HiSST: 2nd International Conference on High-Speed Vehicle Science Technology

11–15 September 2022, Bruges, Belgium

Design and Testing of Reusable CMC Thermal Protection System for Space Rider

M. De Stefano Fumo[1], G. Rufolo[2], R. Gardi[3], R. Fauci[4], A. De Fenza[5], F.M. Pisano[6], G.M. Infante[7], L. Cavalli[8], M.Valle[9]

Abstract

Space Rider is the new challenge of the European Space Agency to have a re-usable fully autonomous on-orbit and re-entry vehicle. Differently from its precursor IXV, the Ceramic Thermal Protection Systems, including also the control surfaces will be provided by the Italian Aerospace Research Centre in partnership with Petroceramics.

The present paper summarizes the status of the new design, the results of manufacturing demonstration and testing activities already executed, on-going and to be performed for the sub-system qualification.

Keywords: *Re-entry, re-usability, TPS, CMC, Testing, Space Rider, VEGA-C, ISiComp®*

Nomenclature

Latin

CMC	computational fluid dynamics	RML	Relative Mass Loss
ESA	European Space Agency	SR	Space Rider
IXV	Intermmediate eXperimental Vehicle	TPS	Thermal Protection System

1. Introduction

Space Rider is an unmanned space robotic laboratory. After launch it will stay in orbit for about two months and then it will return to Earth with its payloads and land on ground. It can be recovered, reconfigured and reused for up to six missions. Such kind of spacecraft, designed to safely came back to Earth, are characterized by Thermal Protection System (TPS) necessary to protect the vehicle from the typical harsh environment encountered during atmospheric re-entry phase, keeping unchanged the vehicle outer mold line. Further, when precise landing is required, hot control surfaces allowing maneuvers are mandatory.

CIRA and Petroceramics are presently in charge of design, manufacturing and qualification of the CMC TPS and Body Flaps Assembly of Space Rider, thanks to the development of a proprietary C/SiC, named

---

[1] *CIRA, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua - Italy, m.destefano@cira.it*
[2] *CIRA, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua - Italy, g.rufolo@cira.it*
[3] *CIRA, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua - Italy, r.gardi@cira.it*
[4] *CIRA, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua - Italy, r.fauci@cira.it*
[5] *CIRA, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua - Italy, a.defenza@cira.it*
[6] *CIRA, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua - Italy, f.pisano@cira.it*
[7] *CIRA, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua - Italy, g.infante@cira.it*
[8] *Petroceramics S.p.a., Viale Europa 2, 24040, Stezzano - Italy, cavalli@petroceramics.com*
[9] *Petroceramics S.p.a., Viale Europa 2, 24040, Stezzano - Italy, valle@petroceramics.com*

ISiComp®, based on LSI process with shorter manufacturing times and using low cost raw materials, leading to a very cost-efficient CMC.

Building on lessons learnt from the successful IXV [1] re-entry demonstration, Space Rider TPS and Hot Structure design has been focused on reducing manufacturing complexity while improving easiness of integration that in turns allows for faster post flight inspection and refurbishment. In parallel with design activities, a fast-paced testing program is being carried out to demonstrate on one side the manufacturing feasibility of the large ceramic components and on the other side the capability to withstand the mission environment from launch to atmospheric re-entry, passing through LEO operations, ensuring full reusability up to six times. Highlights on qualification plan will be shown targeting the completion of the flight hardware manufacturing by Q2 2023.

2. Space Rider Mission Outline

Space Rider aims to provide Europe with an affordable, independent, reusable end-to-end integrated space transportation system for routine access and return from low orbit [2].

It will be launched by Vega-C from Europe's Spaceport in Kourou and it will remain in Low Earth Orbit for about two months during which a wide spectrum of microgravity and IOD/IOV experiments will be performed. At the end of orbital phase mission, it will be de-orbited by means of updated VEGA AVUM acting as service module also during the orbital phase, it will perform a re-entry controlled through the combined use of both RCS and aerodynamic control surfaces and it will land on open fields by means of controlled parafoil descent phase.

