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

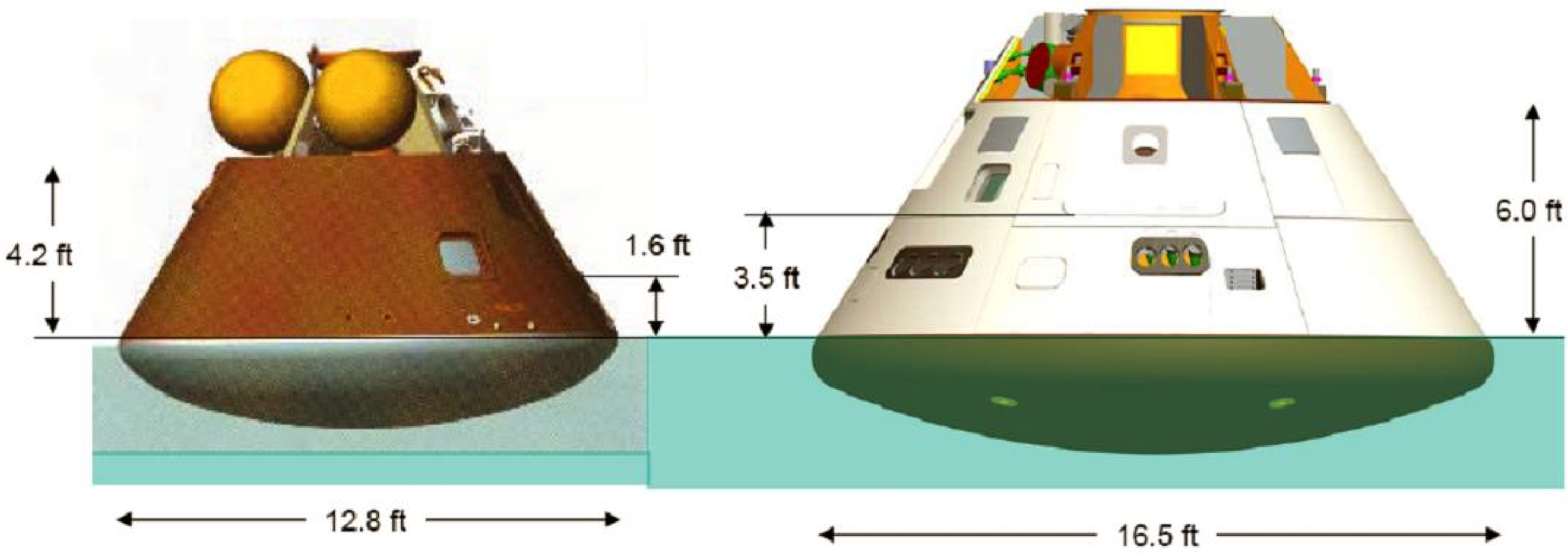
Crew Module –
crew and cargo transport

Service Module –
propulsion, electrical power, fluids storage

Spacecraft Adapter –
structural transition to launch vehicle

Orion vs. Apollo

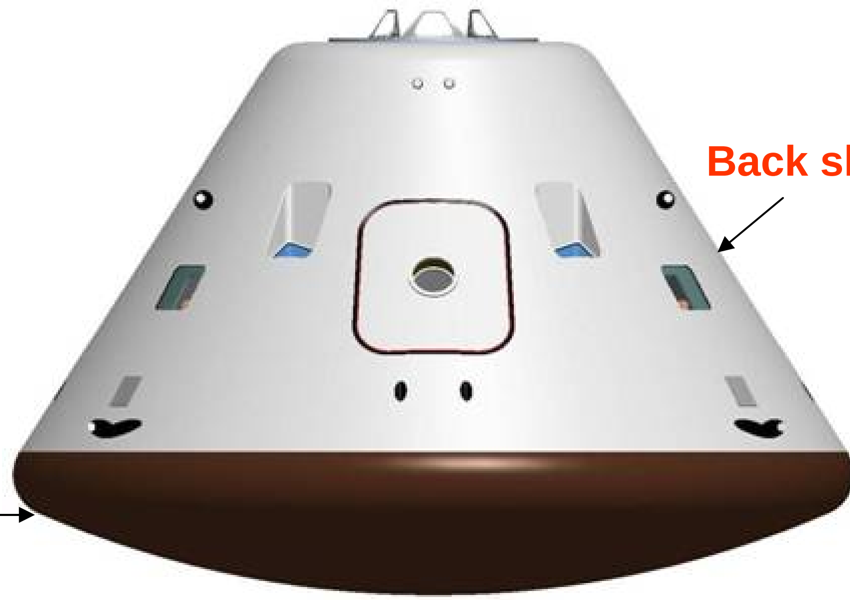
- **Orion shape is derived from Apollo, but approximately 30% larger**
  - Presents challenges to the TPS, including:
    - Increased heat loads
    - Manufacturing challenges



Comparison of Apollo to Orion floating in still water

The Orion TPS Objective

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/cm^2**

Orion Low Earth Orbit (LEO) return conditions:

