Overview of Advanced Technology Development for Orion's Heat Shield

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The Orion TPS Challenge

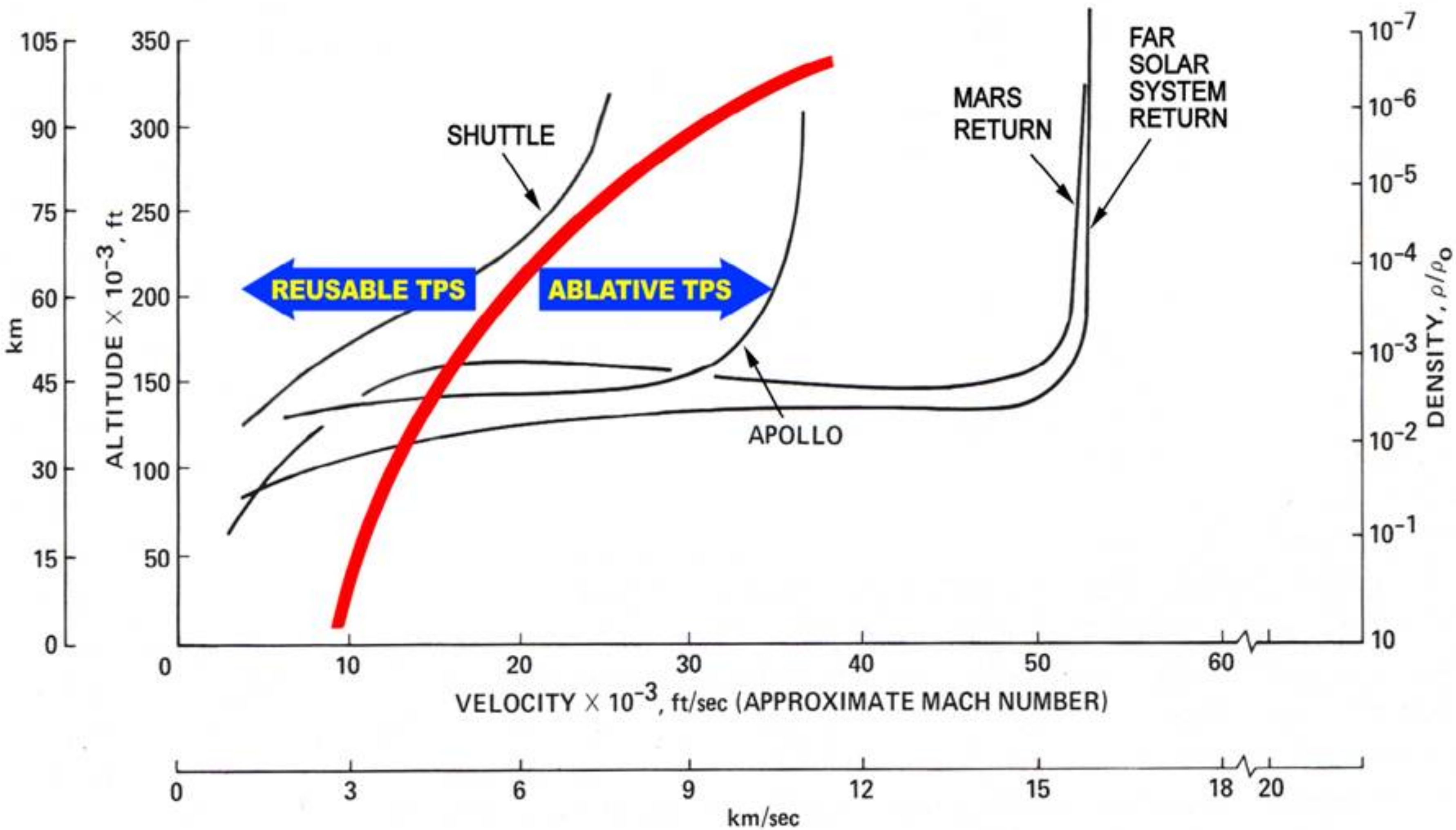
To help the Prime Contractor design and build the Orion TPS….

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 reduce the risk of a Lunar-direct return capable heat shield

Why Ablative Materials for Block 2?



CEV - Ablative TPS Heat Shield Advanced Development Project (ADP)

- **Requirements:**
  - The CEV shall return the crew & cargo from ISS & LRO to the Earth surface.
  - The CEV shall perform skip entry into the Earth's atmosphere of up to 5,750 n.mi (10,650 km) from both nominal and aborted lunar mission trajectories.
  - The CEV shall perform a direct entry from LEO.
  - The CEV shall limit their contribution to the risk of loss of mission (LOM) for a Lunar Sortie, ISS Crew, ISS Cargo and Lunar Outpost missions to no greater than 1 in …
  - NASA will provide both the lunar and LEO-return heat shield designs with supporting evidence for the CEV Preliminary Design Review via an Advanced Development Project
- **Timeframe Needed: CEV TPS Preliminary Design Review (currently 2/12/2008)**
- **Categorization: Critical**
  - Unable to achieve CEV primary mission objectives (Lunar or LEO return)