Fig 1. USV3 DWS "capsule based" concept configurations comparison vs selected criteria

Space Rider is designed to operate at different orbital inclinations, from equatorial to high-latitude. To maximize competitiveness and minimize the recurring cost of each mission, Space Rider is conceived to maximize reusability, has a limited size while maximizing payload capability, and requires minimal refurbishment allowing expensive components of the mission to be reused.

3. TPS & BFA Architecture

3.1. Nose

The Nose, with its 1320x941x414mm3 is the largest monolithic ISiComp® component of the whole SR TPS. The whole Nose assembly is composed by the CMC part, the insulating materials and by the interface elements with the cold structure.

A complex attachment system has been designed to provide the required rigidity, allow thermal expansion of the CMC Nose, and thermal decoupling between the CMC to the cold structure.

The nose is provided with 16 omega shaped attachment points. The omega attachments are co-cured on the "doubler", a belt that provides additional stiffness to the rim of the Nose.

Each of the ISiComp® Omega is connected to one Inconel standoff by means of an Inconel screw. Zirconia insulator separates the CMC from the screws and from the standoffs. Sigraflex washers, placed between CMC and zirconia, cope with the rough surface of the composite. Since the Inconel screw, at high temperature, will expand more than the ceramic clamped parts, disk springs will maintain enough preload also during the re-entry. The standoffs are bolted to the "Nose Ring" that is then mated to the CS with 14 Brackets.

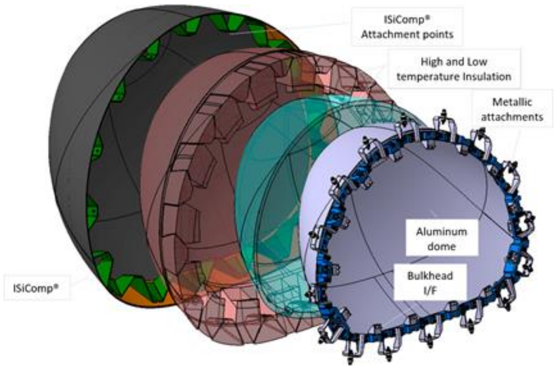

Fig 2. Nose assembly exploded view

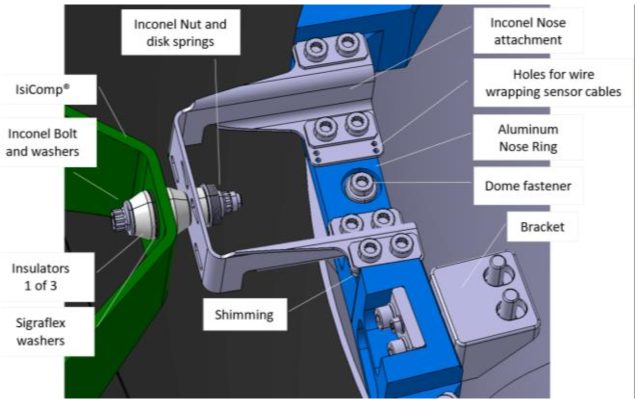

Fig 3. Nose assembly I/F

3.2. Windward

The windward ISiComp® TPS is composed by 5 flat shingles, 16 curved shingles and the two complex and large Hinge TPS elements.

Each shingle is a monolithic piece of ISiComp® and is connected to the cold structure by means of an attachment system designed to provide rigidity, flexibility and thermal barrier as it is for the Nose I/Fs.

Each shingle is composed by a skin, reinforced by Omega shaped ribs and 'T' shaped ribs. The Omega shaped ribs also provide the interface to the attachments. The 'T' shaped ribs lay on geodesic curves that connect the attachment points.

The shape of the Omega is optimized to provide a rigid attachment point and to distribute the loads on the skin.

The volume between the Shingle and the cold structure is filled with insulating materials to stop the radiative and convective heat transfer from the hot CMC skin and the CS, while containing the conductive heat transfer in order to meet the CS temperature requirements. Three additional layers of insulating materials form an almost continuous mat on the cold structure. Junctions in the mats are designed for creating a tortuous path from the junction between the shingles and the CS, interrupting any possible sneak flow.

The attachments connect the CMC shingle to the cold structure and are designed to be stiff in the axial direction, so that they can sustain the pressure load on the shingle, and flexible in plane, with two different rigidities along two orthogonal directions. The two different stiffnesses permit to align the more flexible side in the direction of the expected thermal expansion of the shingle, staying more rigid in the orthogonal direction.

