NASA Crew Exploration Vehicle, Thermal Protection System, Lessons Learned

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Orion System Elements

Orion consists of four functional modules

- **Launch Abort System** -- emergency escape during launch
- **Crew Module** – crew and cargo transport
- **Service Module** – propulsion, electrical power, fluids storage
- **Spacecraft Adapter** – structural transition to launch vehicle

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Orion vs. Apollo

- Orion shape is derived from Apollo, but approximately 30% larger
  - Presents challenges to the TPS, including:
    - Increased heat loads
    - Manufacturing challenges

Comparison of Apollo to Orion floating in still water
Enable the CEV Project Office and the Prime to develop a CEV heat shield…

Orion Lunar direct return (LDR) conditions:
- 11 km/s atmospheric entry
- peak heat rate > 750 W/cm²

Orion Low Earth Orbit (LEO) return conditions:
- 8 km/s atmospheric entry
- peak heat rate > 150 W/cm²

... by initiating an Advanced Development Project to raise the TRL and reduce the risk of a Lunar return capable ablative TPS materials and heat shield systems
Background

- The Exploration Systems Architecture Study (ESAS) commissioned in the summer of 2005 settled on a new Constellation (Cx) human space transportation architecture.

- At the core of the ESAS recommended architecture was a new Crew Exploration Vehicle (CEV – Orion) that would serve as the US human transportation system for Low Earth Orbit (LEO) as well as lunar missions.

- A top risk identified by ESAS for CEV was the development of a heat shield and applicable Thermal Protection System (TPS) materials meeting both LEO and Lunar return requirements:
  - Ablative TPS materials required to support LEO and Lunar missions
  - The US had focused little attention on ablative materials since Apollo era.
  - All applicable ablative TPS materials were at low technology readiness levels (TRL ~ 3-4)

- In Oct 2005, the CEV Project commissioned the CEV TPS Advanced Development Project to address the heat shield development risk.
Heat Shield Operating Environments

- Mechanical Compression
- Internal Pressure
- Aerodynamic Shear
- Aerodynamic Pressure
- Acoustics
- Vibration
- Low Velocity Impact
- Humidity
- Salt
- Water
- Thermal Cycling
- Hypervelocity Impact
- Solar Radiation
- Atomic Oxygen
- Mechanical Shock
- Shock Radiation
- Aerodynamic Shear
- Convective Heat Flux
- Aerodynamic Pressure
- Mechanical Shock
Orion Heat Shield Components

- Carrier structure
  - Dish section
  - Shoulder section
- Ablative acreage TPS
  - Block layout
  - TPS material thickness
- Compression pads
- Separation mechanism
- Main seal
Scope of TPS ADP Primary Objectives

• **TPS materials fabrication and characterization**
  – Development of material constituent, processing and properties specifications
  – Detailed mechanical and thermal material properties testing

• **TPS materials thermal performance capabilities for LEO & Lunar returns**
  – Nominal & emergency entry trajectories – Aerothermal environments
  – Screening and comprehensive TPS materials thermal performance testing
  – TPS materials thermal response models
  – TPS thermal performance margins policy

• **TPS materials thermal-mechanical performance capabilities**
  – Ground, launch, on-orbit, nominal and emergency entry, descent & landing loads
  – Thermal-structural integrated (carrier structure + TPS) testing
  – FEM analysis and design of TPS materials

• **Design for all heat shield components**
  – TPS acreage, carrier-structure, TPS bonding, compression pads, main seals, gap/seams, close-outs, repairs

• **Integrated heat shield design and performance capabilities**
  – Integrated design of all components
  – TPS material lofting and thermal, MMOD and integration sizing
  – Integrated thermal-structural analysis and design of complete heat shield

• **Manufacturing for an integrated 5 meter heat shield**
  – Infrastructure and equipment for full-scale heat shield production (e.g. full scale oven)
  – Production staffing and resources to produce materials meeting spec. at volume
  – Demonstration of full-scale heat shield manufacturing procedures
Other TPS ADP Objectives

