European Directions for Hypersonic Thermal Protection Systems and Hot Structures

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Agenda

♦ Background
  • Comments on prior ESA workshop
  • X-38
  • Hopper

♦ Flight Vehicle Based Technology Development
  • IXV (ESA)
  • EXPERT (ESA)
  • USV (Italy)
  • SHEFEX (Germany)
  • SHyFE (UK)
  • LEA (France)
  • Foton (Russia)

♦ Non-Vehicle Specific Technology

♦ Concluding Remarks
European TPS and Hot Structures Research and Development

- TPS and hot structures research and development critical for future space vehicles
- Developing next generation TPS and hot structures technology (not Space Shuttle derived technology)
- Long-term funding based on technology needs
- Wide industry support and commitment to X-38 program
- Test facilities developed for TPS and hot structures development
  - Thermal/structural test chamber
  - Arc-jet tunnels developed in recent years
- Technology development has broad base
  - Fabrication
  - Testing
  - Large components
  - Fasteners
  - Bearings
  - Oxidation protection
  - Damage repair
  - Life cycle

Wayne Sawyer comments from previous ESA TPS & Hot Structures Workshop
European TPS and Hot Structures Research and Development

♦ Proposing numerous experimental launch vehicles dedicated to or with TPS and hot structures research of prime consideration

♦ Committing significant resources to the development of TPS and hot structures for future space vehicles
  • $20 million spent on C/SiC body flaps for X-38, $50M on X-38 technology by Germany
  • Many companies involved (committing resources) in developing C/SiC hot structure for X-38
  • Large thermal/structural test chamber developed specifically for verification of X-38 hot structure

♦ European TPS & Hot Structures Emphasis
  • Developing ceramic matrix composite and metallic TPS with fibrous insulation
    • Waterproofing not required
    • Larger unit size (reduce part count)
    • More durable (reduced inspection and repairs)
  • Developing ceramic matrix composite and metallic hot structure
  • No ceramic tile development
  • Limited development with blanket insulation

Wayne Sawyer comments from previous ESA TPS & Hot Structures Workshop
X-38 Hot Structures

- **C/SiC leading edge** (flight experiment, 2000°F)
  - MT Aerospace (Germany)

- **C/SiC nose cap & skirts, \( T_{\text{max}} \sim 3200^\circ\text{F} \)**
  - Nose cap provided by DLR (Germany) (C-C, liquid Si infiltration fill cracks, final CVI SiC coating)
  - Nose skirts (2) provided by DASA (Germany)
  - Chin panel provided by MT Aerospace
  - Nose assembly has undergone full qualification (qual units)
    - Vibration
    - Thermal (radiant)
    - Mechanical

- **Metallic rudder** (Dutch Space)

- **C/SiC bodyflaps**
  - MT Aerospace
  - ~$20M
EADS TPS & Hot Structures Hardware for Hopper

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Intermediate Experimental Vehicle (IXV)

♦ Part of ESA FLPP
  • Run by NGL Prime, joint venture of Astrium (F, D) and Finmeccanica (I)
♦ PDR end of 2007, first flight end of 2010
♦ Objectives
  • System design experience for lifting reentry vehicles
  • Flight test in representative environments TPS & Hot Structures for Next Generation Launchers (NGL)
  • ATD data to validate tunnels and CFD
♦ Build on X-38 nose and body flap experience
♦ Both experimental and functional
♦ Leeward and base side utilizes Flexible External Insulation (FEI)
  • FEI 1000, 650,450
  • ODS metallic TPS
♦ Windward side
  • C/SiC shingles of different size
  • C/SiC leading edges, either fixed hot structure or shingle
  • Surface Protected Flexible Insulation (SPFI)
TPS & Hot Structures Technologies on the IXV
IXV C/SiC Hot Windward Surface TPS (Snecma)

♦ TRL 4-5, baseline vehicle technology
♦ Development tasks
  • Base material characterization - long duration PWT tests
  • Sub-assembly test (lift-off, flight, re-entry environment)
    - Structural integrity
      • Sine and random test of hard mounted TPS
      • 2 shingle, seals, interfaces, etc.
    - Structure characterization
      • Modal survey for design assumption correlation purposes
  • Test demonstrator in representative thermal and pressure environment
    - CMC TPS shingle sub-assembly
    - Scirocco PWT 1000 sec
      • Structural integrity in worst thermal environment
      • Insulation performance for support structure
      • Seal integrity and performance
      • Attachment interfaces insulation and stress relief functions
      • Degradation characterization
      • Analysis models verification
IXV CMC Shingle TPS (Snecma)

