High-Temperature Materials

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July 2021
- Why High-Temperature Materials?
  - Industrial Uses
  - Aerospace Vehicles
    - Engines and Motors
    - Hypersonic Thermal Protection
- Thermal Protection Systems (TPS)
  - Different Types of TPS
  - Selecting a TPS
- Historical TPS
  - Apollo
  - Space Shuttle Orbiter
- TPS Now – Post-Shuttle
- Future TPS
- Questions
High Temperature Materials: Industrial Uses

High Temperature = Temperatures $> \sim 300 \text{ F}$

- Energy Production
- Fire Protection
- Electronics
- Material Processing – Ovens

Inconel 718 Turbine
1300 F (700 C)

Carbon Fiber Boards
$>3000 \text{ F in vacuum}$

Alumina Fiber Blankets
2900 F
High Temperature Materials: Aerospace Vehicles

Commercial Aircraft
- Titanium – engine compressor and nozzle
- Carbon cloth phenolic – engine nozzle

Hypersonic Aircraft
- Inconel skin
- Ti Frames
- Fibrous Blankets

Rocket Motors
- Carbon cloth phenolic – engine nozzle
- Ceramic Tiles

X-15 Mach 6+
Orbiter Mach 25+
Above ~Mach 5, the thermal environment drives the need for vehicle thermal protection.

Ref.: Bertin, J.J., ‘Hypersonic Aerothermodynamics’
Approaches to Thermal Protection

● **Radiative Systems**
  - Radiate heat away from surface
  - Design implementation: High emittance surface

● **Heat-Sink Systems**
  - Absorb the heat
  - Design implementation: High specific heat

● **Insulation Systems**
  - Slow the heat wave
  - Design implementation: Low thermal conductivity

● **Ablative Systems**
  - Decomposition of material absorbs heat
  - Design implementation: Prefer charring materials

● **Transpiration Systems**
  - Cool the boundary layer
  - Design implementation: Inject fluid into boundary layer from surface

● **Active Cooling Systems**
  - Cool the surface with internal fluid
  - Design implementation: Heat exchanger with cooling fluid

Ref: ‘Entry Thermal Protection,’ NASA SP-8014, Aug. 1968
Example: Orbiter Space Shuttle Leading Edge

\[ q_{\text{convective}} = \epsilon \sigma T^4_{\text{surface}} \]

- HOT STRUCTURE RERADIATIVE SYSTEM
- INTERNAL INSULATION
- HEAT SINK/CONDUCTION

AERODYNAMIC HEATING
(SURFACE TEMPERATURES TO 2700°F)

\[ \dot{q} \text{ RERADIATION BACK INTO SPACE} \approx 85\% \]

INTERNAL CAVITY RADIATION EXCHANGE

ALUMINUM STRUCTURE

INTERNAL INSULATION

HEAT SINK/CONDUCTION
Example: X-33 Metallic Fillet

Absorb heat into material

$$q_{\text{convective}} = mc_p \Delta T$$

Why on X-33?
Thermal growth of wing resulted in need for gap in Advanced Carbon-Carbon wing leading edge panels. Flow forced into gap was directed to surface by metallic fillet.
**Example: Orbiter Tiles**

\[-k \frac{\partial T}{\partial x} \bigg|_{x=0} = \dot{q}_{\text{convection}} + \dot{q}_{\text{radiation}}\]

**Convective Heating**

**Radiative Heating**

**Radiated Heat Flux**

**Conducted Heat Flux**

**Surface Coating**

**Insulation**

**Adhesive**

**Carrier Structure**
Example: Apollo Heat Shield

Energy management through material consumption

- free stream
- radiation flux in
- convective flux
- radiation flux out
- conduction flux
- material decomposition
- reaction products
- pyrolysis gases
- mechanical erosion
- melt flow
- porous char
- pyrolysis zone
- virgin material
- backup material
TPS: Transpiration System

- TRANSPERSION

DISTRIBUTION CHAMBER
CONTROL VALVE

PERMEABLE MATRIX

\[ \dot{m} \]

\[ \dot{q} \]

PRESSURE SYSTEM
(FOR LIQUID SUPPLY)

ACTIVE TRANSPERSION

FLUID SUPPLY
(GAS OR LIQUID)