Heat Shield Operating Environments

Mechanical Compression

Internal Pressure

Aerodynamic Shear

Aerodynamic Pressure

Acoustics

Vibration

Low Velocity Impact

Humidity

Salt

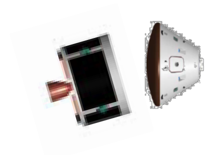
Water

Thermal Cycling

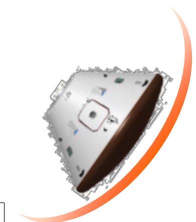
Hypervelocity Impact

Solar Radiation

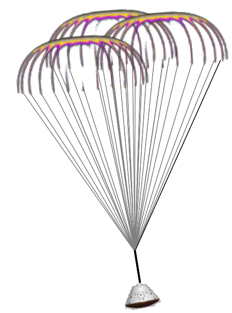
Atomic Oxygen



Mechanical Shock



Shock Radiation



Aerodynamic Shear

Convective Heat Flux

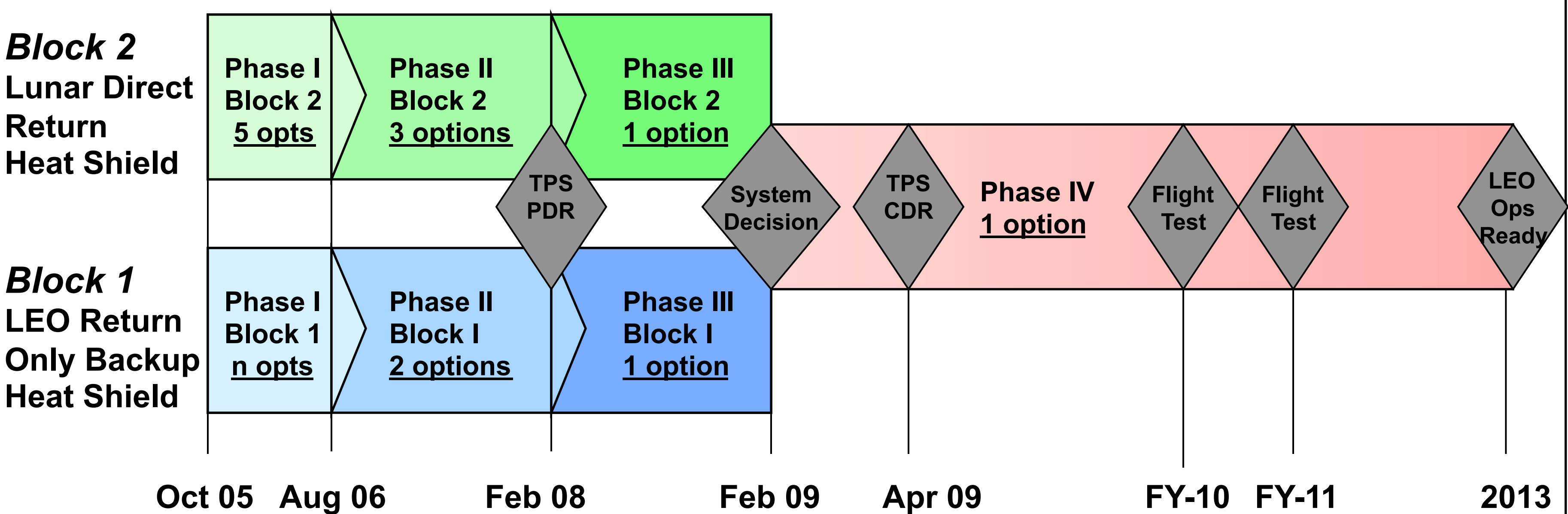
Aerodynamic Pressure

Mechanical Shock

Project Execution

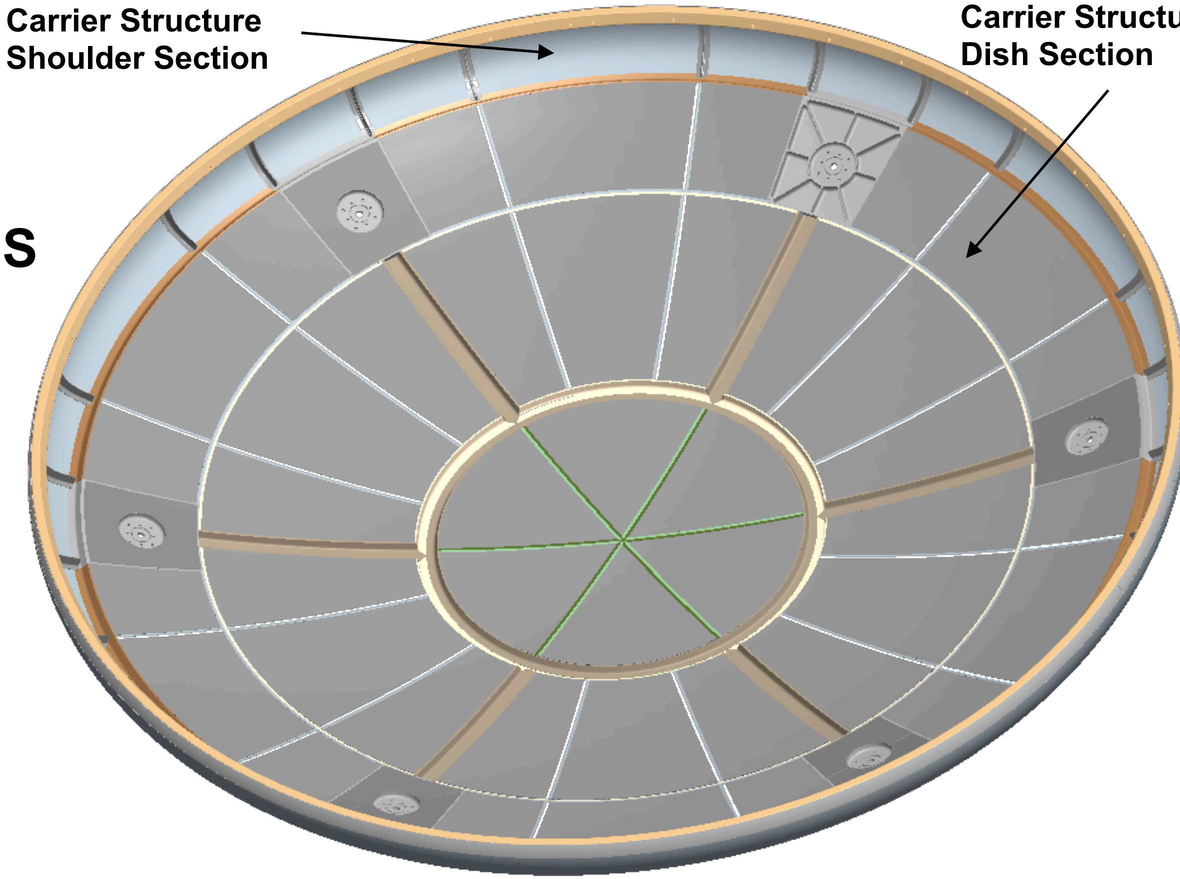
CEV TPS Development Strategy (Critical Path Item)

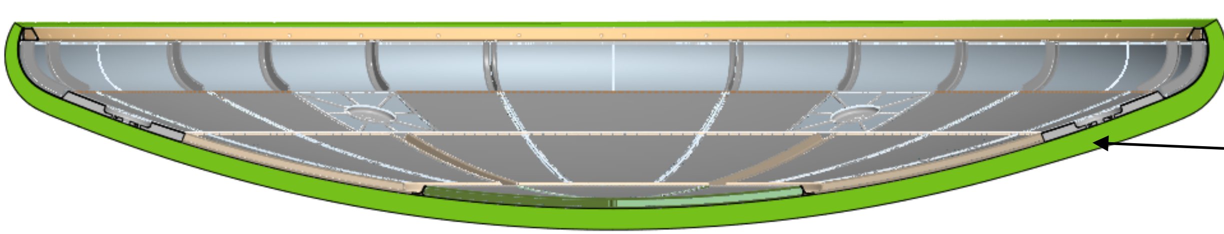
- Block 2 Heat-shield (Lunar and LEO return capable) by Orion IOC → 2014
- Block 1 Heat-shield (LEO return only) parallel development of back-up/off-ramp, maintained up through system decision (between Orion PDR and CDR)
- NASA controls development of Block 1 and 2 heat shields through Orion PDR
- Prime 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 2010 to validate analysis and ground-based testing