♦ Decouple the thermal (insulation) and mechanical functions

♦ Design
  • External C/SiC thermal shield panel
  • Outer oxidation protection system
  • Internal ceramic felt insulation
  • Static high temperature seals
  • Special attachment fixtures combining isolation and thermal stress relief

♦ Tasks
  • Design of panel and attachments
  • Analytical validation of design
  • Manufacturing of complete large shingle
  • Mechanical test of C/SiC panel
  • Testing likely done by now
    - Dynamic
    - Acoustic
    - Thermal
    - Thermo-mechanical
IXV C/SiC Control Surfaces (MT Aerospace)

- Includes hot interface components (bearing, seals, joints)
- X-38 based design and manufacturing
- TRL 4-5, baseline vehicle technology

- Torque driven body flap
  - Prototype roller bearing sub-assemblies
  - Dynamic seals
  - Driving torque load introduction interface
  - Tube to flap frame joint (validating a “one shot” production process of complex composite parts)

- Development tasks
  - Hot verification of structural strength of joint (in-situ joining manufacturing technology) between torque tube and flap frame
  - Thermo-mechanical cycling of body flap demo with IXV T, P profiles
    - Structural integrity of demo in worst thermal mechanical conditions (50 cycles)
    - Dynamic hot seal performance
    - Hybrid (metal & CMC) roller bearings functionality, integrity, and attitude maintenance
Pre-X CMC Flap Development (MT Aerospace)

♦ C/SiC design
♦ Mass is 23.63 kg (7% over goal)
♦ Flap structure
  • Cross-wise stiffeners yields most efficient torsion stiffness (1st eigenmode)
  • 2.5 - 5 mm thick
  • Open box vs closed box for X-38 design
  • Evaluated both 1 and 2 piece
♦ Ceramic bearings
♦ Attachment at hinge line
  • Rectangular C/SiC tubes
♦ Actuation mechanism
  • C/SiC rod vs arc used on X-38
♦ Hot dynamic seals
  • Nextel/saffil
♦ CMC fasteners
  • Fewer than X-38 due to no box cover
IXV Metallic Sandwich TPS

- **Metallic sandwich TPS**
  - Multiple cycles to 900°C
  - Core is stainless steel hollow spheres (Alcatel Alenia Space (I) and Plansee (A))
  - HollowMet core (ODS hollow sphere)

- **TRL 2-4**

- **Passenger experiment on IXV**

- **Development tasks**
  - Material development and characterization for core
    - *Minimize mass for given thermal mechanical load*
  - Thermal cycling of subassembly of ≥ 2 tiles, including interfaces, seals, and insulation
  - Hypervelocity impacts testing (exploit energy absorption of material)
IXV Metallic Honeycomb TPS

♦ TRL 2-4

♦ TIMETAL 1000 for use to 850°C (Astrium)
  • Orthorhombic TiAl (Ti$_2$AlNb) or TiAl reinforced TiB
  • Passenger experiment on IXV

♦ ODS Superalloys up to 1250°C (Dutch Space)
  • IN 617
  • Baseline vehicle technology
  • Windward aft or leeward aft
  • Development tasks
    - Design trades on seals, insulation, and interfaces to cold structure
    - Manufacture and test of selected design
    - Thermal cycling under IXV thermal and pressure profiles (2 TPS tiles)
    - Foils production
    - Core manufacturing
    - External sheet to core brazing
IXV Metallic TPS & Hot Structures (Dutch Space)

♦ AEOLUS team since 1993, lead by Dutch Space
♦ X-38 hot rudder
  • Fab and tested a PM-1000 rudder to 1200°C (1 yr)
  • Requirements changed
  • Qualified Ti/CMC rudder (1 yr)
♦ Sandwich panel
  • PM-1000 facesheets
  • PM-2000 core
  • Vacuum brazing
  • 47 ascent/descent cycles - good condition
  • Low and high speed (hail, 208 m/sec) impact test performed - good performance
♦ New design (post X-38) demonstrated
  • Thermo-mechanical tests performed and compared well to analysis
  • Sandwich panels with inserts and edge members
  • Corrugated webs with stress/strain reducing clips
♦ Extensive materials database developed
♦ Manufacturing development performed

ESA-TPS-2006-Mooij
**European eXPErimental Re-entry Testbed (EXPERT) Flight Experiment TPS (ESA)**

**Configuration:** Blunt cone configuration with a pyramidal shape (called KHEOPS) having four flat surfaces, each with a fixed flap (two fixed flap settings).