The attachments are connected to the CMC by means of an Inconel screws and a self-locking nut. The design permits to install the shingle from the outside, not requiring access to the nut. Zirconia and Sigraflex washers insulate the CMC from the metal. Disk spring maintain preload at high temperature as in the Nose I/F Design.

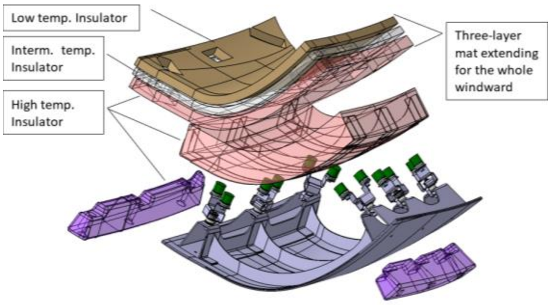

Fig 4. Windward shingle Insulation design

SR TPS must allow the deployment of the landing gears. Then three sets of TPS shingles must allow landing gear doors opening. The insulating material must be cut around the landing door and this makes more critical the creation of a labyrinth in the insulating material to stop the sneak flows. The following image shows the specific design needed for the Nose landing gear seals.

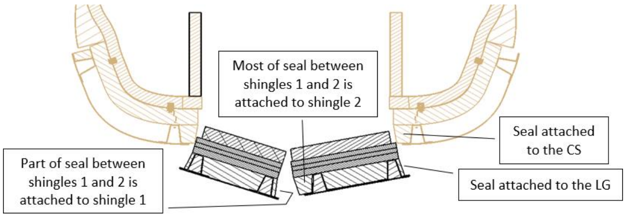

Fig 5. Nose landing gear seals

3.3. Windward

The hinge TPS are the two aft most shingles and, because size and complexity, needed some specific design solutions.

The complex geometry, the excessive curvature and the convex to concave shape of the skin makes impossible to utilize the same Omega legs used for the shingle.

The hinge does mate with a part of the cold structure with a shape particularly complex. This makes the geometry of the insulators more complex and only a small region of the Hinge TPS is covered by the three layers of insulating materials that extend for the whole windward. Moreover, the Hinge TPS is trespassed by the flap supports, and additional seals must be provided for them. The complexity of the cold structure also provides strong limitations to the areas suitable for the attachment's collocations. This last issue made particularly complicated to find a solution able to match the eigen frequencies requirements with the temperature requirement. This forced to design specific attachment, based on the same concept of the other shingles attachments, but substantially different.

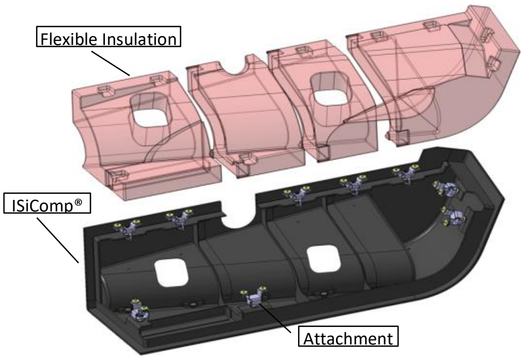

Fig 6. Hinge TPS with attachments and part of the insulation

Hinge TPS is also particularly complex because of its three additional interfaces with the Body Flap: 1) Flap supports pass through the Hinge TPS skin. Allowance is needed for preventing interference due to TPS thermal distortion or supports deflection under aerodynamics loads. 2) The EMA-TPS seals the EMA rod passage through the rear bulkhead and is connected to the Hinge TPS. A rigid sleeve is designed to slide free on the EMA rod, and a bellow made of Nextel and insulating materials, connects the bellow to the aperture, that is designed to accommodate the EMA rod displacements. 3) The Hinge TPS Skin is in contact with the Body Flap CMC body through the Dynamic Seal. It is fixed on the Hinge TPS and slips on the Body Flap Surface while it rotates. The seal must prevent plasma and hot air passing through the gap between the flap and the Hinge TPS Skin and, at the same time, must permit a smooth motion of the flap, generating not excessive friction.

3.4. Body Flap Assembly (BFA)

SR BFA is composed by two monolithic ISiComp® flaps hinged to the vehicle on two secant hinge axes.

