient performance leads to non-minimal mass fraction.

Ablation Mechanisms - 1

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- Surface
  - Transpiration (mass injection into the BL)
  - Surface melting
    - Liquid layer runoff/shear removal
  - Surface oxidation
    - $2C(s) + O_2(g) \Leftrightarrow 2CO(g)$
    - $C(s) + CO_2(g) \Leftrightarrow 2CO(g)$
  - Surface vaporization
    - $SiO_2(l) \Leftrightarrow SiO(g) + 1/2O_2(g)$
  - Surface sublimation
    - $nC(s) \Leftrightarrow C_n(g)$

Ablation Mechanisms - 2

- Surface (concluded)
  - Surface spallation
    - Material structural failure (macroscale)
- Subsurface
  - Pyrolysis
    - Organic resin(s) $\Rightarrow$ pyrolysis gas + char
  - Convective cooling
    - Pyrolysis gas percolation through the char to surface

Ablation Mechanisms - 3

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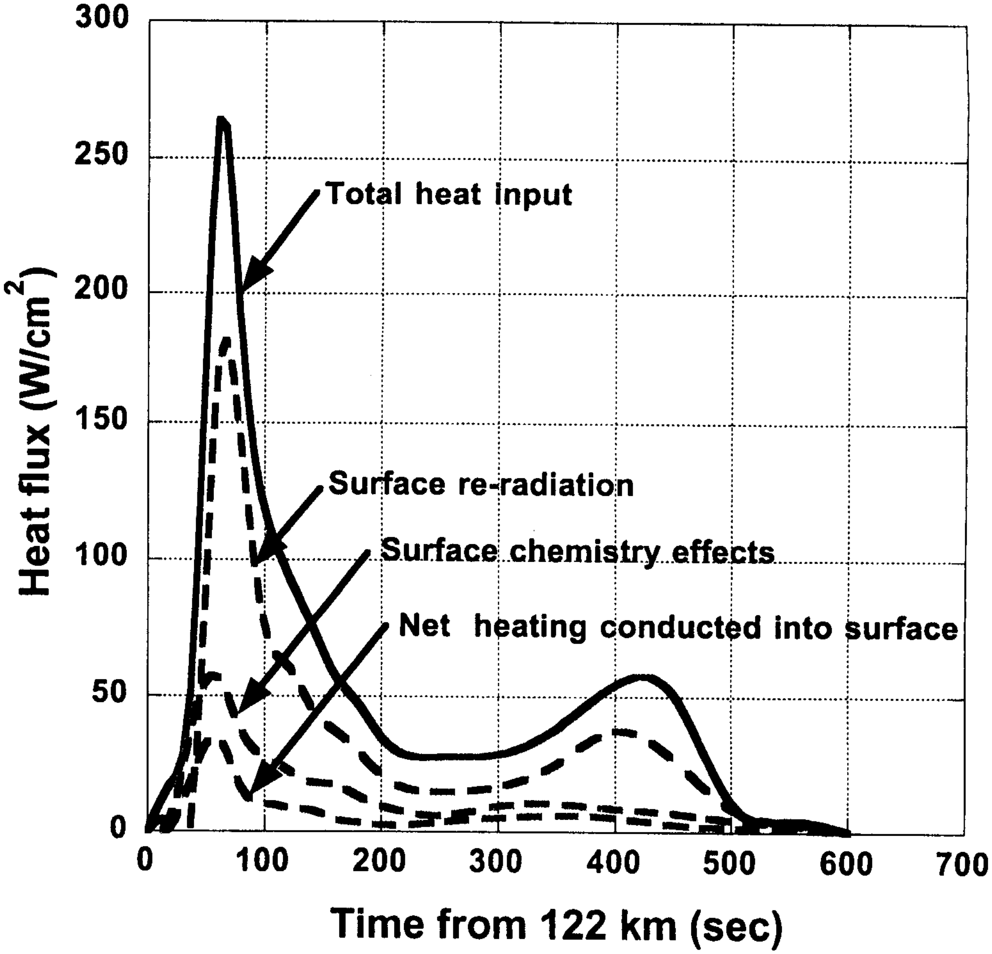
- The plot illustrates how the input *heat flux* is accommodated by the ablative TPS material
- Surface re-radiation is the most effective energy accommodation mechanism
- Only a small fraction of the input heating is conducted into the TPS material