- Relatively large nose radius ($R_N < 0.4 \text{ m}$, $L = 1.7 \text{ m}$, $d = 1.3 \text{ m}$) to minimize stagnation heating rates and ablation pollution
- 5 km/sec, entry path angle $-5.5^\circ$, $3^\circ$ AoA
- Curved corner TPS (4)
- Flaps---study complex physics and X-38 issues; protected with TPS, instrumented on both sides
- Flat panels, including flap box and flaps (1050 mm$^2$, 1100 mm high)
EXPERT C/SiC Nose Cap (DLR)

- Based on X-38 experience (led by DLR Stuttgart)
- Internal flexible insulation below surface
- $q_{\text{max}} = 1,600 \text{ kW/m}^2$
- Material choice C/C-SiC
  - Avoided ablator
    - Geometrical stability
    - Chemical pollution of flowfield
- Load transfer from nose to vehicle cold structure
  - Elevated temperatures
  - Thermal expansion of nose
  - Thin metallic brackets bolted to nose and to cold structure
    - Less susceptible to side loads than X-38 based double bolt-joint design
    - Low complexity and cost
- Active oxidation in dissociated environments is accompanied by a sudden temperature increase of up to 500K.
- Recombination coefficients determined for C/SiC and PM 1000 in $\text{O}_2$ and $\text{N}_2$

IAC-06-D2.5.04
AIAA-2005-3262
AIAA-2005-3309
ESA-TPS-2006-Reimer1
ESA-TSP-2006-Herdrich1
EXPERT Metallic TPS

♦ ODS PM 1000
♦ $q_{\text{max}} = 225 \text{ kW/m}^2$
  • CFD assumed partially catalytic CMC and PM 1000
  • Nose non-catalytic, PM 1000 fully catalytic. Thus 1.2 factor used for conservatism

♦ Extensive FEA performed
♦ Mechanical stiffness to withstand re-entry dynamic pressure and fast depressurization during ascent
♦ Internal flexible insulation below surface
♦ Nose attachment to vehicle and metallic TPS
  • 4 mm step at RT, flush at max temperature
  • Seal designed to seal both hot and cold
  • Used inverted cone which is pulled upwards by expanding metallic TPS and counteracts the downward movement due to drag
  • Inverted cone designed to follow the deformation (~2%) of the PM 1000 metallic TPS
EXPERT CMC Open Flaps (MT Aerospace)

- Fixed at 20° deflection
- Open flap, 396 x 315 x 50 mm
- Two spherical supports at the hinge line
- Static hinge line seal
- Flap support connected to flap main body and PM 1000 cavity via spherical CMC bearings
- All joints CMC to eliminate CTE problems
- Flap box is designed as heat sink since flap is much hotter than metallic TPS capability
- Bearing shells fixed by CMC pins to flap main body
- Hinge seal fibrous saffil core wrapped in 1 layer Nextel clamped between flap leading edge and cavity

ESA-TPS-2006-Lange2
Unmanned Space Vehicle (USV)

♦ Italian Space Agency / CIRA

♦ Technology development
  • Sharp hot structures
    - Wing leading edges
    - Nose cap

♦ Orbital test bed: Flying Test Bed - X (FTB-X)
  • Entry from LEO at 200 km
  • < 20° AoA
  • < 20 min entry
USV Ultra High Temperature Ceramics (UHTC) Nose

♦ Nose design
- Bulk graphite core
- Truncated conical C/SiC frame from PIP (Fabbricazioni Nucleari)
- ZrB2-SiC coating on C/SiC frame by plasma spray (Centro Svilippo Materiali)
- UHTC conical tip from hot pressing (National Research Council Institute for Ceramic Materials)

