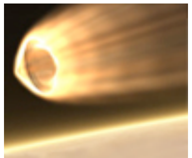

Thermal Protection System (TPS) Design and the Relationship to Atmospheric Entry Environments

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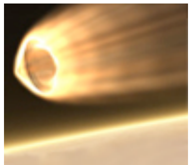
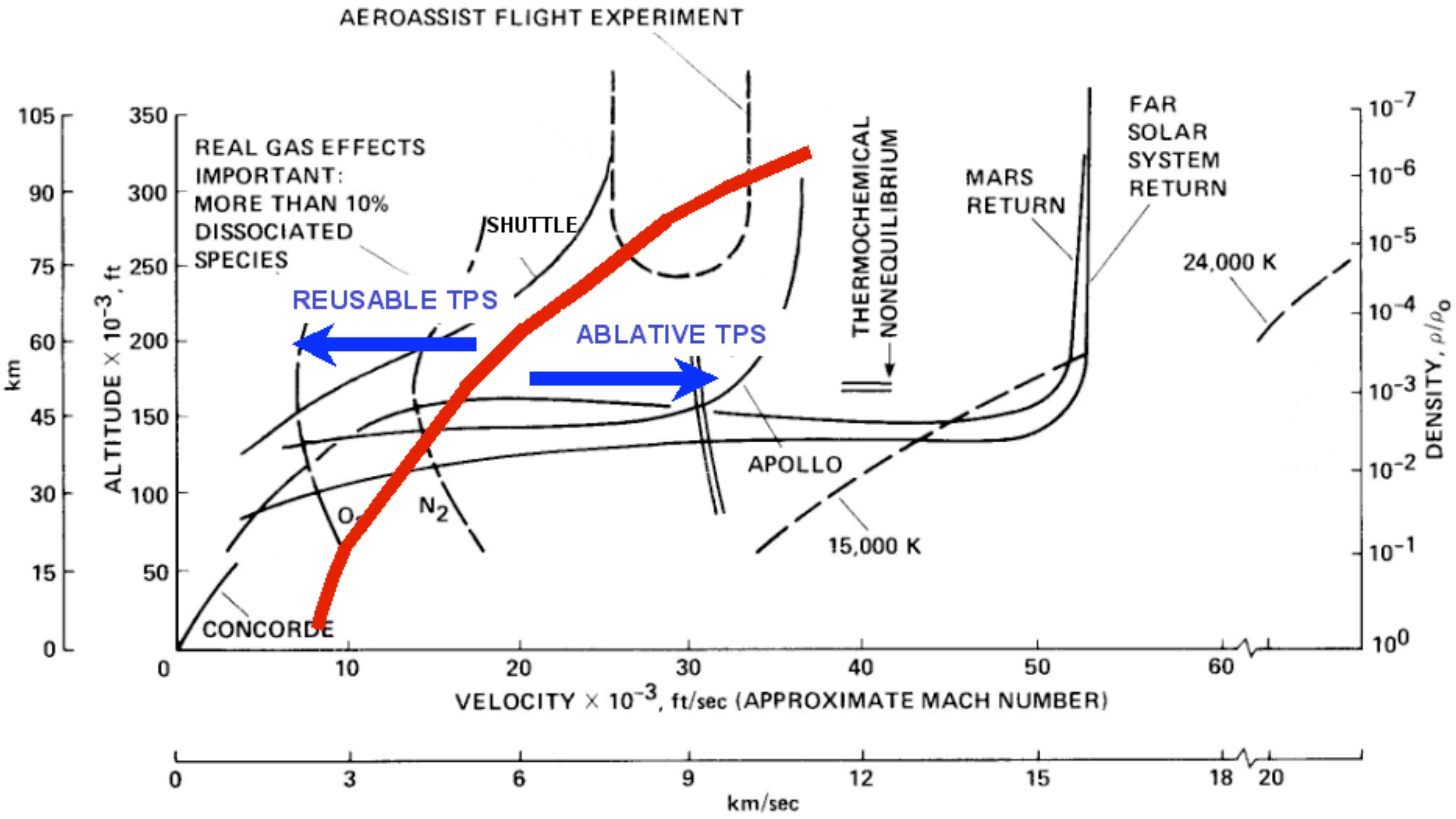
Agenda

- Why Ablative TPS?
- What is ablative TPS?
- Entry environments for planetary probes
  - Key Physical Challenges
  - Sample Entry Environments
- TPS Selection
  - Failure modes
  - Heat flux, pressure, atmospheric composition
  - Heat load
- TPS Testing
- Summary



Why Ablative TPS?



