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Extended Potentials of UHTCMCs in Space Vehicle Extreme Environment Applications - Large System Intergrator View and Expectations

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EXTENDED POTENTIALS OF UHTCMCS IN SPACE VEHICLE EXTREME ENVIRONMENT APPLICATIONS

- LARGE SYSTEM INTEGRATOR VIEW AND EXPECTATIONS -

Conference on Ultra-High Temperature Ceramics: Materials for Extreme Environment Applications IV

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BACKGROUND

BACKGROUND

Classes of TPS

- There are two major classes of TPS used for re-entry vehicles: ablative and reusable.
- Ablative TPS generally comes often in tile form and is per se designed for single use most commonly. They are commonly used in re-entry missions as they are effective in dual heat pulse reentries and high velocity entries.
- One of the main reasons for the use of ablative systems is, that for certain missions, the capabilities of existing reusable systems are by far exceeded, so there is no other choice (historically).
- Reusable TPS is available in a number of different forms and can be repaired. With the retirement of the NASA Shuttle Orbiter, the use of traditional reusable TPS will be probably soon superseded by advanced reusable TPS to be developed including UHTCs.

BACKGROUND

Re-entry Missions: 50's to Today

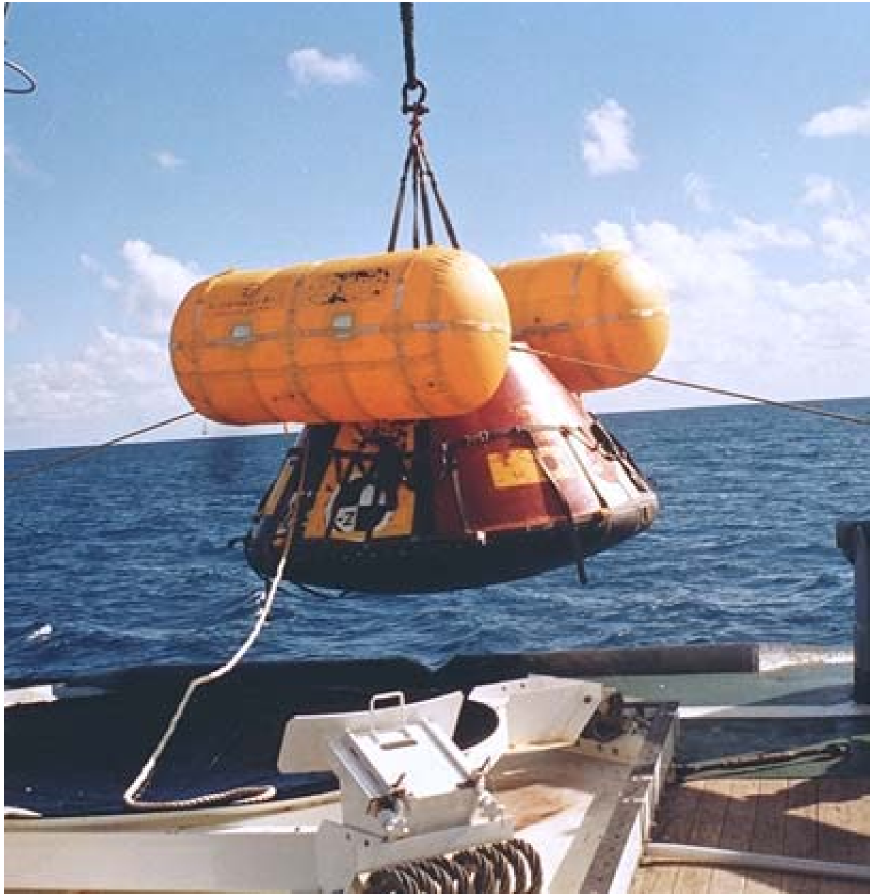
- The X-15 project in 1959 utilized hot-structures which used expensive super-alloys that were rare, and its ability to protect large vehicles like the Shuttle were questioned. Most TPS used insulating technology made of titanium and metallic shingles with insulation installed between the two.
- Lockheed Missiles and Space Company then developed ceramic Reusable Surface Insulation (RSI), which employed the use of ceramic fibers.
- This technological advancement led to the creation of LI-1500 which became Shuttle tiles. They were generally used on the underside of the vehicle and the sides of the fuselage.

BACKGROUND

Re-entry Missions 50's to Today

- For a long time the Space Shuttle Orbiter TPS were the only demonstrated reusable TPS and still showed limitations in its reusability.
- The high temperatures tested the TPS materials to the limits and caused embrittlement, overheating, cracking, flaking and collapsing of edges for the tile TPS. This led to high repair and replacement times, as well as re-waterproofing after each flight.
- The Columbia Space Shuttle was the first to employ RSI tiles as the main form of TPS alongside Felt Reusable Surface Insulation (FRSI) blankets on other components of the shuttle.
- Upgrades led to the decrease of RSI tiles with the replacement of advanced FRSI blankets. This reduced weight, improved the durability of the TPS and reduced fabrication costs, installation costs and installation time.
- The Space Shuttle utilised also reusable CMC components from C/C for the nose cap and the leading edges.

