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INTEGRATED THERMAL PROTECTION SYSTEMS AND HEAT RESISTANT STRUCTURES

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Agenda

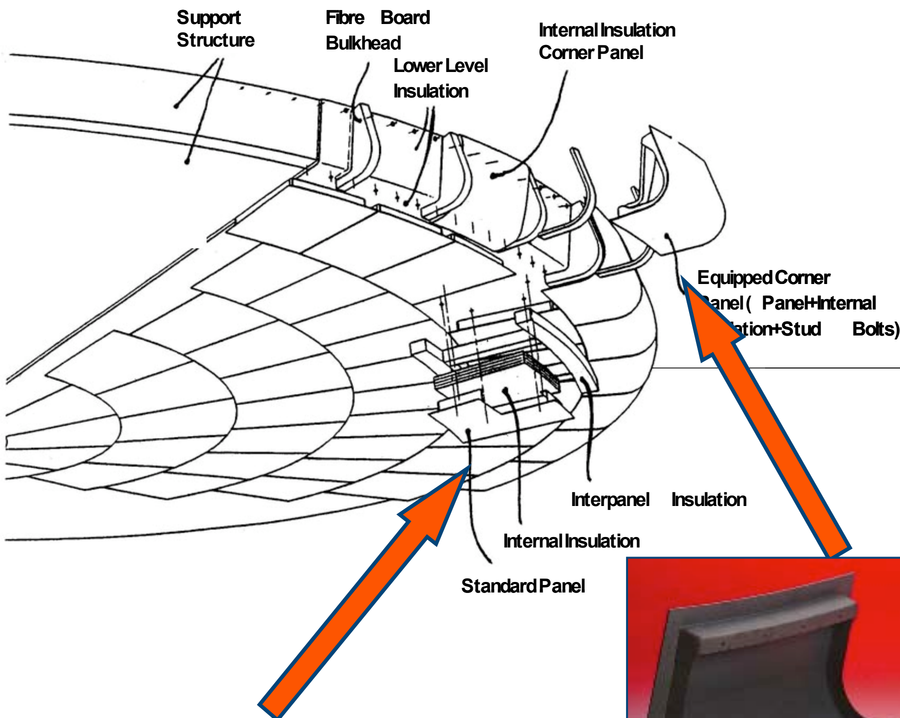
- Overview
- Trajectory and Loads
- CAS
  - Design
  - Thermal Insulation
- Sepcore
  - Design
  - Ablators
- Structural Health Monitoring
- Concluding Remarks

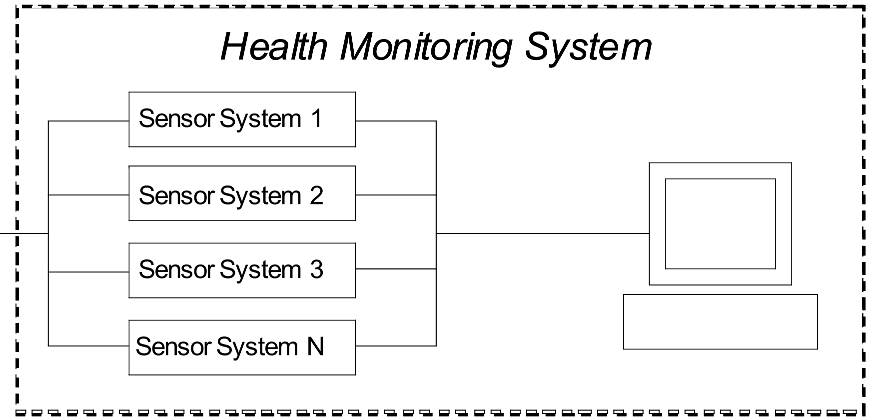
Overview - Modularity

3 DIFFERENT DESIGNS DERIVED FROM THE SAME TECHNOLOGY, ADAPTED TO 3 MISSIONS SCENARIOS

	CAS	I-TPS Sepcore ®	Decelerator
Heat flux ≤ 1 MW/m^2	+	-	+
Heat flux ≥ 1 MW/m^2	-	+	-
Reusability	+	Partial / multi phase	NA
Aero -braking	+	+	+
Aero -capture	+	+	NA
Aero -assist	+	+	NA
Lifting bo dy	TPS	TPS	Hot Structure
Winged vehicle	TPS	TPS	Hot Structure

Overview - Concept Description – CAS

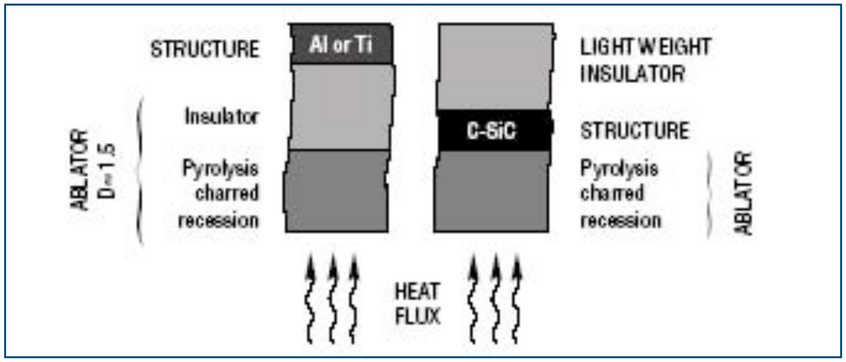




- Aero-dynamic shape and surface is maintained,
- No pollution by ablative residuals,
- Unit construction system design facilitates manufacturing, inspection and maintenance,
- Redundancy for thermal protection functions is provided,
- Reduced mass (compared to ablators),
- MMOD resistance,
- Reduced costs.

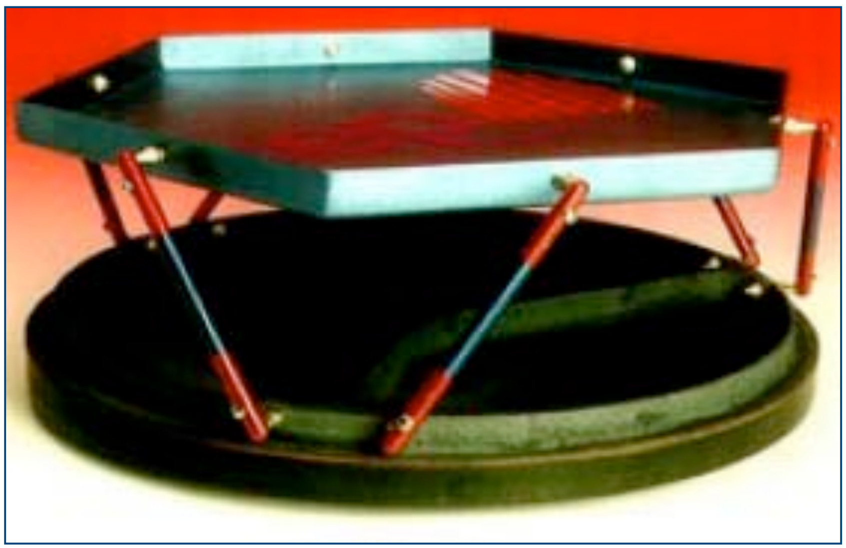
Overview - Concept Description – Sepcore

SEPCORE = CAS + ABLATOR



CAPSULE CONCEPT		ABLATOR	SEPCORE
Aerodynamic structure	(kg)	22	40
External heat shield	(kg)	168	70
Internal insulation	(kg)	0	10
Total mass	(kg)	190	120

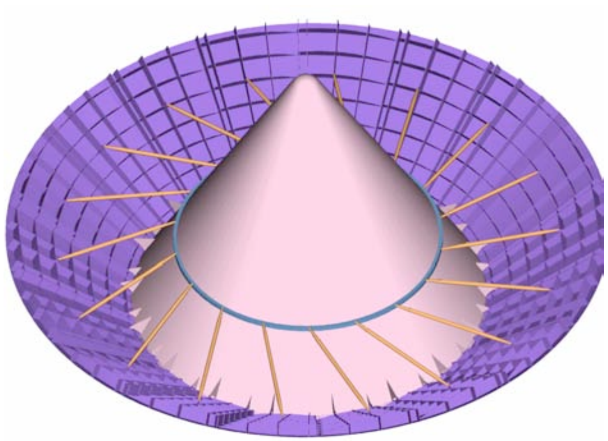
$$\frac{\text{Mass ablator} - \text{Mass Sepcore}^{®}}{\text{Mass ablator}} \approx 30\ \%$$



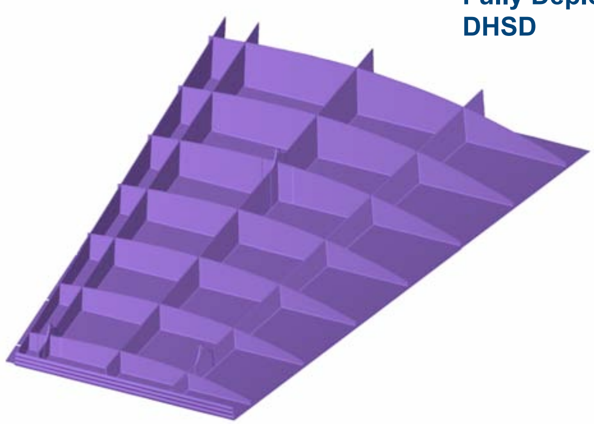
- Adapted to high heat fluxes (over 1 MW/m²)
- Significant mass savings compared to ablator only
- High mechanical strength at room temperature,
- Mechanical strength maintained at high temperature
- Increased robustness
- Partial reusability

Overview - Concept Description – Decelerator

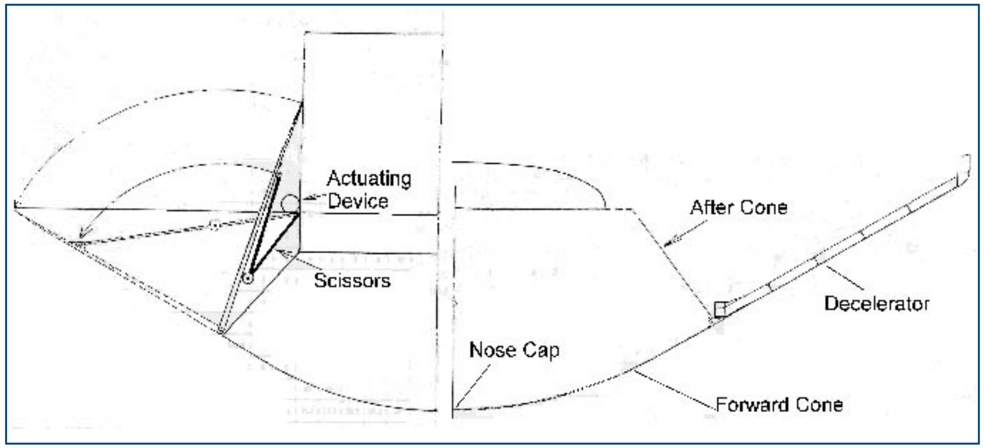
DECELERATOR = CAS + DEPLOYMENT



Fully Deployed DHSD



Single DHSD Petal



- Increase of aerodynamic surface to increase deceleration,
- Compact (when stowed),
- Robustness of thermal protection function,
- Minimum mass increase
- MMOD resistance,
- Reduced costs.