From John Howe, "Hypervelocity Atmospheric Flight: Real Gas Flow Fields," NASA TM 101055, 1989

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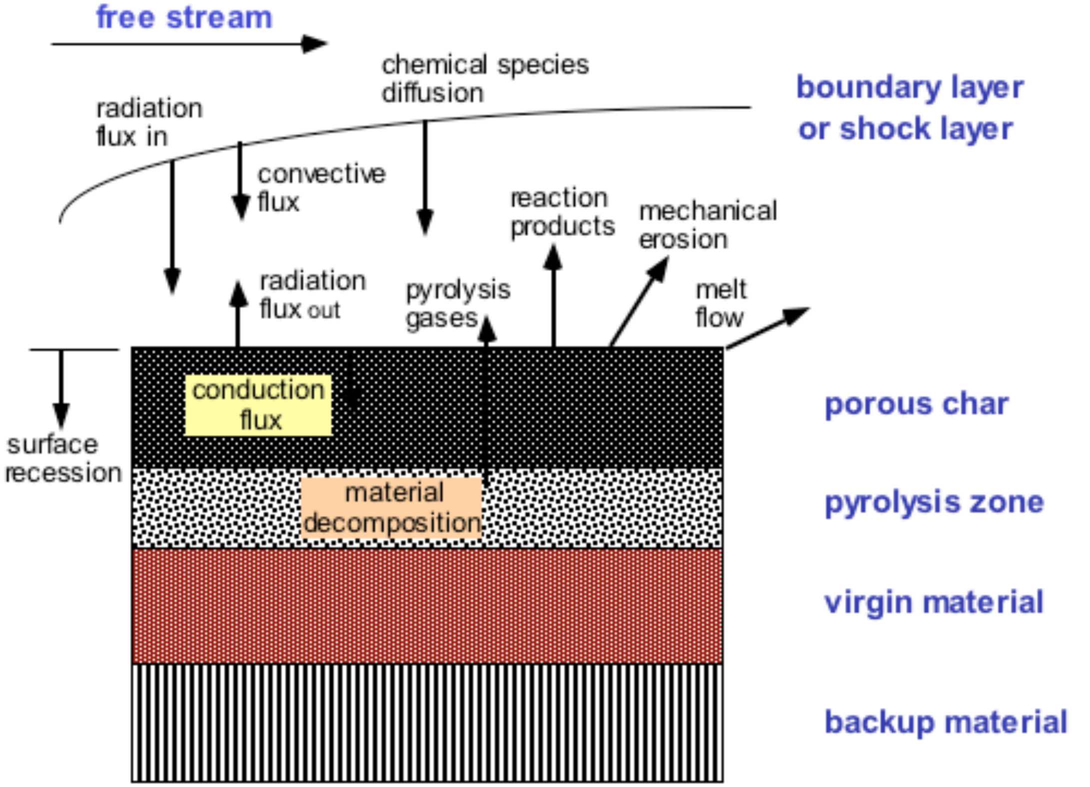
What is ablative TPS?