• Revitalize the ablative TPS industry:
  – For the past 25+ years, NASA-sponsored R&D has focused mostly on reusable TPS materials
    • Ceramic tiles, coatings, blankets (e.g., Shuttle acreage)
    • Oxidation-resistant carbon-carbon (e.g., shuttle WLE)
    • Ultra High Temperature Ceramics (UHTCs)
  – Little work completed on advanced ablative materials, as a consequence, the ablative TPS materials community in the U.S. (very robust in the 60s and 70s) has significantly diminished
  – NASA is really the only customer for this industry – thus it is vital for NASA to make investments not only internally but also in industry

• Train the next generation of NASA entry systems developers
  – Prior to the CEV development NASA efforts were focused on either basic TPS materials R&D or performing TPS operational support
  – Limited efforts were applied to perform end-to-end development of a new heat shield systems for flight vehicles
  – NASA in house staffing lacked training to perform flight hardware development
Initial Materials Development & Selection

- Block 2 (lunar), Phase I, Materials
- Block 1 (LEO), Phase I, materials
Heat Shield Materials

• Block 2 TPS Materials
  – Boeing / FMI: PICA (Baseline)
  – Textron: Avcoat (Primary Alternate)
  – Textron: 3DQP (Alternate)
  – Boeing: BPA (Alternate)
  – ARA: PhenCarb 28
  – Lockheed Martin / CCAT: Advanced Carbon-Carbon / Calcarb

• Block 1 TPS Materials
  – Lockheed Martin: SLA-561V
  – Shuttle tile materials: LI-2200, BRI-18

• Carrier Structure
  – Titanium / Titanium honeycomb (Baseline)
  – GR-BMI Composite / Titanium honeycomb (Alternate)

• Compression Pads
  – Carbon phenolic
  – Fiberglass phenolic
  – Silica phenolic

Critical Path for CEV
No longer considered for CEV
## Candidate Heatshield Ablator Materials for Lunar Return (Block 2) Conditions

<table>
<thead>
<tr>
<th>Vender Material</th>
<th>Heritage Mission &amp; Diameter</th>
<th>Local TPS Approach TTT</th>
<th>System Construction IP</th>
<th>TPS ADP Contracts Density</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARA PhenCarb 28</td>
<td>MDU, TRL = 4 (2007) 1 m</td>
<td>Uniform TTT – in Honeycomb</td>
<td>Segmented with seams</td>
<td>Phase I 450 kg/m³</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>Boeing / FMI PICA</td>
<td>Stardust, TRL = 4 (2006) 0.9 m</td>
<td>Uniform TTT bonded with RTV/SIP/RTV</td>
<td>Blocks/Tiles w/ filled gaps/seams</td>
<td>Phase I, Phase II 270 kg/m³</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>LM / LCAT ACC / CalCarb</td>
<td>Genesis, TRL = 4 (2004) 1.35 m</td>
<td>Dual layer system</td>
<td>Monolithic or segmented</td>
<td>Phase I 1500 / 180 kg/m³</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Textron Avcoat</td>
<td>AS-501, TRL = 4 (1967) 3.9 m</td>
<td>Uniform TTT – in Honeycomb</td>
<td>Monolithic w/ honeycomb seams</td>
<td>Phase I, Phase II 540 kg/m³</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>Textron 3DQP</td>
<td>DoD ?, TRL = 3 (?)</td>
<td>Dual layer with integration layer</td>
<td>Segmented w/ tongue &amp; groove</td>
<td>Phase I, Phase II 1600 / 220 kg/m³</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>Boeing BPA</td>
<td>Coupons, TRL= 3 (2005) 1 m</td>
<td>Uniform TTT – in Honeycomb</td>
<td>Monolithic or segmented</td>
<td>Phase II 540 kg /m³</td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>
5 Materials Selected for Block 2 Phase I Screening Tests Coupons

- Boeing PICA
- ARA PhenCarb 28
- Textron Avcoat
- Textron 3DQP
- Lockheed Martin ACC/CalCarb
Block 2, Phase I Testing in Arcjet
Three arcjet test series were performed
- Block 2 peak heating - 1000 W/cm² @ 30 sec --- Ames IHF
- Block 2 skip dual-pulse 400 / 150 W/cm² --- Ames AHF
- Block 1 nominal entry – 130 W/cm² @ 200 sec --- Ames IHF
**Block 1 SLA-561V & Shuttle Tile Status**