Agenda

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- **Trajectory and Loads**
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  - Thermal Insulation
- Sepcore
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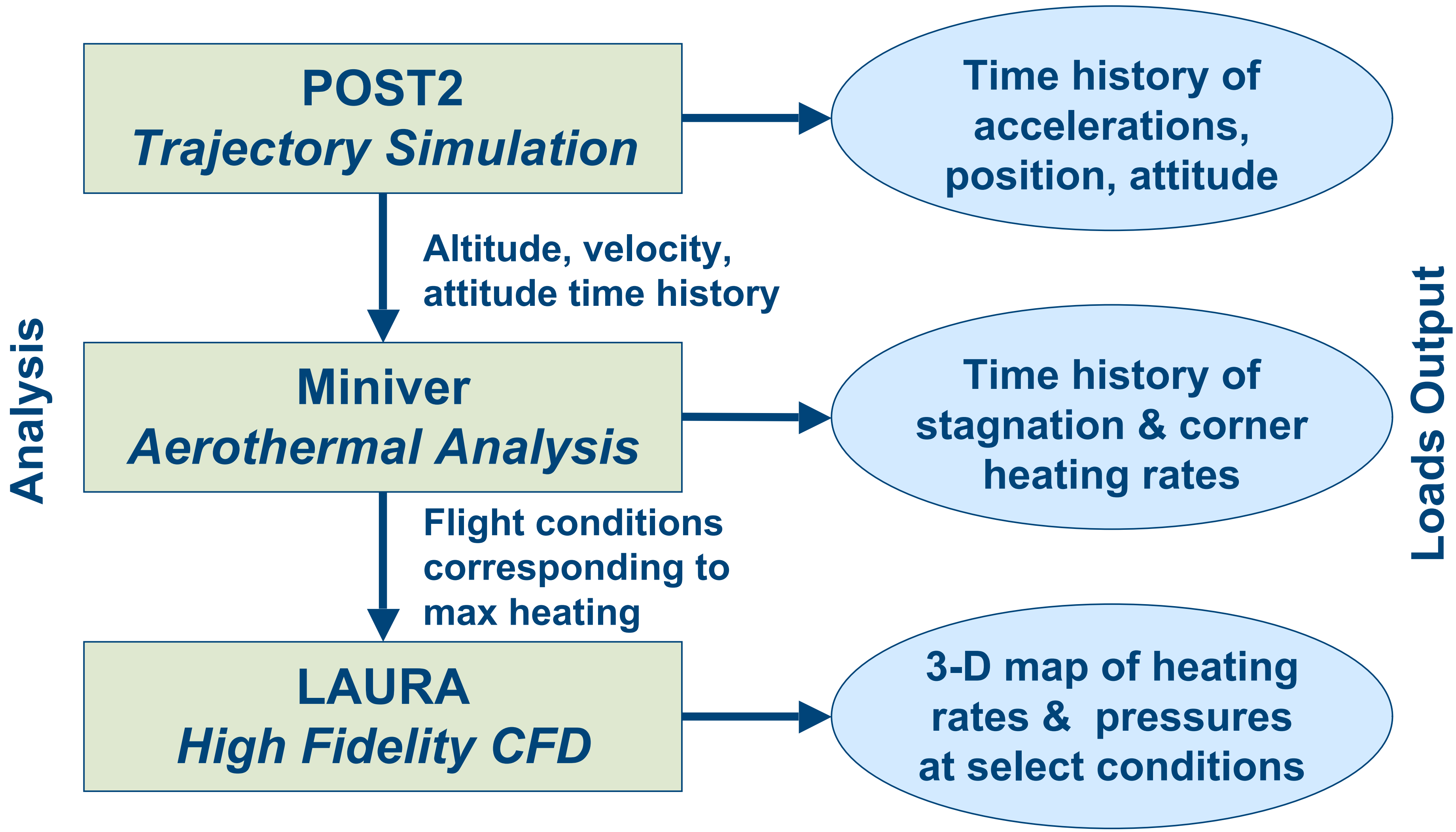
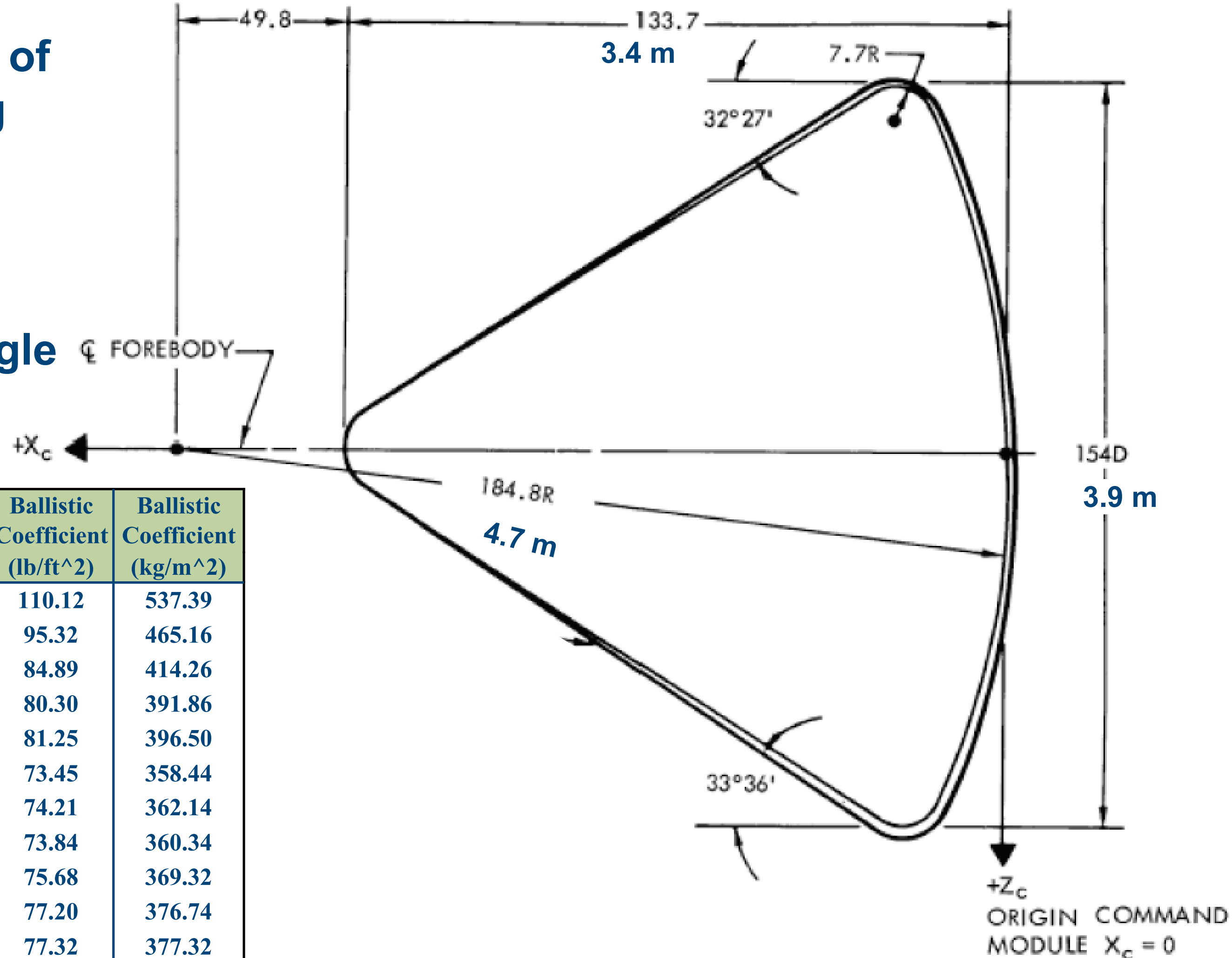
Loads Development Process



Baseline Vehicle Geometry and Characteristics

- **Command module center of gravity is offset providing aerodynamic trim at non-zero angle of attack**
- **This provides trajectory shaping through bank angle modulation**



Mach ( )	Angle of Attack (deg)	C_L ( )	C_D ( )	Lift/Drag ( )	Ballistic Coefficient (lb/ft^2)	Ballistic Coefficient (kg/m^2)
0.4	167.14	0.24465	0.85300	0.28682	110.12	537.39
0.7	164.38	0.26325	0.98542	0.26714	95.32	465.16
0.9	161.70	0.32074	1.10652	0.30110	84.89	414.26
1.1	154.87	0.49373	1.16970	0.42208	80.30	391.86
1.2	155.13	0.47853	1.15600	0.41395	81.25	396.50
1.35	154.01	0.56282	1.27880	0.44013	73.45	358.44
1.65	153.22	0.55002	1.26570	0.43455	74.21	362.14
2.0	153.14	0.53247	1.27210	0.41858	73.84	360.34
2.4	153.62	0.50740	1.24120	0.40881	75.68	369.32
3.0	154.14	0.47883	1.21670	0.39353	77.20	376.74
4.0	156.12	0.44147	1.21480	0.36340	77.32	377.32
10.0	156.79	0.42856	1.22460	0.34996	76.70	374.30
≥ 29.5	160.06	0.38773	1.28910	0.30076	72.87	355.61

Mission Definition Design Space

Departure Planet	Arrival Planet (Atmosphere)	Entry Mode	Aerodynamic Mode
Moon	Earth (air)	Direct	Ballistic
Mars	Mars (CO_2)	Aerocapture	Lifting
Earth			

Baseline Mission

Moon → Earth → Direct → Lifting

Mission Nomenclature

- LDR - Direct Entry from Lunar Return Conditions
- LAC - Aerocapture into Earth Orbit from Lunar Return Conditions
- MDR - Direct Entry from Mars Return Conditions
- MAC - Aerocapture from Mars Return Conditions
- LEO - Entry from Low Earth Orbit

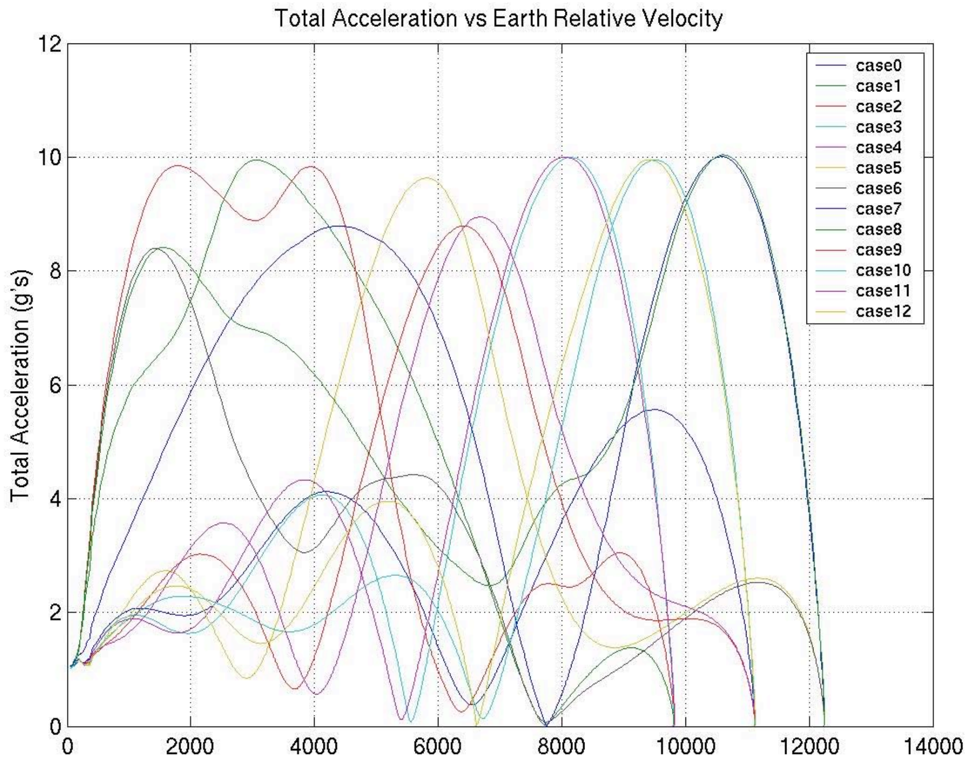
Entry into Mars (CO_2) Atmosphere not considered in trade space

Direct Earth Entry from Luna: Trade Matrix

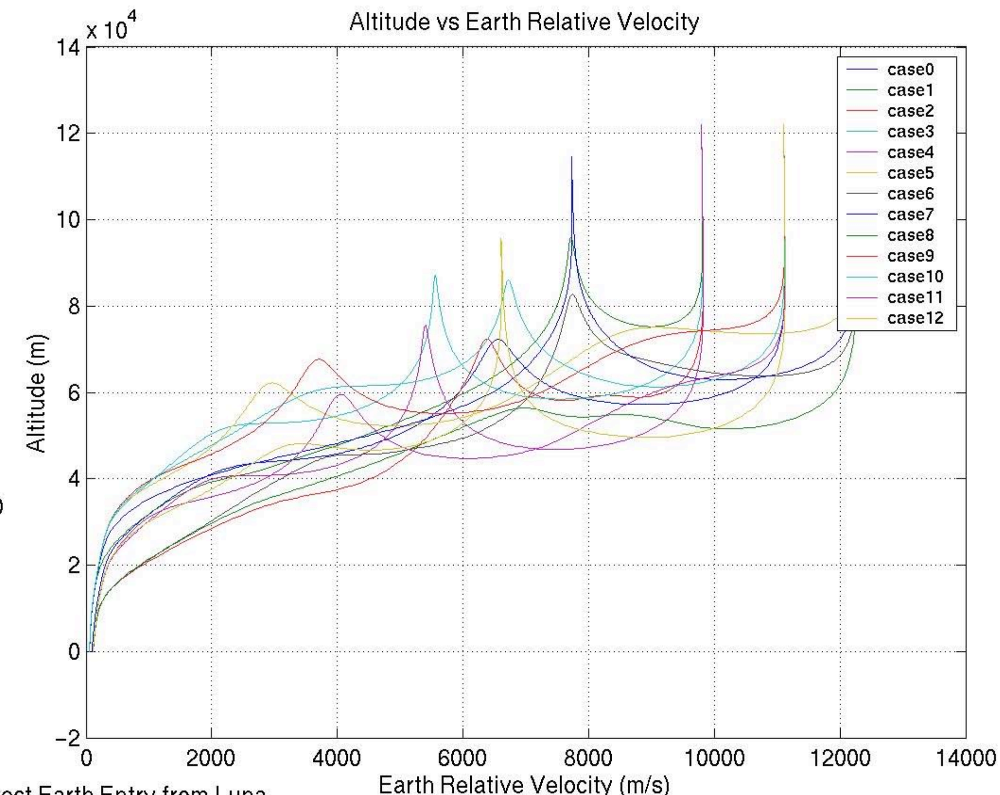
English			
case #	initial velocity (ft/s)	initial flight path angle (deg)	ballistic coefficient (~M30) (psf)
0	36334	-5.80	73
1	32038	-3.99	25
2	32038	-5.21	100
3	32038	-6.65	25
4	32038	-7.11	100
5	40031	-5.09	25
6	40031	-5.61	100
7	40030	-6.63	25
8	40031	-7.40	100
9	36334	-4.63	25
10	36334	-6.73	25
11	36334	-5.13	100
12	36334	-7.29	100

Metric			
case #	initial velocity (m/s)	initial flight path angle (deg)	ballistic coefficient (~M30) (kg/m^2)
0	11075	-5.80	356
1	9765	-3.99	122
2	9765	-5.21	488
3	9765	-6.65	122
4	9765	-7.11	488
5	12201	-5.09	122
6	12201	-5.61	488
7	12201	-6.63	122
8	12201	-7.40	488
9	11075	-4.63	122
10	11074	-6.73	122
11	11075	-5.13	488
12	11075	-7.29	488