- **8 km/s atmospheric entry**
- **peak heat rate > 150 W/cm^2**

… by initiating a 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.**

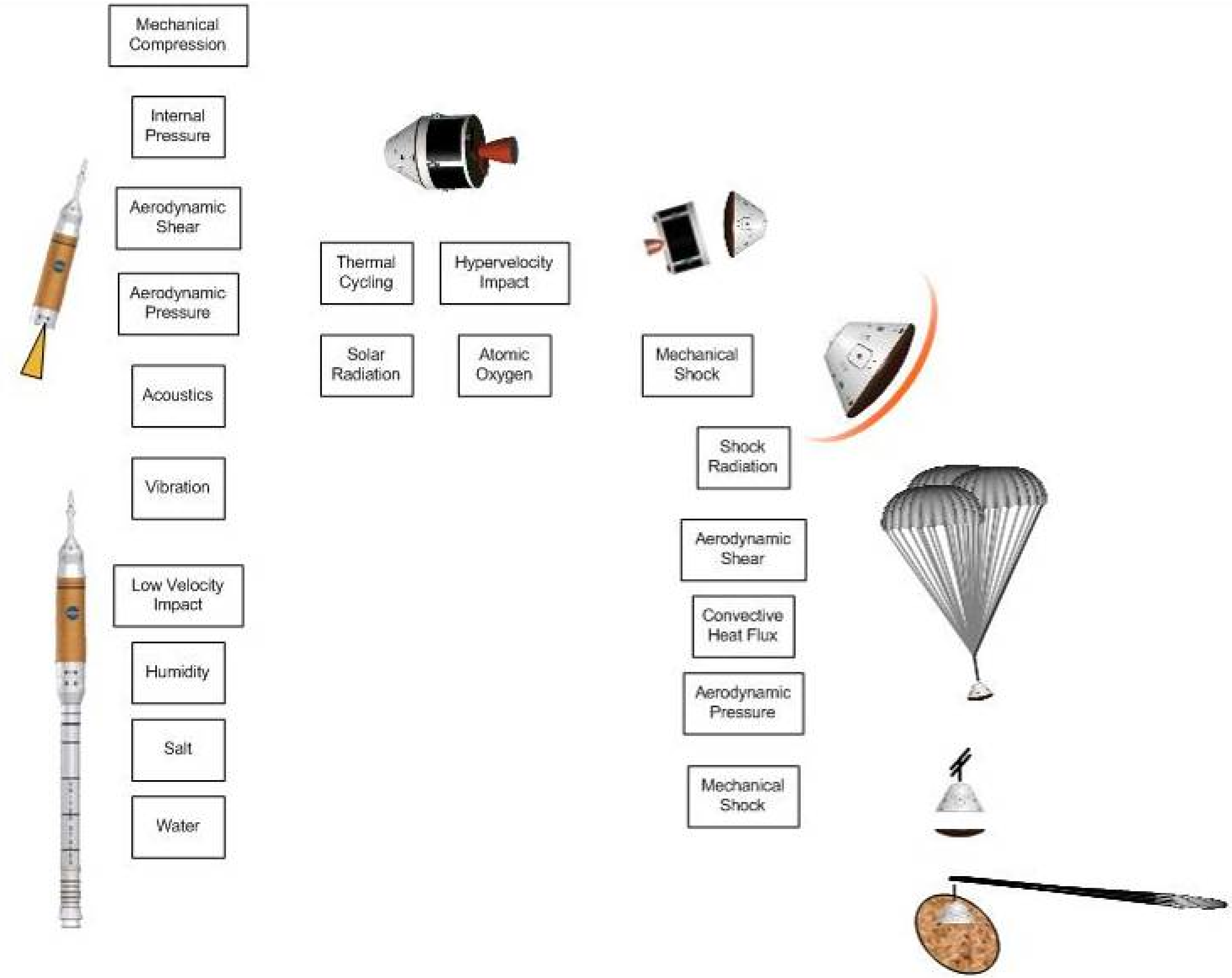
- **At the core of the ESAS recommended architecture was a new Crew Exploration Vehicle (CEV – Orion) that would serve as the US human transportation system for Low Earth Orbit (LEO) as well as lunar missions**