Flap design is more critical than the rest of the TPS because, beside the thermal and structural requirements, the BFA has to perform as control surface, embedding movable parts, able to operate at high temperature under aerodynamic load.

Each flap is connected to the vehicle structure by means of two ALM Titanium-alloy supports that, with two commercial, high temperature, spherical plain bearings, create the hinge line. The motion is transferred from the EMA, located internally in the vehicle, to the flap, by means of a Ti-alloy EMA Rod, provided, as well, with high temperature spherical joint. The two EMA-Rods pass through the transom structure and TPS and a specific EMA-TPS system is designed in order to prevent hot air flow, while providing the needed mobility for the actuation.

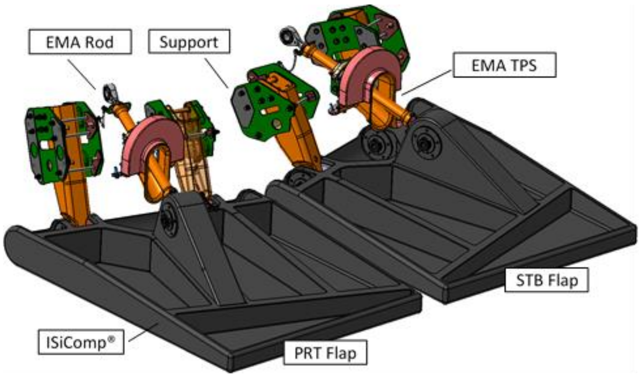

Fig 7. BFA with supports EMA Rods and EMA TPS

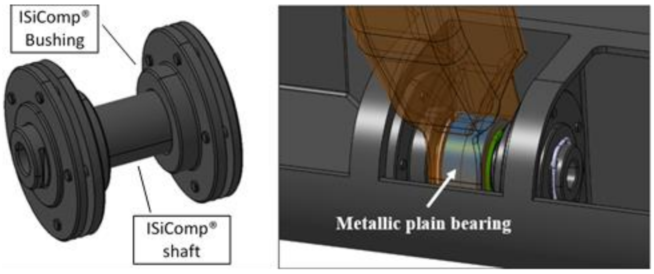

Fig 8. Detail of one Support with metallic plain bearing and CMC Hinge

The plain bearings are specifically manufactured on CIRA specification in order to provide the needed preload between ball and race, for preventing rattling. Each ball is then mated to a ISiComp® shaft that is then coupled with two ISiComp® Bushings. The bushing are "in situ" joined to the Body Flap CMC main structure, in order to provide a solid and reliable structure. All the parts are machined with high precision, to prevent rattling in the vibrating launch environment.

Additional flexible insulating material prevent the radiative heating from the Flap structure to the metallic support. This design allows the metallic components to operate within temperature requirements.

4. Manufacturing & Development Test

4.1. Manufacturing Demonstrators

In order to demonstrate the capability to manufacture large and complex CMC shapes a series of manufacturing demonstrator were realized. Full scale Body Flap, Nose, Hinge Port and the large flat shingle have been completed following all the process route.

Two engineering models were realized for Body Flap. One of them was used for dynamic and static development test campaigns experiencing the same loads foreseen for qualification. All tests were successful. Fig 9 shows the very complex geometry with stiffener and EMA support in a CMC single piece (about 700 mm x 900 mm x 300 mm).

Fig 9. CMC BFA Engineering Model

The second manufacturing Item was the EM of the Shingle 7. Fig 10 shows the omega stiffener based architecture. The shingle is long about 1 m and large about 40 cm.

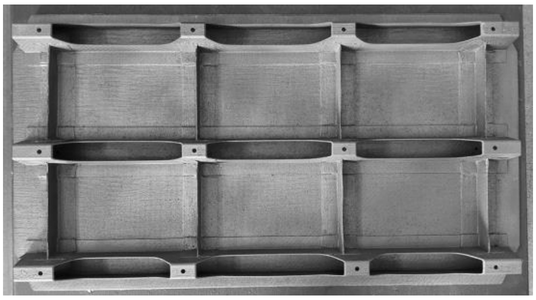

Fig 10. CMC Shingle #7 Engineering Model

Here below is reported the EM of the Hinge TPS where the leg attachment type is clearly visible with respect to other components making use of omega attachments. Main sizes are (about 300 mm x 965 mm x 300 mm).