Direct Earth Entry from Luna: Trajectory Data

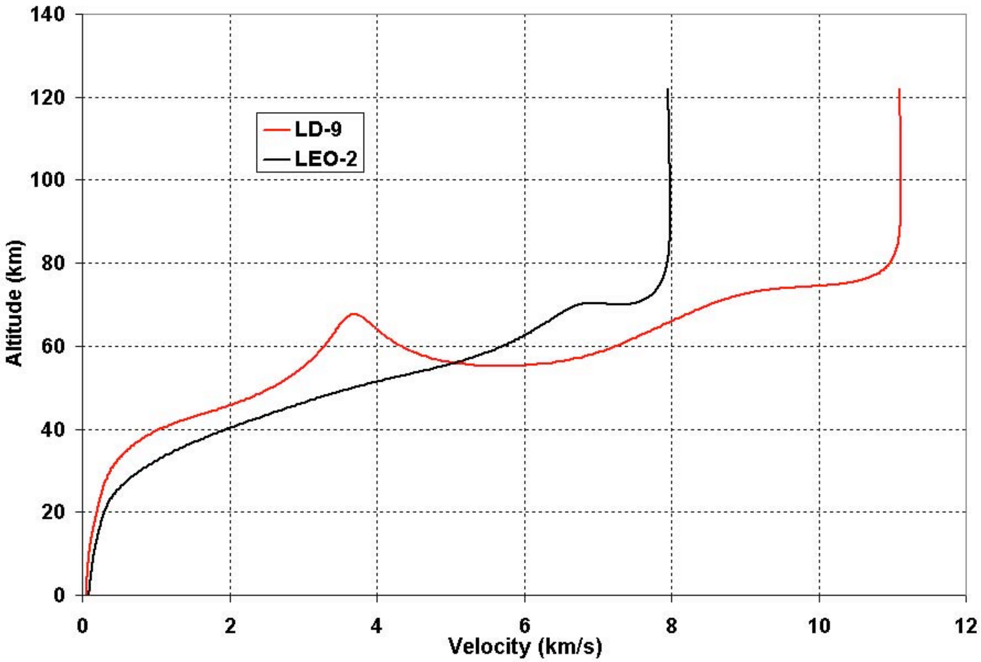


Direct Earth Entry from Luna

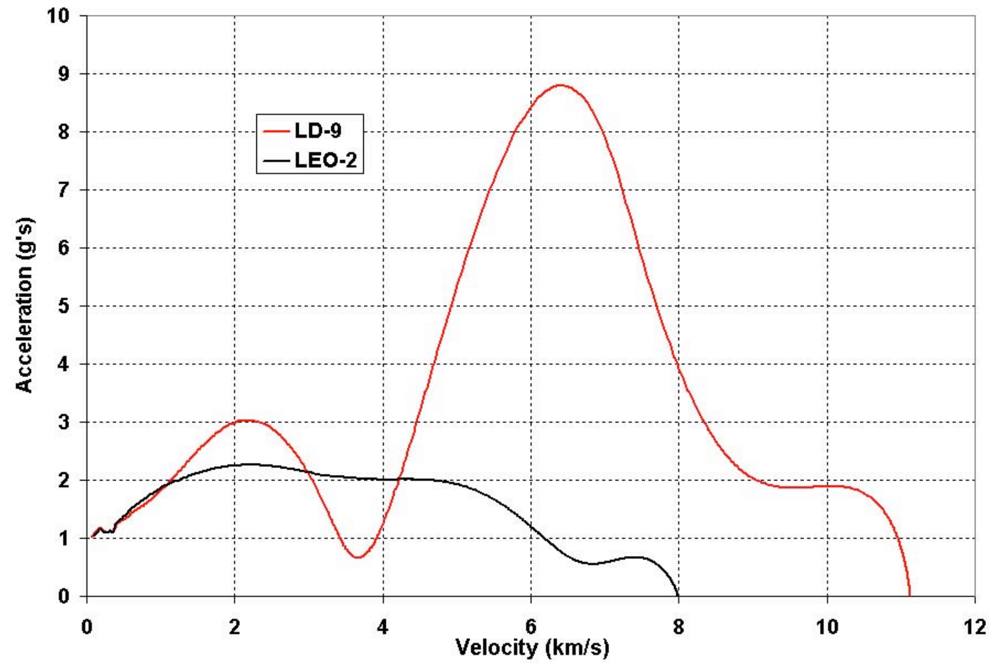


Direct Earth Entry from Luna

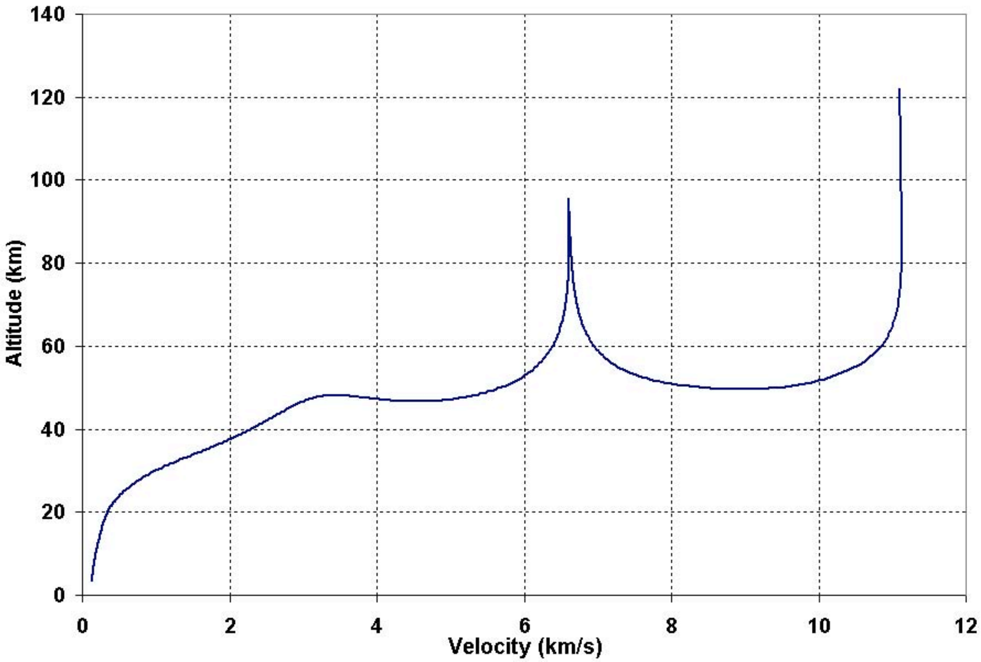
Reference Trajectory for CAS



- **Initially selected LD-9**
  - 11 km/s, 122 kg/m² ballistic coefficient, shallow entry angle
  - eventually determined to be too hot
- **Selected LEO-2 as baseline**
  - 8 km/s, 356 kg/m² ballistic coefficient

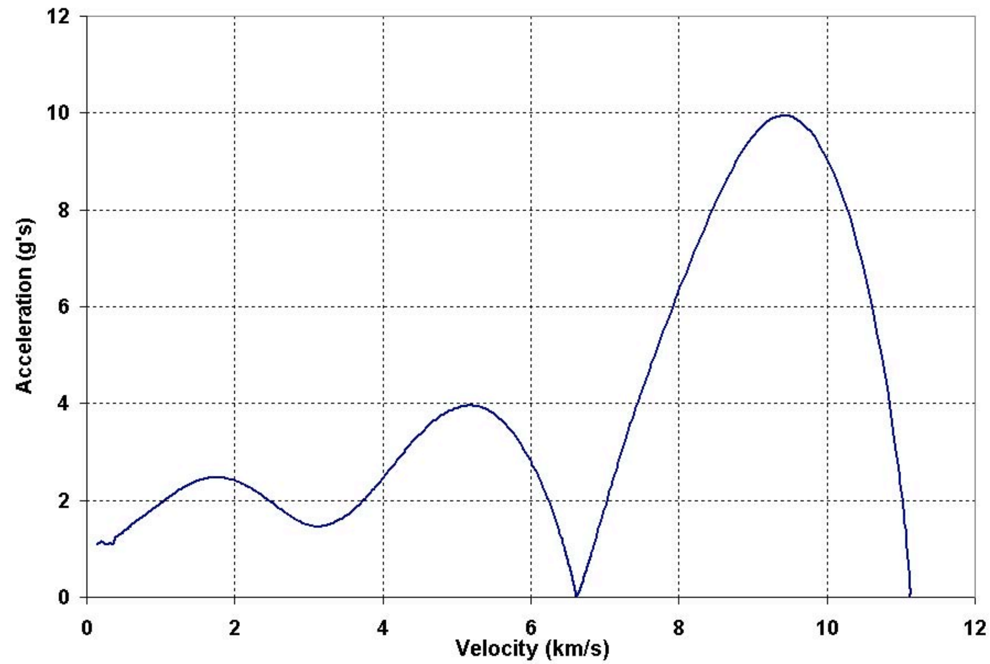


Reference Trajectory for Sepcore



Selected LD-12

- 11 km/s entry velocity
- 488 kg/m^2 ballistic coefficient
- Steep entry angle



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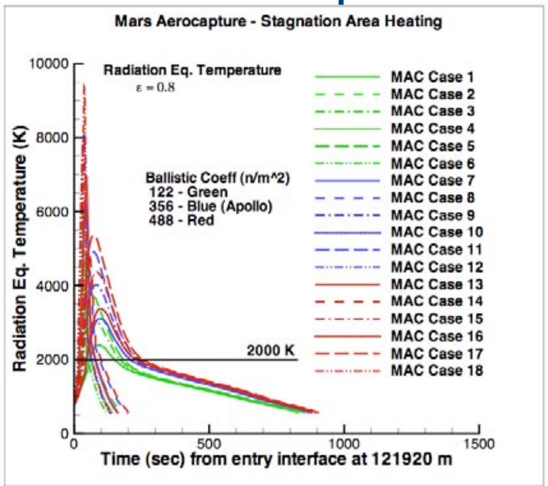
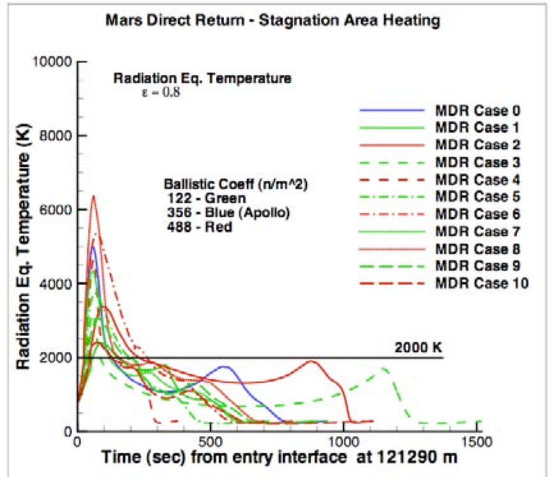
Phase I Environments Summary