Apollo Flight AS-501, Body Point 705



Ablation Mechanisms - 4

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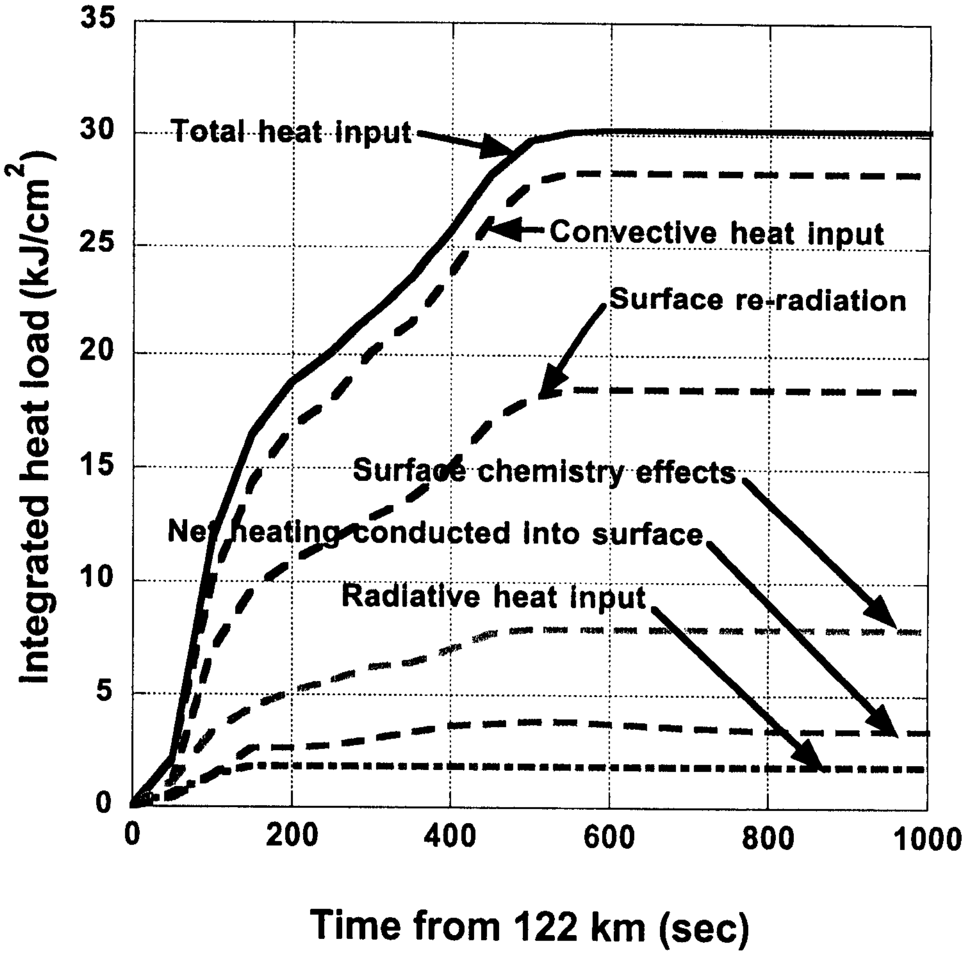
Apollo Flight AS-501, Body Point 705

- This plot illustrates how the input *heat load* is accommodated by the ablative TPS material
- Surface re-radiation is the most effective energy accommodation mechanism (≈60%)
- Only a small fraction of the input heating is conducted into the TPS material (≈10%)



Ablation Mechanisms - 5

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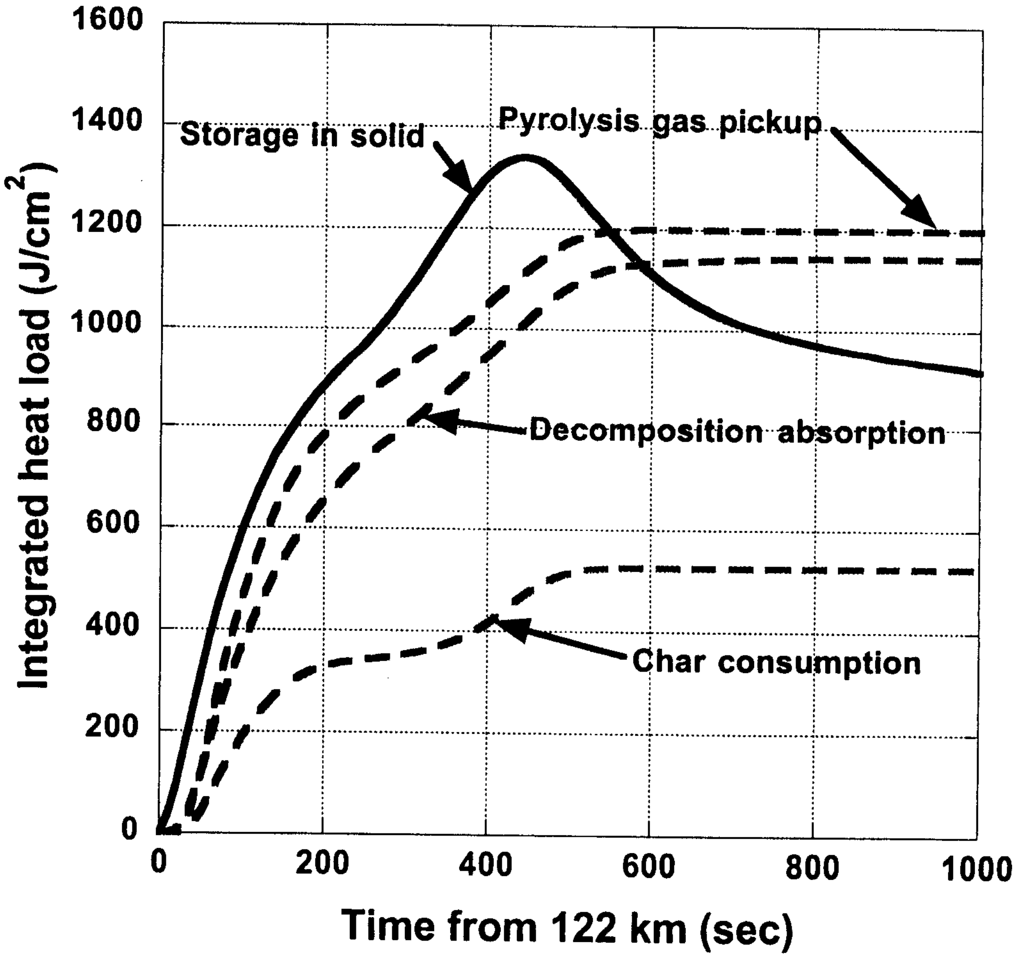
- This plot illustrates how the net energy conducted into the charring TPS material is accommodated by subsurface mechanisms
- Less than 50% of the energy is stored; pyrolysis processes absorb an even greater amount
- Recession-related energy absorption was relatively small due to small surface recession

