Thermal Protection System Needs

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The Boeing Company

March 11, 2011
Outline

• History
• TPS Materials
• TPS Testing
• TPS Analysis
TPS History
## TPS Mass Fraction – Historic Crewed Vehicles

<table>
<thead>
<tr>
<th>DATE</th>
<th>MERCURY</th>
<th>GEMINI</th>
<th>APOLLO</th>
<th>SHUTTLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of flight</td>
<td>6 flights</td>
<td>10 flights</td>
<td>11 flights</td>
<td>133 (131) flights</td>
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<tr>
<td>AREA</td>
<td>32 FT²</td>
<td>45 FT²</td>
<td>365 FT²</td>
<td>11 895 FT²</td>
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<tr>
<td>WEIGHT</td>
<td>315 LB</td>
<td>348 LB</td>
<td>1465 LB</td>
<td>18 904 LB</td>
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<tr>
<td>WT/FT²</td>
<td>10.2</td>
<td>7.5</td>
<td>3.9</td>
<td>1.7</td>
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<tr>
<td>MATERIAL</td>
<td>ABLATOR (FIBERGLASS-REINFORCED LAMINATED PLASTIC)</td>
<td>ABLATOR (DOW CORNING DC 325)</td>
<td>ABLATOR (AVCO 5025-39)</td>
<td>Rigidized silica fibers</td>
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<tr>
<td>DENSITY</td>
<td>114 LB/FT³</td>
<td>54 LB/FT³</td>
<td>33 LB/FT³</td>
<td>9-22 LB/FT³</td>
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<tr>
<td>USAGE</td>
<td>1 FLIGHT</td>
<td>1 FLIGHT</td>
<td>1 FLIGHT</td>
<td>133 (131) FLIGHTS</td>
</tr>
</tbody>
</table>

| Vehicle Weight     | 2724 lb       | 4861 lb       | 11500 lb      | 180,000 lb    |
| TPS Mass Fraction  | 11.6%*        | 7.16%*        | 12.8%         | 10.5%         |

* TPS Mass only includes heat shield, and not the metallic backshell
TPS Materials
Current Status

• Reusable Materials developed for Space Shuttle Orbiter
  – Maximum Operational Temperature – 2900F
• Early NASA missions (Mercury, Gemini, Apollo) used new ablative TPS
• Proposed Orion TPS
  – Apollo AVCO – Textron
  – Ames PICA
Orbiter TPS Configuration

- RCC - Re-inforced 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

OV-103 & subs shown
# Candidate ablative heat shield TPS materials for Mars and Titan

<table>
<thead>
<tr>
<th>Density</th>
<th>TPS</th>
<th>Supplier</th>
<th>Flight Qual or TRL</th>
<th>Potential Limit</th>
<th>Entry at Mars</th>
<th>Earth Return</th>
<th>Titan</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heat flux, W/cm²</td>
<td>Pressure atm</td>
<td>MSL Class</td>
<td>MSL Class</td>
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<tr>
<td>Low-Mid</td>
<td></td>
<td></td>
<td></td>
<td>120 (&lt;300)*</td>
<td>&lt; 1</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td></td>
<td>SLA 561V</td>
<td>LMA</td>
<td>Mars</td>
<td>~ 1200</td>
<td>~ 1</td>
<td>✗</td>
<td>✗</td>
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<tr>
<td></td>
<td>PICA</td>
<td>FMI</td>
<td>Stardust</td>
<td>~ 1000</td>
<td>~ 1</td>
<td>✗</td>
<td>✗</td>
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<tr>
<td></td>
<td>BPA</td>
<td>Boeing</td>
<td>TRL 3-4</td>
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<td>~ 1</td>
<td>✗</td>
<td>✗</td>
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<tr>
<td></td>
<td>Avcoat</td>
<td>Textron</td>
<td>Apollo</td>
<td>~ 1000</td>
<td>~ 1</td>
<td>✗</td>
<td>✗</td>
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<tr>
<td></td>
<td>AQ60#</td>
<td>EADS</td>
<td>Huygens</td>
<td>~ 250</td>
<td>&lt; 1</td>
<td>✗</td>
<td>✗</td>
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<tr>
<td></td>
<td>Acusil® II†</td>
<td>ITT</td>
<td>DOD MSL</td>
<td>100</td>
<td>&lt; 1</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td></td>
<td>SRAM Family</td>
<td>ARA</td>
<td>TRL 5-6</td>
<td>~ 300*</td>
<td>~ 1</td>
<td>✗</td>
<td>✗</td>
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<tr>
<td></td>
<td>Lower density Phen-Carb</td>
<td>ARA</td>
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<td>~ 1</td>
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<td>✗</td>
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<tr>
<td>Mid</td>
<td>ACC</td>
<td>LMA/C-Cat</td>
<td>Genesis</td>
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<td>&gt; 1</td>
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<td>Mid-density PhenCarb</td>
<td>Several</td>
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<td>✗</td>
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<tr>
<td>High</td>
<td>3DQP</td>
<td>Textron</td>
<td>DOD</td>
<td>~ 5000</td>
<td>&gt; 1</td>
<td>✗</td>
<td>✗</td>
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<tr>
<td></td>
<td>Heritage Carbon phenolic</td>
<td>None</td>
<td>None today but several can</td>
<td>Venus, Jupiter</td>
<td>10,000-30,000</td>
<td>&gt;&gt; 1</td>
<td>✗</td>
</tr>
</tbody>
</table>