Orion Heat Shield Components

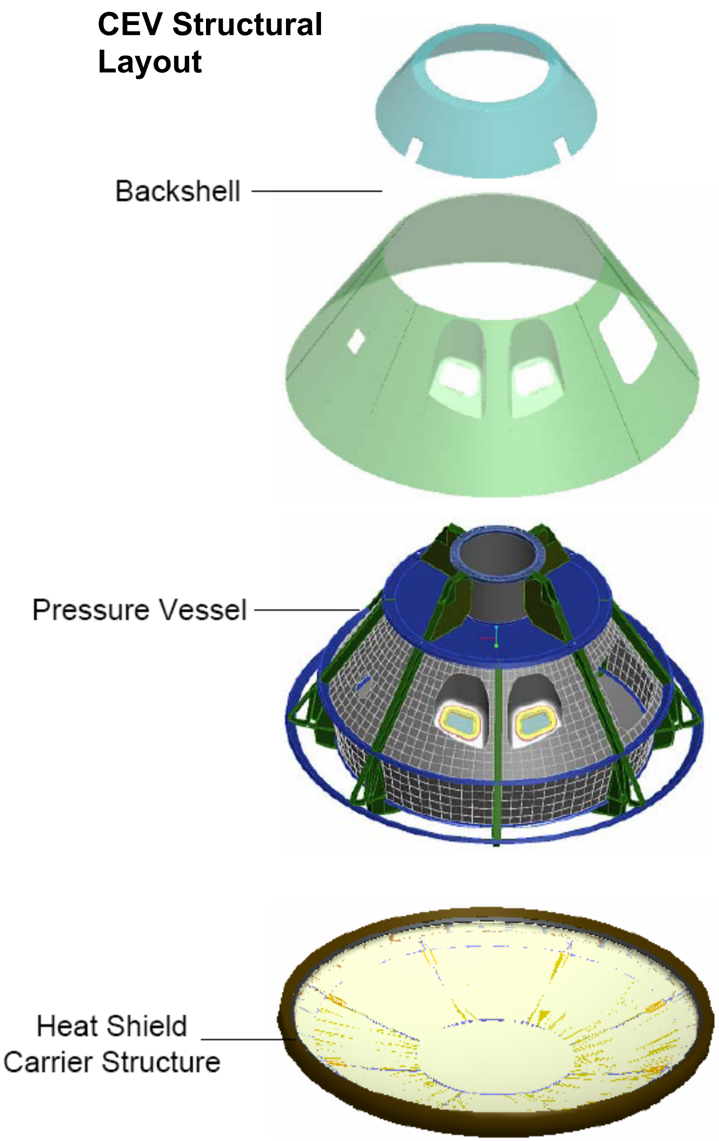
- **Carrier structure**
  - Dish section
  - Shoulder section
- **Ablative acreage TPS**
  - Block layout
  - TPS material thickness
- **Compression pads**
- **Separation mechanism**
- **Main seal**

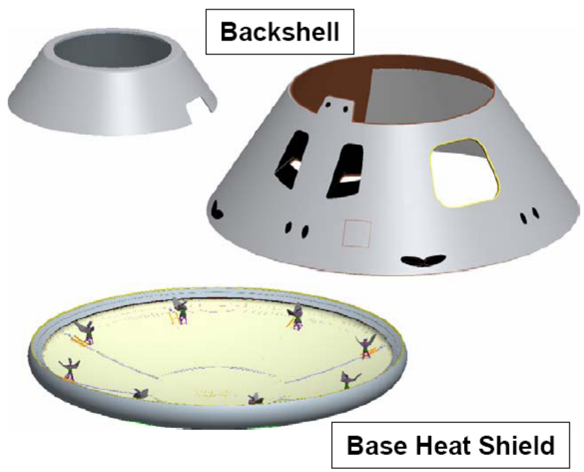


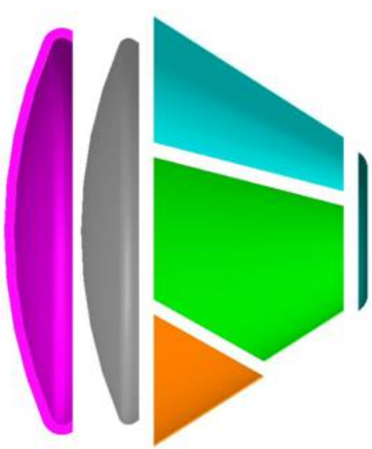


Interfacing with CEV and Prime Reference Configuration Development

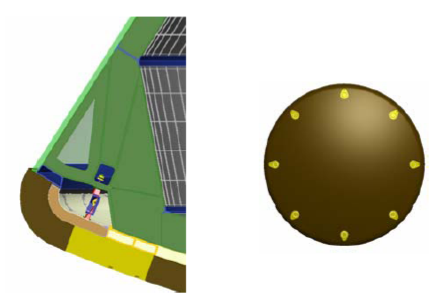
- **N-DAC1 completed Jan 2006**
- **N-DAC2 completed Apr 2006**
- **N-DAC3 completed Aug 2006**
- **Lockheed Martin Selected as Prime Sep 2006**
- **RAC3 completed Dec 2006**
- **Weight reconciliation completed Feb 2007**
- **DAC1 completed June 2007**







TPS Split Lines



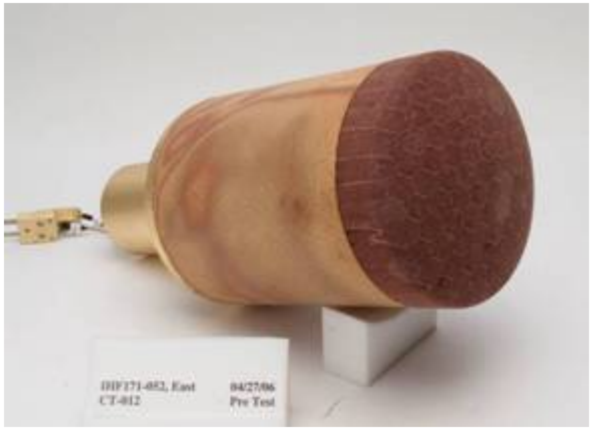
Heat Shield Materials

- **Block 2 TPS Materials**
  - ARA: PhenCarb 28
  - **Boeing / FMI: PICA (Baseline)**
  - Lockheed Martin / CCAT: Advanced Carbon-Carbon / Calcarb
  - **Textron: Avcoat (Alternate)**
  - **Textron: 3DQP (Alternate)**
  - **Boeing: BPA (Alternate)**
- **Block 1 TPS Materials**
  - Lockheed Martin: SLA-561V
  - **Shuttle tile materials: LI-2200, BRI-18 (Back-up)**
- **Carrier Structure**
  - **Titanium / Titanium honeycomb (Baseline)**
  - **GR-BMI Composite / Titanium honeycomb (Alternate)**
- **Compression Pads**
  - Fiberglass phenolic
  - Silica phenolic
  - Carbon phenolic

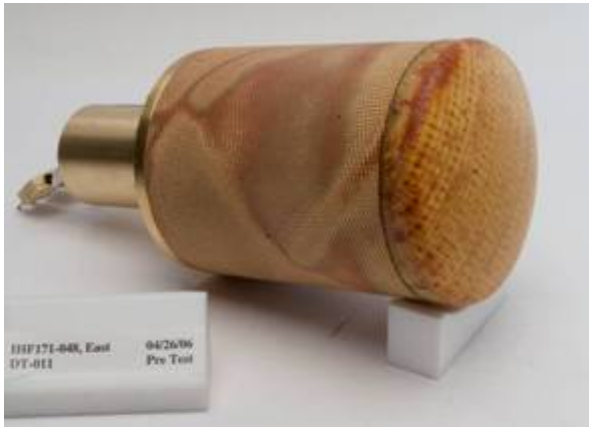
5 Materials Selected for Block 2 Phase I Screening Tests Coupons