ABLATING
MATERIAL

PERMEABLE MATRIX

\[ \dot{m} \]

\[ \dot{q} \]

STRUCTURE

PASSIVE TRANSPERSION

HOLES OR SLOTS

\[ \dot{m} \]

\[ \dot{q} \]

FLUID PASSAGE

FILM COOLING

\[ \dot{q}_{\text{CONVECTION}} + \dot{q}_{\text{COMBUSTION}} + \dot{q}_{\text{RADIATION}} = \dot{q}_{\text{CONDUCTION}} + \dot{q}_{\text{RERADIATION}} \]
Example: Shuttle Main Engines

Liquid hydrogen flows thru tubes. Cools nozzle and preheats hydrogen

Brazed Stainless Steel Nozzle
How to Select a TPS
Missions Drive Environments

![Graph of Relative Velocity vs. Altitude with labels for Space Shuttle, Lunar, and Asteroid.]
Reentry Environments Drive TPS Selection

![Graph showing heat flux over time for different mission scenarios.]

- **Apollo Missions**: Single-Use Ablators
- **Shuttle Missions**: Reusable Tiles
- **STS-121 Entry Heating**: Reusable Tiles
- **BP1101**: Reusable Tiles
But, It’s More Than Reentry Heating

Mission Sequence of Environments

**On the Pad**
- Humidity
- Rain
- Lightning

**Launch**
- Vibro-acoustic
- Over-pressure
- Debris impact

**Ascent**
- Aeroheating
- Rapid pressure decrease
- Plume Heating
- Debris impact

**Separation Event**
- Pyro shock

**On-Orbit**
- Temperature Cycles
- Vacuum
- Atomic oxygen
- MMOD impact

**Reentry**
- High heating
- Dissociated Air

**Landing**
- Heat shield separation
Other Considerations

Penetrations thru TPS

- Doors
  - ET Umbilical
  - Landing gear
  - Hatches
- Windows
- Antennas
- Reaction Control System Jets
- Launch Abort Attachment
- Orion

TPS Mass

WEIGHT

TIME

Manufacturing Processes & Supply Chain

OV-103
Flt 27
Lost Elevon Tile

Shock Events

ET Separation

PICA Failure
TPS Testing

**Radiant Heat Tests**
- Radiant Heating
  - Variable heat
  - Variable pressure
- Large Test Articles
  - TPS assemblies
  - TPS penetrations
- Thermal Conductivity
- Thermal Model Validation
- Thermal induced deflections

**Arc-jet Tests**
- Reentry Aerothermological Simulation
  - Dissociated gas
- Small Test Articles
  - TPS materials
  - TPS penetrations
- Thermal/chemical behavior
- Thermal Response Model Validation

**Structural Tests**
- Structural Flexure
- Medium Test Articles
  - TPS assemblies
  - TPS penetrations
- Structural Model Validation
X-15 Ramjet Flight Test

**What Happened?**
Burn through and near-structural failure of pylon.

**Why?**
Underestimated heating due to shock/shock interaction.

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Columbia Accident

**What Happened?**
Loss of vehicle and crew.

**Why?**
Ascent impact damage to Carbon-carbon leading edge.

http://history.nasa.gov/x15lect/intro.html

Columbia Accident Investigation Board, Aug. 2003
Historical Thermal Protection Systems

**Good Reference**
Manned Spacecraft Entry Vehicles

- MERCURY: 74.50 in, 115 in, 11 ft, 13 ft
- APOLLO: 11 ft, 121.52 ft, 46.33 ft, 78.06 ft
- GEMINI: 19 ft

Image showing the dimensions and designs of these spacecrafts.
## Comparison of Manned Entry TPS