Image Source: http://stratocat.com.ar/fichas-e/1996/TPS-19960714.htm



BACKGROUND

Re-entry Missions 50's to Today

- The heatshield of the Atmospheric re-entry Demonstrator (ARD) comprised of Aleastrasil tiles, an ablative thermal protection material.
- These tiles contained silica fibers randomly orientated within the compound and impregnated with phenolic resin. ARD successfully re-entered the atmosphere with low degradation of the Aleastrasil tiles.
- First experiments of European reusable TPS were flown on ARD (CMC-tiles, Flexible ceramic blankets)
- Experience with ablative TPS systems is large in the U.S./Russia with the Apollo/Soyuz missions and subsequent exploration missions to Mars and Earth return missions like Stardust.

BACKGROUND

Re-entry missions 50's to today

- The Orion MPCV is a joint project between NASA and the ESA, with Orion command module built by Lockheed Martin and the European Space Module (ESM) designed and manufactured by Airbus Defence and Space. The crew module uses a number of TPS materials including FRSI blankets and alumina tile insulation.

- There is increased interest in the further advancement of TPS, particularly in ultra high temperature composites due to their perceived benefit in re-entry vehicles. Not only is there an interest to use this technology in space re-entry vehicles, but also hypersonic aerospace vehicles as well as components for propulsion systems.

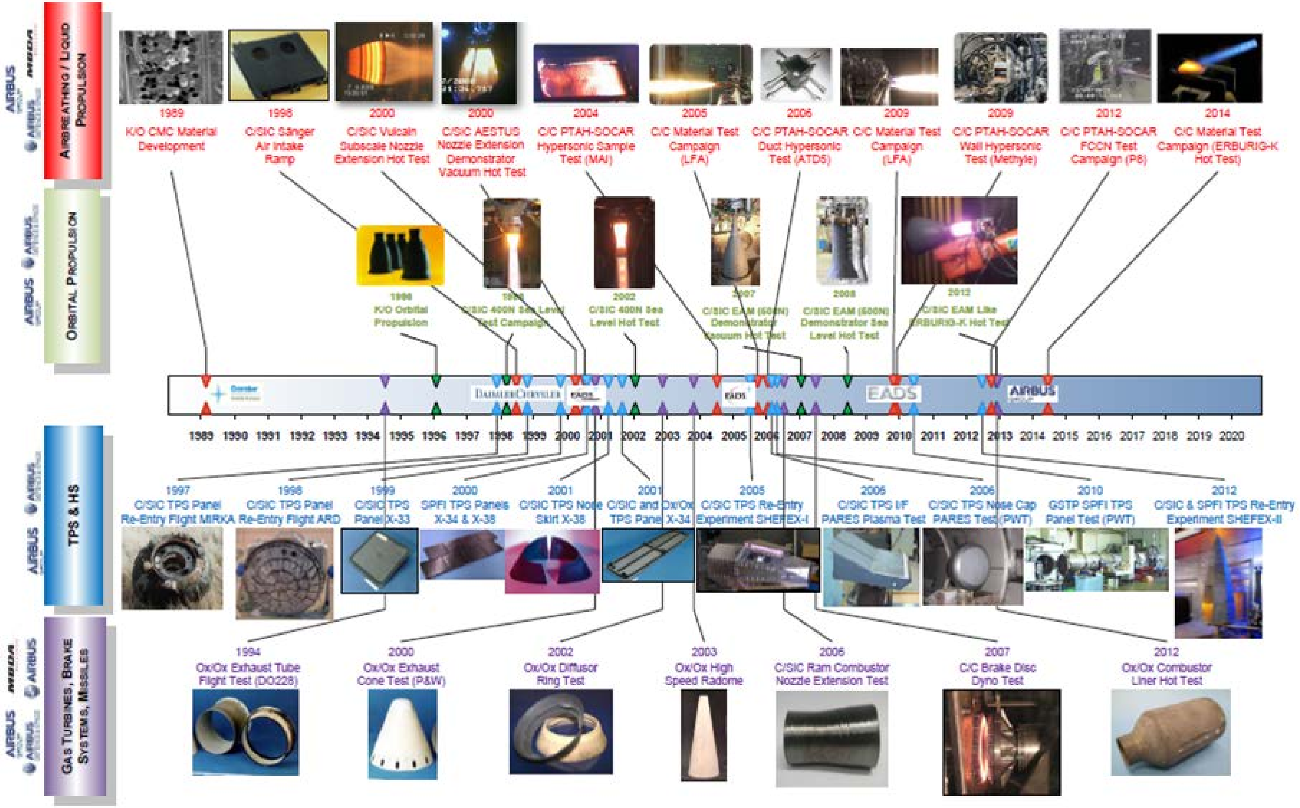
BACKGROUND

Ceramic Matrix Composites (CMCs)

- CMCs during their early development were planned for use for leading edges, acreage, hot structures and in the propulsion system.
- Ceramic composites with SiC reinforcements are preferential due to their numerous benefits; improved mechanical properties, higher thermal shock resistance, improved oxidation resistance, uniform distribution of high aspect ratio reinforcement microstructures, reduced risk of catastrophe failure and improved failure toughness. However, SiC-based CMCs utilizing carbon fibers are limited w.r.t. their upper limit use temperature when reusability is required.
- Next class of material with improved capabilities will be UHTC's.
- Current problem with UHTCs for propulsion application is their lack of resistance to oxidation and tendency to corrode as a result of contact with combustion gases. Diboride or SiC materials can be used together with additives, such as rare earth oxides or LaB_6, to improve their resistance to oxidation in higher temperatures.
- Silicon carbide (SiC) is used to enhance the oxidation resistance of ultra high temperature ceramics (UHTC) and limit diboride grain growth.