Boeing PICA

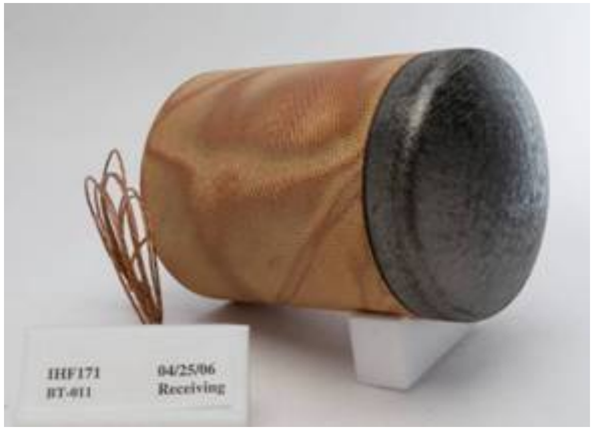
ARA PhenCarb 28



Textron Avcoat

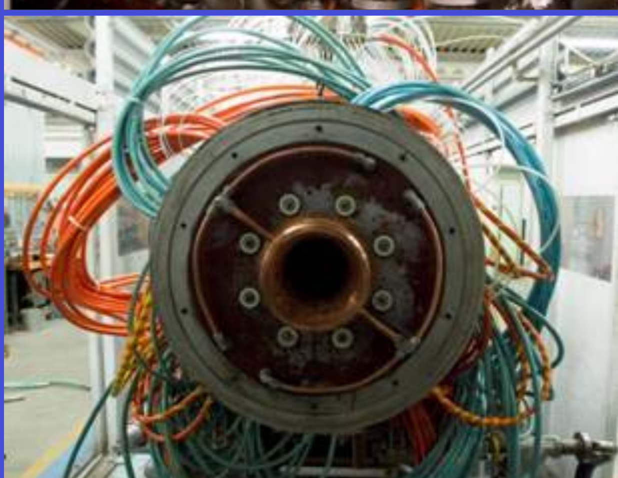


Textron 3DQP



Lockheed Martin ACC/CalCarb

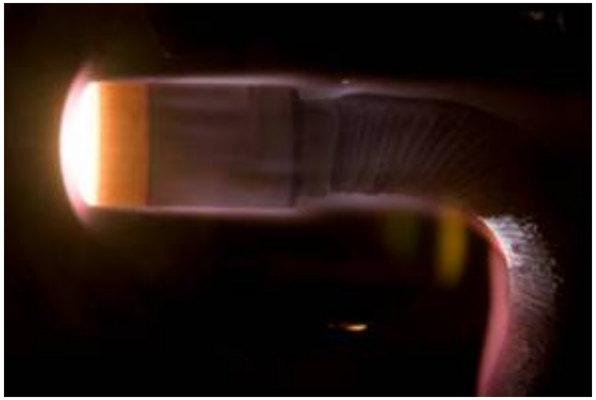
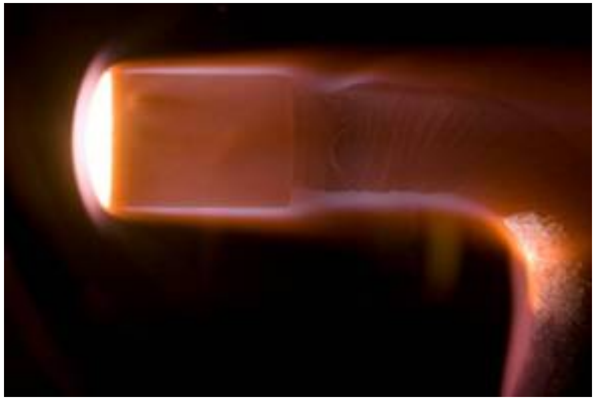
Block 2, Phase I Testing in Arcjet

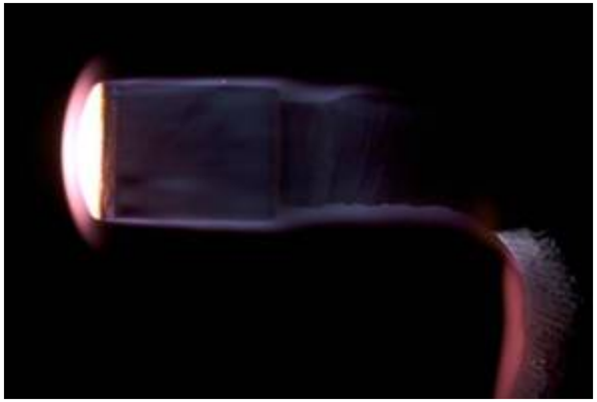
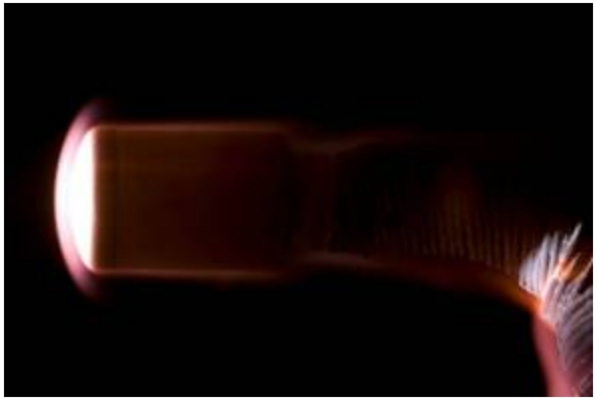


Block 2 Phase I
Stagnation Arcjet Testing

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

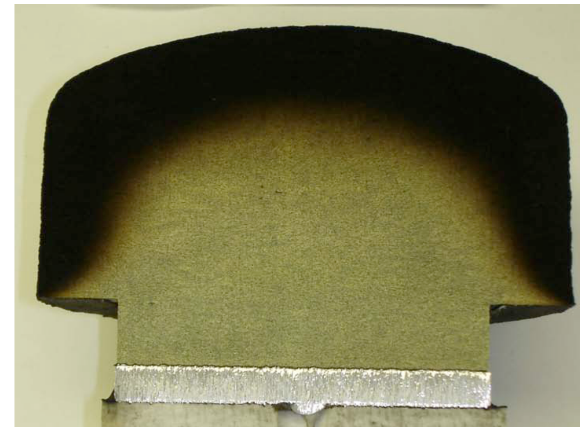



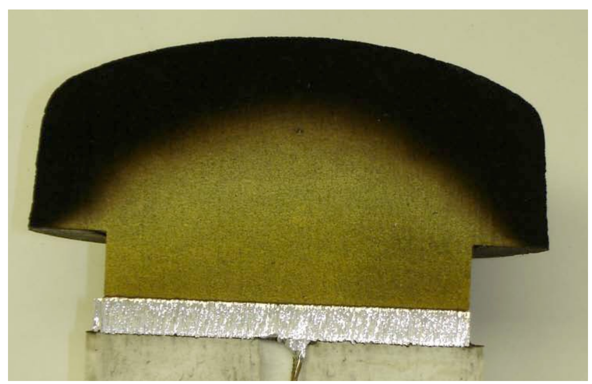
PICA Material Performance

Stardust Cored Sample

Phase I Arcjet, 1000 W/cm^2



Phase I Arcjet, 130 W/cm^2



Phase I Arcjet, Dual-pulse

Block 2 PICA Status & Challenges

- **Boeing / FMI production of PICA materials**
  - 18 Production lots of PICA completed, on schedule, using production size equipment, with new and old equipment
  - PICA coupons and panels for NASA testing on schedule and within specifications
  - Material properties testing underway and only slightly behind schedule
- **Development of thermal-ablation model**
  - Working on update to PICA response model but the effort is proving more challenging and involved than originally anticipated
  - Tiger team has developed a complete model update plan
- **PICA block layout and gap/seam design**
  - Current manufacturing limits of PICA is 42" x 24" x 10"
  - Initial looks at deflection limits and PICA strengths indicate PICA flight panels may be limited to a maximum dimension of ~20"
  - Initial Boeing/FMI design features joined PICA panels --- however, initial NASA analysis indicates possible problems with resulting stresses in PICA

Block 2 BPA, Avcoat & 3DQP

- **Boeing BPA**
  - Initial coupon arcjet testing with in-depth thermal couples planned for late June and July
  - Need to develop a coarse thermal response model within the first 120 days post award to evaluate material viability
  - Contract kick-off occurred on May 24^{th}
- **Textron Avcoat/ 3DQP**
  - Initial coupon arcjet testing with in-depth thermal couples planned for late June and July
    - Tests are particularly important as they will establish whether or not original Avcoat thermal performance can be reproduced
    - If Avcoat proves its performance capability, it will become the focus of the Textron award, if not 3DQP will become the focus of the award
  - Contract kick-off occurred May 23^{rd}