♦ UHTC primary focus area
- Core/shell configuration
  - ZrB2 core
  - (Zr,Hf)B2 shell
- Electrical Discharge Machining (EDM), and its effect on the surface
  - Cu, Zn contamination
  - Decreased flexure strength
- Mechanical assembly
  - Coupling pin (UHTC material to reduce thermal stress)
  - Contact pressure not important
  - Compressive stresses key

AIAA-2005-3266    IAC-05-C2.3.05
AIAA-2005-3267    IAC-06-C2.4.04
AIAA-2005-3267    IAC-06-C2.4.05
USV Wing Leading Edge (Italy)

♦ Advanced Structural Assembly (ASA) program funded by ASI
♦ Wing test article for PWT test
  • Leading edge (interchangeable options)
    - Actively cooled: Inconel
    - UHTC
  • Hybrid sandwich panel up to 2000°C (windward surface)
    - C/C facesheets
    - C foam core - evaluating both co-processing and secondary bonding
  • Leeward surface MMC (CSM)
    - Ni sheets and SiC/Al₂O₃ fibers

ESA-TPS-2006-Fossati-1
USV UHTC’s

♦ Multiple fabrication routes studied
  • Sintering aids
  • Reactive hot pressing starting from solid precursors
  • Spark plasma sintering for densification
  • Introduction of second phases (SiC and MoSi₂) to improve oxidation resistance and mechanical properties

♦ Complex shaped components via Electrical Discharge Machining
  • Compared diamond tool machining vs EDM on ZrB₂-SiC
USV UHTC Emissivity and Catalycity

♦ Compositions
- A: ZrB2 + SiC + sintering aid (MoSi$_2$)
- B: ZrB2 + HfB2 + SiC + sintering aid

♦ Total hemispherical emissivity $10^{-3}$ and 200 Pa
- A: large difference due to pressure. 200 Pa higher $\varepsilon$ due to oxide layer
- B: small difference due to pressure

♦ Catalycity
- Just composition A so far

<table>
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<tr>
<th>Total hemispherical $\varepsilon$, Composition A</th>
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<td>200 Pa</td>
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<tr>
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<tr>
<td>1319</td>
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<tr>
<td>1485</td>
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<td>1681</td>
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| 10$^{-3}$ Pa |
| T (K) | $\varepsilon^\cap (T)$ |
| 1100  | 0.60                 |
| 1416  | 0.55                 |
| 1556  | 0.61                 |

ESA-TPS-2006-Scattela
IAC-06-C2.4.04
USV UHTC Oxidation

- 1200 min
- Dry, flowing air
- 1450°C
- Mass from TGA
- XRD & SEM
  - Presence of ZrO₂ and Zr/HfO₂
  - External glassy layer (Si-O-like system)
    - 100 µm for A
    - 50 µm for B
Sharp Edge Flight Experiment (SHEFEX)

♦ Funded by DLR

♦ Objectives
  • Evaluate performance of multi-faceted leading edges
  • Compare numerical data with flight results

♦ Flight Oct 27, 2006
  • Mach 7 between 90-20 km
  • 300 km apogee
SHEFEX (DLR)

- TPS, hot structures experiment, Oct. 2005 flight
  - Apogee 211 km
  - 550 sec
- ~3 ft long, 1.5 ft diameter
- Test flat, facetted, panels
- Seals and attachments included in test
- Primarily CMC’s with some metallic TPS
- CMC panels utilizing DLR’s liquid silicon infiltration (LSI) process
  - Central post with flexible standoffs at the corners (thermal expansion not suppressed)
  - Fibrous matt insulation under cover plate
  - CMC fastener connects panel to central post.
- C/C-SiC leading edge
- WHIPOX (Wound Highly Porous Oxide) seals
  - Oxide fibers (Nextel) embedded in porous mullite or alumina matrix
- Passenger experiments
  - 2 ceramic (EADS)
  - 2 metallic (Plansee)
  - Ceramic (MT Aerospace)
- Aluminum structure
- All in-flight instrumentation integrated into TPS
Sustained Hypersonic Flight Experiment (SHyFE)

♦ Funded by UK Ministry of Defense

♦ Objective
  • Design and fly a prototype ramjet capable of sustained hypersonic flight