- **SLA-561V TPS material performance issues**
  - MSL stagnation thermal ablation testing showed excellent stagnation heating performance up to 300 W/cm²
  - However, arcjet tests at low heating (90 – 150 W/cm²), high shear and high pressure (medium enthalpy) conditions showed material failures
  - Material was dropped from consideration for CEV (7/07)
  - Mars Science Laboratory (MSL), which had baselined SLA-561V, switched their baseline material to PICA (11/07)
    - CEV testing of SLA-561V revealed the performance problems for MSL
    - If it were not for the PICA work by the TPS ADP, MSL would not have had an alternate material system, and would not be flying in 2009

- **Shuttle tile material performance issues**
  - Initial coupon testing of Shuttle tiles indicated excellent performance for BRI-18 (coated), LI-2200 (coated & uncoated)
  - Stagnation arcjet tests of gap/seam articles showed that at LEO heating and pressure conditions the material exhibits gap performance problems
  - Material was dropped from consideration for CEV heat shield utilization

- **Both candidate Block 1 materials have been eliminated from consideration for the heat shield**
Baseline PICA
Development Status
PICA Heat Shield Overview

- **PICA**
  - Local thickness tailored to heat load
    - 232 individual sizing points
    - PICA blocks mounted to axisymmetric carrier structure
      - Uses +/- 1” OML deviation
  - Block layout design
    - RTV-SIP-RTV bond to carrier structure
    - Gap/Seam configuration not finalized
  - 16 pcf
Block 2 PICA Status

- **Boeing / FMI production of PICA materials**
  - All PICA coupons / panels for NASA testing completed on schedule and within specs
  - Initially planned PICA material properties testing completed
  - PICA full-scale MDU completed 1 month ahead of schedule

- **Material properties & development of thermal-ablation model**
  - NASA V&V testing of PICA material properties and database complete
  - Completed updated 1-D & multi-D PICA thermal response model
  - Additional targeted materials properties testing in work (thermal and mechanical)

- **PICA and integrated performance testing**
  - Comprehensive acreage PICA stagnation and shear arcjet testing complete
  - Initial PICA gap/seam configuration stagnation and shear arcjet testing complete
  - Comprehensive thermal-structural testing of acreage PICA and initial gap/seam configurations attached to flight-like carrier structure completed
  - Additional alternate gap/seam configuration testing underway (arcjet and thermal-structural)
  - Additional bondline performance (arcjet), thermal gradient (solar tower), pyro-shock, compression pad (arcjet), main seal (arcjet), MMOD (arcjet) and integrated system (arcjet) testing in work

- **PICA block layout and gap/seam design**
  - Current manufacturing limits of PICA is 42" x 24" x 10"
  - Deflection limits and PICA strengths indicate PICA flight panels may be limited to a maximum dimension of < 20”, with current limits set around 10”
  - Initial Boeing/FMI design features joined PICA panels --- however, NASA analysis indicates serious problems with resulting stresses in PICA
  - NASA team has developed an alternate PICA block layout design
  - NASA team has shifted to an uncoupled gap/seam design and is considering 4 options
PICA MDU Manufacturing
Flight Environments vs. Arcjet Test Environments: Heat Flux vs. Pressure

Does not include launch abort cases, one of which has stag pressures between 100–120 kPa, with corresponding heat fluxes between 80–200 W/cm².
Ames AHF Arcjet Testing of Gaps/Seams
In Depth PICA Thermal Couple Data vs. Thermal Response Model Predictions

Titan Multi-Dimensional Predictions

[Graph showing temperature profiles for TC9, TC8, TC7, TC6, TC10, TC5, and FIAT TC5 with conditions: 246 W/cm², 8.5 kPa, 42 s]
Thermal Vacuum Testing

Modal Testing of Bend Coupons

Acreage Panel (with seam)
Vibration Test (X and Y-axis)

Acoustic Panel installed in TAFA
Exposed Side (Flow is left-to-right)
Alternate TPS Material Development Status
CEV TPS Development Strategy
(Critical Path Item)

- **Baseline** Heat shield (Lunar and LEO return capable) by Orion IOC → 2014
- **Alternate** Heat shield (Lunar and LEO return capable) parallel development, maintained up through system decision (between Orion PDR and CDR)
- NASA develops **Baseline & Alternate** heat shield designs up to Orion PDR
- Prime takes over responsibility of heat shields after CEV PDR – w/ NASA oversight
- Back shell TPS development controlled by Orion Prime – w/ NASA oversight
- Possible flight test program beginning in 2014 to validate analysis and ground-based testing