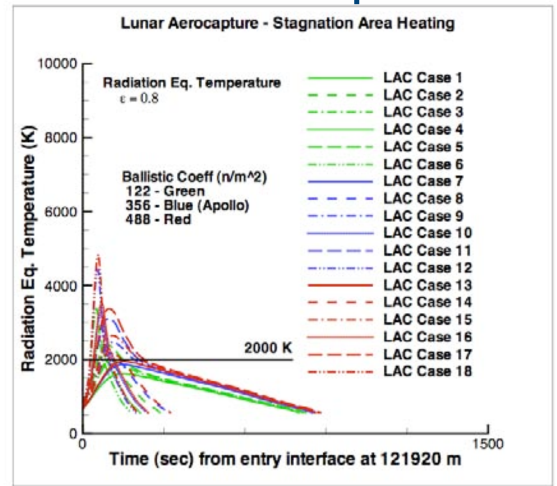
Mars Aerocapture



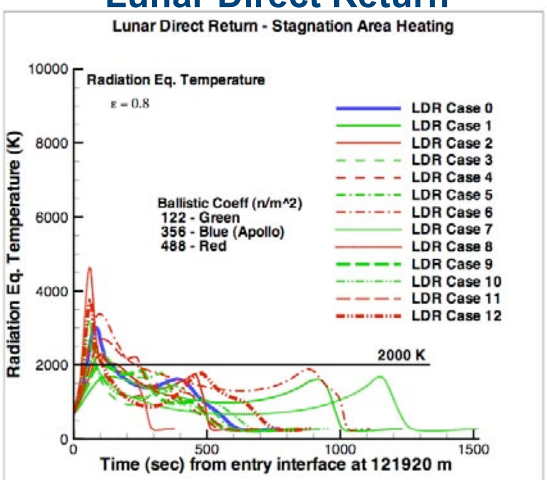
Mars Direct Return



Lunar Aerocapture

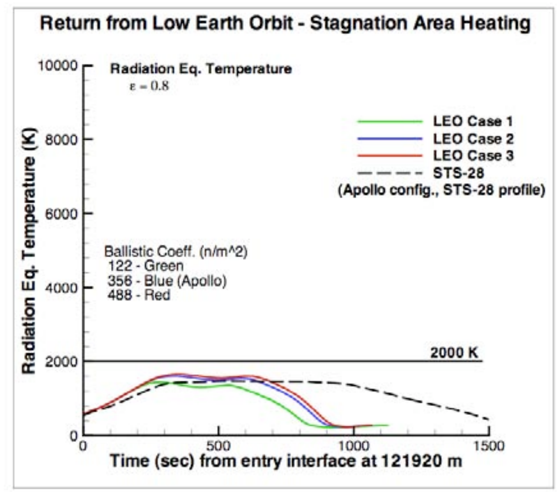


Lunar Direct Return



Radiation Equilibrium Temperature, K

LEO Return



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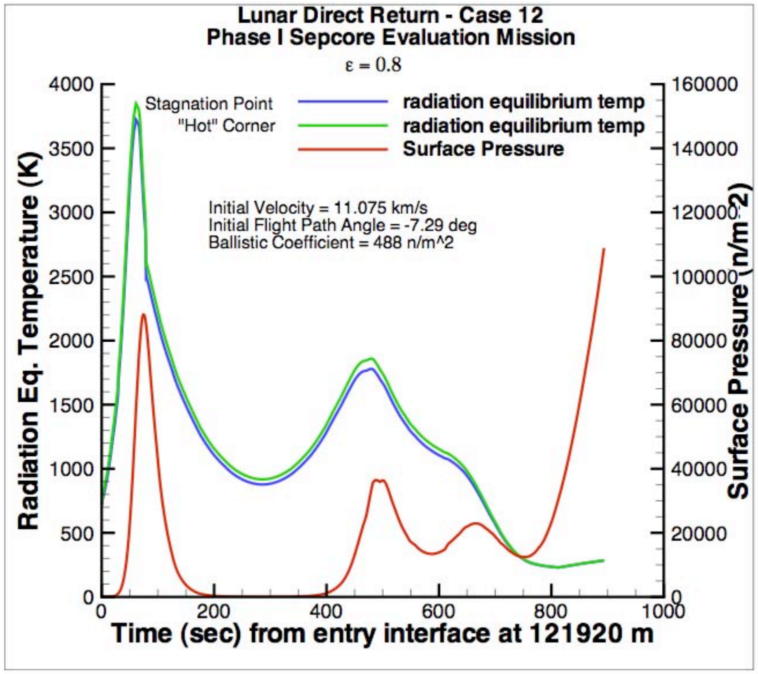
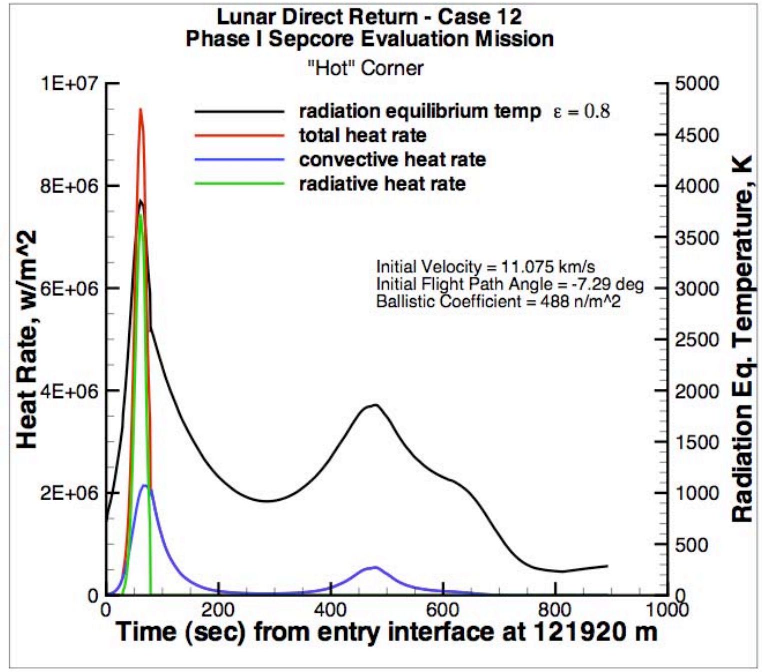
Lunar Direct Entry - Phase I Sepcore Evaluation

Case 12



"Hot" Corner vs Stagnation Pt Radiation Eq. Temperature Comparison
Case 12



Relative Heating Rate Component Contribution
Case 12

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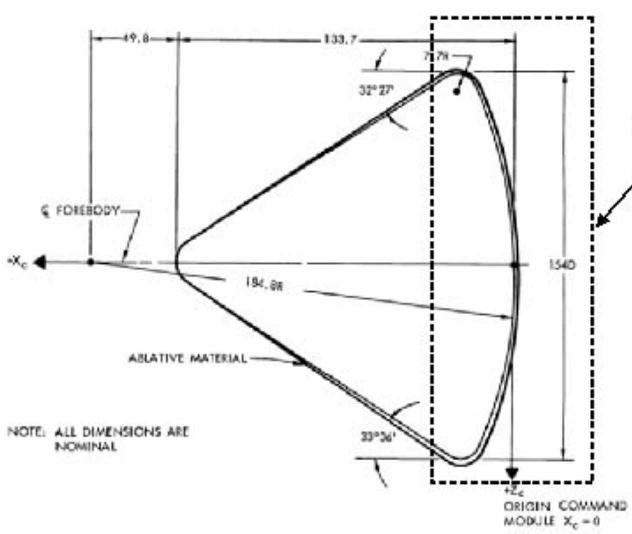
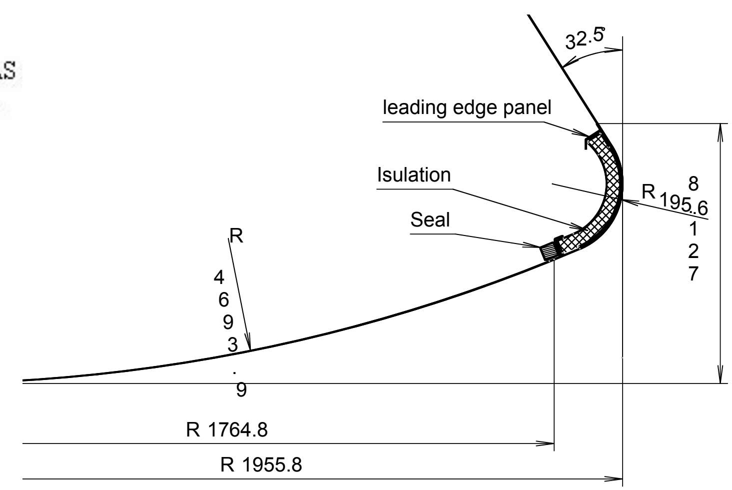
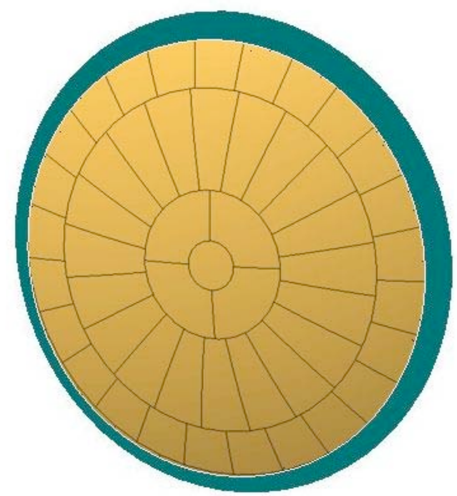
Overall CAS Geometry

- The CAS represents the blunt aft body of an Apollo-shaped re-entry vehicle
- It is mainly composed of :
  - an annular array of equipped leading-edge elements
  - a circular array of equipped panels
  - the underlying cold structure of the blunt aft body
- Preliminary panel distribution derived from past experience

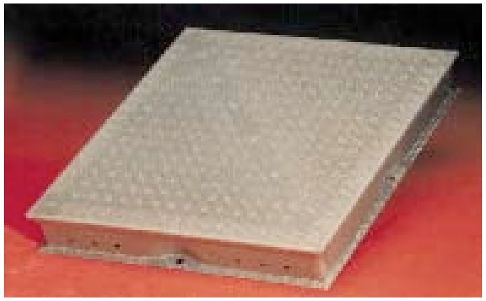




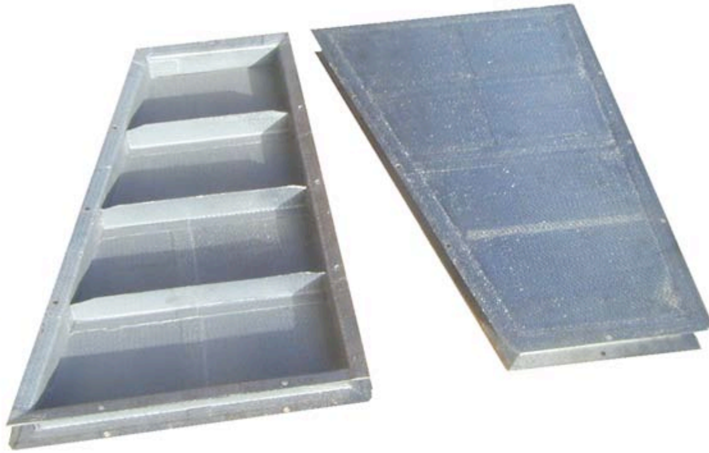


CMC Panels

- **Concept trade-off performed on previous designs :**



Hermès



Generic Shingle

CHA

X-38 chin panel

Trade-off criteria :

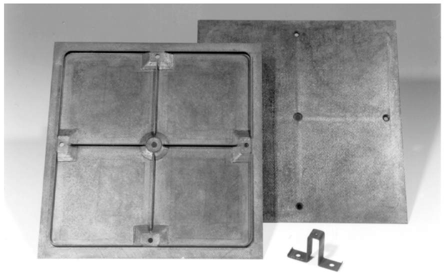
-external assembly capability

-State-of-the-art material

-Manufacturability

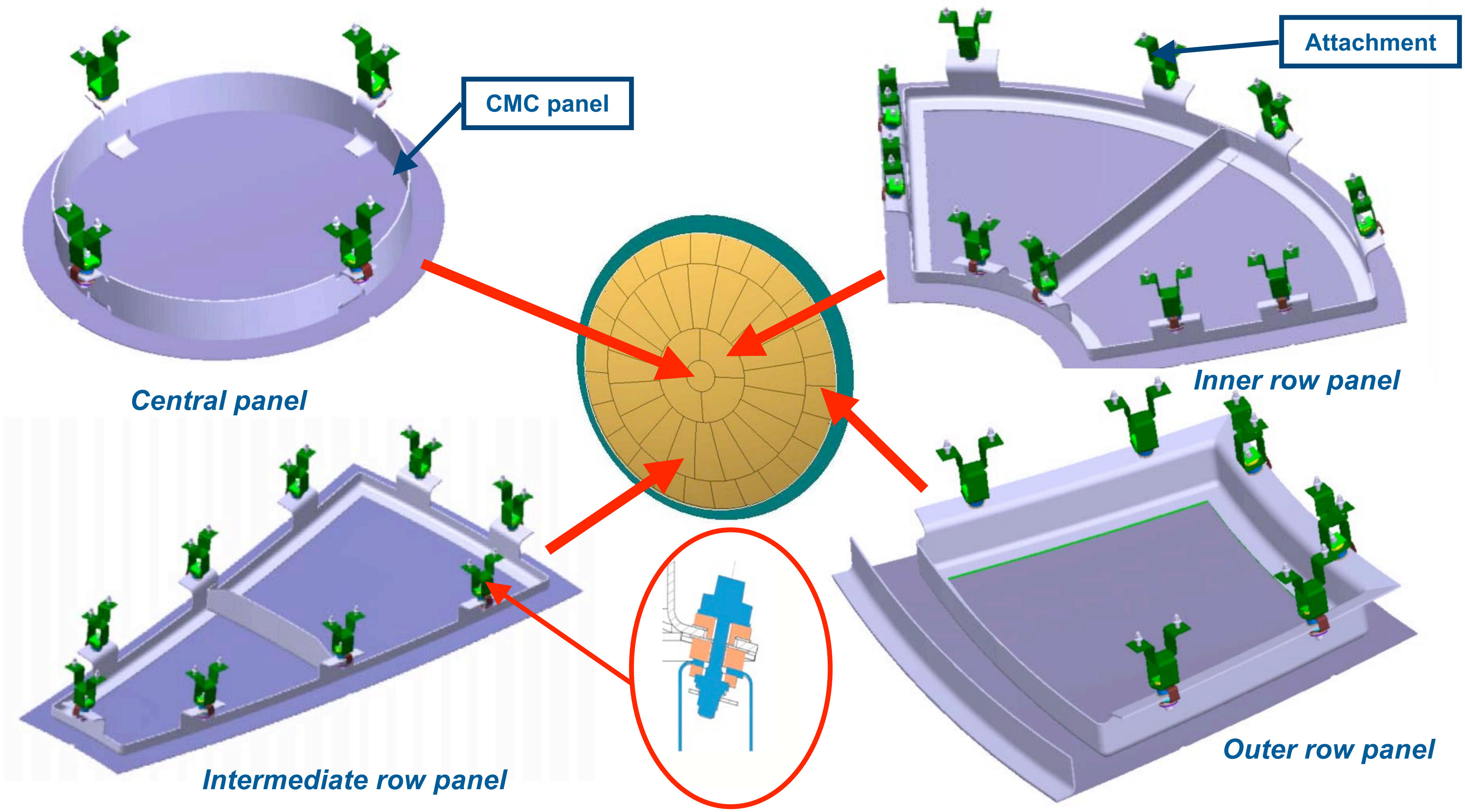
-Maintainability

-Technical performance



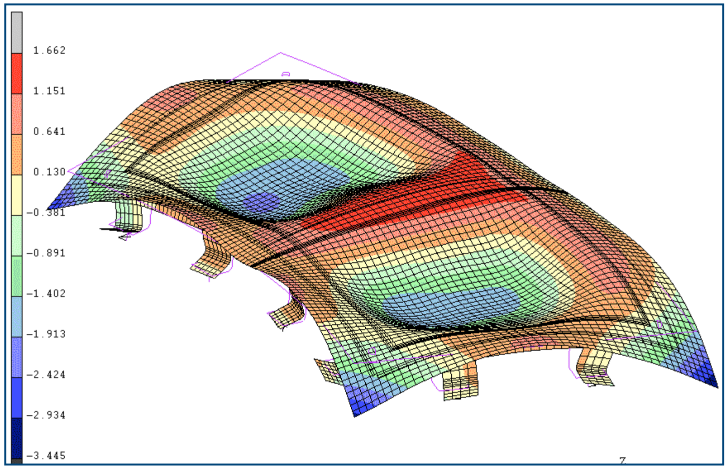
FESTIP

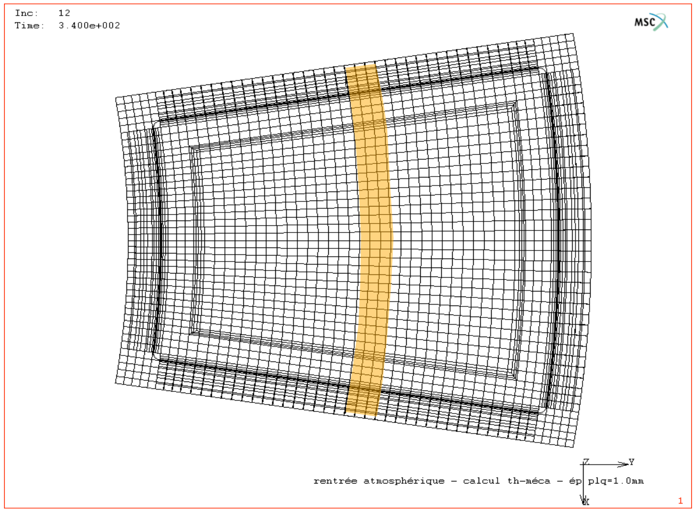
CMC Panels Design



CMC Panels Analysis

- **Thermo-mechanical analysis to verify :**
  - **Geometrical definition**
  - **Maximum displacements**
  - **Allowable strains**
  - **Mass optimization**