BACKGROUND

Timeline of CMCs



BACKGROUND

CMC Missions

Space Shuttle

- For the NASA Space Shuttle, reinforced C/C was used for the leading edges and the nose cap as temperatures can exceed 1260°C. Heating occurs over a longer time and therefore leading edges and nose caps need to be blunt to reduce the excessive heat associated with sharp leading edges during re-entry.

BURAN

- Similar to the Space Shuttle, the BURAN launch vehicle also implemented reinforced C/C in its nose cap and leading edges of the wings.

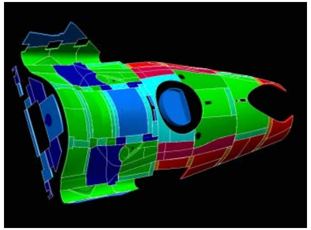
Image Source: NASA 04pd1683.jpg

Image Source: NASA 04pd0538.jpg

Image Source: DLR
http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10664/1151_read-4614/#/gallery/6918

BACKGROUND

CMC Missions



X-38

- The X-38 had body flaps and nose cap made complete out of CMCs including fasteners and bearings. Hybrid control surfaces on the X-38 and X-43 vehicles also used CMCs combined with a lower temperature material such as titanium.

SHEFEX

- The SHEFEX experiments also employed ceramic tiles in each of the three SHEFEX designs (I, II and III). The ceramic tiles are used the same way to protect the outer surface of the vehicle during re-entry.

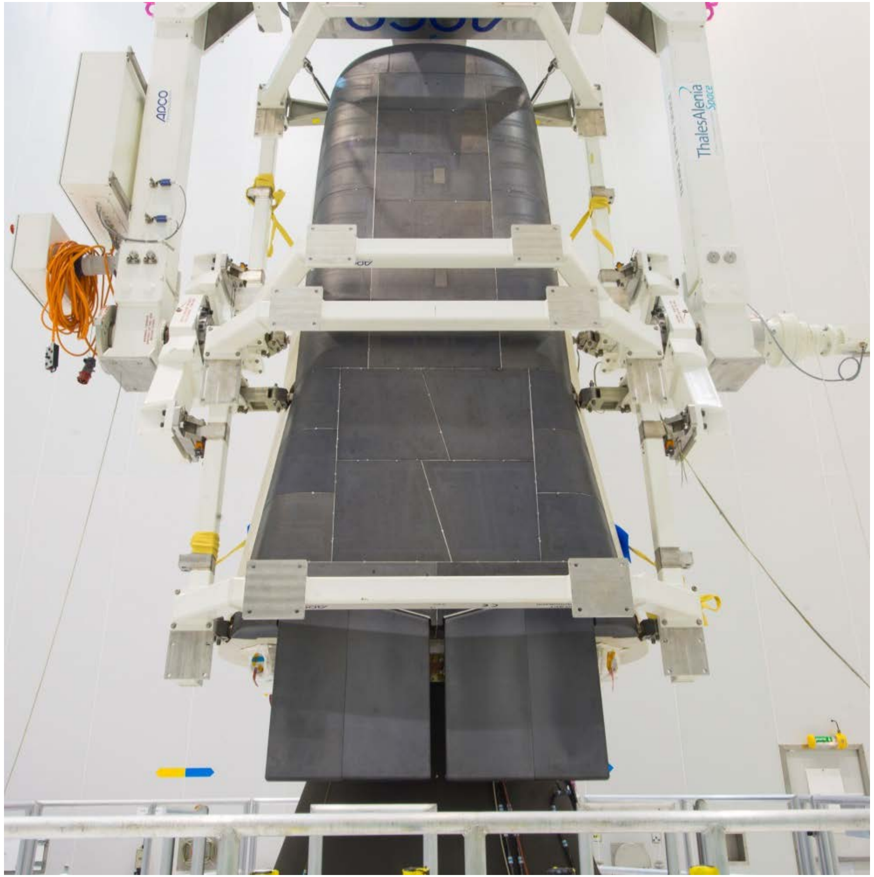
Image Source: ESA
http://www.esa.int/spaceinimages/Images/2015/01/IXV_installation_on_its_payload_adapter2

BACKGROUND

CMC Missions

IXV

- The TPS of the IXV vehicle is probably the most advanced CMC TPS at the moment. Complete windward side including nose and control flaps are made from CMC.
- IXV has successfully flown in Feb 2015 and demonstrated the capabilities of state-of-the-art CMC.



BACKGROUND

The reason for blunt-body shapes

Aerothermodynamics

- Temperatures occurring in the stagnation area of a re-entry vehicle depend on the vehicle shape. The **heat flux** increases with decreasing **nose radius**

$$\dot{q} = \frac{a}{\sqrt{R_n}} \left(\frac{\rho_\infty}{\rho_{sl}}\right)^{0,5} \left(\frac{U_\infty}{U_{co}}\right)^{3,15}$$

- The minimum radius is thus also limited by available materials if reusability is the objective. The Shuttle nose is a good indicator when a large-scale re-entry vehicle is considered

- UHTC(MC) can help a lot in enabling slender vehicles with high L/D!