Energy management through material consumption



free stream

chemical species diffusion

radiation flux in

convective flux

boundary layer or shock layer

reaction products

mechanical erosion

radiation flux out

pyrolysis gases

melt flow

surface recession

conduction flux

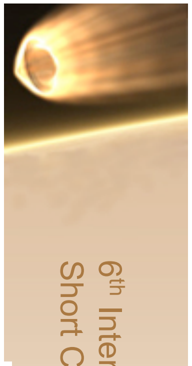
material decomposition

porous char

pyrolysis zone

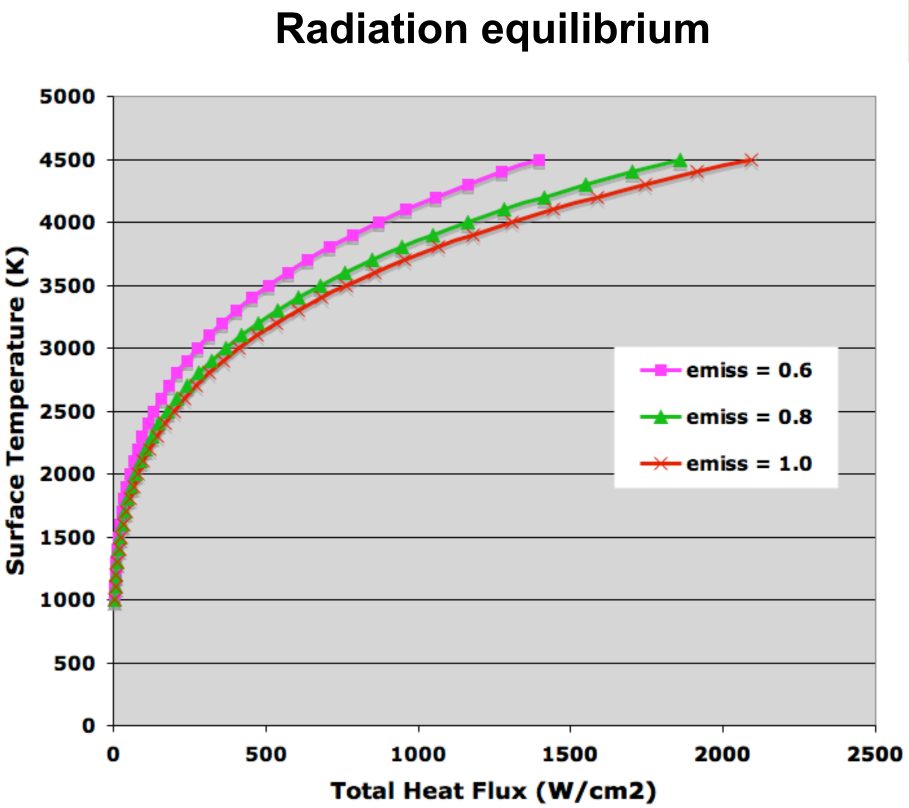
virgin material

backup material

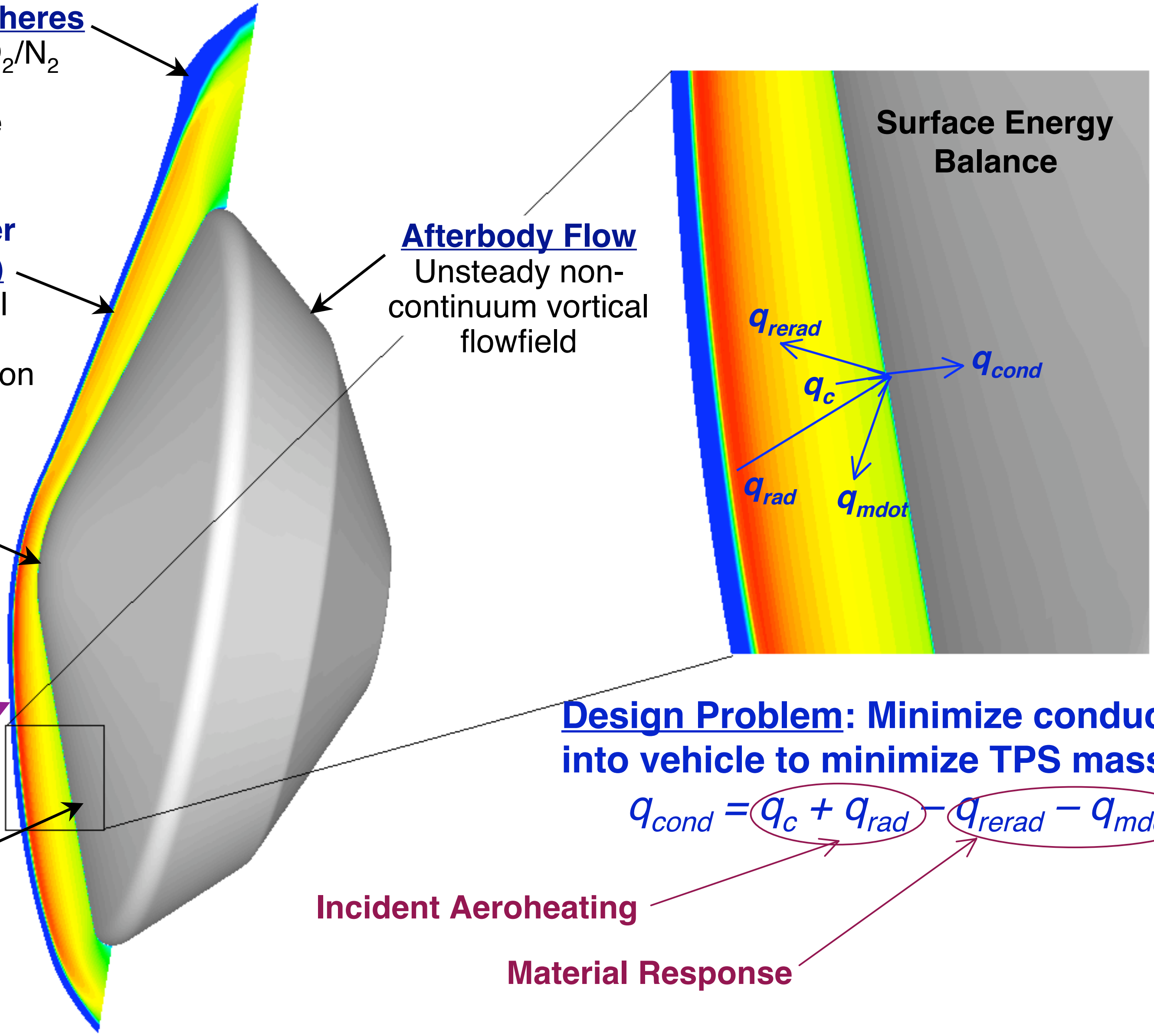


How hot is *hot*?

- *All* materials are (potentially) ablative materials
  - If exposed to typical entry heating, any material will get to temperatures where it will either melt, vaporize, oxidize, sublime, etc.
- For comparison, the temperature of the sun is ≈ 6000 K
- The gas near the heated TPS surface (behind the shock) is at much *higher* temperature



Aerothermodynamics of Planetary Entry



Planetary Atmospheres
Mars&Venus: CO_2/N_2