Total heatshield mass budget (w/o leading edges)

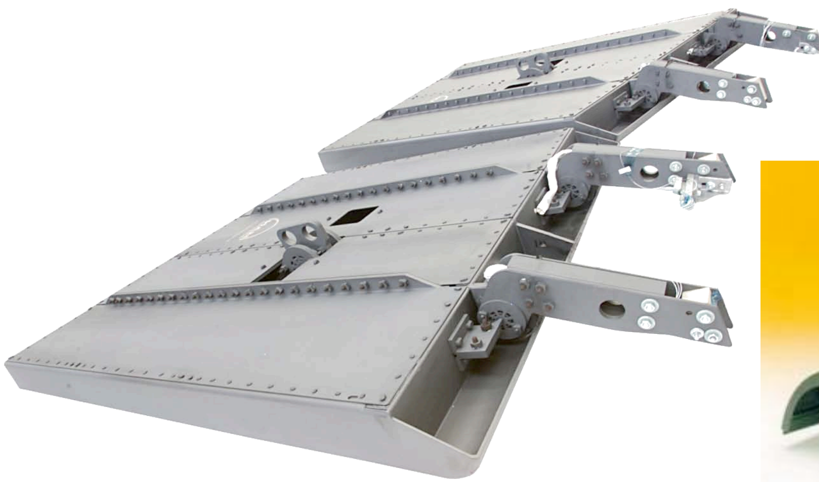
Elements	*Mass (kg)*
Central CMC panel	0.5
Inner row CMC panels	10.1
Intermediate row CMC panels	26.5
Outer row CMC panels	20.5
Attachments	22.9
Seals and internal insulation	88.3
TOTAL	**168.8**

Areal mass : 16.45 kg/m²

CMC Leading-Edge Design

Keraman® CMC Material

- Reference: X38-V201 NASA-CRV Prototype Vehicle
- Material: Keraman® C/SiC, 2D-Carbon fiber fabric with SiC matrix
- Process: Gradient-CVI infiltration process
- Qualification: Body Flap, Leading Edges & Chin Panel

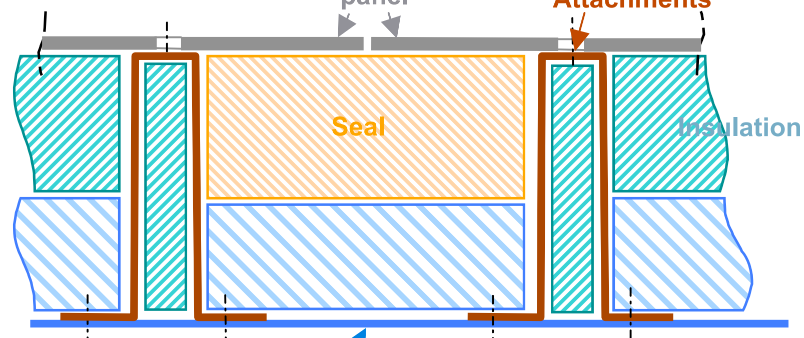


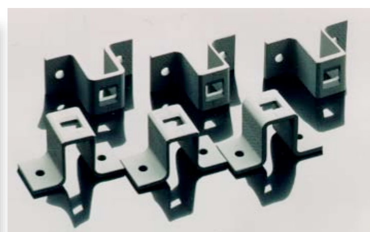
- Material TRL: 8 **(acc. to X-38 specification up to 12x life-cycles)**

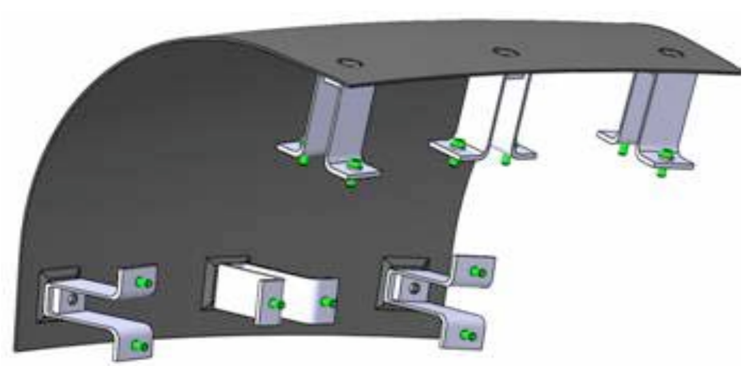
CMC Leading-Edge Design

CMC panels directly attached to CMC stand-offs (i.e. X-38 Leading Edge)

- **Only with CMC fasteners directly bonded to hot surface → no risk of thermal mismatch**
- **C/SiC omega-shaped standoffs**
- **Direct access from outside (--- > accessibility & maintainability in space)**
- **Simple panel design**
- **High TRL for applications up to 1600°C**
  Ceramic fasteners TRL = 8
  Attachment concept TRL = 5

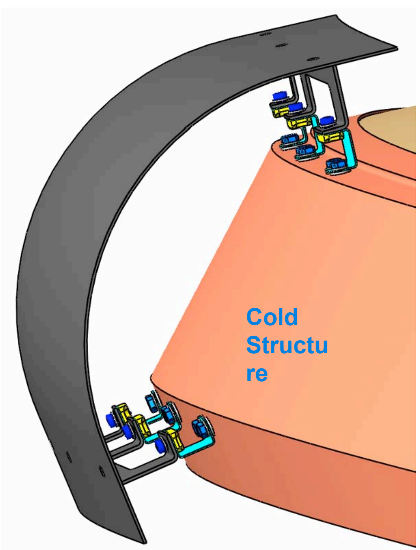


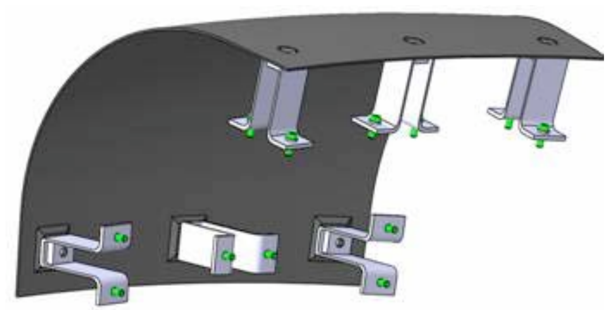


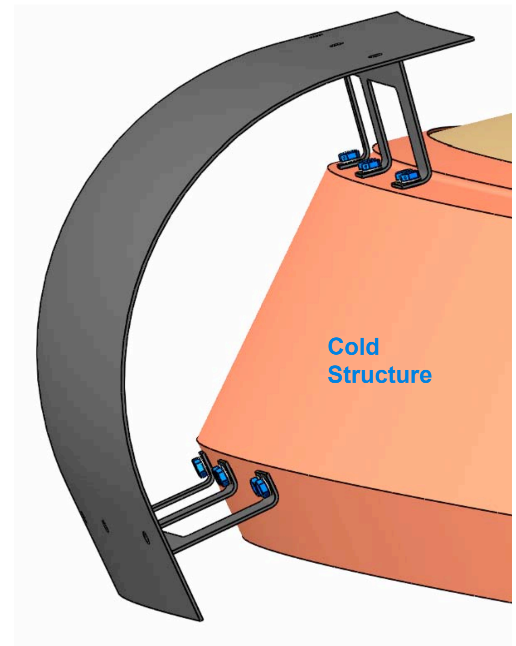


CMC Leading-Edge Design

- Several concepts investigated
- Pros and cons assessed in terms of:
  - TRL level
  - Maintainability
  - Simplicity
  - Manufacturability







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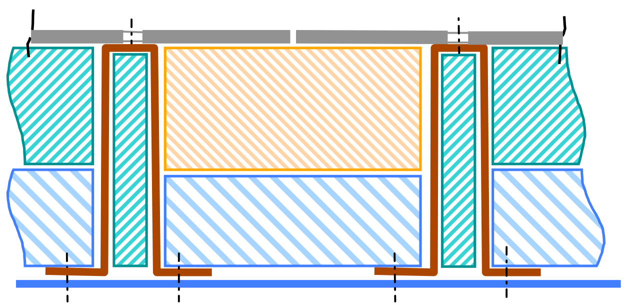
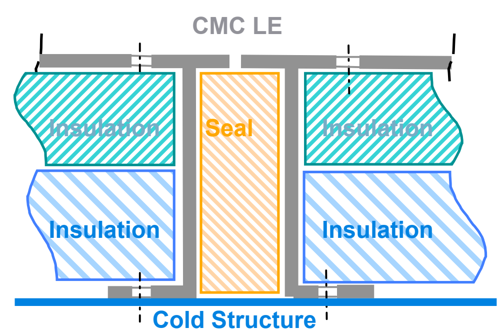
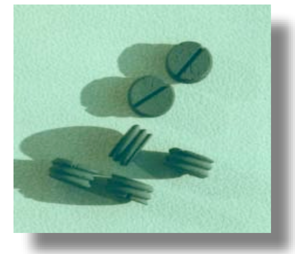


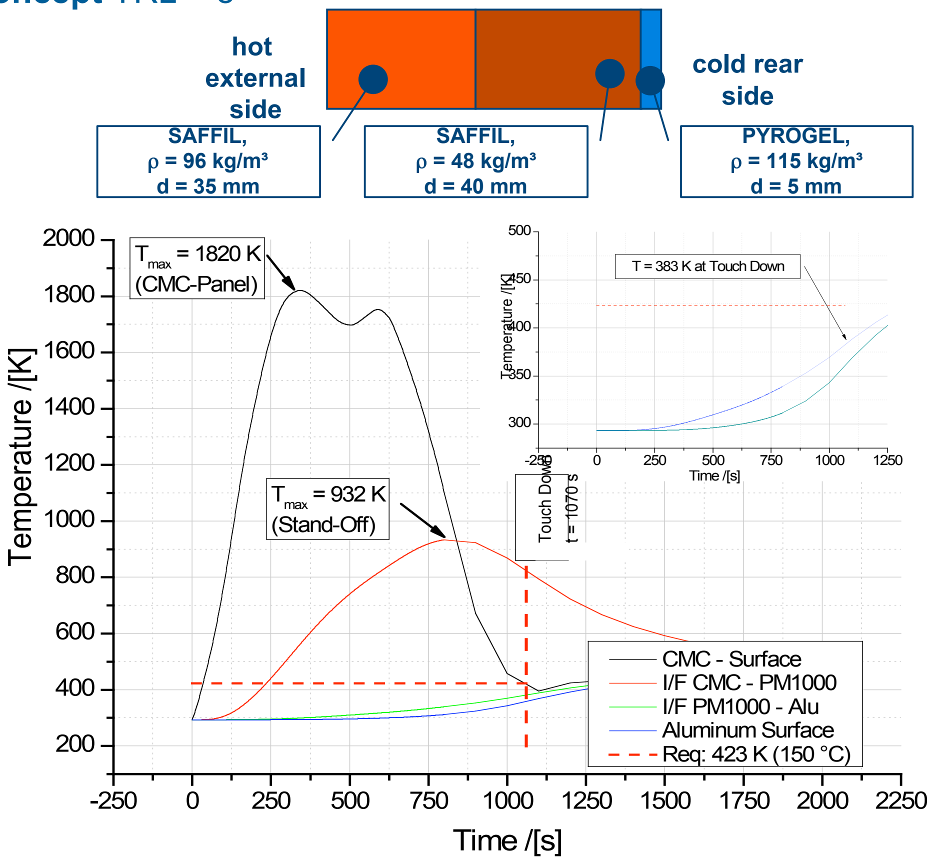


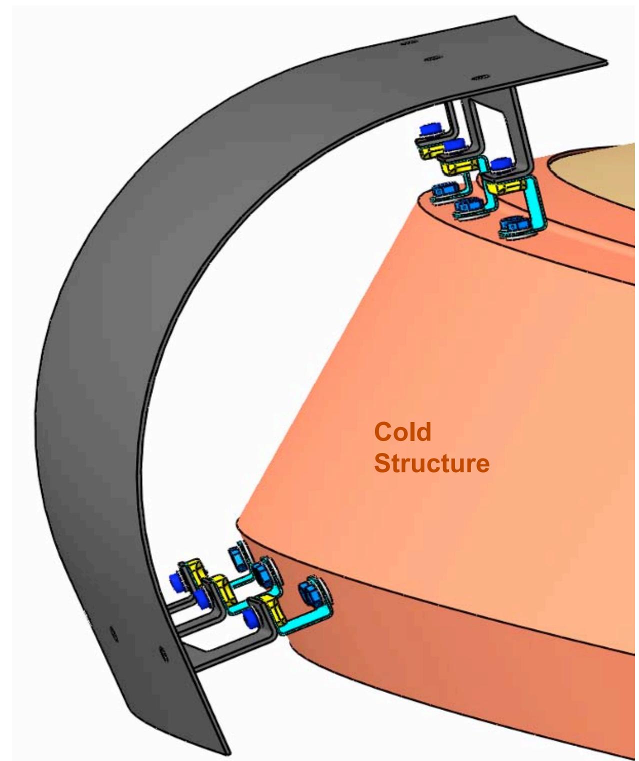
CMC Leading-Edge Design

CMC panels with metallic stand-offs (similar to X-38 Nose Assembly)

- **Ceramic and metallic standoffs**
- **Metallic fasteners and ceramic plugs**
- **Fixation at "medium" temperatures**
- **Attachment concept** TRL = 8