- **Fully capable**
- **Potentially capable, qual needed**
- **Capable but heavy**
- **Not capable**

†RF transparent  # European Supplier  * (heat flux limit is lower with high shear, higher at low shear)

Note: Reliability requirements for MSR EEV can only be met by heritage carbon phenolic TPS
Candidate ablative back shell TPS materials for Mars and Titan

<table>
<thead>
<tr>
<th>Density</th>
<th>TPS</th>
<th>Supplier</th>
<th>Flight Qual or TRL</th>
<th>Potential Limit</th>
<th>Mars Direct</th>
<th>Mars</th>
<th>Titan</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heat flux, W/cm²</td>
<td>Pressure atm</td>
<td>Size ~MPF</td>
<td>Size (MSL)</td>
</tr>
<tr>
<td>Low</td>
<td>SLA-561V⁺</td>
<td>LMA</td>
<td>Mars</td>
<td>&lt;120 (&lt;300)*</td>
<td>&lt;1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>SRAM Family</td>
<td>ARA</td>
<td>TRL 5-6</td>
<td>~300</td>
<td>~1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AQ60</td>
<td>EADS</td>
<td>Huygens</td>
<td>~250</td>
<td>&lt;1</td>
<td>0</td>
<td>0</td>
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<tr>
<td></td>
<td>SIRCA†</td>
<td>Ames</td>
<td>Mars</td>
<td>~150</td>
<td>&gt;1</td>
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<td>Acusil® II†</td>
<td>ITT</td>
<td>DOD MSL</td>
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<td></td>
<td>SLA-561S</td>
<td>LMA</td>
<td>Mars</td>
<td>&lt;20</td>
<td>&lt;1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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- Potentially capable, qual needed
- Capable but heavy
- Not capable

† RF transparent
‡ European Supplier
* (heat flux limit is lower with high shear, higher at low shear)
TPS Testing
Apollo Heat Shield Evolution
(Materials – Arc Jet Utilization)

1960 - 61

- Screening Evaluations (Materials)
  - Phenolic Nylon
  - GE Epoxy Ablator
  - AVCO 5026-22 (66 lb/ft³)

1962

Primary Contractor
AVCO

(Materials)
5026-22 (66 lb/ft³) (Tiles)

5026-39 HCG (33 lb/ft³)

AVCO Model 500
AVCO 10MW
AVCO ROVERS

1969

North American / Rockwell
Monitoring & Backup

(Materials)
5026-39
DC325 (Gemini)
GE ESM1000
Thermolag (T500-13)
Purple Blend (LARC)

Chicago Midway
Plasmadyne
Rocketdyne (Rockets)
GE MALTA (Rockets)

Independent NASA Monitoring & Backup

(Materials)
Chance Vought (Burnt Toast)
Melamine Phenolics
Thermolag
Honeycomb Fill Thermolag

NASA MSC
NASA Ames
NASA LARC
Plasmadyne
General Electric
Aerotherm
Boeing

Arc Jet Facilities Used

Estimated Number Of Tests

<table>
<thead>
<tr>
<th>AVCO</th>
<th>North American Monitoring</th>
<th>Independent NASA Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>~5000</td>
<td>&gt;1000</td>
<td>&gt;2000</td>
</tr>
</tbody>
</table>

- Apollo Ablator
- Backup Ablators
- CM/SM Umbilical
- Antennas
- Tension Tie Bolts
- T/C Plugs
- Ablator Sensors
- Apollo 6 Sideburns Experiment
- EASEP Canister

Courtesy of Don Tillian
Time-proven Approach to Materials Screening, Characterization and Modeling
Thermophysical Properties: Thermal Response Modeling

1. **Specific Heat of Virgin Material**
   - Function of temperature.