Block 1 SLA-561V & Shuttle Tile Status & Challenges

- **SLA-561V TPS material performance issues**
  - MSL stagnation thermal ablation testing showed excellent stagnation heating performance up to 300 W/cm^2
  - However, recent tests at high shear and high pressure (low enthalpy) conditions showed material performance limitations that raise serious concerns regarding its use on CEV (and MSL)
  - Material is no longer on critical path for CEV
- **Shuttle tile material performance issues**
  - Initial coupon testing of Shuttle tiles indicated excellent performance for BRI-18 (coated), LI-2200 (coated & uncoated)
  - Possible turbulent heating and catalytic efficiencies are a concern
  - Recent stagnation arcjet tests of gap/seam articles showed that at LEO heating and pressure conditions the material exhibits gap performance problems that raise serious concerns regarding its use on CEV
  - Final material status for CEV applicability is currently being addressed

Status 18 Months In:

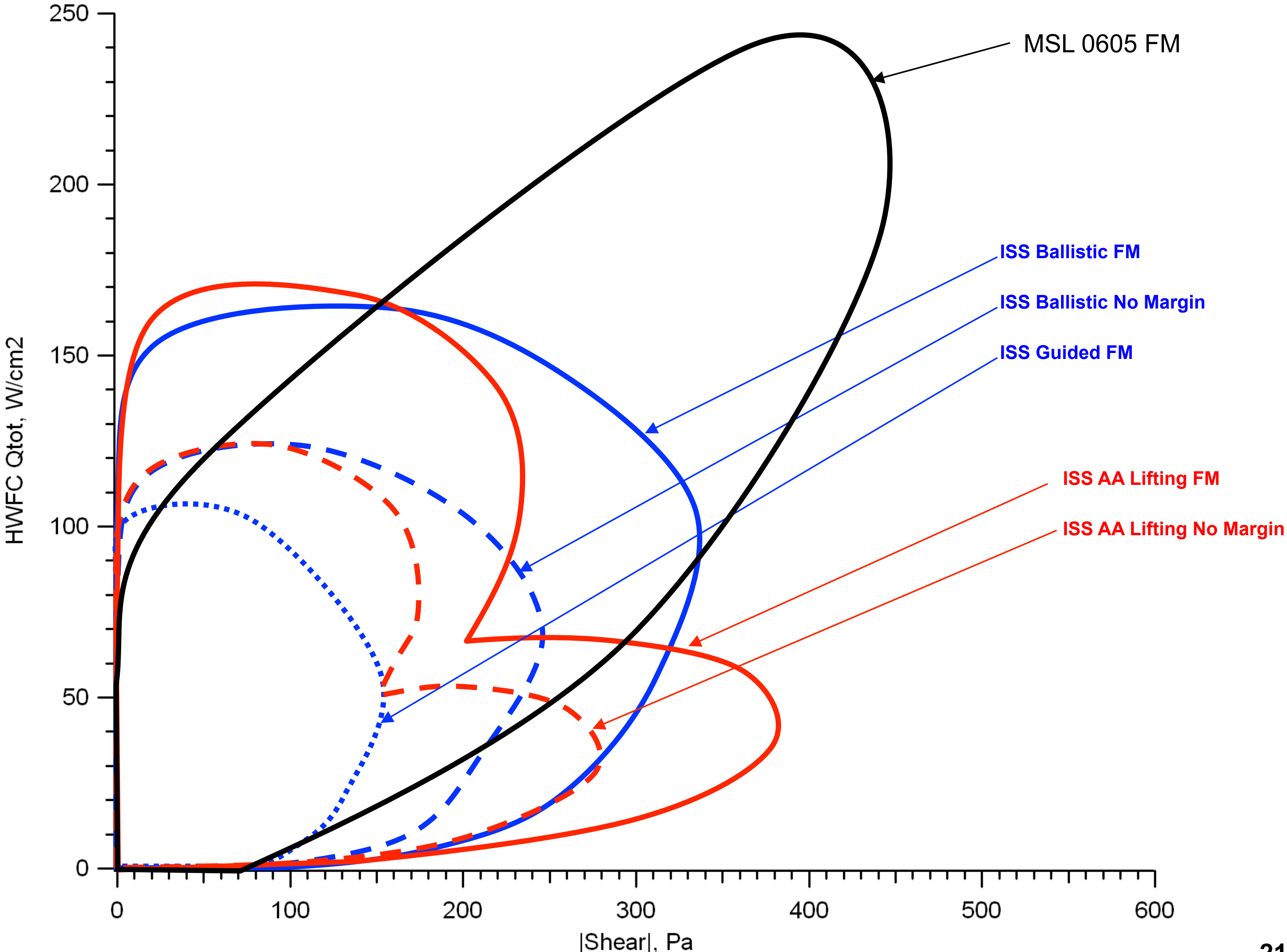
- **Some things did not happen as planned:**
  - Procurement efforts proved more time consuming
  - Only one Block 2 vendor was awarded
  - Alternate Block 2 vendors awards occurred later than ideal
  - CEV SRR slipped significantly
  - CEV and TPS sub-system PDRs slipped 3 months
  - Obtaining needed Arcjet testing at either ARC or JSC is not reliable
- **Dramatic changes have already taken place:**
  - Regrouped to develop Alternate Block 2 procurement
  - Working with the Prime to support design cycles
  - Working with Boeing/FMI on design and development of PICA solution
  - Collaborative work with MSL on SLA 561 V solution
  - More focused on detailed analysis to support the design work
- **More changes will be necessary:**
  - Elimination of one or both of the Block 1 material options from critical path means that added focus will be necessary for Alternate Block 2 materials
  - Need a large number of successful tests over the next 6 months
  - Greater focus on all PDR products