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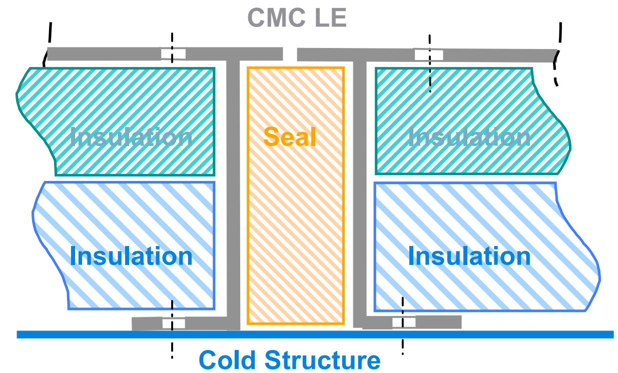
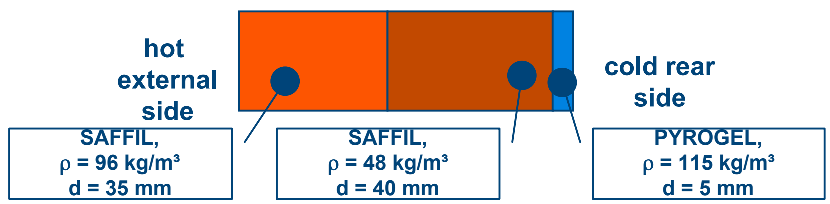
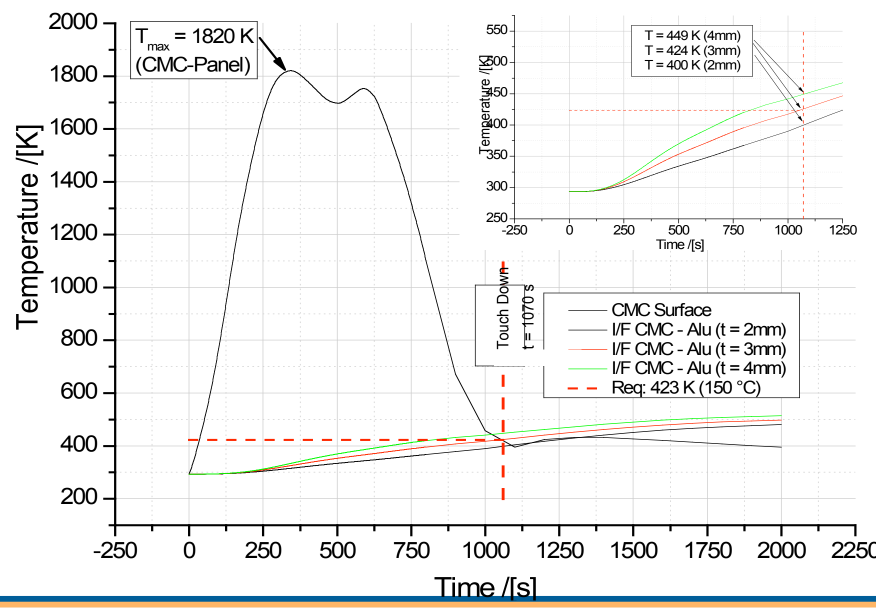
CMC Leading-Edge Design

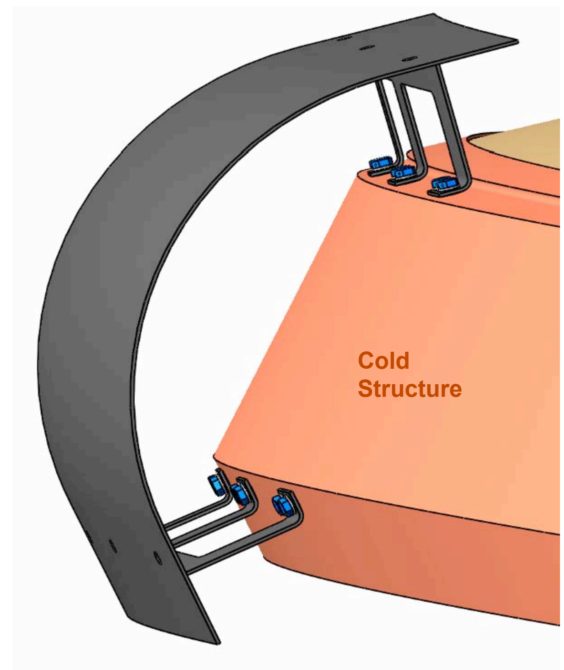
CMC panels directly attached to cold structure

- **Integral ceramic standoffs**
- **Metallic fasteners** (off-the-shelf) **and ceramic plugs attachment concept TRL = 5**
- **Fixation at "cold" temperatures** (direct fixation on cold structure)



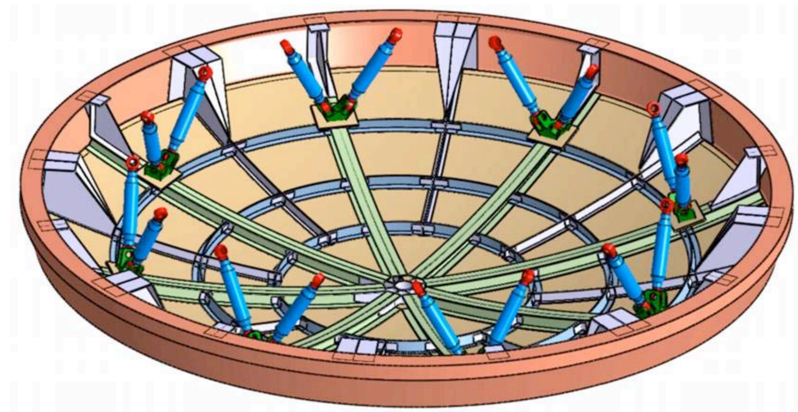




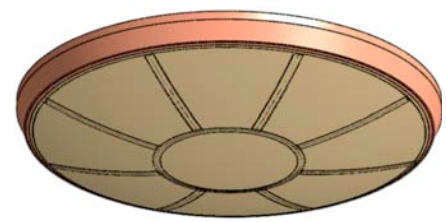


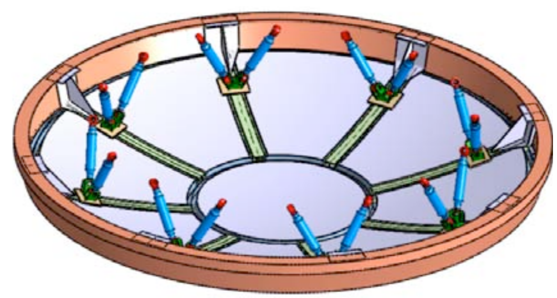
Cold Structure Design

- **Main characteristics :**
  - **Made from aluminum alloys**
  - **Shape of cold structure underneath panel array identical to OML (reduced by panel height)**
  - **Cold structure shape adapted to Leading Edge thermal & mechanical design needs**
  - **Design will match with internal insulation lay-out and attachment concept**
  - **Mechanical attachment to the vehicle pressurized compartment realized by means of hinge rods**



Courtesy MT Aerospace



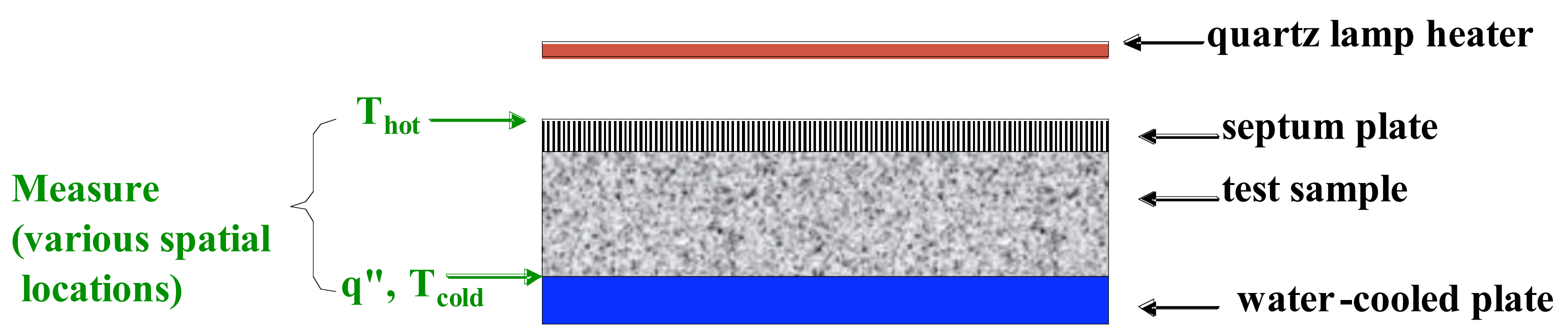


Agenda

- Overview
- Trajectory and Loads
- **CAS Design**
  - Design
  - **Thermal Insulation**
- Sepcore
  - Design
  - Ablators
- Structural Health Monitoring
- Concluding Remarks

Thermal Insulation

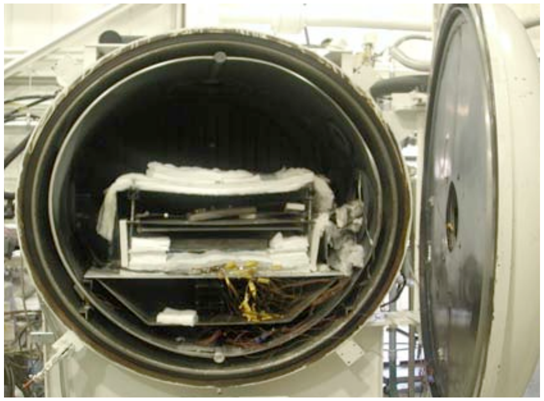
- The temperature range of thermal conductivity apparatus was extended to 1250°C (replaced ceramic radiant heater with quartz lamp array heater):
  - Cold side temperature: 20˚C (water cooled)
  - Hot side temperature: 100 – 1250˚C
  - Pressure: 0.0001 – 760 torr
  - Specimen size: 30 x 30 x 2.5 cm (12 x 12 x 1 in.)
  - Measure: T_{hot}, T_{cold}, q" (thin film heat flux gage), L
  - Calculate: apparent thermal conductivity, k_a



Thermal Insulation

- Performed steady-state thermal tests on selected fibrous insulation samples 350K ≤ T ≤ 1350K, 0.0001 ≤ P ≤ 760 torr
- Used thermal modeling in conjunction with measurements to determine pertinent parameters for gas/solid conduction and radiation heat transfer

Insulation	Density (kg/m^3)	Temperature limit (°C)
Zirconia felt	240 (15 pcf)	2310 (4200°F)
Alumina blanket	96 (6 pcf)	1650 (3000°F)
Cerachem	96 (6 pcf)	1430 (2600°F)
Q-fiber felt	48, 96 (3, 6 pcf)	1000 (1800°F)



Setup in 5 x 5 ft vacuum chamber at LaRC

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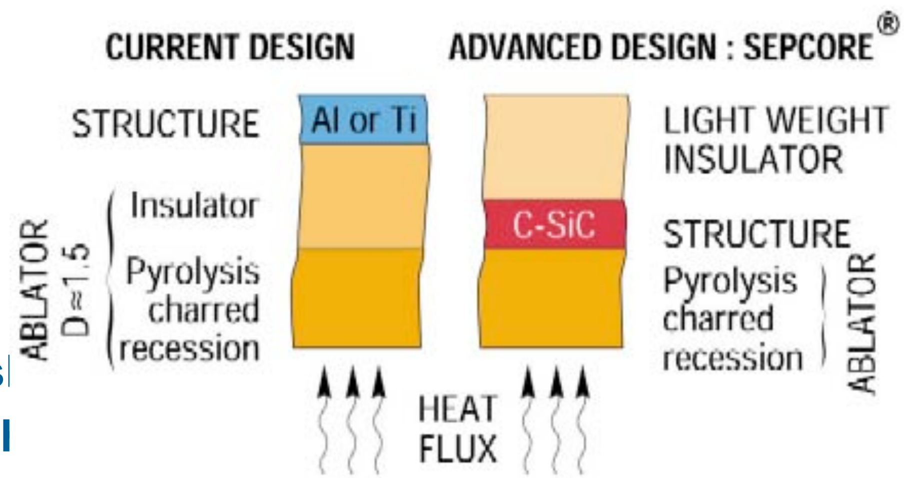
Principle Of Sepcore®

- Objective is to minimize thickness of ablator required on a TPS element by :
  - Attaching it to a hot CMC structure instead of a cold metallic structure
  - Sizing the layer of ablator so that the temperature at the CMC/ablator interface remains within CMC allowable
  - Introducing lightweight insulation at the rear side of the CMC structure