Apollo Flight AS-501, Body Point 705



Ablative Materials Testing - 1

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Environment Simulation

- Arc Plasma Facilities
  - Cannot simulate all environmental parameters simultaneously $(\dot{q}, H, p, \tau, \ldots)$
  - Need to understand the anticipated ablation mechanisms at the conditions of interest and their sensitivity to environmental parameters
  - Surface temperature is a key parameter
    - Must be measured in every test
  - Installing subsurface thermocouples is an art
    - Conductive chars, effects of T/C mass, etc.

Ablative Materials Testing - 2

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Environment Simulation

- Arc plasma facilities (concluded)
  - Post-test evaluation
    - Surface recession
    - Shape change
    - Sectioning
    - Char depth
    - Char thickness
    - Char chemistry/density? (profiling)

Ablative Materials Testing - 3

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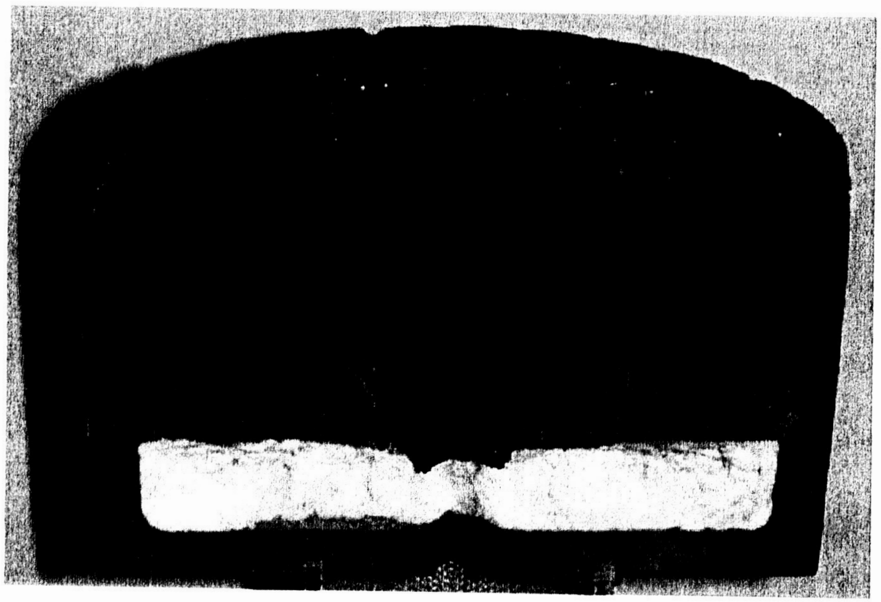
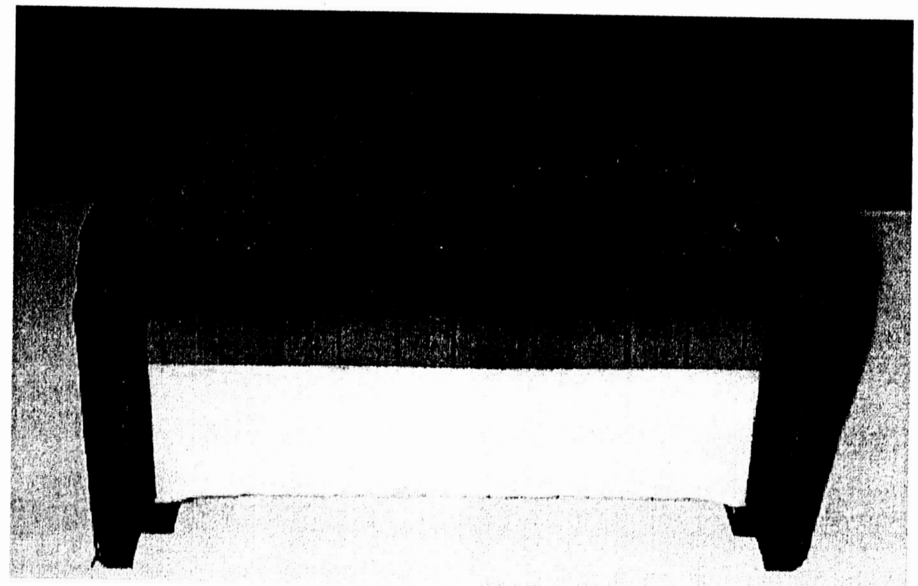
Apollo 5026-39/HC-G