2. **Thermal Conductivity of Virgin Material**
   - Functions of temperature, pressure and orientation, if appropriate
     - Open porosity so thermal conductivity has dependence on pressure
     - Preferential orientation of fibers in the in-plane direction resulting in ~2x great thermal conductivity in-plane versus through the thickness

3. **Specific Heat of Char**
   - Measure on arcjet char
   - Derive from known (or derived) composition using rule of mixtures

4. **Optical Properties of Virgin Material (Emittance)**

5. **Optical properties of Char**
   - Measure on arcjet char
   - Estimate from known composition and properties of similar materials

6. **Thermal conductivity of char as function of temperature**
   - Initial values using laboratory measurements
   - Final (design) values determined from in-depth thermocouple temperatures of arc jet tested samples

7. **Transition zone properties estimated using local density relationship**
Thermochemical Properties: Thermal Response Modeling

1. Thermo Gravimetric Analysis (TGA) Experiments:
   • Inert gas, low temperature rise rates
   • Residual mass fraction defines char yield.
   • Data fits provide decomposition kinetic constants.

2. Differential Scanning Calorimetry (DSC) Experiments:
   • Inert gas, low temperature rise rates
   • Data provides heat of reaction for pyrolysis reactions as function of temperature.

3. Elemental composition of virgin material.

4. Heat of combustion of virgin material
   • Derive from heat of formation measurements

5. Elemental composition of char:
   • Derive from known constituents and char yield data.
   • Measure from arcjet char
   • For multi-constituent ablative materials char composition may be dependent on environment experienced during reentry
     • Example carbon to silica ratio in char may vary with conditions

6. Heat of formation of char
   • Derive from known constituents and existing data

Courtesy: Bernie Laub
Properties Required for Thermo/Structural Design

• Mechanical/Physical Properties
  – Tension (Strength and Modulus)
  – Compression (Strength and Modulus)
  – Flexure (Strength and Modulus)
  – Shear (Strength and Modulus)
  – Coefficient of thermal expansion
  – As functions of temperature
  – As functions of orientation
    • Materials such that have significantly different mechanical properties IP vs TTT.
    • Honeycomb materials also have strong and weak directions (ribbon direction vs perpendicular to ribbon direction) as well as differences IP vs TTT
  – Glass transition point (Tg)

• System Level Testing
  – Strength of bond between ablator and carrier structure
  – CTE mis-match of ablator to structure
TPS Analysis
Ablation Analysis

• Ablation analyses – 1960 - 1970
  – Heat of Ablation
  – Thermochemical (Charring Ablators)

• Ablation analyses – Today
  – 4 Ablator Workshops Held
    • In-depth physic and Chemistry
    • Gas surface Interaction and Catalysis
    • Roughness modeling with Gas Blowing
    • Ablation Model Code Intercalibration Test Cases
Factors That Influence TPS Design

- Aerothermal Environment
  - Peak conditions (heat flux, shear, pressure) maybe used to screen suitability of a given material
  - Total heat load will be used to size the thickness and therefore total mass of the heat shield
- Strength/Stiffness (Airloads/Vibroacoustic)
  - Limits of ablator material will drive things such as carrier structure design (stiffness) and block layout for segmented approaches
- Thermal Gradients
- Venting Characteristics
- Outgassing
- Space Environment
  - LEO: Atomic Oxygen
  - UV
  - Long Term Space Exposure
- Damage Tolerance/Impact Resistance
- Repairability
- Refurbishment
TPS Environments for Certification

- Natural Environments
  - Temperature – atmospheric
  - Thermal – vacuum
    - Solar radiation – thermal
  - Pressure
  - Fungus
  - Meteoroids
  - Humidity
  - Lightning
  - Ozone
  - Rain
  - Salt spray
  - Sand/dust
  - Solar radiation – nuclear
  - Wind

- Induced Environments
  - Temperature
    - Ascent heating
    - On-orbit and entry heating
  - Pressure
  - Acoustics
  - Shock
  - Random vibration
  - Structural loads
    - Limit and ultimate
  - Acceleration

- Miscellaneous Environments
  - Life – full and limited
  - Fluid compatibility