Image Source: NASA

Shuttle nose

Image Source: DLR

SHEFEX

BACKGROUND

Ultra High-Temperature Ceramics (UHTCs)

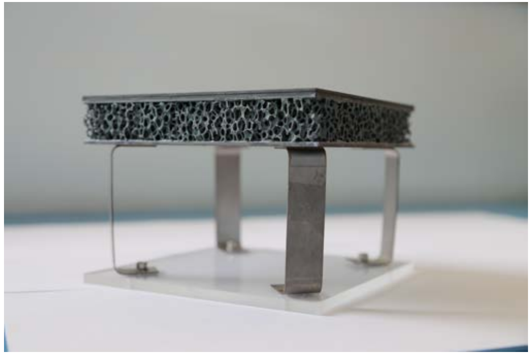
- Monolithic UHTCs have revealed the ability to display 'graceful' fracture behavior and thermal shock tolerance. This new generation of ceramic materials shows the potential to be used other than TPS and potentially in propulsion applications.
- These characteristics are dependent on the matrix material used with ceramic fibers. Zirconium diboride is a common material and some research has been conducted, however research conducted as of today is yet to prove that these UHTCs can be used as aero-propulsion materials for longer than a few minutes.

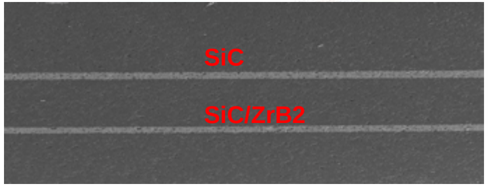
BACKGROUND

Ultra High-Temperature Ceramics (UHTCs)

- UHTC for TPS application has still a size problem, inadmissible high stresses and some other problems caused by its monolithic structure.

- To overcome some of these problems a concept called SMARTEES studied in the frame of an EU FP7 project has been introduced. The concept is based on numerous very thin “UHTC” laminated together. This concept has been successfully demonstrated on relatively small scale and reached a maturity of TRL4.





BACKGROUND

Ultra High-Temperature Ceramic Matrix Composites (UHTCMCs)

- UHTCMCs are proposed to overcome the problem of thermal stress concentration in monolithic UHTCs
- UHTCMCs are proposed to be suitable for the future of civilian hypersonic flight in the use of nose tips, leading edges and air intake systems and other high loaded regions. These applications can also be utilized in re-entry vehicles as the material would be able to withstand the high temperature and high velocity environment of both hypersonic and re-entry vehicles.
- The use of UHTCMCs as propulsion components is also being investigated including high and low pressure turbine vanes and blades, combustion chamber liners and turbine vanes.

02

MAJOR REQUIREMENTS

MAJOR REQUIREMENTS

Re-entry and hypersonic aerospace systems

Technical requirements

- Near-zero ablation
- High dimensional stability
- High thermal shock resistance
- High maximum temperature without material properties degradation
- Tailorable thermal properties for different applications
- High structural performance and resistance to damage with self-healing ability
- Reusability

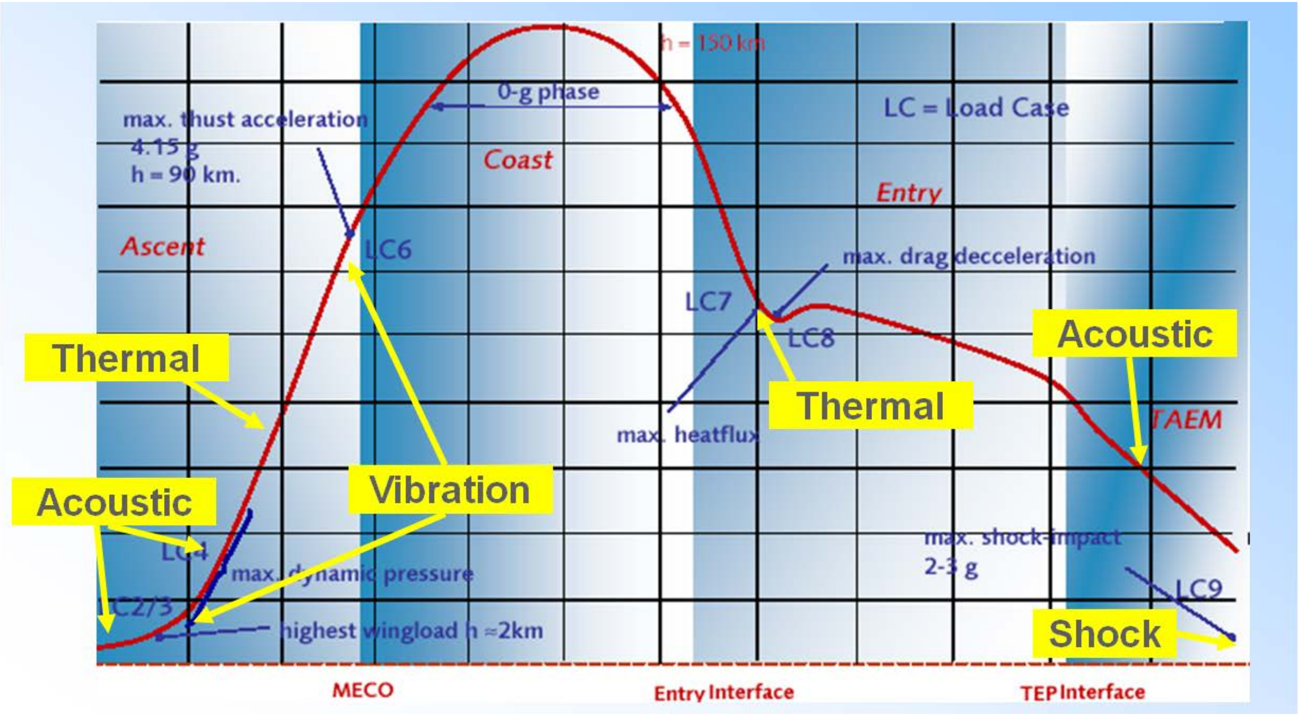
Economic requirements

- Comparable or lower cost than for existing solutions (aim)