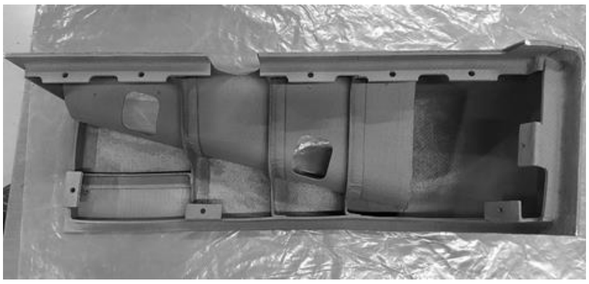

Fig 11. CMC Hinge Port Engineering Model

The CMC nose cap is the largest component. The picture below shows the inner view highlighting the 16 peripheral omega attachments.

Fig 12. CMC Nose Engineering Model

4.2. BFA Development Test

A wide range of different test campaigns has been planned to be performed during the Space Rider BFA development program in agreement with the BFA Design, Development, Verification/Qualification Plan. Some of the most significant experimental tests already performed are summarized here after:

ATOX Testing

The atomic oxygen testing has been performed in the LEOX facility of ESA ESTEC [5]. Assuming the whole duration of a full set of 6 missions, each one 2 month long, the Space Rider Re-entry Module shall be designed so as to withstand exposure of ram-oriented external surfaces materials, as is the case of the C/SiC Body Flap, to a fluence of 1.0·1022 (AO)/cm2, without degrading their performances.

Surface analysis in term of SEM, microscope inspections and thermo-optical properties before and after tests do not shown any relevant degradations or significant change.

Some consumption of residual carbon on the surface of an uncoated sample was observed. Three points bending tests performed on two samples for each type and no significant mechanical changes are observed.

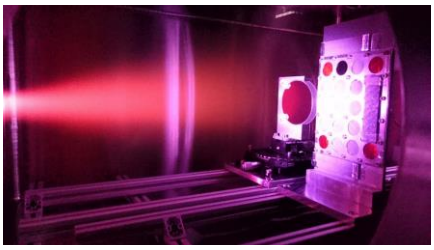

Fig 13. LEOX facility for ATOX Test

Mass loss analysis shows very low value up to about 1.5 x1021 AO/cm2 for coated and oxidized samples with an increase for higher values. Considering the worst-case scenario for coated or oxidized samples a very conservative reduction of about 7 microns for flight is obtained. This value is well within the coating thickness of ISiComp® (about 50 µm) also when considering a full set of 6 missions.

Catalysis

The first goal of this test campaign was to evaluate catalytic behavior of the ISiComp® material. In order to develop a theoretical model of the catalytic behavior, after test activities performed in PWT, a numerical rebuilding has been carried out, by means of CFD, in order to determine the atoms recombination rates at the surface.

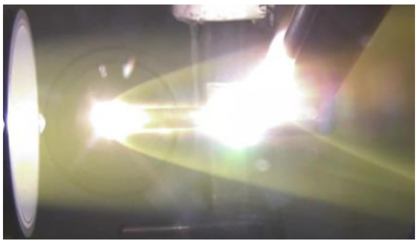

Fig 14. SCIROCCO Flat faced specimen configuration

The analysis of the experimental data and the re-building of the tests showed a heat flux less than 55% of the fully catalytic assumption, that is a value conservative with respect to trajectory design at system level where only a 70% of fully catalytic value was assumed [6].

Oxidation

A test campaign has been performed at CIRA-SCIROCCO Plasma Wind Tunnel aimed to evaluate performances of ISiComp® material used for Space Rider Body Flaps. In detail oxidation behavior has bene checked. The achieved condition corresponds to the maximum temperature foreseen in flight but with a lower pressure of about 3000 Pa versus about 5000 Pa. From passive to active oxidation point of view this is conservative and therefore the verification that no active oxidation occurs on this condition guarantee that no active oxidation is foreseen during flight. Fig 14 shows the SEM and EDX map where the SiC coating (red) and thin Silica layer (green) are highlighted.