Titan: N_2/CH_4
Giants: H_2/He
Earth: N_2/O_2

Hot Shock Layer (up to 20000 K)
Thermochemical nonequilibrium, Ionization, Radiation

Boundary Layer (2–6000 K)
Turbulence, Ablation product mixing, Radiation blockage

"Cool" Surface (2–3000 K)
Surface kinetics, Ablation

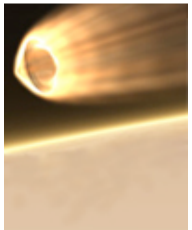
Afterbody Flow
Unsteady non-continuum vortical flowfield

Design Problem: Minimize conduction into vehicle to minimize TPS mass/risk

$$q_{cond} = q_c + q_{rad} - q_{rerad} - q_{mdot}$$

Incident Aeroheating

Material Response



Energy Loss over Time

- ***Reentry generates a lot of energy:***

	Energy (MJ)		
	MER	Genesis	Galileo Probe
Atmospheric Interface	1260	1414	1.07×10^6
Parachute Deploy	105 (92%)	84 (94%)	1.28×10^5 (88%)
End	0.2 (99.98%)	0.9 (99.94%)	18 (99.998%)

- ***Fortunately, most of this energy does not reach the surface***
  - >90% of total energy is dissipated via the bow shock heating the atmospheric gases