Acusil I



Cross-sections of post-test arc jet samples illustrate important material performance characteristics (e.g., char depth, char thickness, transitions in char chemistry, cracking, delamination, etc.)

Ablative Materials Testing - 4

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Environment Simulation

- Other test facilities
  - Combustion facilities
    - Is surface chemistry important?
    - Is free-stream enthalpy important?
  - Laser facilities
    - Is surface chemistry important?
    - Is free-stream enthalpy important?
    - Is absorption length important?

Ablative Materials Testing - 5

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Thermophysical & Thermochemical Properties

- Standard tests for thermochemical properties (e.g., TGA, DSC)
  - Controversy over applicability of heating rates
  - Chemical composition of virgin material
  - Chemical composition of (post-test) char
- Standard tests for measuring thermophysical properties of *virgin* material $(\rho, c_p, k, \varepsilon)$
- No tests for measuring properties of char
  - Oven prechars are <u>not</u> representative
  - Best derived from T/C data correlation

Ablative Materials Modeling - 1

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- Mathematical models/codes developed in the 60s
  - Munson & Spindler (Avco)
    - First to formulate the equations describing the in-depth energy transfer in a charring material (1963)
  - Every aerospace prime contractor developed their own (proprietary) code based on Munson & Spindler
    - REKAP, CHAP, STAB, etc.
  - Kratsch, Hearne & McChesney (Lockheed) first to describe surface ablation chemistry in terms of non-dimensional mass loss rates (1963)
  - Kendall, Rindal & Bartlett (Aerotherm) first to develop thermal response codes for charring materials (ACE, CMA) with consideration of surface and in-depth chemistry (1968)
    - Requires model for enthalpy of pyrolysis gases $= f(T, p)$
    - Employs surface boundary conditions coupled to surface thermochemistry solutions

Ablative Materials Modeling - 2

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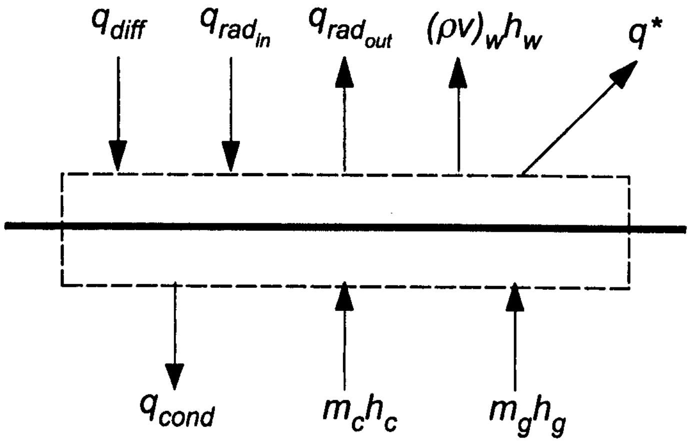

$$\rho c_p \frac{\partial T}{\partial \theta}\Big)_x = \frac{1}{A}\frac{\partial}{\partial x}\left(k A \frac{\partial T}{\partial x}\right)_\theta + \left(h_g - \bar{h}\right)\frac{\partial \rho}{\partial \theta}\Big)_y$$

$$+ \dot{s} \rho c_p \frac{\partial T}{\partial x}\Big)_\theta + \frac{\dot{m}_g}{A}\frac{\partial h_g}{\partial x}\Big)_\theta$$

FM5055 Carbon Phenolic
Thermochemical Equilibrium
Pressure = 0.10 atm