Beyond the Orion TPS ADP

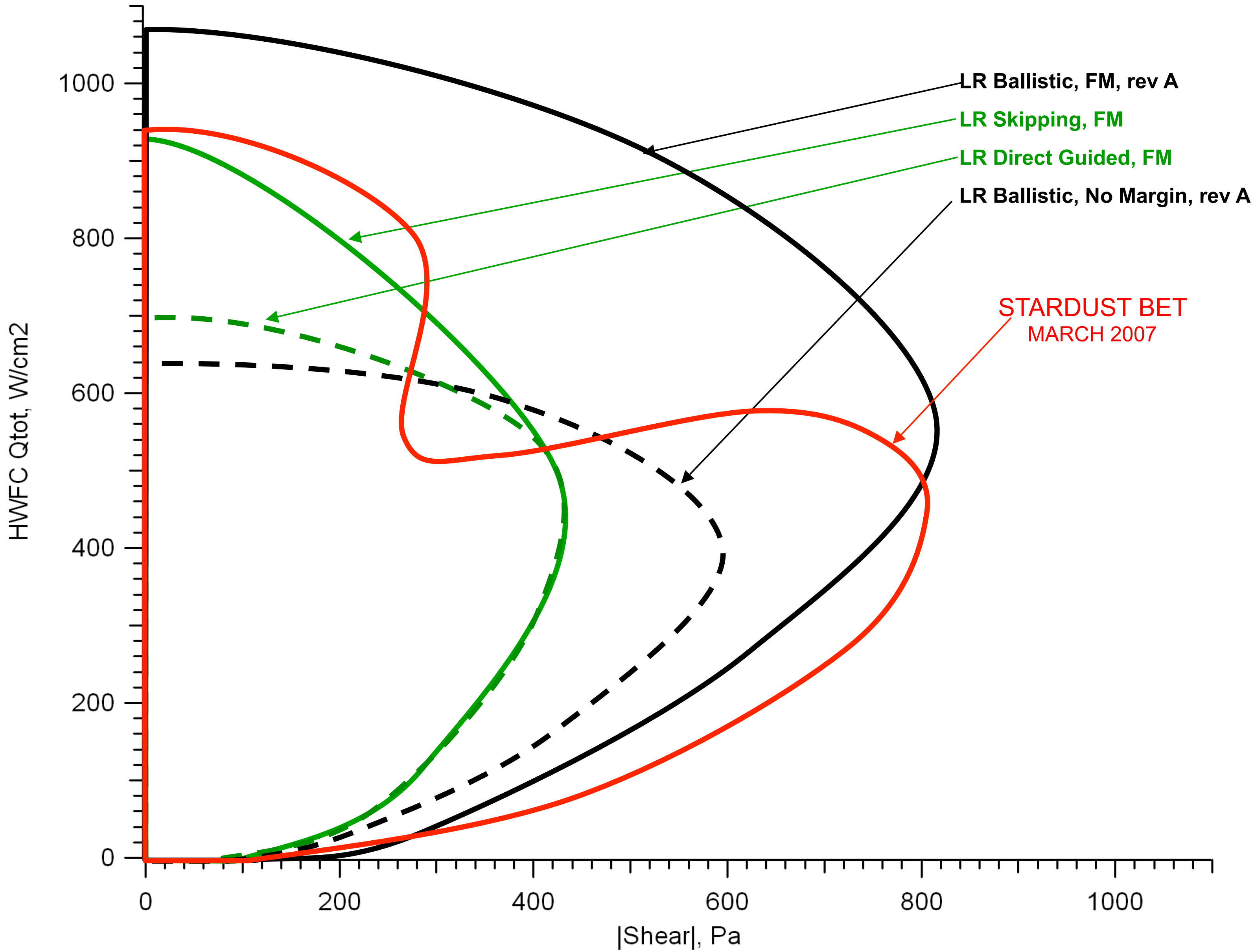
TPS Testing is Needed to Certify the Orion Heat Shield

TPS Risks	Likelihood	Consequence	Certification	Sustaining Engineering
Low Earth Orbit (LEO) Return				
LEO Combined Environment Risk of Shear, Heat Flux, and Pressure / Ground to Flight Traceability	2	5	X	X
Gaps/Seams in the LEO Combined Environment	2	5	X	
Lunar Direct Return (LDR)				
Effect of Turbulence on Material Response (Ablation Efficiency / Recession Rate)	3	4	X	
Heating Augmentation / Differential Recession of Compression Pads	3	4	X	
In-depth radiation / Effect of Radiation on Material Response	3	5	X	X
LDR Combined Environment Risk of High Shear, Heat Flux, and Pressure / Ground to Flight Traceability	3	5	X	X
Gaps/Seams in the LDR Combined Environment	4	5	X	

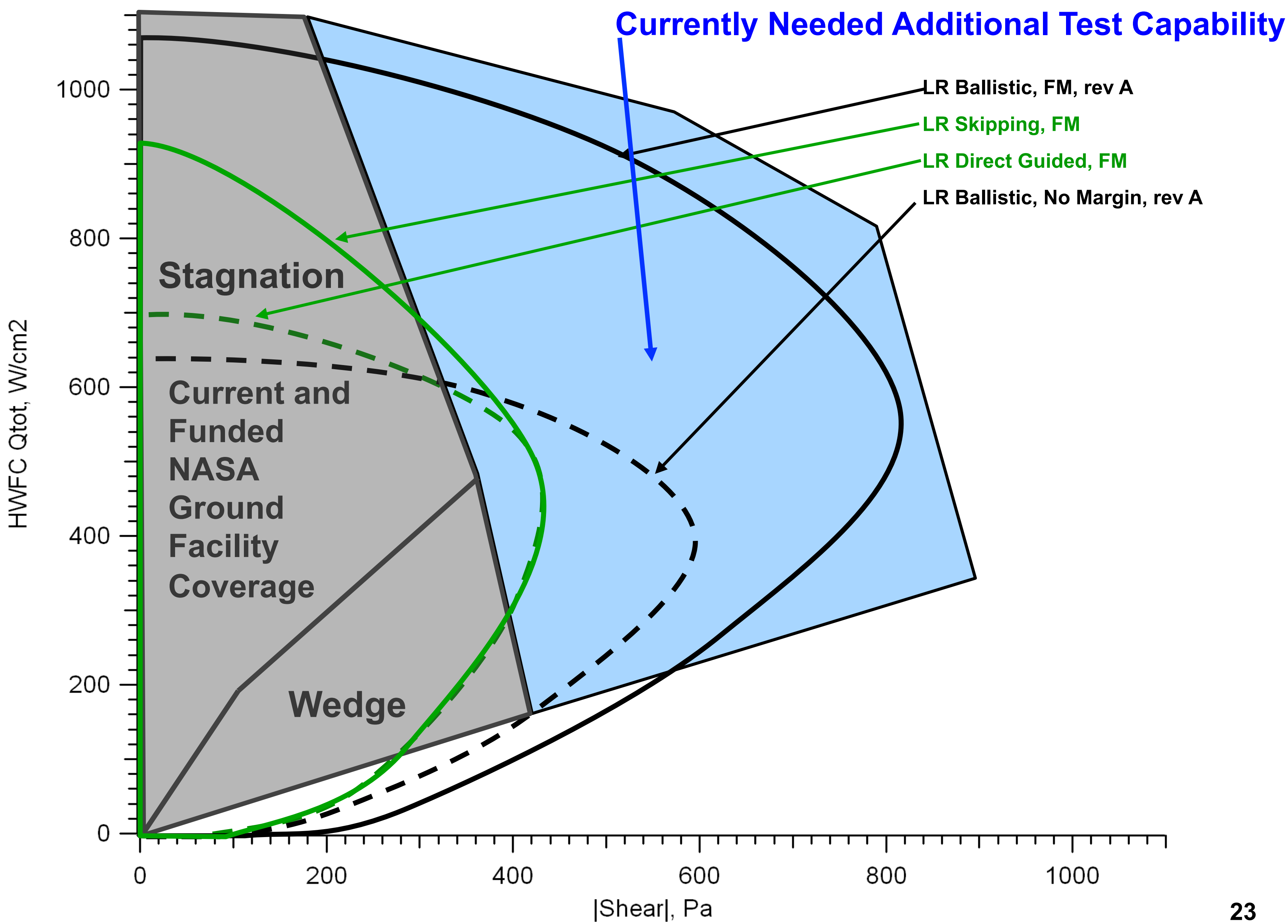
CEV LEO Entry Aerothermal Environments



CEV Lunar Entry Aerothermal Environments



CEV Lunar Entry Aerothermal Environments



Mitigation Recommendation

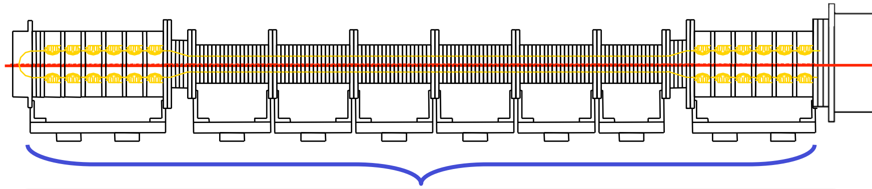
- **Class A Upgrade at ARC**
  - Allow for **lunar return ground testing** of the Orion Heat Shield TPS
  - Enable the **sustaining engineering** that will necessarily follow Orion lunar operations
- **LE-X Flight Test Program**
  - **Qualify Orion TPS** for lunar nominal and ballistic return
  - Demonstrate lunar return skip entry guidance as a part of **lunar return certification**
- **Both flight and ground components are necessary.**
  - If a ground facility component is not authorized, a risk will persist due to an inability to conduct sustaining engineering for lunar return TPS.
  - If a flight test component is not authorized, the a certification risk will remain unmitigated and TPS will not be qualified prior to crewed lunar return.