**Baseline**
Lunar Direct Return Heat Shield

- **Blk 1 / Alt** Backup Heat Shield

**TPS Development Timeline**
- **Phase I**
  - **Base** 1 op
  - **TPS PDR**
  - Oct 05 - Aug 06
- **Phase II**
  - **Baseline** 1 op
  - **TPS CDR**
  - Spring 08
- **Phase III**
  - **System Decision**
  - Spring 09 - Summer 09
  - **Flight Test**
  - FY-10
  - **Flight Test**
  - FY-11
  - **LEO Ops Ready**
  - 2013
Alternate Block 2 Background

- Only one Block 2 contract was awarded Boeing/FMI – Aug 2006
- Regrouped to develop Alternate Block 2 procurements
- Two Alternate Block 2 contracts were awarded – May 2007
  - 2 Textron materials Avcoat & 3DQP
  - Boeing BPA
- Each Alt Block 2 contract was built with 120 day initial period
- Alternate Block 2 Decisions:
  1. Selection between Avcoat and 3DQP of the leading Textron material
     - Avcoat 10/1/07
  2. Continuation of Boeing BPA Contract
     - Decision postponed till 3/31/08
  3. Selection of the “Primary Alternate” TPS (between Avcoat & BPA)
     - Goal is to produce a PDR level heat shield design using the Primary Alternate material by TPS PDR
     - Avcoat selected as the Primary Alternate – 11/30/07
Alt Block 2 Material Performance

3DQP shear arcjet testing at AEDC
BPA shear arcjet testing at AEDC
BPA stagnation arcjet testing JSC
Avcoat stagnation arcjet testing JSC
AVCOAT Heat Shield Overview

• AVCOAT 5026-39 HC/G Material
  – Apollo heritage material
  – Filled epoxy novalic in fiberglass-phenolic honeycomb
  – Large H/C gore sections bonded to substructure with HT424
  – Hand gunning process to fill H/C cells with ablator
  – 33 pcf virgin density

Apollo H/C Installation
Block 2 Avcoat Status

• Textron production of Avcoat materials
  – Initial coupon fabrication showed poor material quality & very slow production
  – Coupon quality & production rates are now at adequate and sustainable rates
  – Avcoat coupons and panels for initial NASA development testing complete by July
  – Avcoat full-scale (1/4) MDU completion set for Aug/Sep
  – Phase 1 of an automated gunning study complete by Aug

• Material properties & development of thermal-ablation model
  – Initially planned Avcoat material properties testing complete
  – Resurrected the original 1-D Avcoat thermal ablation models (STAB, CMA)
  – Additional and NASA V&V testing of material properties for Avcoat in work
  – Updating thermal response models using new material property and arcjet data

• Avcoat performance testing
  – Significant acreage Avcoat stagnation and shear arcjet testing completed
  – Avcoat seam arcjet testing begins later this summer
  – Comprehensive thermal-structural testing of acreage Avcoat and seam configurations attached to flight-like carrier structure set for later this summer
  – Additional integrated thermal-structural, bondline performance (arcjet), thermal gradient (solar tower), pyro-shock, and integrated system (arcjet) testing in work

• Avcoat overall design and manufacturing
  – Honeycomb gore sections limited to 40 inch
  – Flight heat shield manufacturing equipment installed: gunning booths, full-sized oven, tile-rotate table, digital x-ray and paint booth
  – Detailed thermal-structural analysis and design underway at Textron; NASA IV&V thermal-structural analysis to confirm Textron work
  – Textron is studying different H/C concepts for shoulder regions (molded, flexcore)
  – Textron is also examining different H/C splice approaches
Avcoat MDU Manufacturing
Avcoast Automated Gunning Study

Phase 1 – started initial feasibility tests
Complete Aug 2008

Phase 2 starts after TPS material down select
Resurrected Avcoat Evolution

Phase 1 Avcoat
970 W/cm², 14 sec

“Spring ’07” Avcoat
953 W/cm², 30 sec

Phase 2 Avcoat
1008 W/cm², 40 sec
Lessons Learned
Key Lessons not to Forget:

• Detailed TPS thermal performance requirements are difficult to specify:
  – The n-vector (convective heat-flux, radiative heat-flux, pressure, enthalpy, shear, boundary layer properties, chemistry, etc.) of environments is complex
  – Environmental requirements change considerably during early vehicle design
  – Sorting out safety margins for environmental parameters based upon baseline and emergency entry modes remains challenging
  – Development of an adequate thermal response model is difficult and time consuming

• Thermal testing beyond margined environments is necessary:
  – The vehicle performance requirements tend to change during development
  – Need to test for material performance “cliffs”
  – Facility measurement capabilities has large uncertainties (+/-20 %)
  – Ground-to-flight traceability presents materials qualification challenges

• The capability of current ground test facilities is limited:
  – There are only 3-4 applicable US arcjet test facilities today compared to 20-25 facilities during the Apollo era
  – The available facilities offer limited (incomplete coverage for CEV) and are prone to a high rate of down time
  – Even an ideal ground test facility will not fully replicate flight environments forcing difficult ground-to-flight traceability efforts
  – Flight test validation of material performance may be required
Key Lessons not to Forget:

• The key thermal performance limits for a given TPS material are often not determined by considering the parameter maximums
  – Glass melt/flow/fail must be carefully characterized for silica based materials such as SLA-561V and Avcoat
    • The phenomenon is experienced at moderate heat fluxes (75 – 150 W/cm²), but due to glass vaporization, not experienced at higher heat fluxes
  – Lower enthalpy conditions resulted in SLA material failure compared to higher enthalpy conditions
  – Limited CEV testing has shown that some TPS materials experience differences in material response that are a function of environment history

• The development of TPS materials is a careful balance between thermal performance and thermal-structural integrity
  – Regardless of whether the heat shield design is a tiled system (PICA), or a monolithic system (Avcoat), thermal-structural capabilities are critical
  – Detailed thermal response must be understood for the integrated system not just for acreage TPS material
  – Penetrations and closeouts require significant work and are difficult manage prior to PDR due to changing requirements
Key Lessons not to Forget:

• Thermal-structural analysis and design proved more challenging than expected:
  – Statistical (A-basis) material properties do not exist for most TPS materials
  – Obtaining mechanical properties across a wide temp. range is challenging and for TPS materials often produce large variations
  – TPS Mechanical failure modes are poorly understood & difficult to substantiate
  – Standard material property testing processes are problematic for TPS materials
  – Establishing an acceptable thermal-structural margins policy requires significant work
  – TPS materials are characterized by highly non-linear mechanical properties
  – Ablative TPS materials present additional challenges due to pyrolysis and ablation
  – Developing a credible and validated series of FEM models for an integrated heat shield to assess various load cases requires significant experience/time
  – Thermal-structural design and analysis based upon FEM is insufficient – combined environment testing, with thermal gradients and mechanical loads is needed

• Restarting the manufacturing of previous TPS materials takes significant time and resources:
  – Constituents usually require some changes due to changes in safety or precursor material availability
  – Following a known recipe and process is often not enough, significant fabrication experience is required to produce quality and consistency
Key Lessons not to Forget:

• **Manufacturing challenges occur at multiple levels:**
  – Producing consistency even at the coupon level proved challenging for some materials
  – Every step in scale-up from coupon → panel → section → heat shield, can result in processing, consistency, thermal-structural, or integration difficulties
  – Establishing necessary infrastructure requires significant time (~ 1.5 years)
  – Creating a volume production capability requires significant resources

• **Non Destructive Evaluation (NDE) and bond verification techniques remain problematic**
  – More time and effort are needed to develop digital x-ray based 3-dimensional scanning
  – Alternate NDE methods need much more work

• **The current success of CEV TPS materials and heat shield designs does not represent a long term TPS development strategy**
  – Prior to the CEV TPS ADP effort, ablative TPS work was neglected for 40 years
  – The TPS ADP was an expensive, high risk, critical path approach to recover
  – Without the fortuitous timing of the CEV TPS ADP PICA heat shield effort, MSL would have had no TPS options to meet their Sep ‘09 launch window
  – While PICA & Avcoat are viable for CEV, neither system is ideal – lower mass, increased robustness materials are possible (too low TRL for CEV IOC)
  – NASA / US are short of efficient, robust TPS materials for future exploration missions: high mass Mars entry, outer planets, Venus, extra-Lunar Earth return