  - can be achieved via reusability

MAJOR REQUIREMENTS

Example Trajectory with Load Environments



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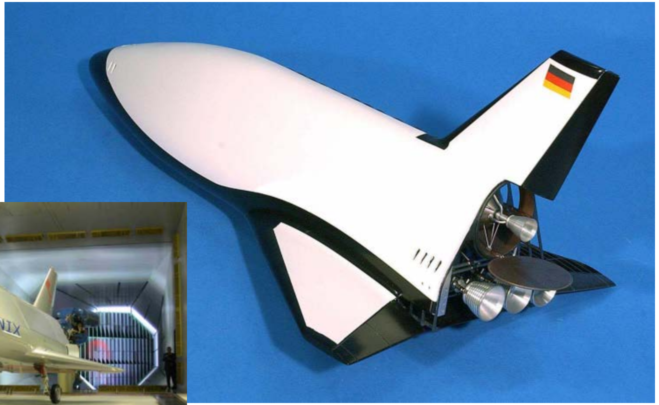
MISSIONS AND CAPABILITIES

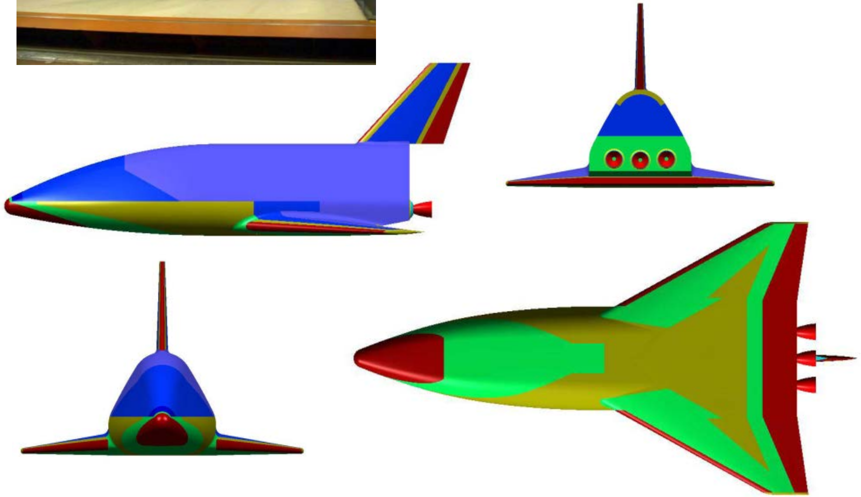
MISSIONS AND CAPABILITIES

Past Missions with UHTCMC Potential

HOPPER RLV

- The German TETRA program included the design of a unmanned, autonomous reusable launch vehicle (RLV), HOPPER and its scale prototype model, Phoenix. Unfortunately the project was cancelled due to high cost / political reasons.
- Various ceramic and metal based TPS/hot structures were proposed for this vehicle. Among them were alumina-fiber reinforced and C/SiC CMC's. The CMC was favored due to its high mass saving potential which would have improved the vehicles center of gravity, resulting in improved maneuverability.
- A revival of this project could potentially utilize the use of UHTCMCs.





MISSIONS AND CAPABILITIES
Hot Structures

Leading Edges and Scramjet Cowls

- Heat flux increases when leading edge radius decreases. Hypersonic vehicles that require a lower radius will create high heat fluxes, which will be a problem with some of the current TPS materials.
- CMCs have somewhat inadequate creep resistance and poor oxidation resistance so are limited in their maximum use temperature to below ~1700°C.
- UHTCMCs have been highlighted as potential solutions due to a melting point exceeding 3200°C and their resistance to ablation. The additional of self-healing additives will address the issue of oxidation and corrosion stability.

Image Source: https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-040-DFRC.html

04

STATE OF THE ART

STATE OF THE ART

European Developments

C3HARME

- The purpose of C3HARME is the design, development, manufacturing and testing of a new class of UHTCMCs with self-healing ability based on C or SiC fiber preforms combined with UHTC suitable for application in extreme aerospace environments.
- The goal is to introduce advancement of existing ceramic materials in terms of increased capability to withstand severe environments while still achieving efficiency, reliability, cost-effectiveness and scalability.

STATE OF THE ART

Other Developments

Skylon (UK)

- Currently in development, is the UK spaceplane Skylon, developed by Reaction Engines Limited (REL) which has a targeted speed of Mach 5 as an air-breathing vehicle and Mach 25 as a rocket.
- The fuselage aero shell is planned to be made of fibre reinforced ceramic, corrugated for stiffness and is the outer layer of two layers of skin.