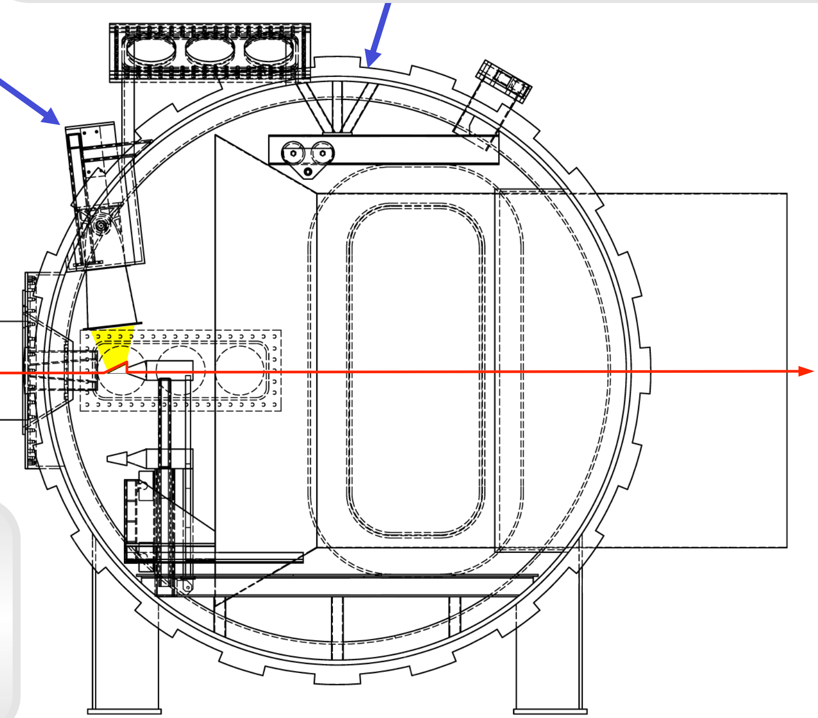
New Segmented and Radiant Heaters Enable Heat Shield Certification and Sustaining Engineering

The Agency will have the only large radiative and convective heating facility in the world.

Test Chamber/Model Support
- Water-cooled horizontal cylinder, 10' dia, one end opens completely
- Linear transverse, vertical injection system
- 4 models capability

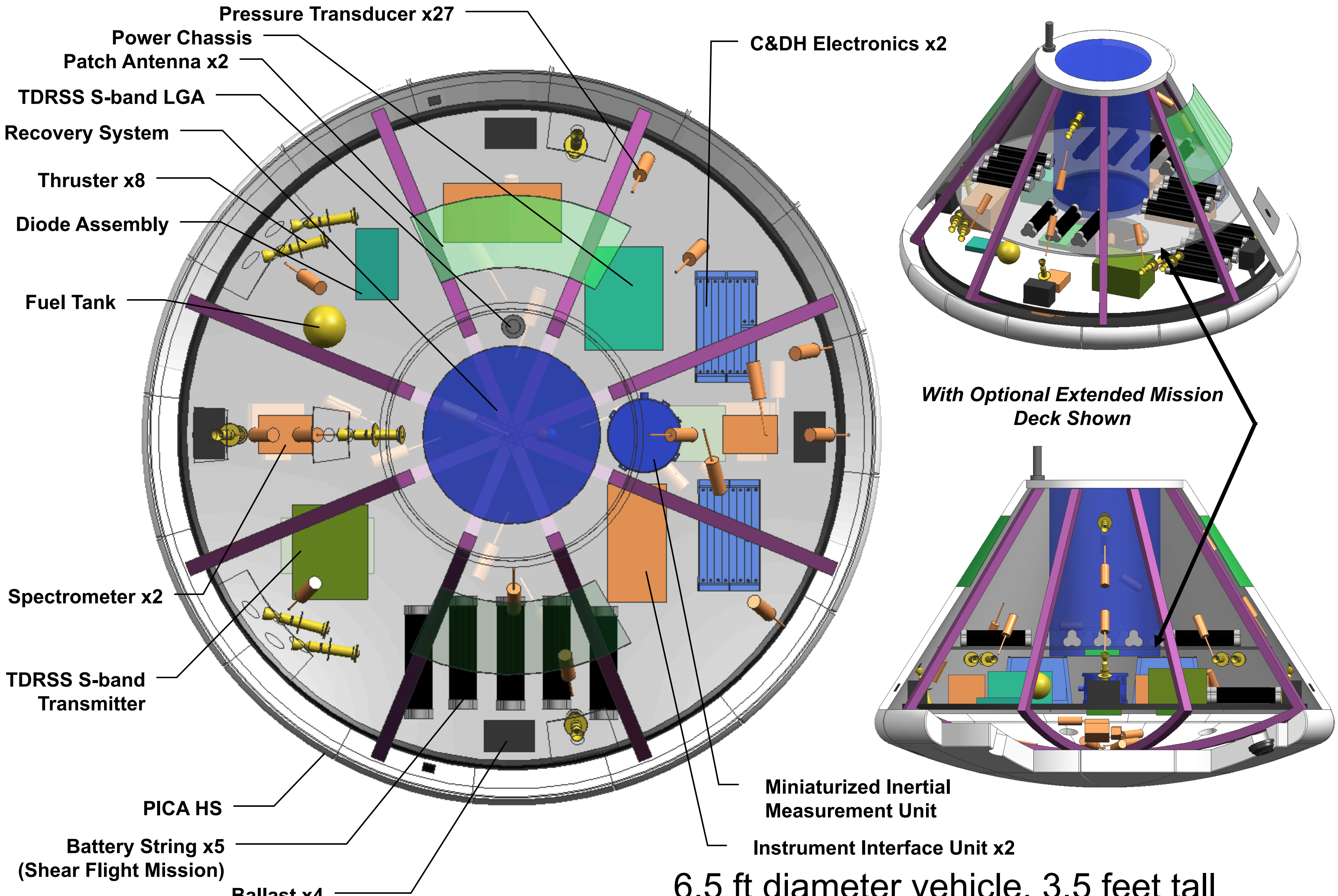
Radiant Heating System
- Source Vortek Lamp
- 400 W/cm^2
- Radiation Spectrum Approximates Flight





New Segmented Arc Heater
- Length = 175", L/D = 40, D* = 3"
- Nominal 100 MW, Max pressure = 40 atm
- Typical nozzle Mach 2.2, Test flow 4.66" dia