- **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**

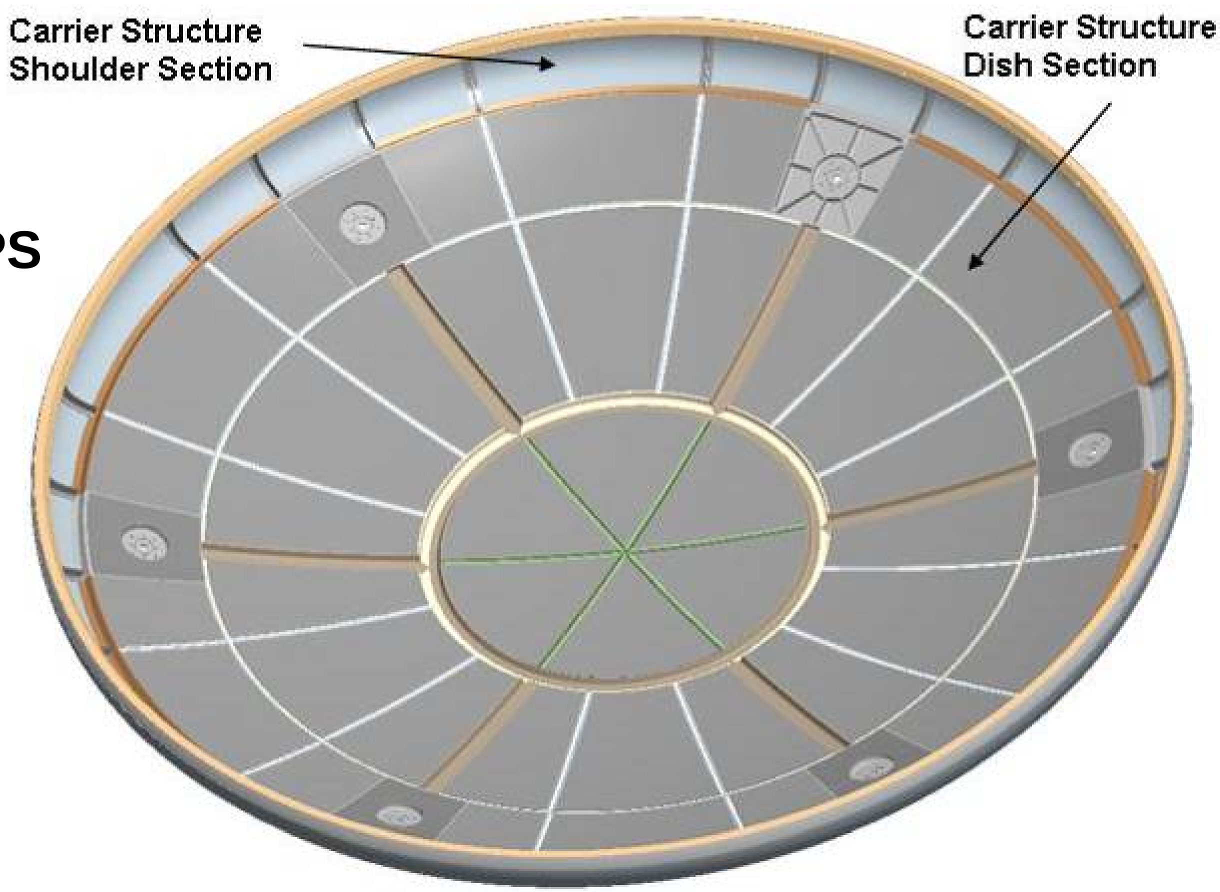
Heat Shield Operating Environments

CEV TPS Advanced Development Project Office



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

Critical Path for CEV
No longer considered for CEV

- **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

Candidate Heatshield Ablator Materials for Lunar Return (Block 2) Conditions

Vender Material	Heritage Mission & Diameter	Local TPS Approach TTT	System Construction IP	TPS ADP Contracts Density	Image
ARA PhenCarb 28	MDU, TRL = 4 (2007) 1 m	Uniform TTT – in Honeycomb	Segmented with seams	Phase I 450 kg/m³	
Boeing / FMI PICA	Stardust, TRL = 4 (2006) 0.9 m	Uniform TTT bonded with RTV/SIP/RTV	Blocks/Tiles w/ filled gaps/seams	Phase I, Phase II 270 kg/m³	
LM / LCAT ACC / CalCarb	Genesis, TRL = 4 (2004) 1.35 m	Dual layer system	Monolithic or segmented	Phase I 1500 / 180 kg/m³	
Textron Avcoat	AS-501, TRL = 4 (1967) 3.9 m	Uniform TTT – in Honeycomb	Monolithic w/ honeycomb seams	Phase I, Phase II 540 kg/m³	
Textron 3DQP	DoD ?, TRL = 3 (?) ?	Dual layer with integration layer	Segmented w/ tongue & groove	Phase I, Phase II 1600 / 220 kg/m³	
Boeing BPA	Coupons, TRL= 3 (2005) 1 m	Uniform TTT – in Honeycomb	Monolithic or segmented	Phase II 540 kg /m³	

5 Materials Selected for Block 2 Phase I Screening Tests Coupons

Boeing PICA

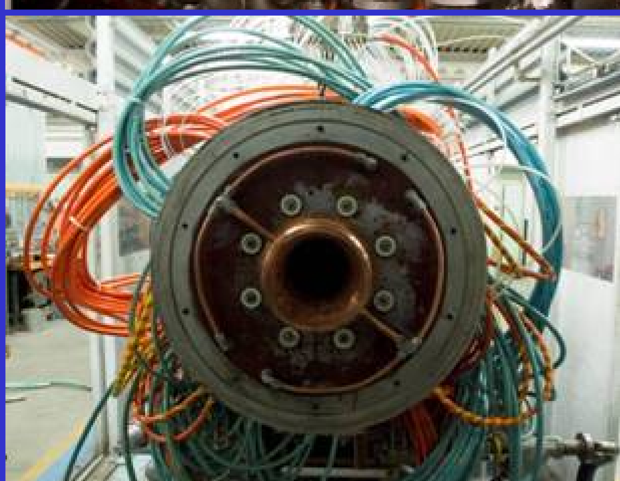
ARA PhenCarb 28

Textron Avcoat

Textron 3DQP

Lockheed Martin ACC/CalCarb

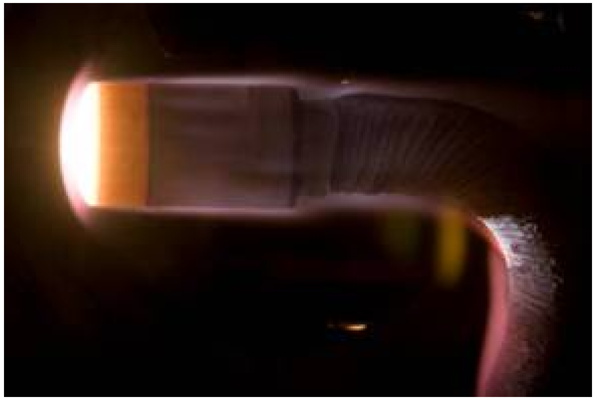
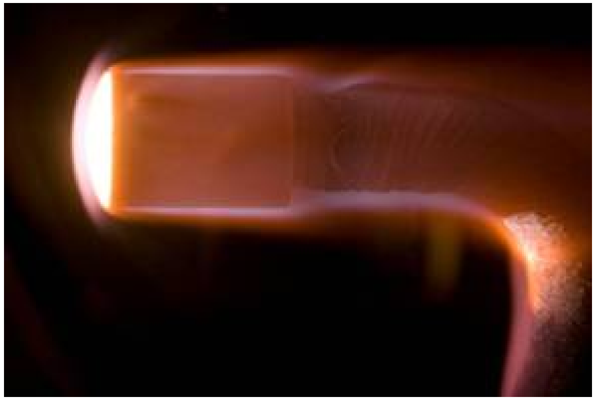
Block 2, Phase I Testing in Arcjet

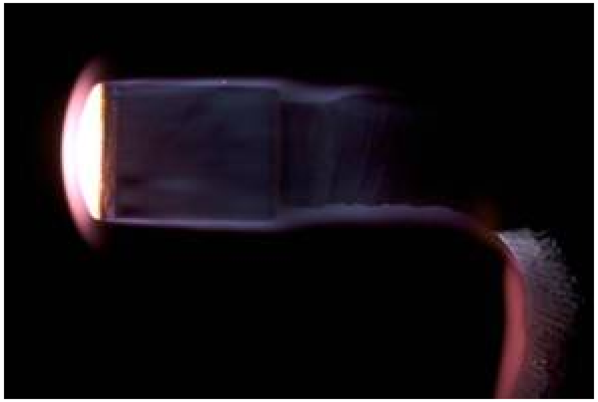
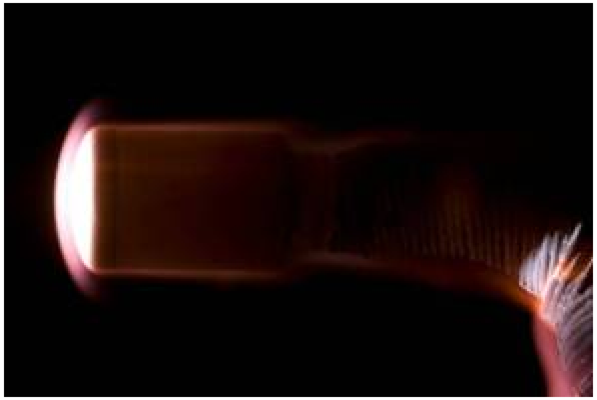