Image Source: From HOTOL to SKYLON, Roger Longstaff
18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference

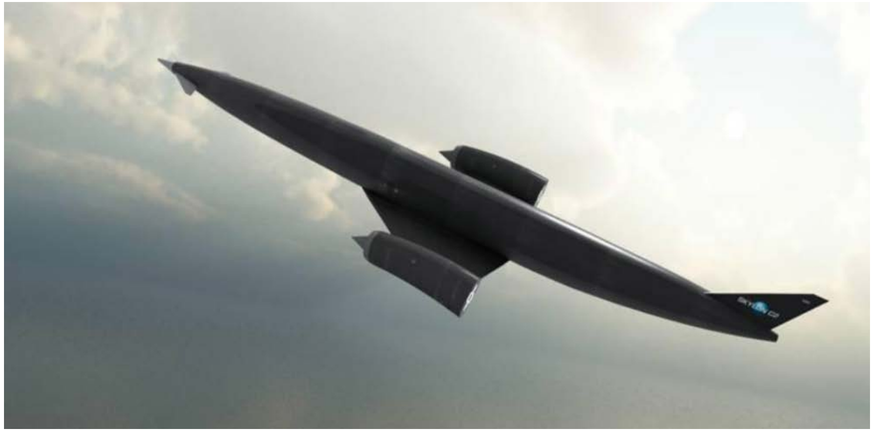
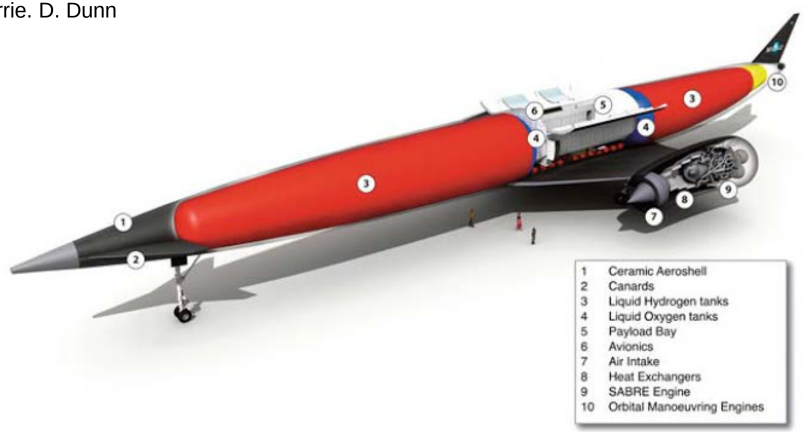


Image Source: Materials and Processes for Spacecraft and High Reliability Applications, Barrie. D. Dunn



STATE OF THE ART

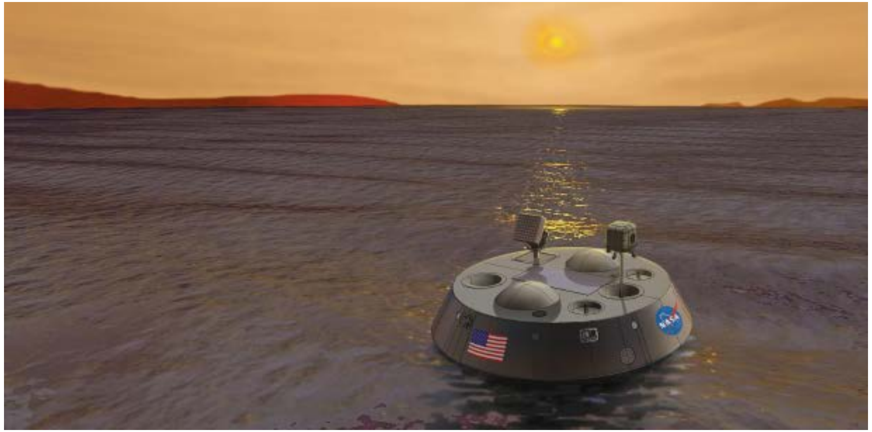
Other Developments

US

- NASA Ames Research Centre has been developing a lightweight TPS, Toughened uni-piece Fibrous Reinforced Oxidation-resistant Composite (TUFROC), as part of X-37 wing leading edge research and development.
- This thermal protection material is suitable for atmospheric re-entry for leading edge and nose cap applications.
- It has been proposed for use on the Dream Chaser Spacecraft being developed by the Sierra Nevada Corporation as well as the Titan Explorer orbiter aero-shell.

Image Source: NASA Armstrong
https://www.nasa.gov/centers/armstrong/features/dreamchaser_arrives_at_armstrong.html

Image Source: https://www.spaceanswers.com/futuretech/nasas-titan-space-boat/



STATE OF THE ART

Other Developments

US

- The X-51A wave rider built by Boeing for the US Airforce is an unmanned research scramjet aircraft for hypersonic flight at Mach 5.
- It utilizes C/C composites on the leadings edges of the fins and cowls.
- The thermal protection consists of BRI-16 tiles, Boeing Rigid Insulation (BRI), which are ceramic fiber insulation impregnated with an infrared retardant coating.

Image Source: https://storiesbywilliams.com/tag/x-51a-waverider//

Image Source: https://www.turbosquid.com/3d-models/x-51-waverider-3d-obj/918264

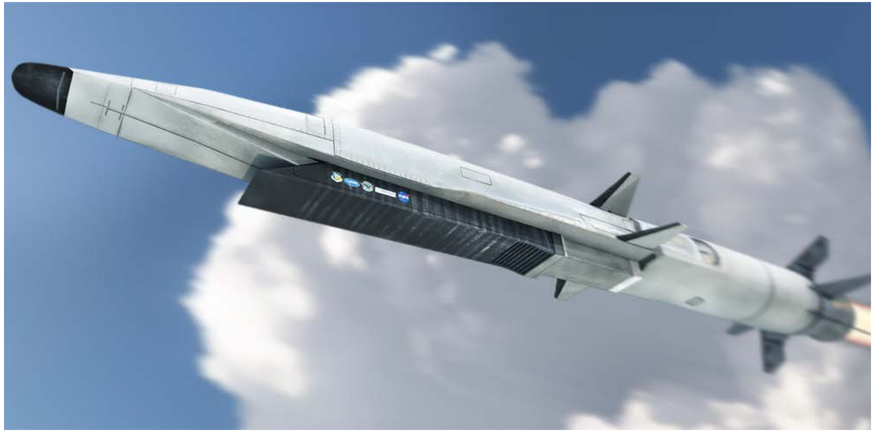


Image Source: http://www.spaceflightinsider.com/organizations/china-national-space-administration/china-debut-powerful-next-generation-long-march-5-launcher-thursday/