Stardust Capsule

The McGraw-Hill Companies www.AviationNow.com/awst $6.00 JANUARY 23, 2006

AVIATION WEEK & SPACE TECHNOLOGY

STARDUST Hypersonic Time Capsule

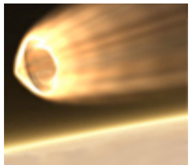
Page 20

About the Cover

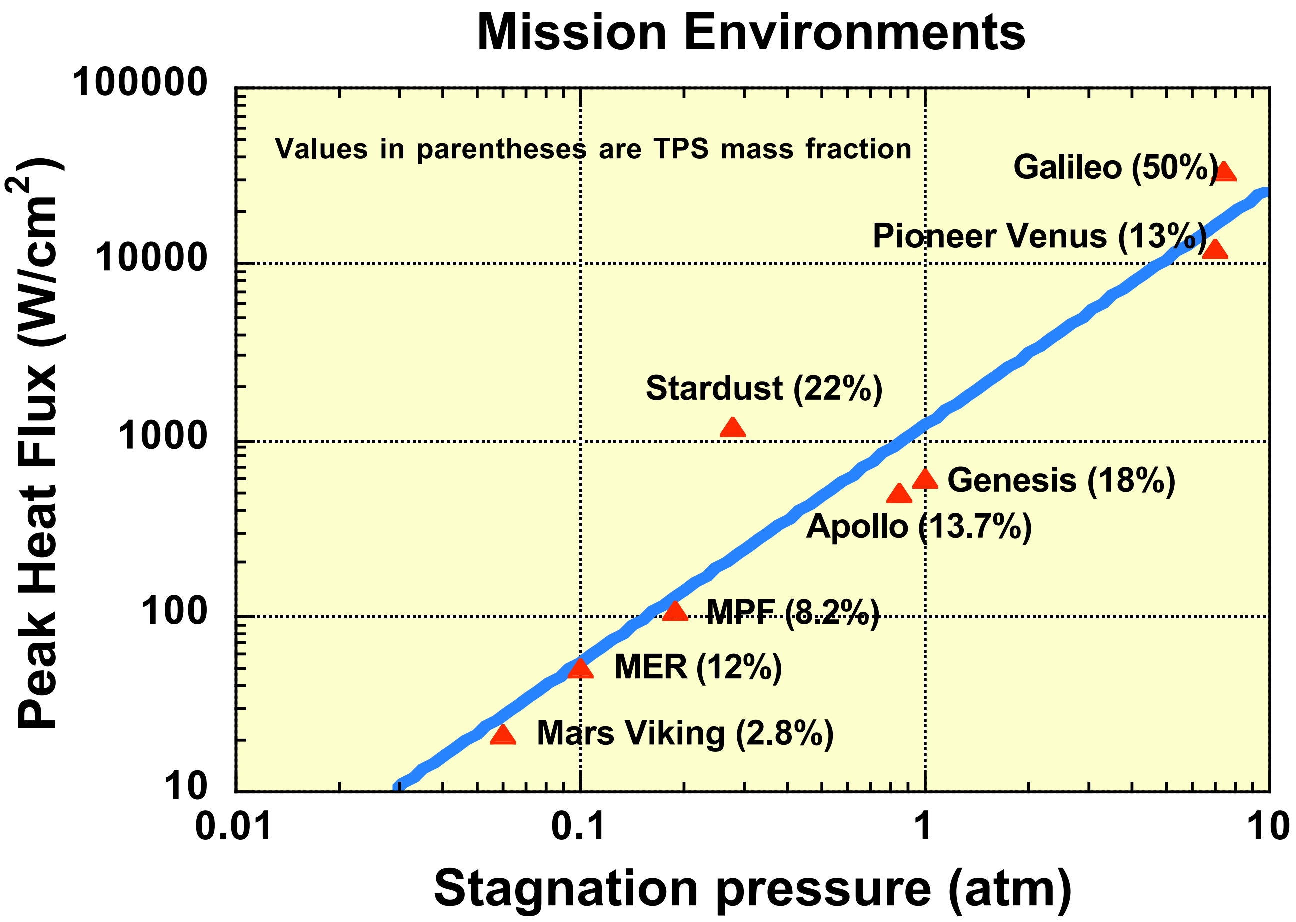
The fastest reentry on record of any man-made object produced this meteor-like image in the night sky above Nevada as the Stardust return capsule streaked to a perfect landing in Utah (see p. 20). Besides returning dust from Comet Wild 2, the capsule's blazing reentry was studied by meteorologists. It also confirmed NASA's modeling techniques for deep space return missions. Utah State University's Mike Taylor captured this image from a DC-8 observation aircraft flown on behalf of NASA Ames Research Center. On the

Robots for Lunar Exploration

Page 44



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.)

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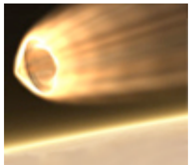


Representative Environments

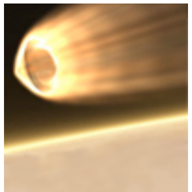
Planned missions will require TPS able to survive a broad range of entry conditions

Direct Entry

	Venus	Earth	Mars	Jupiter	Saturn	Titan	Neptune
q (kW/cm^2)	2-7	0.6-2	0.05-0.5	30-60	2-5	0.05-0.25	2-10
Q (kJ/cm^2)	10-20	10-40	5-10	200-500	50-150	2-6	100-400
p (atm)	10	0.25-0.5	0.25-0.5	5-10	0.5-5	0.25	0.5-5