Block 2 Phase I
Stagnation Arcjet Testing

Three arcjet test series were performed

- **Block 2 peak heating - 1000 W/cm^2 @ 30 sec --- Ames IHF**
- **Block 2 skip dual-pulse 400 / 150 W/cm^2 --- Ames AHF**
- **Block 1 nominal entry – 130 W/cm^2 @ 200 sec --- Ames IHF**

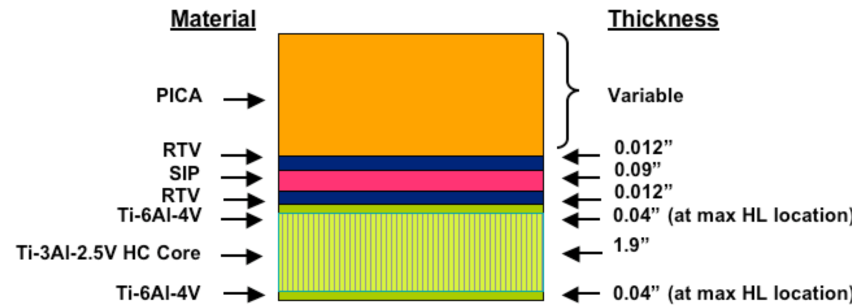
Block 1 SLA-561V & Shuttle Tile Status

- **SLA-561V TPS material performance issues**
  - MSL stagnation thermal ablation testing showed excellent stagnation heating performance up to 300 W/cm^2
  - However, arcjet tests at low heating (90 – 150 W/cm^2), 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**