LE-X Flight System Description



6.5 ft diameter vehicle, 3.5 feet tall

Benefits and Opportunities of LE-X for Broader NASA and Entry System Communities

- **Demonstrates large capable entry systems technology**
  - PICA Segmented heat shield capable of many missions besides CEV
- **Demonstrates precision hypersonic guidance with skip entry**
  - Skip entry GN&C is a precursor demonstrating all technologies prior to aero-capture
- **Radiative heating meassurements**
  - 11 to 12 km/sec entries ensure significant radiative heating component and a rare opportunity to directly measure the spectral data and induced heating
- **Ablation products (blowing) and the effects on boundary layers and convective heating**
- **Geometric singularity (e.g. compression pad) and turbulence interactions and the effects on convective heating**
- **Follow-on testbed:**
  - Advanced TPS materials
  - High velocity entry testing (14 km/sec Mars return)
  - Supersonic decelerators
  - Aerocapture demonstrations

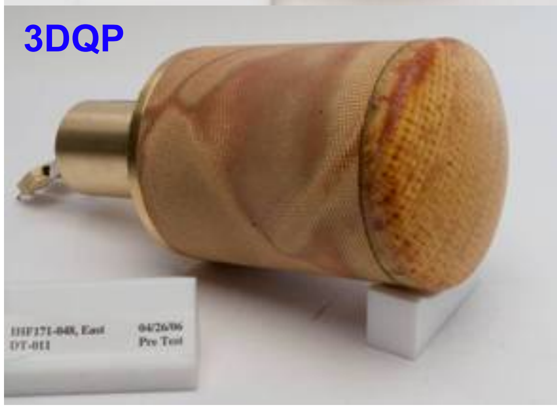
Backup

SMD Partnership

- **SMD has used the same basic entry systems technology for all Mars missions since 1960s**
  - Direct entry
  - 70 deg sphere-cone
  - SLA-561V TPS
- **SMD will need advances in entry system technologies to enable more capable Mars and outer planetary moon missions**
  - Aero capture
  - Alternate entry shapes
  - New ablative TPS materials
- **LE-X presents an opportunity SMD to invest in these technology needs while leveraging participation from other mission directorates**

Follow-On Testbeds: Current and Future TPS

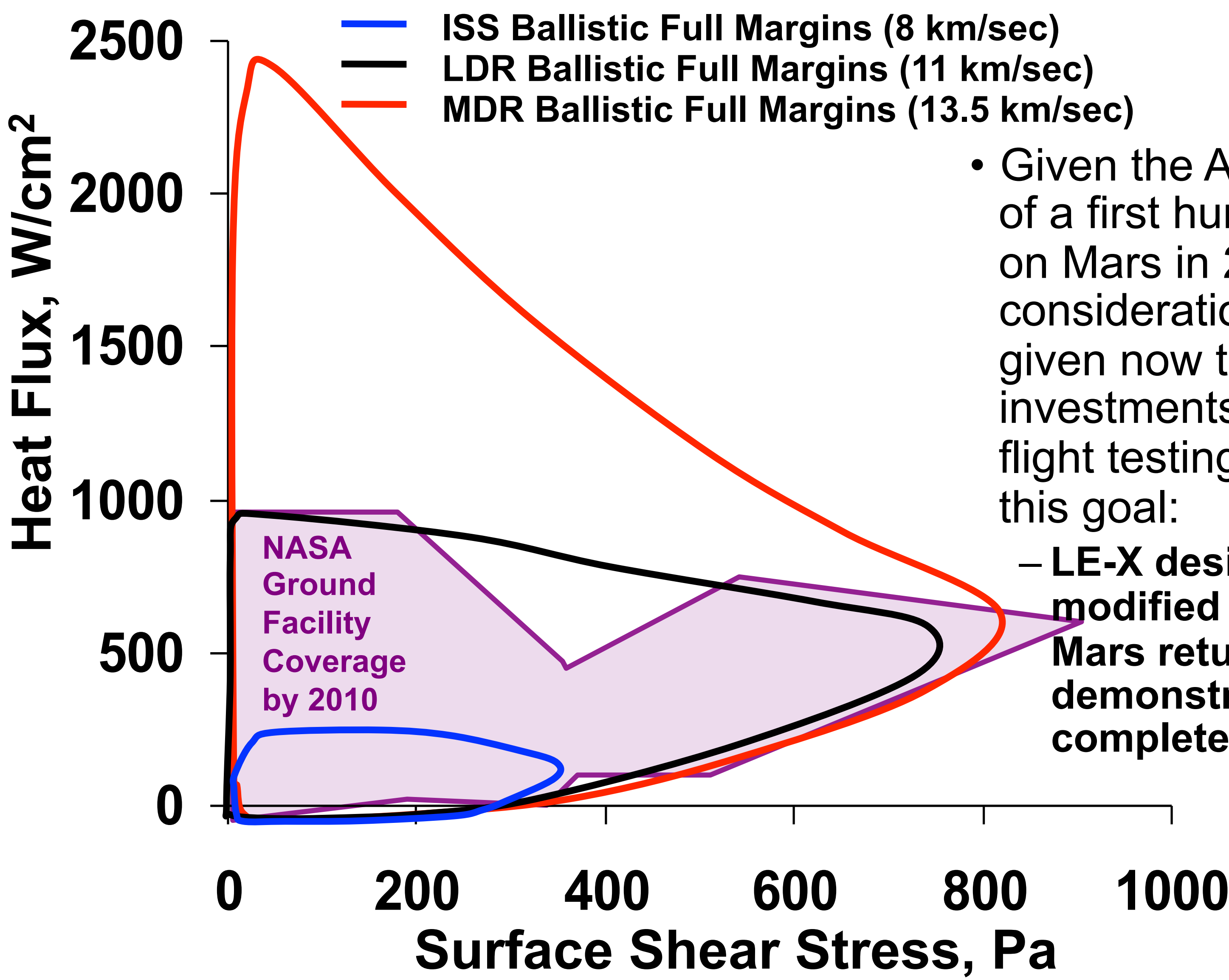
- **The initial two LE-X missions will demonstrate a large segmented TPS technology (PICA) applicable to multiple future missions**
- **The TPS ADP is currently studying three additional medium TRL TPS materials for CEV and high potential for high performance missions**
  - Avcoat 5026-39 (Apollo material)
  - Textron 3DQP HD/LD (Dual layer)
  - BPA (Boeing Phenolic Ablator)
- **For higher entry velocities and heating rates new materials beyond those in the current pipeline will be needed**
- **All current and future materials under will need of flight test demonstrations**



Radiative Heating and Spectral Bow Shock Measurements and Modeling

- **The lack of appropriate flight spectral data and uncertainty in the modeling of the bow shock radiative heating leads to corresponding uncertainty in requirements for new heat shield design**
- **At higher entry velocities planned for future missions radiation will dominate heating – corresponding uncertainties will increase**
- **Spectral-radiometric data from previous flight experiments have been important in characterizing the modeling of complex flow issues such as thermochemical non-equilibrium and electronic excitation**
- **However, more data and effort are needed to reduce uncertainties and improve current modeling capabilities**
- **Successful implementation of LE-X and resulting measurements will:**
  - Provide unprecedented data for radiative modeling development
  - Provide operational correlations of vehicle performance and radiation
  - Establish test bed with the possibility of low cost, higher velocity successors

Agency Planning Required for Mars Direct Return (MDR)



- Given the Agency interest of a first human landing on Mars in 2034, consideration should be given now to the investments needed in flight testing to achieve this goal:
  - **LE-X design can be modified to test for Mars return once lunar demonstration is complete.**