Re-usability

Two test campaigns were performed at two different temperature levels and time of 1250°C for 4200 s and 1450°C for 5100s (6 cycles), to qualify the ISiComp® for the reusability under conditions representative of 6 atmospheric re-entry flights as for Space Rider requirement. Validation has been accomplished through SEM analysis and residual strength measurement of material samples after testing in Plasma Wind Tunnel for 6 cycles simulating the 6 re-entry (Fig 15). No mass loss was detected, SEM analysis shows good behavior of coating and excludes fibers oxidation and residual strength in line with virgin sample values.

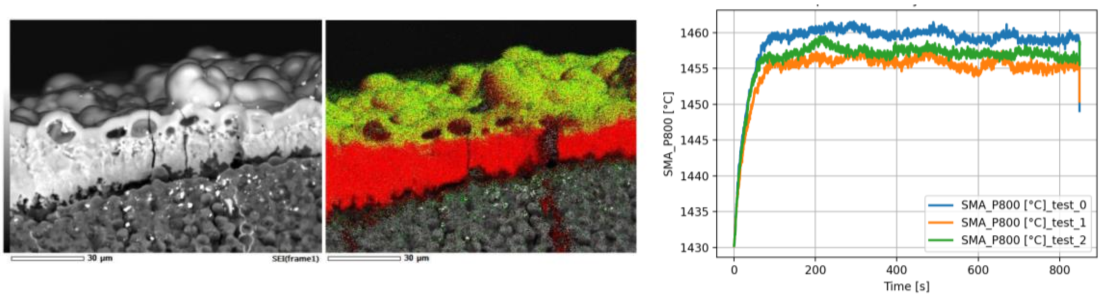

Fig 15. EDX maps of the coating of the top of the disk and Three of the six temperature profile on test specimen during the second reusability test campaign.

BFA Attachment Bearing Breadboards Loaded Tests

The purpose of these tests has been to verify the capabilities of the designed mechanical connections between the CMC flap and the metallic structure to operate properly under thermal and mechanical loads. The experimental set-up (see Fig 16) included an ad-hoc designed furnace to heat the breadboard (representative of the actuator/flap hinge) meanwhile the mechanical load is applied. A maximum load of 18 kN and 540°C temperature have been applied. Six cyclic loads, as for SR reusability plan, were successfully performed.

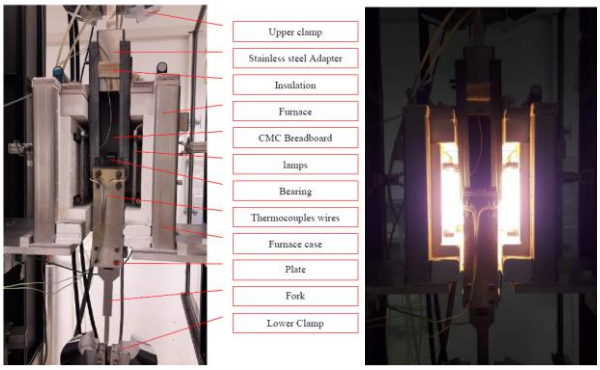

Fig 16. Left: test set up details; Right: breadboard under test

BFA Development Dynamic Tests

The goals of these tests have been to evaluate the capability of control surfaces to withstand dynamic loads (sine vibration, random vibration) at launch and to validate numerical dynamic structural models.

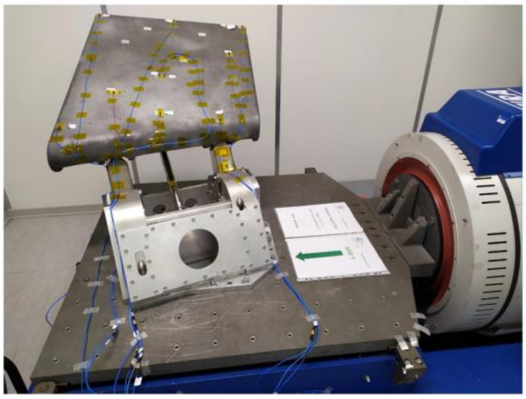

Fig 17. BFA dynamic test - IP-Y axis configuration

A full scale BFA assembly model (both CMC and metallic parts) has been connected to mechanical test facilities (CIRA SHAKER TIRA TV 59335-440) by using a dedicated fixture and has been exposed to IP and OOP:

- Resonance search;
- Sine vibration (as specified by system and launch authorities);
- Random vibration (as specified by system and launch authorities).