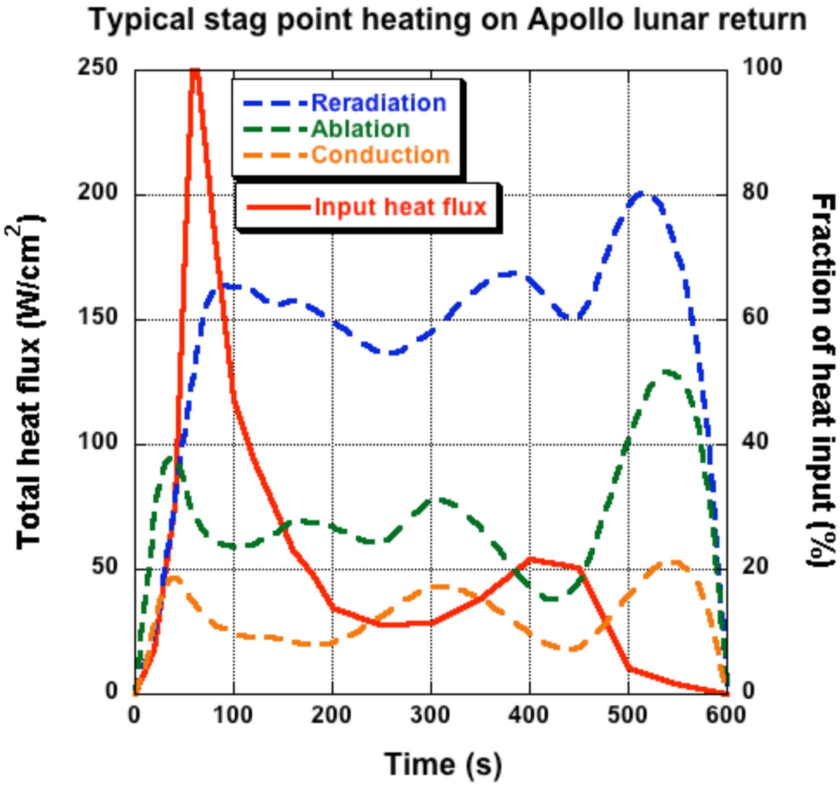
Aerocapture

	Venus	Earth	Mars	Jupiter	Saturn	Titan	Neptune
q (kW/cm^2)	1-2	0.5-1	0.05-0.3	N/A	3-10	0.05-0.15	3-10
Q (kJ/cm^2)	40-80	20-50	10-30	N/A	200-500	5-12	500-2000
p (atm)	0.3	0.25	0.25	N/A	0.5-1	0.1	0.5-1.5