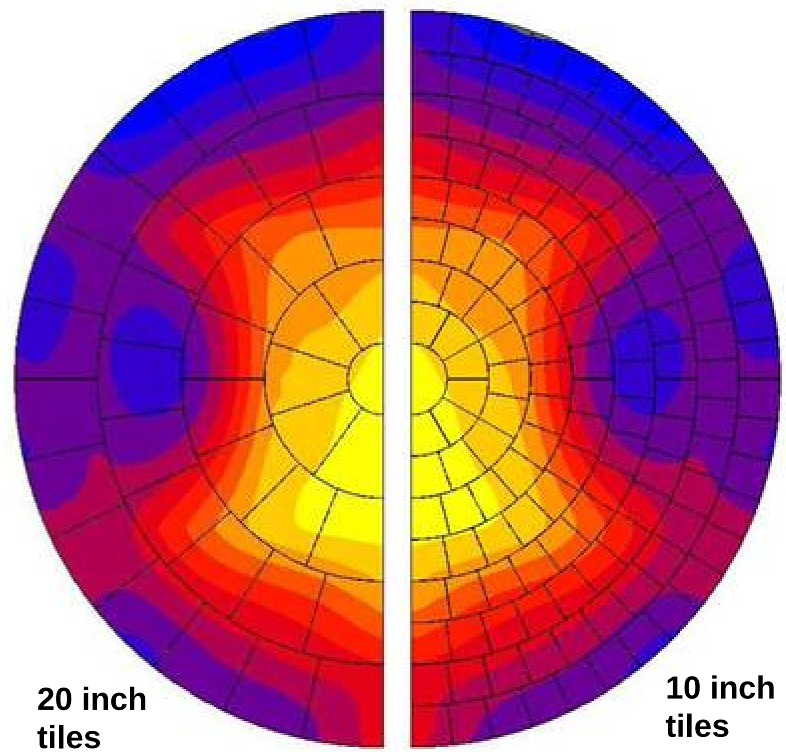
Baseline PICA Development Status

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



PICA HS MDU



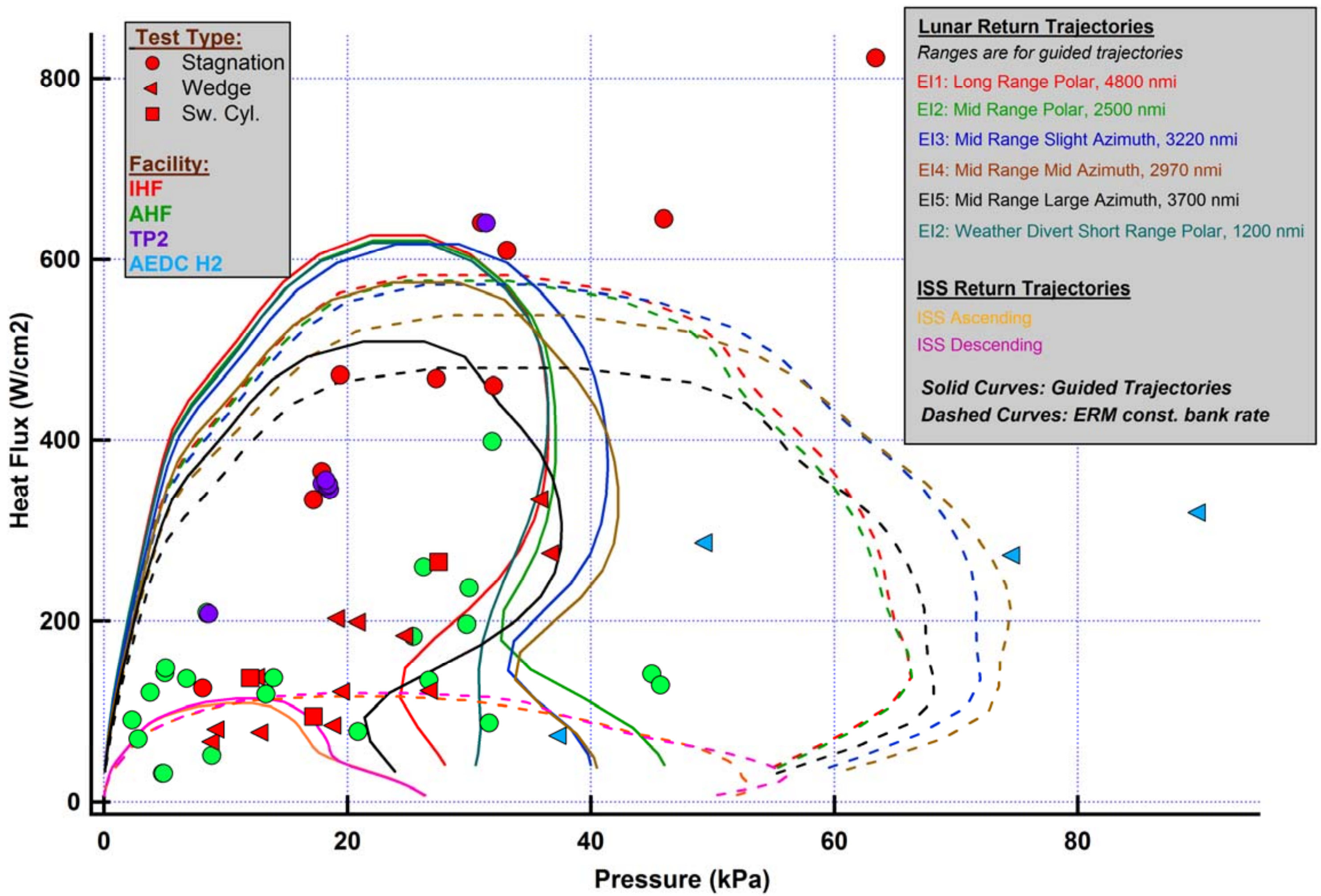
Current ADP Block Layout

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

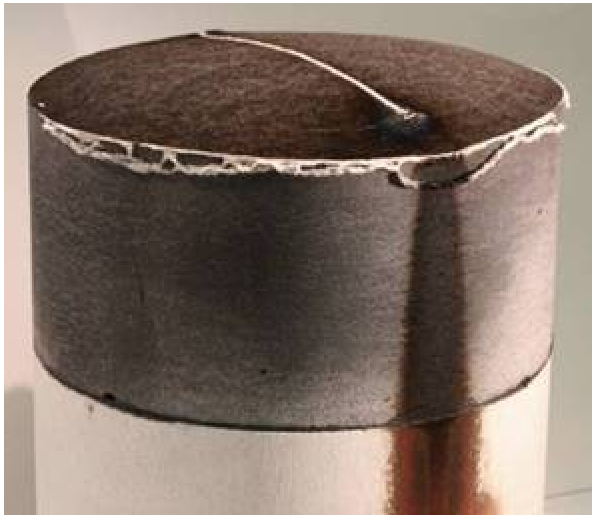
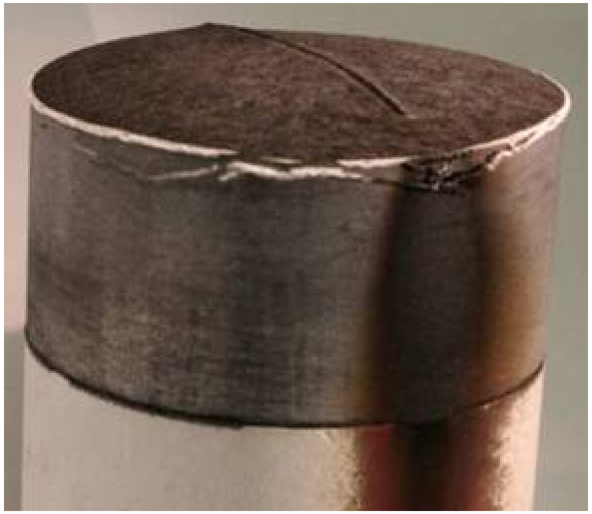
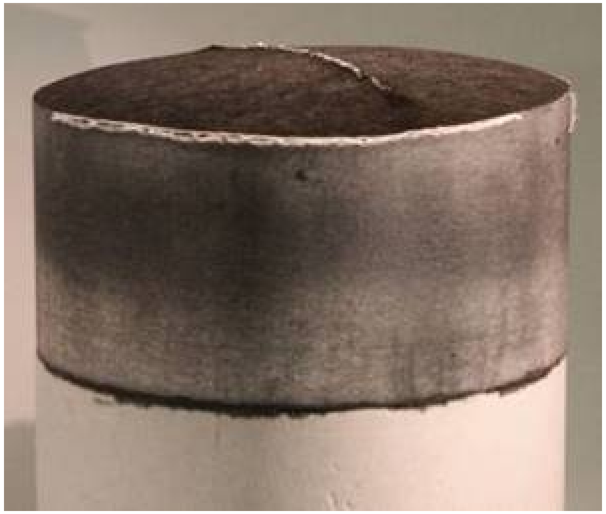
Flight Environments vs. Arcjet Test Environments: Heat Flux vs. Pressure



Does not include launch abort cases, one of which has stag pressures between 100–120 kPa, with corresponding heat fluxes between 80–200 W/cm^2.