CMC Hypervelocity Impact Testing

Objective of the test campaign has been to characterize the behavior of the ISiComp® material with respect to the effect of MMOD (Micro-Meteoroids and Orbital Debris) impacts. During the SR six missions with 2 months duration the BFA & TPS will be exposed to a certain flux of MMOD depending on the orbit characteristic. The test campaign shall assess the entity of damage occurring on the BFA and/or TPS when hit by a statistically relevant MMOD. Furthermore, some test foreseen in CIRA PWT (Plasma Wind Tunnel) shall assess the capability of the damaged BFA to withstand the re-entry environment.

A first test campaign was performed at Space Gun Test Facility at Fraunhofer EMI [7].

Tests have been performed by using projectiles consisting of aluminum spheres with a diameter up to 5.0 mm, and at a velocity range beyond 6.0 km/s. Test articles consisted in a scaled body flap model and some CMC TPS plates. Some results are summarized in Fig 18.

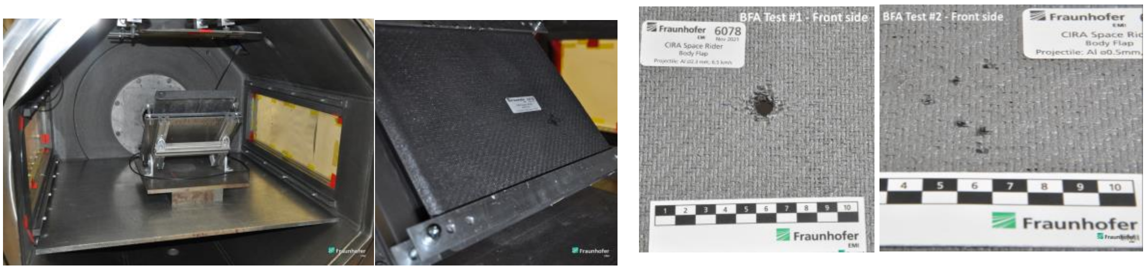

Fig 18. BFA scaled model within Space Gun Test Facility, test #1 sphere dia; 2.3mm V = 6,5 km/s – and test #2 5 spheres dia 0,5; mm V = 4,9 km/s

4.3. TPS Development Test

Attachment Mechanical Tests

In order to assess the mechanical strength of the designed mechanical connections between the shingles and the underneath cold structure, three different load conditions (tensile, shear-X and shear-Y) have been investigated.

For each test condition, two different types of test have been performed:

1. failure test, to quantify the maximum load carrying capability of the component: the ultimate load;
2. life cycle test, to assess reusability of the component for six re-entry flight.

In life cycle tests, the same test has been repeated six times on the same test article. Moreover, at the end of the last load cycle a failure test is performed on the same test article.

Experimental results highlight that the ultimate loads for all load cases are always higher than the operative loads ensuring the mechanical capability proof of the joint.

Fig 19. Tensile test and shear Y set-ups

In addition to the mechanical capability proof, have been successfully verified also the single mission and the reusability capability proofs. Furthermore, experimental ultimate strengths are in line with numerical predictions and no significant reductions are observed after life cycle tests.

Insulation Stack-up Tests

The purpose of these tests is to validate thermal model of the identified insulation stack-up materials.

Thermal test considering the CMC Panel and the different layers of insulation, including a sample of the cold structure, will be tested at representative flight conditions of both re-entry (HT) and orbital phase (LT). The test article is instrumented with thermocouples located at different depth of the stack-up. For HT tests a dedicated furnace have been realized to guarantee a max temperature on CMC up to 1600°C and keeping the lateral side as much adiabatic is possible. Test campaign is on-going.

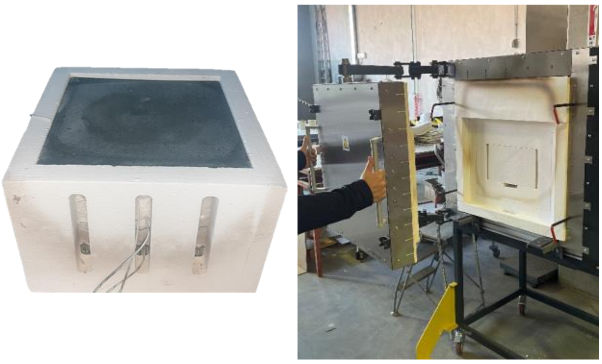

Fig 20. Insulation stack-up set-up and test furnace

Metallic Attachment Tests

The purpose of these tests is to verify the mechanical strength of the designed metallic connections between CMC Nose Omega and the metallic ring and of the CMC Windward Omega and Leg and the Cold Structure.