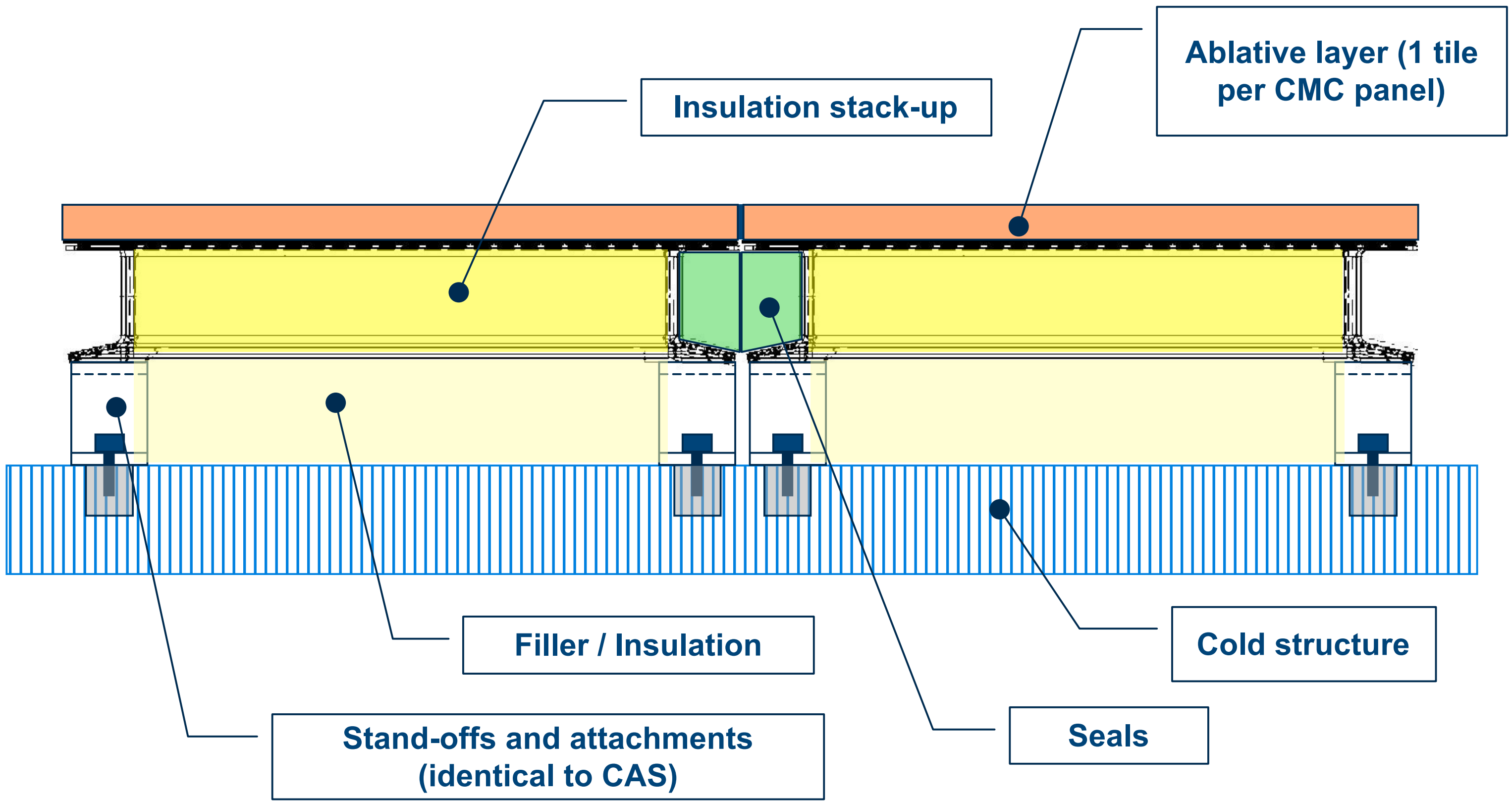


- Significant heats… blators
- Adapted to high l…

Snecma Propulsion Solide
SAFRAN Group
NASA
MR & D Materials Research & Design
MT AEROSPACE

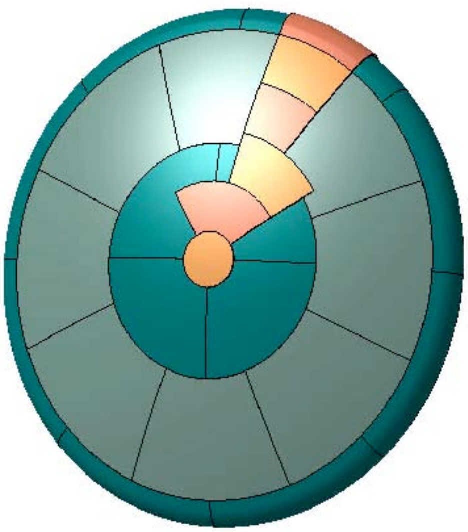
Sepcore® Architectures

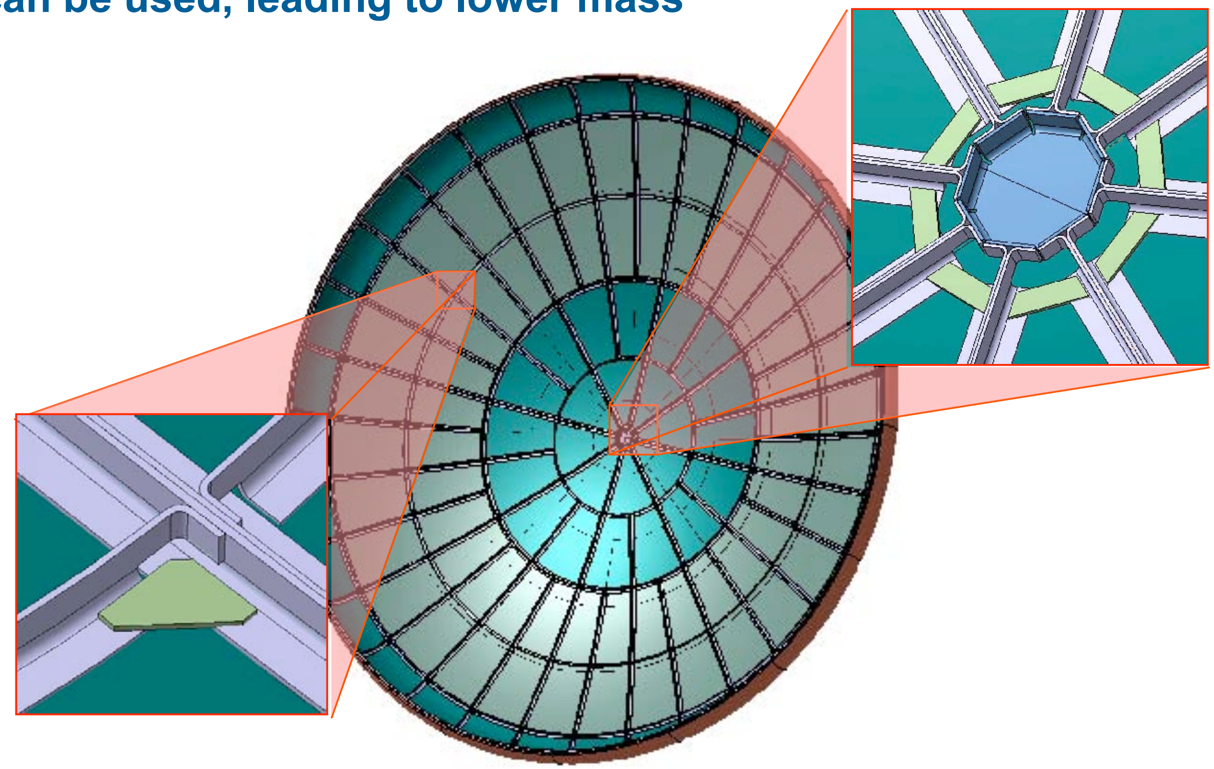
- **Concept A :**
  - **Ablative tiles are attached to CMC panels, fixed on a cold structure**
  - **Minor modifications of CAS panels to attach an ablative layer**



Sepcore® Architectures

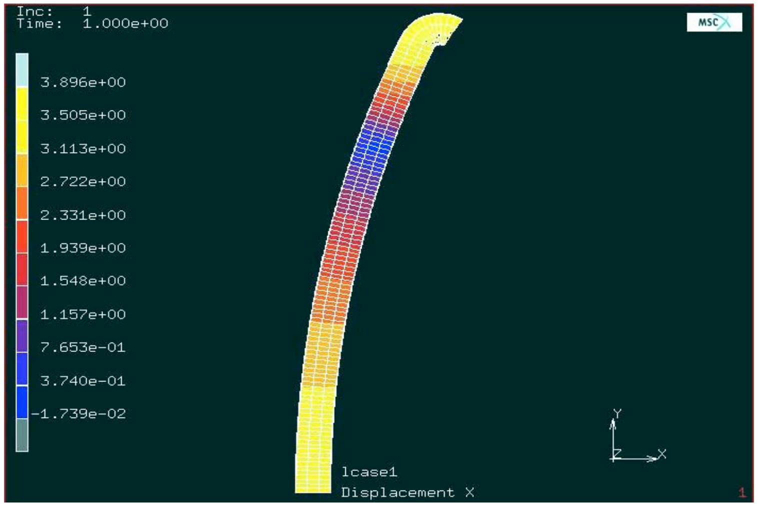
- **Concept B :**
  - **Ablative tiles are attached to hot structure made of CMC**
  - **Same type of CMC material than for CAS panels, but very different architecture (skin attached by screws or rivets to a web of stiffeners)**
  - **Full potential of Sepcore® can be used, leading to lower mass**





Sepcore® Preliminary Sizing

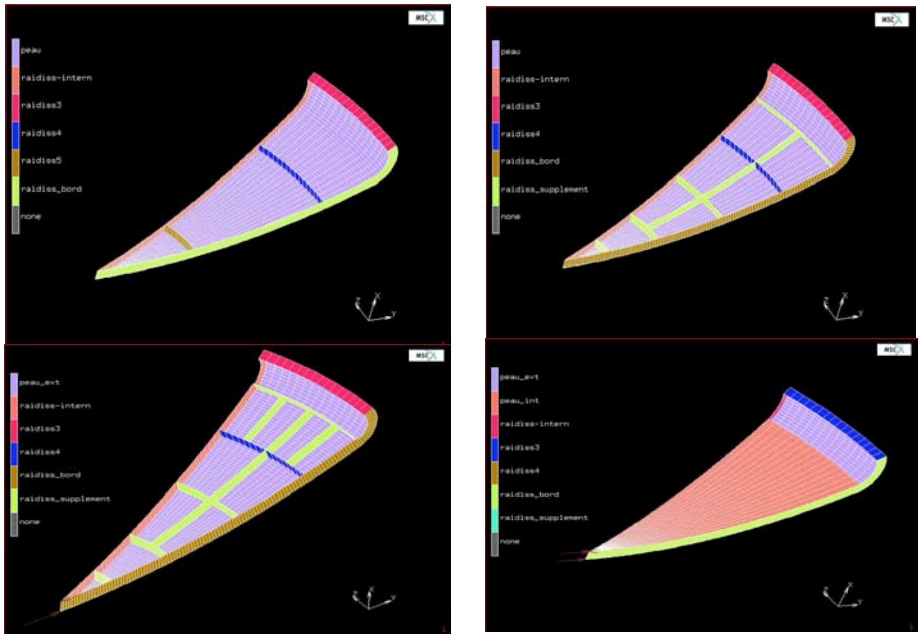
- **Cold structure sizing (concept A)**
  - **Sizing criterion : max. displacement of structure = 3 mm**
  - **Boundary conditions :**
    - Structure clamped at R=1,3 m
    - Pressure on front face = 88 000 Pa (difference between wall pressure and atmospheric pressure
  - **2D axi-symmetric model of sandwich structure (aluminum honeycomb and C / epoxy skins)**
  - **Approximate weight** 280 kg

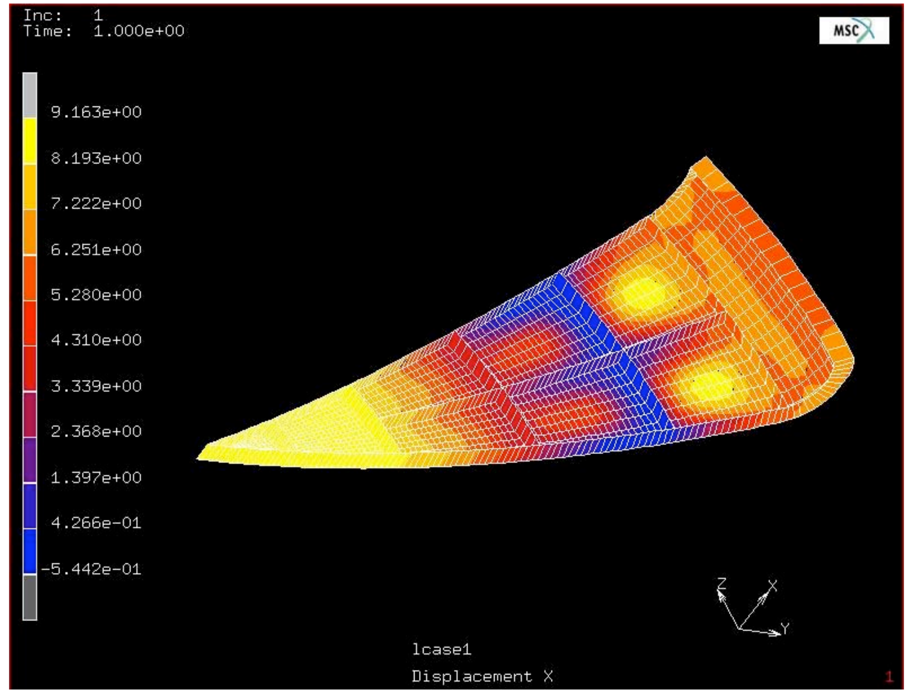


	Honeycomb thickness	Skins thickness	Honeycomb density	Displacement	Mass of structure
#1	120 mm	0.5 mm	50 kg/m3	10.0 mm	148 kg
#2	120 mm	0.5 mm	130 kg/m3	6.2 mm	332 kg
#3	120 mm	1.5 mm	50 kg/m3	4.5 mm	213 kg
#4	120 mm	1.5 mm	130 kg/m3	2.7 mm	397 kg
#5	120 mm	2.0 mm	50 kg/m3	3.5 mm	246 kg
#6	120 mm	2.0 mm	130 kg/m3	2.0 mm	430 kg
#7	80 mm	2.0 mm	50 kg/m3	4.5 mm	207 kg
#8	80 mm	2.0 mm	130 kg/m3	2.9 mm	330 kg

Sepcore® Preliminary Sizing

- **Hot structure sizing (concept B)**





- **4 configurations analyzed :**
  - I. 16 radial stiffeners + 3circum. stiffeners
  - II. 32 radial stiffeners + 6 circum. stiffeners
  - III. id + inner skin
  - IV. 64 radial stiffeners + 6 circum stiffeners + inner skin
- **CMC Thickness = 3 mm**
- **Stiffener height 60 mm for I, II, III, 80 mm for IV**
- **Estimated mass : 250 x 1.3 = 325 kg**