♦ Vehicle
  • Weight ~ 30 kg, 1.5 m long, 7 in. dia.
  • Sounding rocket boost to M 4 at 15 km, accelerate to M 6 at 32 km, cruise for 200-300 km
  • Ballistic climb from M 4 to M 6 that takes ~ 60 sec.
  • Diesel fuel
  • Shock on lip is M 4.8

♦ First flight Aug 2009, second flight 2010

♦ Thermal management
  • Minimize heat ingress from combustion chamber (2400K) to center body components

♦ C/SiC used for vehicle construction
  • MT Aerospace fabrication
  • Air-breathing propulsion experiment
  • Practically the entire flight exp is C/SiC, except a Ti tank
    - MT Aerospace is fabricating the C/SiC via CVI
    - The fuel flows in an annulus between 2 C/SiC tubes
    - The fin roots are bonded to the body
    - MT Aerospace has eliminated a lot of the bolts by bonding and some other creative techniques that they have not discussed
MBDA and Onera (France)

- 6 flight tests 2010 - 2013 in range of M 4-8
- 4.5 m long
- Not recovered
- 20-30 sec flight

One of the key required technologies is fuel-cooled composite structures for combustion chambers

- C/SiC actively cooled combustion chamber being worked

AIAA-2003-6918
AIAA-2005-3433
AIAA-2006-7925
AIAA-2006-8072
AIAA-2005-3434
LEA PTAH-SOCAR Actively Cooled Composites

♦ MBDA / EADS ST
♦ Duct structure
  • Obtained by weaving with stitching yarns through removable mandrel
  • 100 x 100 x 130 mm$^3$
  • Pin-fin coolant channel
  • No machining of channels (stitched)
  • Back-up structure required
  • 10 kg/m2, with backup structure 30% lighter than metallic cooled structure
  • Utilized CVI followed LSI (liquid silicon infiltration) for rapid (days vs weeks for CVI), low-cost densification

♦ Hot test
  • Cooled by air
  • Tested at M 7.5 conditions
  • Supersonic combustion air/H2
  • Twelve 10 sec tests

♦ Next step - larger structures

AIAA-2003-6918
AIAA-2005-3433
AIAA-2006-7925
AIAA-2006-8072
AIAA-2005-3434
LEA CMC Cooled Combustion Chamber

♦ Snecma and Onera (through PWR & AFRL, A3CP program)
♦ Snecma C/SiC (Sepcarbinox)
  • Brazed 2 panels
  • Machined grooves in the hot side panel
  • Integrated manifolds on cold side
  • 115 x 40 mm with 3 channels
♦ Tested at AFRL radiant facility
  • JP7 fuel coolant
  • 1.21 MW/m² max heat flux
  • 6.9 MPa (1000 psi)
  • Good correlation with analysis
♦ Same panel tested in an Onera scramjet engine test facility
  • H2 for combustion
  • Up to 1.5 MW/m²
DLR Coatings Flown on FOTON

♦ FOTON is a Russian flight experiment (15 days in orbit)
♦ C/C-SiC via Liquid Silicon Infiltration (LSI)
  • CFRP via process such as RTM
  • Pyrolysis at 900°C in Ar leads to porous C/C
  • Siliconizing at 1600°C in vacuum includes LSI and formation of SiC matrix
♦ Developed yttrium silicate coating
  • Performed well in PWT tests
  • Flew on FOTON
    - 1 and 2, CVD SiC + yttrium silicate via low pressure plasma spray
    - 3, CVD SiC + titanium oxide slurry via “painting”
FOTON and EXPERT
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Actively Cooled CMC Thrust Chamber (DLR)

- C/C used for inner material, porosity 13-22%
  - 0°/90° lay-up
  - 10 mm thick
  - Temperature gradients 1000°C/mm due to low k (1-1.2 W/mK)
  - 30 mm chamber diameter

- CFRP jacket
  - Internal pressure loads
  - Longitudinal compression loads due to attachments and thrust
  - 5 mm thick
  - Searching for H2 barrier

- Permeability of multiple CMC’s measured
- Numerous hot tests performed
Multi-Layer Insulation (MT Aerospace)

♦ Medium Temperature (~1000°C)
  - Weight limit (by ESA) of 4 kg/m² and 40 mm thick
  - Nextel 312 fabric containment
  - Pryogel superior to Microtherm (density, vibration, humidity, handling)
  - Consists of IMI and Pyrogel (6 mm)

♦ High Temperature (~1600°C)
  - ESA limits: 80 mm, 8.5 kg/m²
  - Nextel 440 fabric containment
  - IMI with Zircar APA-2 for highest temperature regions and Pyrogel for lower temperature regions.