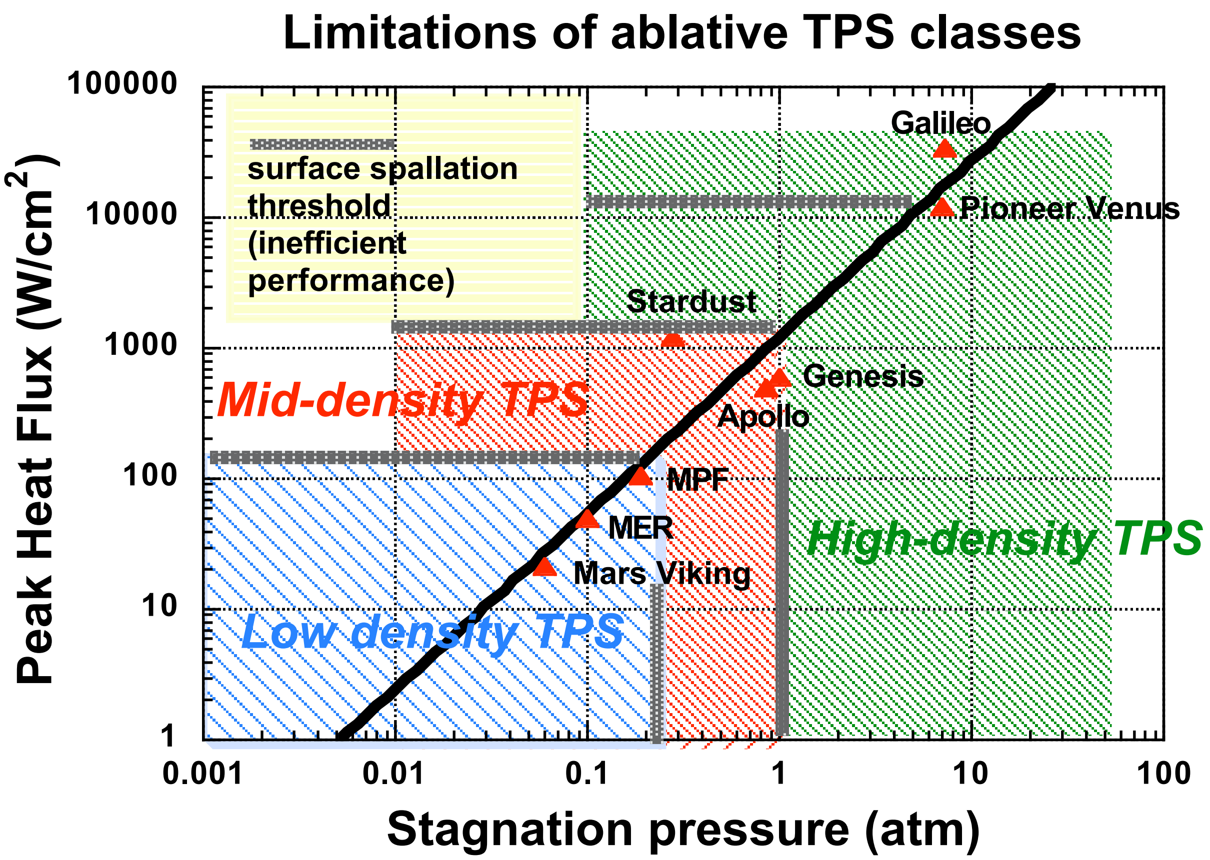


How do ablative materials manage energy?

- Surface reradiation is the most effective energy rejection mechanism (60-80%)
  - Carbon or materials that form carbonaceous chars are desirable as they attain very high surface temperatures and have high emissivity
  - Ablation, even in the presence of exothermic oxidation, consumes energy (20-40%)
  - Only a small fraction of the incident heating is conducted into the TPS material (10-20%)



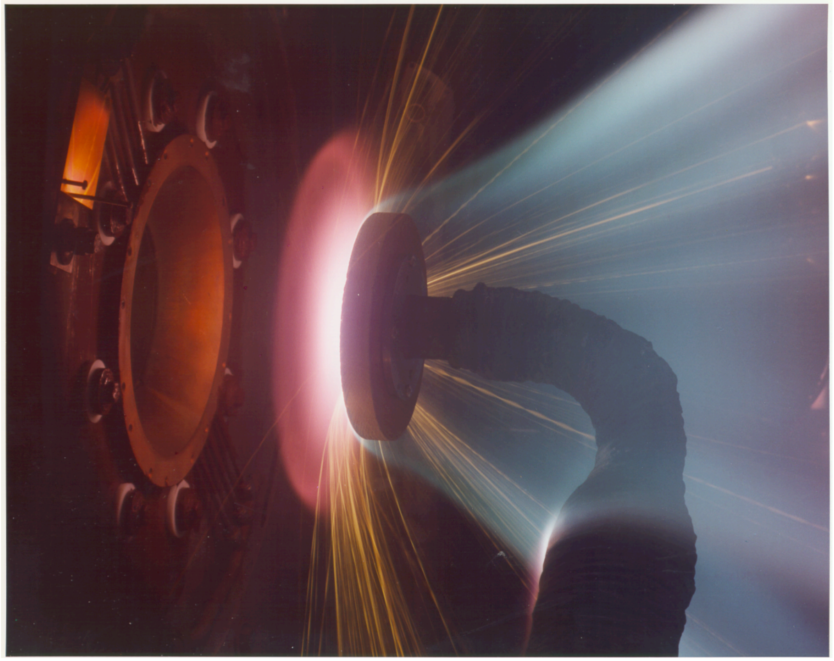
Material Performance Limits



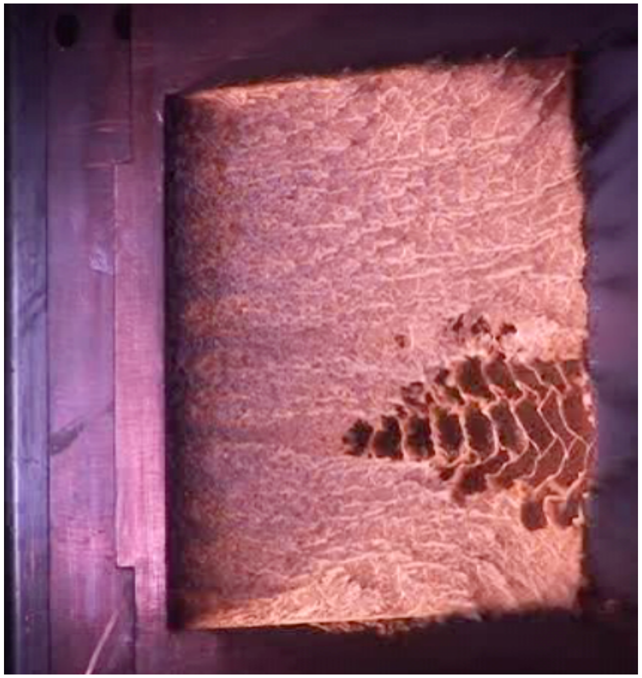
Optimal performance regime is balanced between ablative and insulation efficiency. When material is used outside of optimal zone, inefficient performance leads to non-minimal mass fraction.