<table>
<thead>
<tr>
<th></th>
<th>MERCURY</th>
<th>GEMINI</th>
<th>APOLLO</th>
<th>SHUTTLE</th>
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</thead>
<tbody>
<tr>
<td><strong>DATE</strong></td>
<td>10/7/58</td>
<td>3/23/65</td>
<td>10/11/69</td>
<td>4/12/81 – 7/21/11</td>
</tr>
<tr>
<td><strong>No. of flight</strong></td>
<td>6 flights</td>
<td>10 flights</td>
<td>11 flights</td>
<td>135 (133) flights</td>
</tr>
<tr>
<td><strong>AREA</strong></td>
<td>32 FT²</td>
<td>45 FT²</td>
<td>365 FT²</td>
<td>11 895 FT²</td>
</tr>
<tr>
<td><strong>WEIGHT</strong></td>
<td>315 LB</td>
<td>348 LB</td>
<td>1465 LB</td>
<td>18 904 LB</td>
</tr>
<tr>
<td><strong>WT/FT²</strong></td>
<td>10.2</td>
<td>7.5</td>
<td>3.9</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>MATERIAL</strong></td>
<td>ABLATOR</td>
<td>ABLATOR</td>
<td>ABLATOR</td>
<td>Rigidized silica fibers</td>
</tr>
<tr>
<td></td>
<td>(FIBERGLASS-REINFORCED LAMINATED PLASTIC)</td>
<td>(DOW CORNING DC 325)</td>
<td>(AVCO 5026-39)</td>
<td></td>
</tr>
<tr>
<td><strong>DENSITY</strong></td>
<td>114 LB/FT³</td>
<td>54 LB/FT³</td>
<td>33 LB/FT³</td>
<td>9-22 LB/FT³</td>
</tr>
<tr>
<td><strong>USAGE</strong></td>
<td>1 FLIGHT</td>
<td>1 FLIGHT</td>
<td>1 FLIGHT</td>
<td>135 (133) FLIGHTS</td>
</tr>
</tbody>
</table>
AVCO 5026-39 HCG  
(Filled Epoxy Novalac in Fiberglas-Phenolic Honeycomb)  
Now manufactured by Textron

Heat shield Core from Apollo 11
Apollo Ablator Thickness & Surface Recession Distribution

- Preflight Ablator Thickness
- Measured Postflight Ablator Thickness
- Predicted Postflight Ablator Thickness

Thickening, in.

Surface Recession

Ablator Bondline

270° Meridian

90° Meridian
Physical Model of a Charring Ablator

Original Material Surface

Char Layer Zone
1. Aerodynamic Heating (convective and radiative)
2. Heat Blockage
3. Ablation Gas Flow
4. Reradiation
5. Surface Recession
6. Combustion
7. Conduction
8. Deposition
9. In-depth Radiation

Reaction Zone
1. Material Degradation
2. Ablation Gas Flow
3. Conduction

Virgin Zone (plastic)
1. Conduction

Backup Structure
1. Conduction
2. Heat Loss to Cabin Environment
Space Shuttle Orbiter TPS Configuration

- **RCC** - Reinforced Carbon-Carbon
- **HRSI** - High-temperature Reusable Surface Insulation
- **LRSI** - Low-temperature Reusable Surface Insulation
- **AFRSI (FIB)** - Advanced Flexible Reusable Surface Insulation
- **FRSI** - Flexible Reusable Surface Insulation
- **Penetrations - seals and thermal barriers**
Space Shuttle Orbiter RCC Components

- Nose Cap and Seals
- Chin Panel and Seals
- Wing Leading Edge Panel
- Forward ET Attach Point Arrowhead
- RCC Plates
HRSI Tile System

High-temperature Reusable Surface Insulation Tile Attachment System

- Reaction-Cured Glass Coating
- Tile-to-Tile Gap
- Tile Densified Layer
- Koropon-Primed Structure
- Filler Bar
- Strain Isolation Pad
- Room Temperature Vulcanizing Adhesive
Orbiter TPS: Operational Issues

Flight Processing

On-Orbit Inspections

Protruding Gap Filler

EVA During STS-114
Launch Vehicles Need TPS

Aerodynamic Heating Heating

Plume-induced Heating

Space Shuttle
Retired 2011

Space Launch System
1st Launch 2021
Current TPS

Multi-Purpose Crew Vehicle
Orion Heat Shield

SpaceX Dragon Capsule

Avcoat (Apollo) but in Block Form

Note: SpaceX makes their own PICA.

Phenolic Impregnated Carbon Ablator (PICA)

Mars 2020
TPS in the Future

**Increase Robustness**

3-D Woven Carbon Fibers Infiltrated with Resin

**Reduce Weight**

Graded Ablator
High Density to Lower Density

**Improve Manufacturing/ Reduce Costs**

Conformable Ablator Infiltrated Felts

Let’s 3D Print it!
Questions??