STATE OF THE ART

Other Developments

China

- Much of research for the Chinese space program are conducted by universities in under the financial support from government initiatives.
- Research into UHTCs have not been found (in open literature) to be linked to any project in particular but many universities have conducted research into $ZrSi_2$ based ceramic composites.
- Hypersonic technology, such as the WU-14/DF-ZF, appears to be more focused on defence applications and as a result there is a lack of information available in the public domain. However, it has been reported that this vehicle has capabilities for up to Mach 9.

STATE OF THE ART

Other Developments

Russia

- Russia reportedly is in development on ‘Project 4202’, a secret missile program which includes the Yu-71 and Yu-74 gliders.
- In the public domain no information about any glider is available including the current status on successful flights.

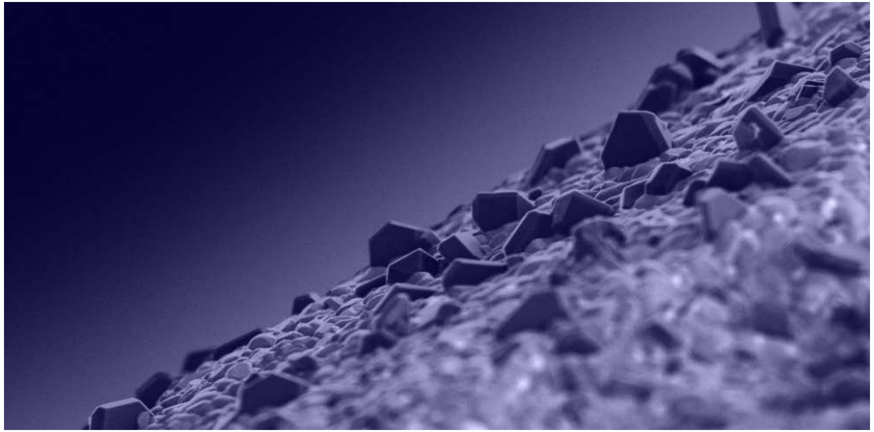
05
FUTURE DEVELOPMENTS

FURTHER DEVELOPMENTS

C3HARME

- C3HARME hope that the development of the UHTCMC would be used in two outlined applications:
  - Near-zero erosion nozzle inserts that aim to maintain stability during the firing of combustion chambers in high performance rockets.
  - Near-zero ablation TPS tiles that aim to resist the high heat fluxes during launch and re-entry into Earth's atmosphere due to in reactive gases and thermos-mechanical stresses.

Image Source: https://c3harme.eu/

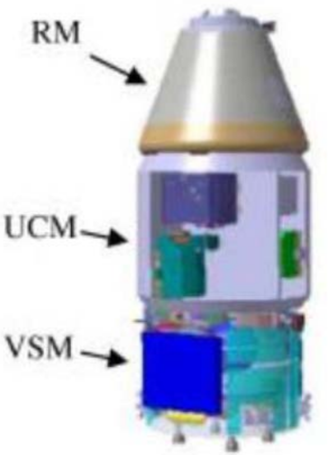


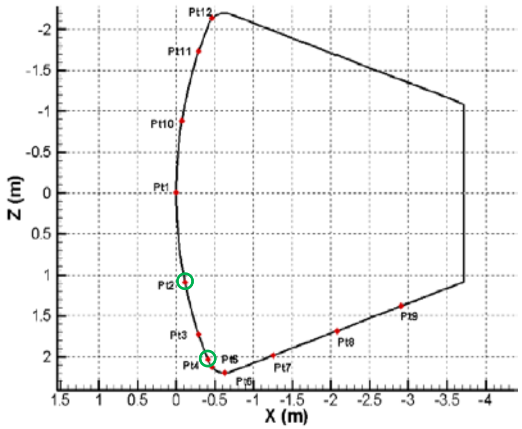
EXPECTATIONS CONCERNING FUTURE DEVELOPMENTS

Summary of C3HARME specification

Material specifications

- Primarily based on ARV re-entry conditions for the front shield
- Points 2 & 4 are critical for pressure, heat flux/load





Req. Id	Specification	Remarks
C³HARME-MAT-01	• Maximum temperature o 2300 °C	Based on $\varepsilon = 0.8$ and $\dot{q} = 1988\ kW/m^2$
C³HARME-MAT-02	• Density o <5 g/cm³	-
C³HARME-MAT-03	• Residual porosity o < 10 %	-
C³HARME-MAT-04	• Critical thermal shock ΔT_C o ≥ 1500 ⁰C	-
C³HARME-MAT-05	• Fracture toughness o > 10 MPa/√m	-
C³HARME-MAT-06	• Thermal conductivity* o ⊥ 30-100W/(m·K) o ‖ 40-150W/(m·K)	⊥- direction perpendicular to fibres ‖ - direction parallel to fibres Those requirements are also related to satisfying ΔT_C
C³HARME-MAT-07	• Specific heat capacity o Any that would satisfy the Thermal Requirements (diffusivity)	
C³HARME-MAT-08	• CTE o ⊥ $<7 \cdot 10^{-6}$/°C o ‖ <2·10 /°C	
C³HARME-MAT-09	• Modulus o 50-100 GPa	
C³HARME-MAT-10	• $\varepsilon_{crit} > 0.2$ %	
C³HARME-MAT-11	• Flexural strength o >200 MPa	
C³HARME-MAT-12	• Interlaminar shear strength o 10-50 MPa	-
C³HARME-MAT-13	• Maximum recession rate o $5 \cdot 10^{-2}$ mm/s	At peak stagnation pressure and heat flux
C³HARME-MAT-14	• Self-healing ability	-