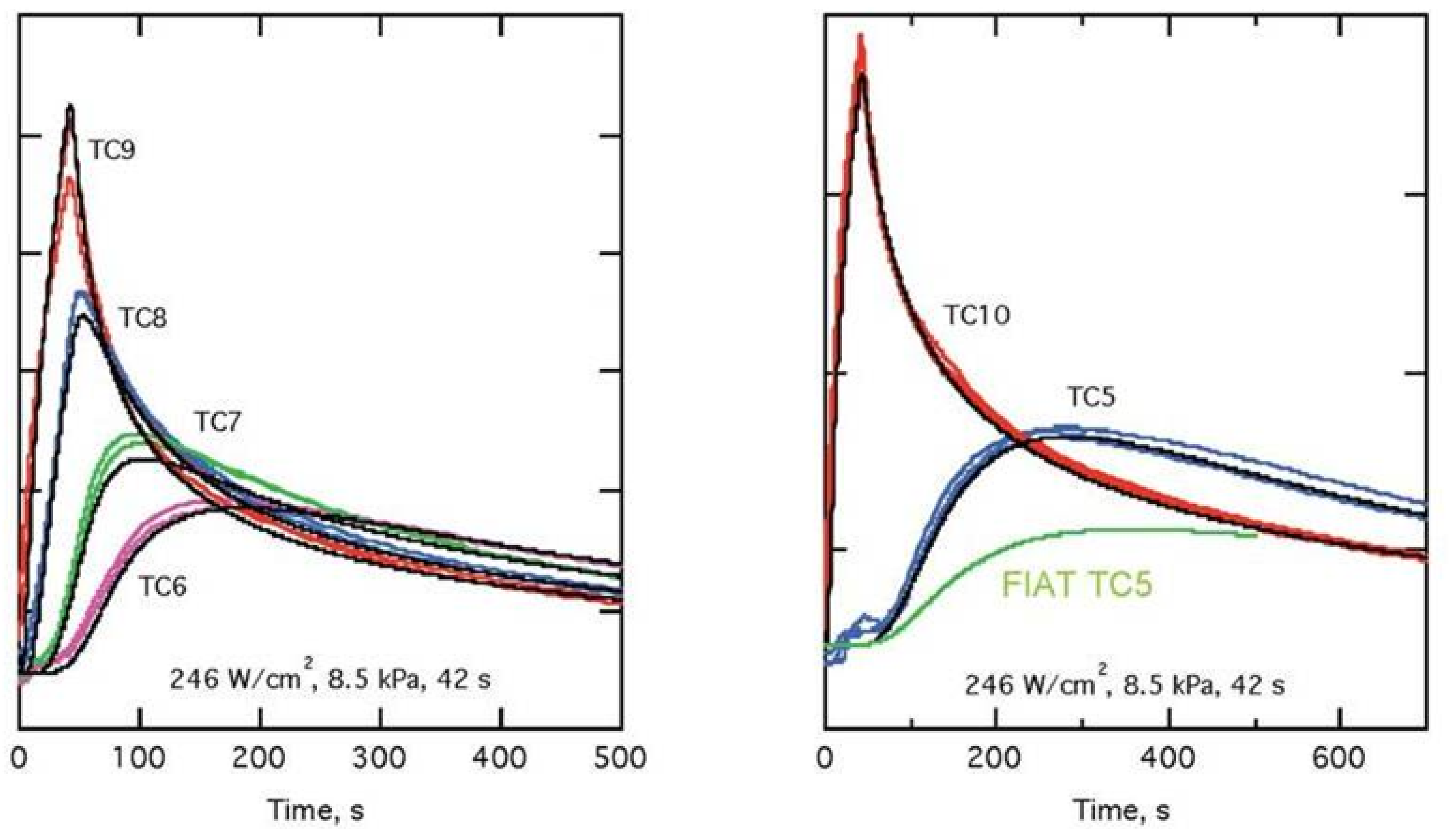
Ames AHF Arcjet Testing of Gaps/Seams



In Depth PICA Thermal Couple Data vs. Thermal Response Model Predictions

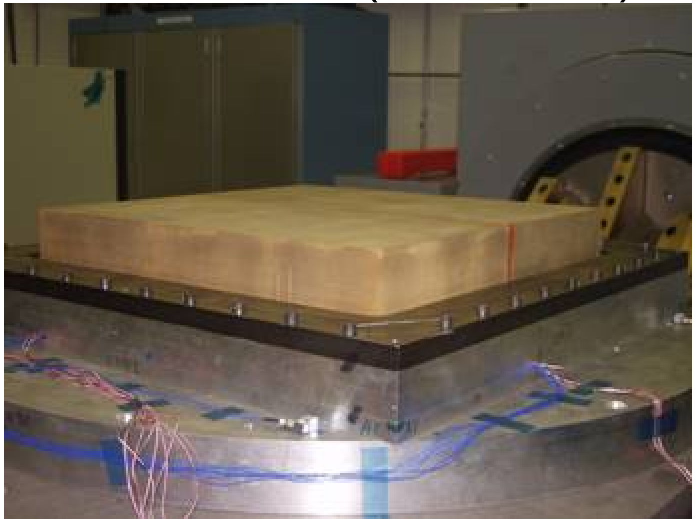
Titan Multi-Dimensional Predictions



Thermal Protection System Advanced Development Project - LaRC Testing

Thermal Vacuum Testing

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



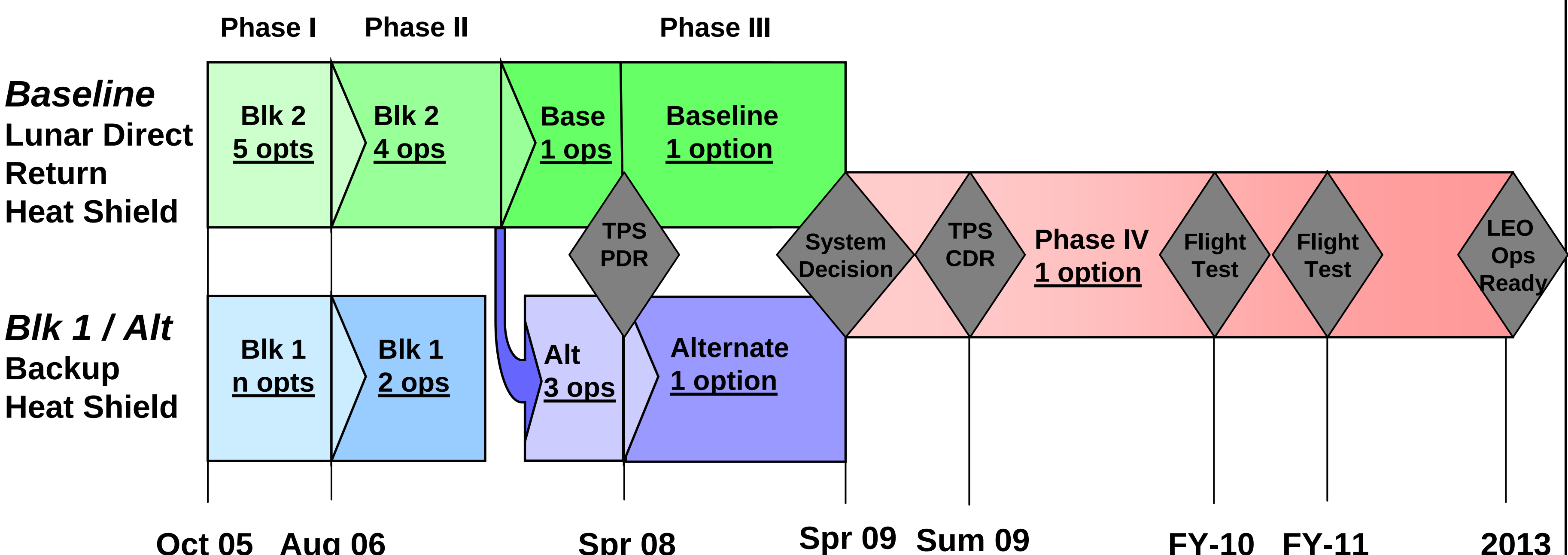
Modal Testing of Bend Coupons

Acoustic Panel installed in TAFA Exposed Side (Flow is left-to-right)

Alternate TPS Material Development Status

CEV TPS Development Strategy (Critical Path Item)