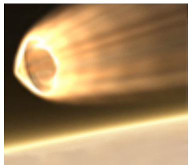
Example failure modes

Spallation



Loss of liquid layer





TPS Selection

- Objective is *minimum* TPS mass with reliable performance
  - *Reliable performance* implies that material failure modes are well understood and environmental conditions leading to failure will not be encountered (or approached) for the selected mission
  - Low density materials are (typically) better insulators than high density materials
  - High density materials are (typically) better ablators than low density materials
- Ablation is good - it absorbs energy
  - Too much ablation may not be good if it leads to shape change that influences aerodynamics
- TPS selection involves a balance between ablation and insulation performance and manufacturability
  - Select the lowest density material that can handle* the range of environmental conditions (heat flux, pressure, shear, atmosphere)
  - Material should provide effective insulation for imposed heat load
  - Procedures for material fabrication, installation, inspection, etc., should be established and, preferably, demonstrated

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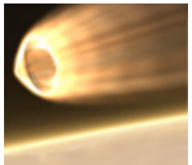
*Material should have demonstrated reliability at extreme conditions of interest

TPS Testing

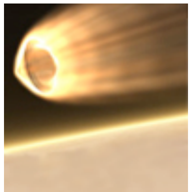


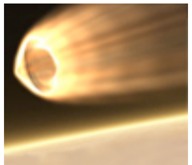
Arc Plasma Facilities

- Have been used for over 40 years to study TPS material performance
  - Two classes:
    - Low enthalpy, high pressure, high heat flux (high β vehicles)
    - High enthalpy, low pressure, low-moderate heat flux (low β vehicles; lifting entry, aeroassist, aerocapture, planetary entry, etc.)
- Significant flexibility
  - Pressure: nozzle geometry, test article design, gas mass flow rate
  - Enthalpy: gas mass flow rate, electrical power
  - Gas composition: most facilities operate with air, but tests have been conducted with N_2, CO_2, H_2/He, etc. gas streams
- Amenable to sophisticated *(non-intrusive)* diagnostics
  - Surface visibility (film or video), surface pyrometry, PLIF, emission spectroscopy, etc.
- Capability to *simultaneously* simulate conditions representative of flight (e.g., $H, \dot{q}, p$) is rare.
  - Requires strategic test planning
  - Typically, cannot simulate time-varying conditions (trajectories)

TPS Testing (concluded)

- Inability to simulate the actual flight environment in arc jets results in significant uncertainties in ground test to flight traceability
- Well-designed ground-test program should cover the *range of conditions* anticipated in flight
  - Typically, ground tests cannot simulate some aspects of the flight environment
    - Turbulent flow
    - High shear
    - High pressure gradient
    - Combined convective/radiative heating
- *Mechanism-based modeling* allows extrapolation with some confidence
  - Identification of surface response mechanisms and development of high fidelity model significantly reduces performance uncertainties in flight
  - Remaining uncertainties can only be addressed through flight test with instrumented TPS





Summary & Conclusions

- Atmospheric entry qualifies as an *extreme environment*
- Selection of an ablative TPS for a given mission is governed by the severity of the entry environment
  - High density materials minimize ablation but result in a heavy TPS
  - Low density materials minimize insulation thickness and result in a light TPS
  - Optimum material (among those available) is the lowest density material that does not produce excessive ablation while performance is far from failure thresholds
- Arc plasma facilities produce the best simulation of the entry environment
  - Actual flight conditions (typically) cannot be simulated
  - Requires testing over broad range of conditions to understand performance mechanisms
  - Mechanism (physics- and chemistry-) based models enable extrapolation from ground test to flight
- Ablative materials have been successfully used for thermal protection for 50 years and will continue to be used in the foreseeable future