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FURTHER DEVELOPMENTS

TRL 6 and Beyond

Exploitable Results

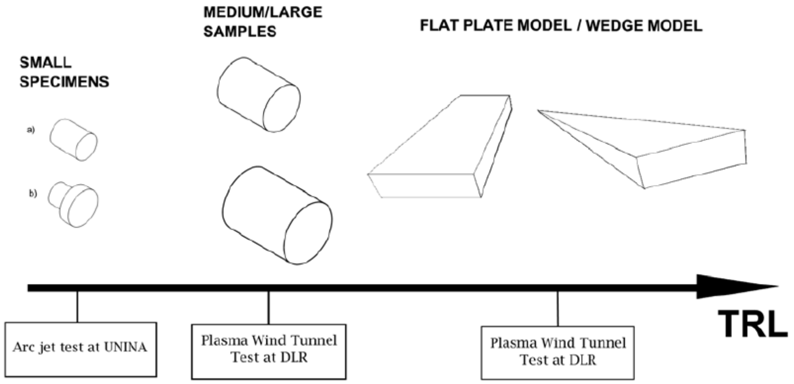
- The C3HARME project has highlighted a number of exploitable results for the use of UHTCMCs beyond the previously mentioned applications.
- The development would allow for:
  - Advancement of the understanding of high temperature behavior and chemical properties of a material;
  - Developments in the manufacturing of UHTCMC manufacturing through sintering and non-sintering technologies;
  - Design and assembly of UHTCMC components in structural and propulsion systems and their application in extreme operating space environments.

FURTHER DEVELOPMENTS

Image Source: C3HARME – Deliverable 1.4: Design of prototypes & Test conditions for applications 1, 2

Testing

- Testing will be completed on both proposed applications of the C3HARME project with the aim of testing in increments with the creation of a small specimens, medium/large samples and then a model similar to the final target application. TRL will progress throughout the testing campaign.
- The project begins at TRL 3-4 and will aim for the achievement of TRL5-6 (prototype demonstration in operational environment).



FURTHER DEVELOPMENTS

Testing – Application 1: Nozzles

- The nozzle material will be tested a number of times by different institutes. The first set of tests will be performed at UNINA and start at free jet tests progressing to complete nozzle tests.
- Solid rocket tests will be performed at AVIO where the chemical composition and heat fluxes of the test specimens will be analysed.
- Vertical Free Jet (VMK) tests will be performed at DLR where subscale nozzles will be tested with solid propellants at high pressures.

FURTHER DEVELOPMENTS

Testing – Application 2: TPS

- The near-zero ablation TPS will also be tested in the method of increments starting with a small specimen and progressing to model tiles.
- The preliminary tests will be performed by UNINA with the small specimens to identify the most promising materials and compositions. This final goal of this step is TRL4.
- The medium/large sized specimens and tiles will be tested by DLR using plasma wind tunnel testing. The larger samples will determine and investigate 2D effects while the flat plate or wedge tiles will aim to reach TRL6.
- The final geometry will be defined and optimized during the course of the project.

FURTHER DEVELOPMENTS

Flight Experiments

- Beyond TRL 5-6 for C3HARME flight experience could be acquired by operational & actual environment testing using vehicles similar to:

  - SHEFEX (Sharp Edge Flight Experiment): vehicle unintended for actual operation and proposed as an experiment by DLR to investigate using sharp corners and edges for re-entry into Earth’s atmosphere for the benefit of cheaper (simpler), safer and flexible solution to external TPS.

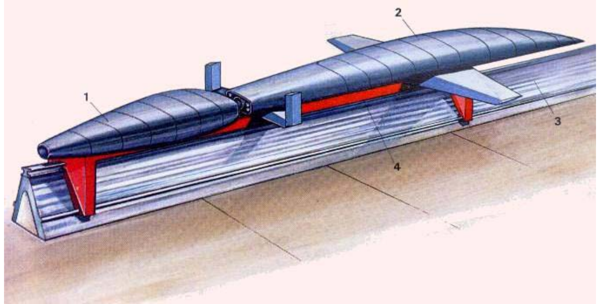
  - IXV (Intermediate eXperimental Vehicle): also proposed as an experiment, an ESA project for suborbital re-entry vehicle to investigate technologies and critical systems for autonomous controlled re-entry from Low Earth Orbit (LEO). The first ever lifting body to perform full atmospheric re-entry from orbital speed.

- Successful completion of TRL6 of C3HARME will allow for the advancement to TRL7 (operation in space environment) through potential testing of vehicles in LEO.

06
CONCLUSION

CONCLUSION

- **Promising new technology**
- **Potential to extend load range of reusable TPS**
- **Potential to allow specific TPS design and enhanced missions**
- **Early Development**
- **C3HARME Session VI Tuesday afternoon**



QUESTIONS ?