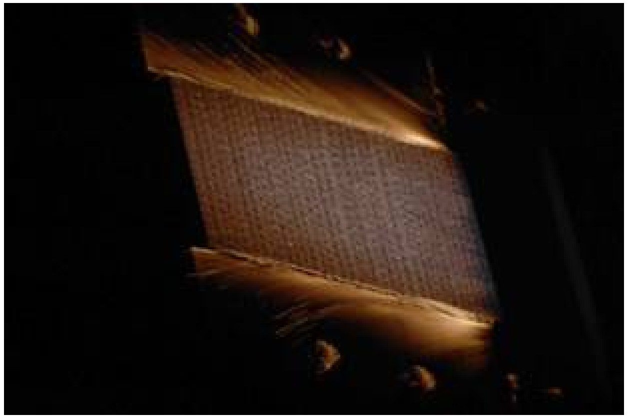
- **Baseline Heat shield (Lunar and LEO return capable) by Orion IOC → 2014**
- **Alternate Heat shield (Lunar and LEO return capable) parallel development, maintained up through system decision (between Orion PDR and CDR)**
- **NASA develops Baseline & Alternate heat shield designs up to Orion PDR**
- **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**

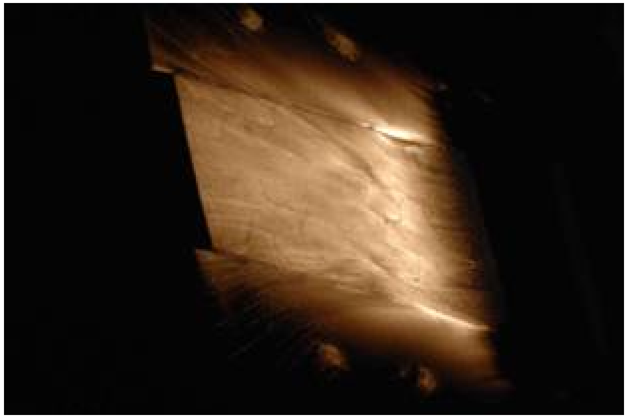


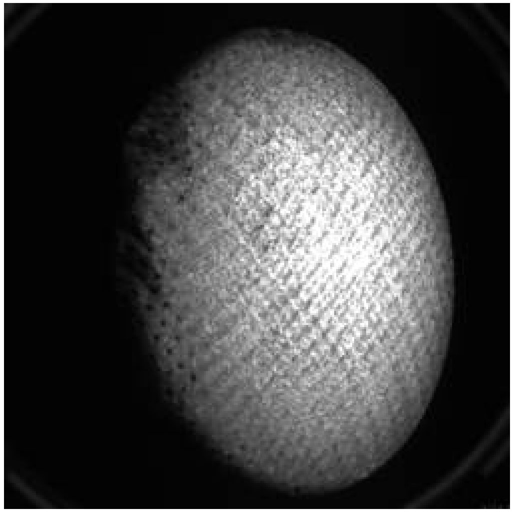
Alternate Block 2 Background

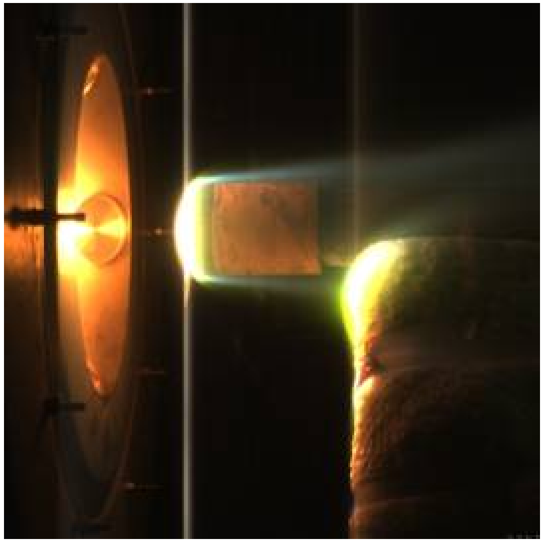
- **Only one Block 2 contract was awarded Boeing/FMI – Aug 2006**
- **Regrouped to develop Alternate Block 2 procurements**
- **Two Alternate Block 2 contracts were awarded – May 2007**
  - 2 Textron materials Avcoat & 3DQP
  - Boeing BPA
- **Each Alt Block 2 contract was built with 120 day initial period**
- **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**