♦ Seals (DLR)
  - Saffil filled Nextel 312 bag impregnated by MTMS (up to 1300K)
  - Saffil filled Nextel 440 bag impregnated by MTMS (up to 1900K)
  - Kept in place by C/SiC guard
Flexible External Insulation (FEI) (EADS)

♦ Improvement of FEI blankets
  • New high emittance coating developed with improved stability
  • New less toxic waterproofing for initial and re-waterproofing
    - Preferred MTES (methyl triethoxy silane) over standard MTMS (methyl trimethoxy silane)
  • Refurbishment and repair procedures defined
  • Applied to FEI-1000 blankets and subjected to environmental testing for 10 flights.
    - Waterproofing and coating refurbished after 4 cycles
Hybrid Metal/CMC Winglet Hot Structure (Alenia)

- Design and analysis complete
- 1/3 size of X-38, removed hinge step
- Outboard panel and wing leading edge
  - MT Aerospace C/SiC, 3 mm thick
- Inboard panel divided into 3 panels
  - Plansee PM 2000, 1 mm thick with 2 mm thick ribs
- Seals
  - Nextel wrapped saffil
- Fabrication and PWT test planned
ULTIMATE Metallic TPS (EADS)

♦ EADS (Astrium)
♦ Load carrying metallic box with standoffs and internal insulation
  - Outer surface honeycomb sandwich (10 mm thick, hexagonal cells)
  - TiAl?
  - Omega standoffs
♦ Fabrication and test
  - 200 x 200 mm (final design 500 x 500 mm)
  - Single panel test
    - Vibration
    - Acoustic
    - Thermal test to ~850°C
  - Assembly tests
    - Vibration
    - Thermal IR
    - PWT
♦ SHEFEX flight
  - Similar to ULTIMATE design
Passive To Active Oxidation (Germany)

- PWT tests ranging from 50 - 7000 Pa and 1650 - 1950°C with peak to 2300°C
- At steady state 1720°C/800 Pa, a small increment in energy (1 mm closer) caused a small hot spot that within 30 sec. covered the entire sample with a temperature of 2050°C
- Test very reproducible
- Also observed at 1700°C/50 Pa, 1800°C/2000 Pa, 1840°C/3500 Pa, 1940°C/7000 Pa
- Temperature jump occurring at passive to active transition
- What causes temperature rise?
  - Test done with nitrogen plasma and little oxygen (few Pa)
    - 1460°C/690 Pa temperature rose to 1850°C with little erosion
  - Strong evidence of nitrogen recombination during active oxidation
  - Half energy released during active oxidation from oxidative reactions, half from nitrogen recombination

ARV2001-Hilfer
IAC-02-I.3.05
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Key TPS & Hot Structures Players in Europe

♦ MT Aerospace - CVI C/SiC hot structures fabrication and design
♦ Plansee - High temperature metal (Ti, superalloy, and refractory metals) fabrication
♦ DLR - LSI C/C-SiC hot structures and general hot structures design
♦ Snecma - CVI C/SiC acreage TPS fabrication and design
♦ Dutch Space - metallic TPS and hot structures fabrication and design
♦ EADS/Astrium - complete portfolio of acreage TPS, TPS and hot structures design
♦ IABG - Hot structures testing
♦ ESTEC - ESA’s “field center”
♦ CIRA - Italy’s Aerospace R&D Center, world’s largest PWT
Observations

♦ Strong emphasis on CMC and metallic acreage TPS
  • Europe considers CMC shingle TPS a higher TRL than metallic TPS. In the US, we have the opposite view.
♦ In general, companies have niche technologies and little competition in that area, lots of collaboration
♦ Many of the companies have both the fabrication and design expertise in the same company
♦ They seem to be focused on developing technology for flight experiments
♦ They understand that flight experiments sometimes fail and move on
♦ Europeans are doing a lot of good work. Get papers and follow their progress