	Displacement	Mass of structure
I	13.7 mm	123 kg
II	9.2 mm	137 kg
III	5.6 mm	203 kg
IV	3.9 mm	221 kg

Sepcore® Preliminary Mass Budget

Apollo size heatshield, 10 MW/m²

MASS (kg)	Reference : Ablator on cold structure	Sepcore concept A		Sepcore concept B	
	C / phenol*	PICA	C / phenol	PICA	C / phenol
Ablator	1,360	66	390	66	390
CMC parts	-	115	115	325	325
Insulation	-	150	150	150	150
Cold structure	280	280	280	-	-
TOTAL	1,640	611	935	541	865

*** sizing made by SPS on material similar with NASA but not identical :** comparison with ablator sizing of Sepcore with C/phenolic ablator

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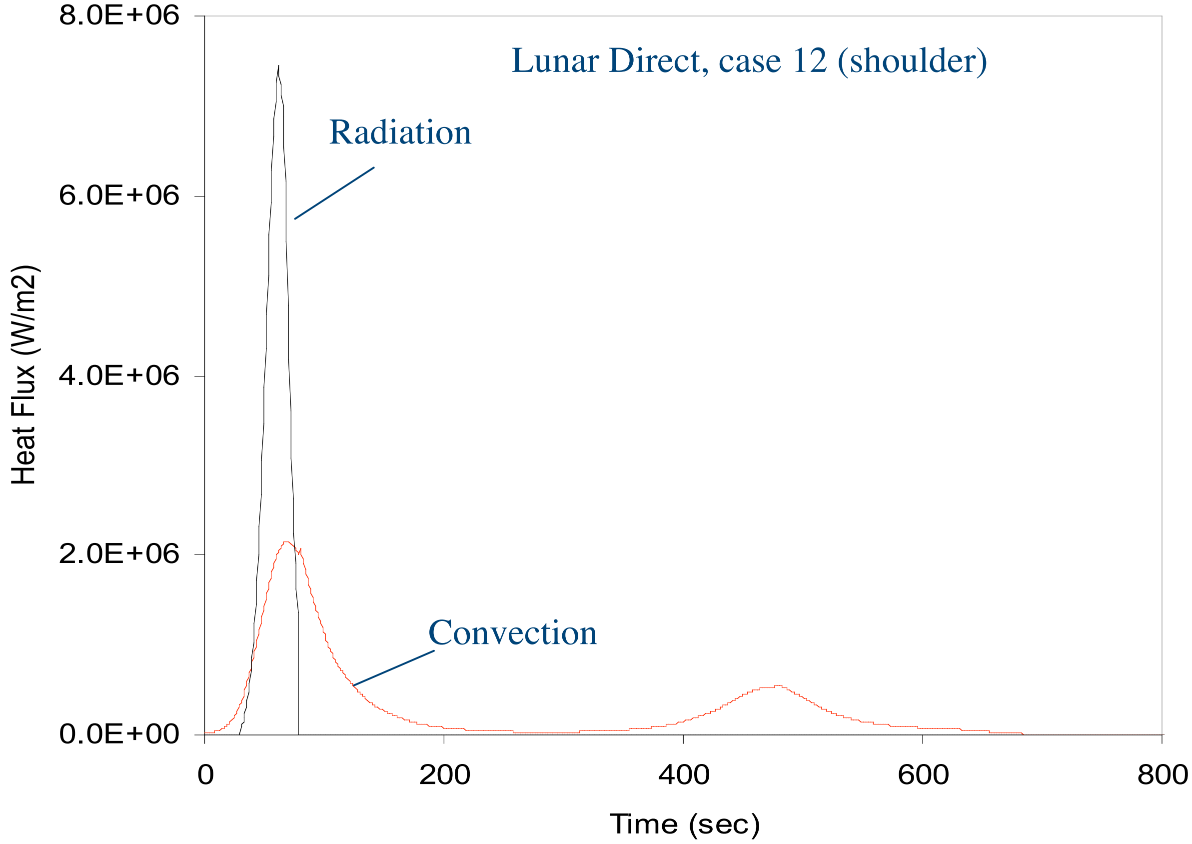
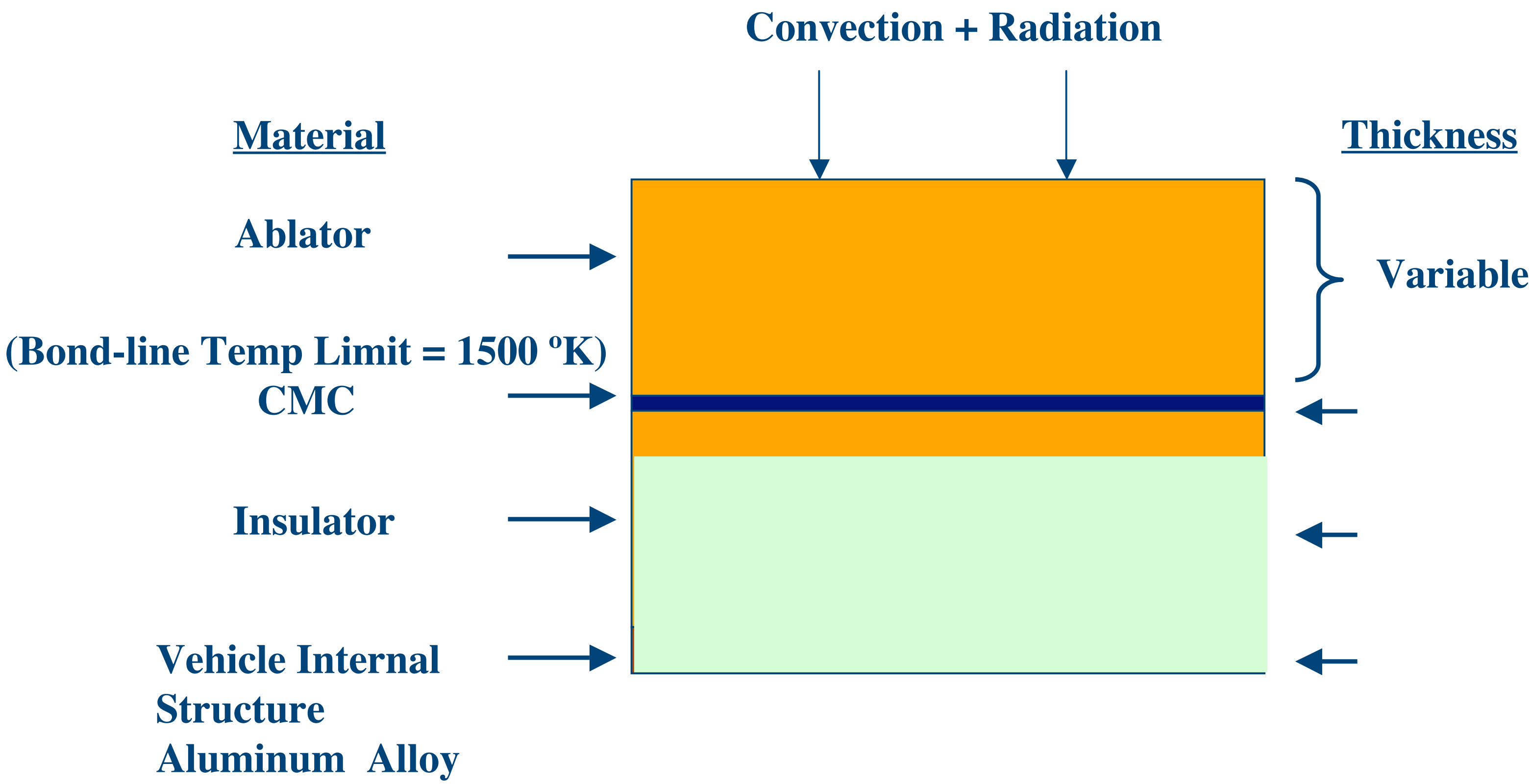
Aerothermal Environments Used for Ablator Sizing

- **Lunar Direct Entry, case No.12**
- **Aerothermal environments are based on those predicted by LaRC's engineering code, not LAURA CFD**



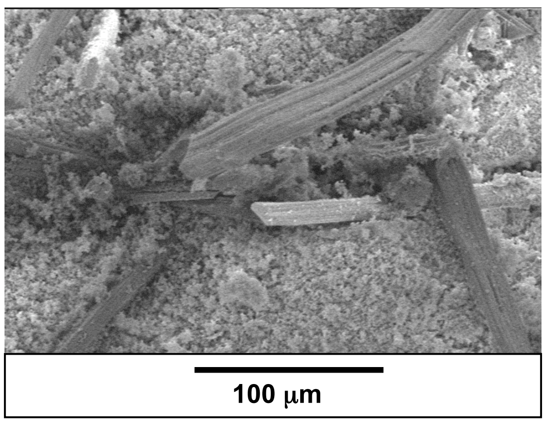
TPS Stack-up for Ablation and Thermal Response Simulation

- **As specified in SEPCORE Preliminary Specification developed by Snecma:**

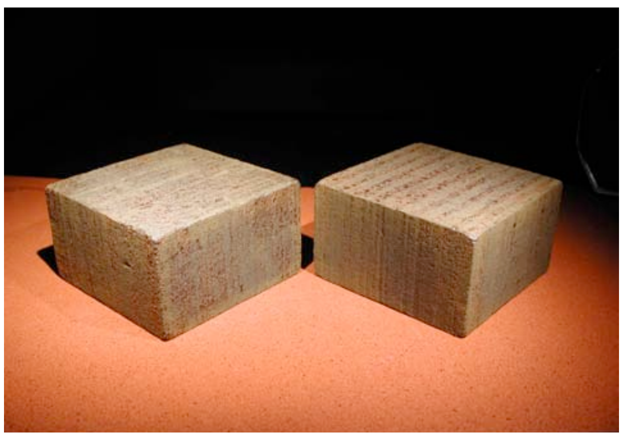


Ablative TPS Materials

- Generic fully dense carbon phenolic composite
- PICA (Phenolic Impregnated Carbon Ablator)
  - Developed by NASA ARC
  - Used on Stardust Sample Return Capsule, will re-enter the Earth atmosphere in 2006
  - Manufactured by Fiber Materials, Inc.



Scanning electron Micrograph of PICA material



PICA samples

Stardust spacecraft

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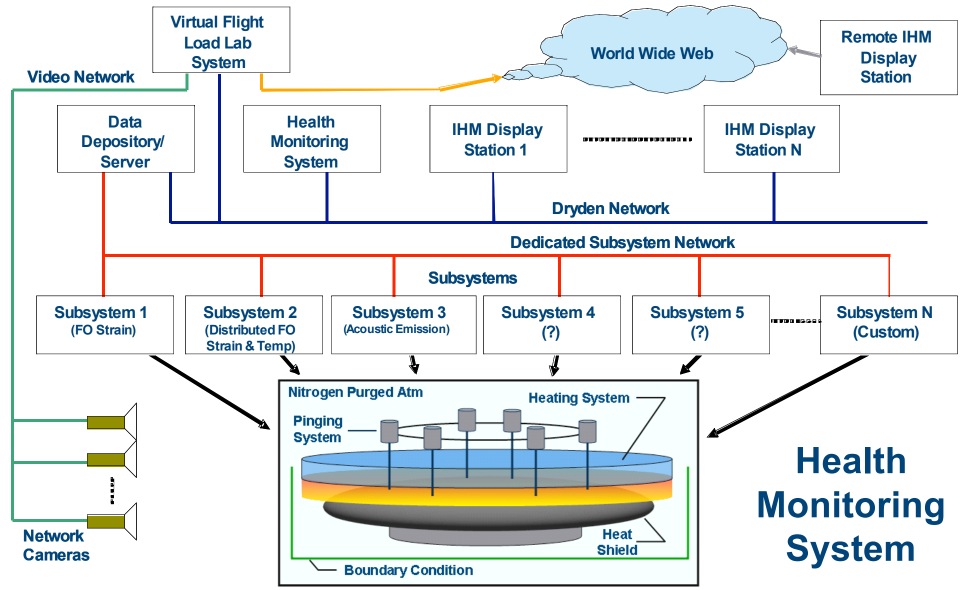
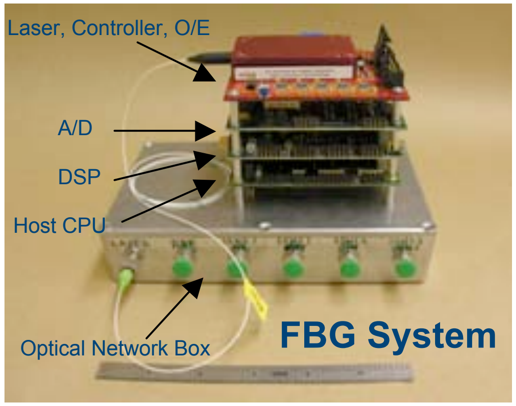
Health Monitoring System Development

- Established notional approach for a health monitoring system to support large-scale heat-shield testing
- Identified potential high-temperature acoustic emission (AE) sensors and potential heat shield locations
- Continued development of AE sensor multiplexing technology
- Miniaturized and increased channel count and data rate of existing Fiber-Bragg Grating (FBG) system for strain and temperature monitoring
- Initiated sensor attachment technique development on customer supplied C/SiC specimen



Health Monitoring System

High-Temp AE Sensor (-200 to 540 C)



FBG System

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Concluding Remarks

- The Snecma-led TPS task for NASA's Exploration Initiative began the development of three complementary TPS approaches
  - CAS
  - Sepcore
  - Deployable Decelerator
- Significant work was performed on the trajectory and loads definition, and on the CAS design
- The task was cancelled by NASA as part of a major restructuring of the Exploration Initiative