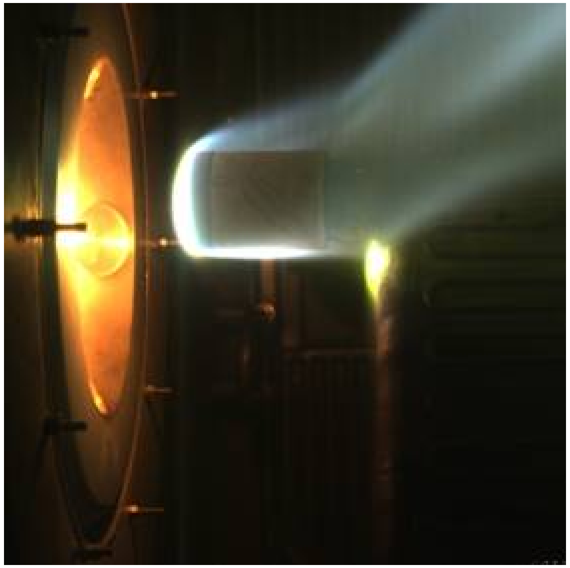
Alt Block 2 Material Performance


3DQP shear arcjet testing at AEDC


BPA shear arcjet testing at AEDC

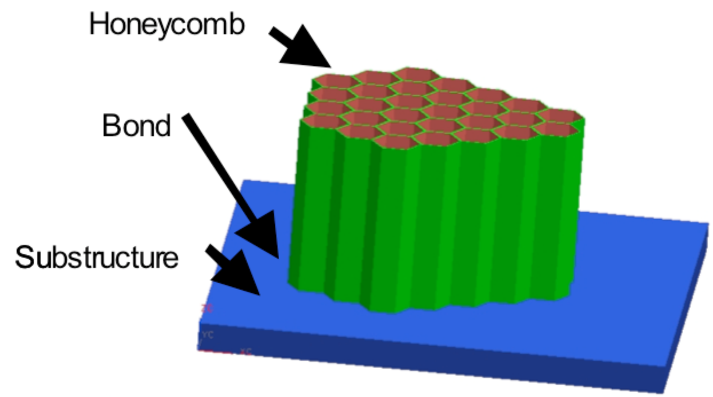

3DQP stagnation arcjet testing


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



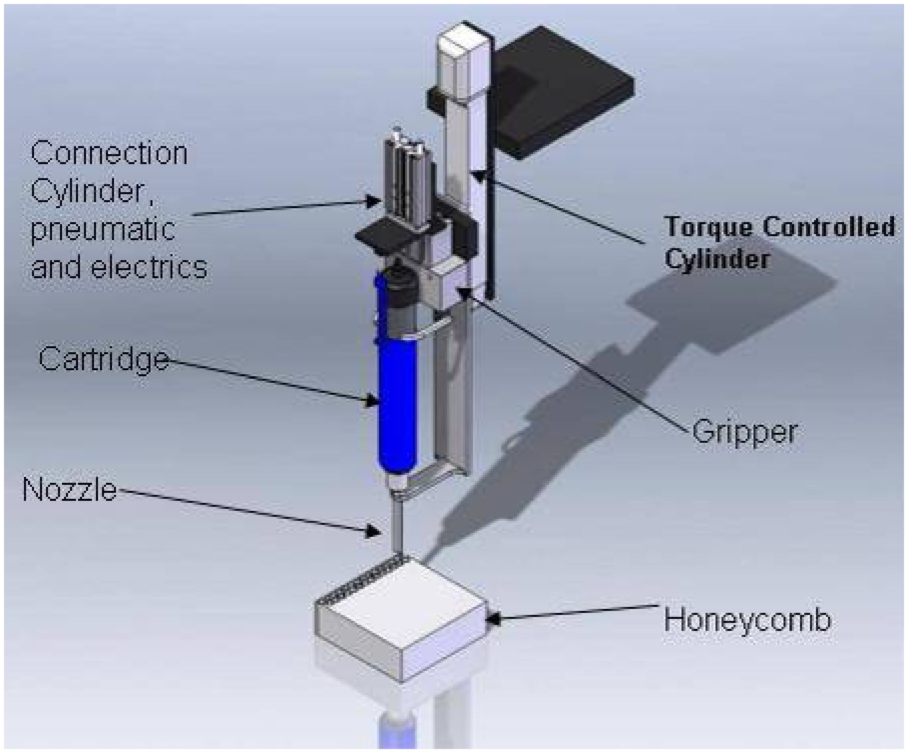
Apollo H/C Installation

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

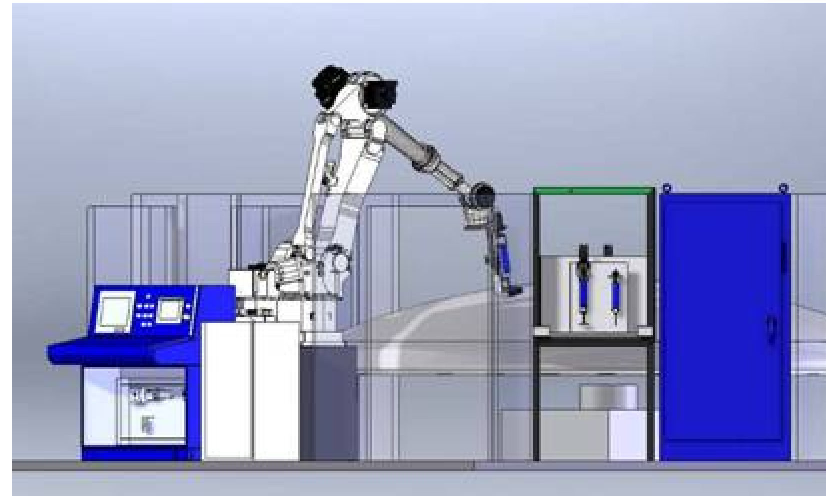
Avcoat MDU Manufacturing

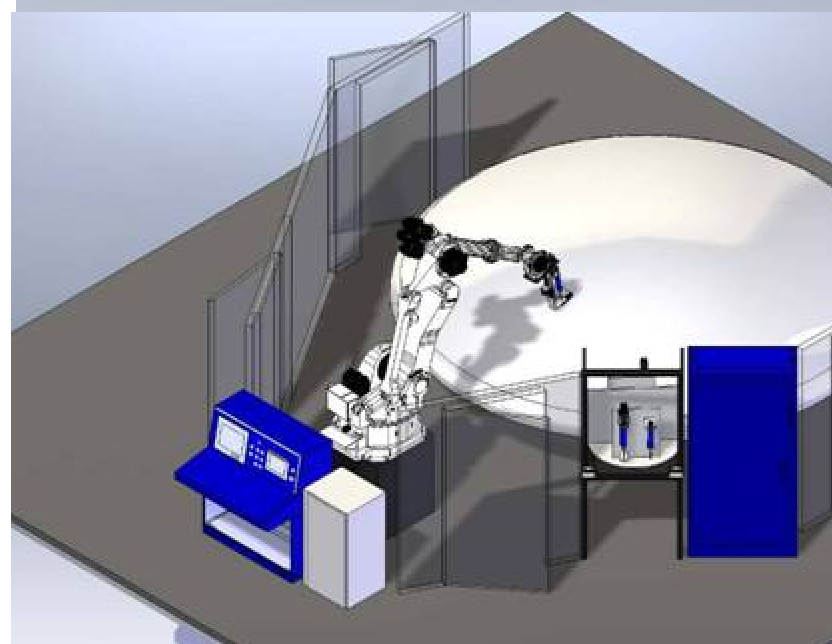
Avcoat Automated Gunning Study



Phase 1 – started initial feasibility tests
Complete Aug 2008

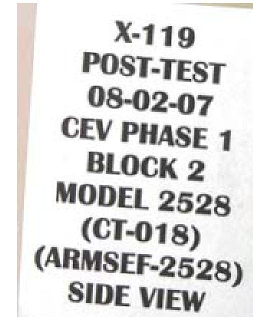
Phase 2 starts after TPS material down select





Resurrected Avcoat Evolution

Phase 1 Avcoat
970 W/cm^2, 14 sec



"Spring '07" Avcoat
953 W/cm^2, 30 sec

Phase 2 Avcoat
1008 W/cm^2, 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/cm^2), 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