The mechanical connections at room and high temperature between the CMC components and the metallic structure shall be tested by means of dedicated breadboards.

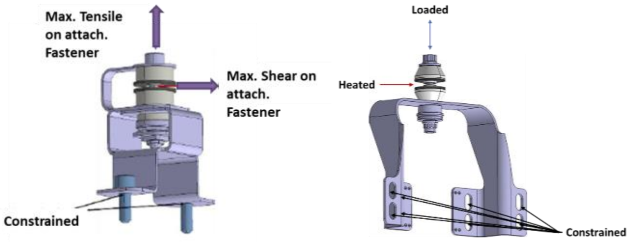

Fig 21. Windward & Nose attachments to be tested

5. Qualification Roadmap

Following the successful achievement of the S/S Critical Design Review objectives in 2021 as well as the completion of the main development tests, a comprehensive qualification roadmap will be implemented covering all the critical aspects of the Space Rider mission profile.

In line with the Space Rider requirements, a prototype model philosophy at subsystem level will be applied, which encompass the manufacturing and assembly of Qualification Units of: a complete Nose Assembly, a representative sub-set of Windward Shingles, a complete port side Hinge TPS Assembly and a complete Body Flap Port Assembly.

Each assembly, composed by CMC parts, insulation stack-up and attachments will be subjected to the following test sequence:

- Integration Test
- Dynamic Tests (Modal, Sine, Random Acoustic, Shock)
- Static Test
- Kinematic Test (Only for BFA)
- Thermomechanical Test
- Plasma Wind Tunnel Test (only for Shingle and BFA with dedicated sub-scale test article)

All the tests are conceived to be representative of the full envelope of Space Rider six missions.

All the qualification test above listed will be performed within CIRA facilities. Only for nose and shingle dynamic testing an external facility will be rented and operated by CIRA personnel.

6. Conclusion

An overall picture of the activities performed for the design and development of the Space Rider Thermal Protection System has been provided. An extensive development program has been put in place to demonstrate the suitability of the technology to withstand the space environment from launch to re-entry including in-orbit permanence for a minimum of six missions. Starting from the IXV architecture, the design of the Space Rider TPS and BFA has been significantly modified in order both to be adapted to the ISiComp® technology and to make easier the integration which in turn will allow for faster post flight inspection and refurbishment.

An extensive qualification program is currently under preparation. Qualification units of all main assemblies – nose, shingles, hinge TPS and body flap – will be manufactured and tested against the complete mission environment taking also into account reusability constraints.

7. Acknowledgments

The authors wish to thanks: Thales Alenia Space – Italia, Space Rider Prime contractor, and the European Space Agency, leading the Space Rider Program, for their contribution to the activities; the Italian Space Agency, for its continuous support first to the development of the ISiComp® technology and after to the implementation of the Space Rider Program. Furthermore, the authors wish to emphasize the effort of all CIRA and PETROCERAMIC researchers and personnel who contributed to the achievements obtained so far.

References

1. Tumino G., Angelino E., Leleu F., Angelini R., Plotard P., Sommer J. : The IXV project: the ESA re-entry system and technolologies demonstrator paving the way to European autonomous space transportation and exploration endeavours. 3rd FLPP Industrial Workshop, 15 October 2008.
2. Fedele A., Guidotti G., Rufolo G., Malucchi G., Denaro A., Massobrio F., Dussy S., Mancuso S., Tumino G. : "The Space Rider Programme: End user's needs and payload applications survey as driver for mission and system definition". Acta Astronautica. 152. 10.1016/j.actaastro.2018.08.042.
3. MMPDS, Metallic Material Properties Database and Standardization Handbook, 16th Edition, July 2021.
4. ECSS-E-ST-10-03C Space Engineering: Testing, 01/07/2012.
5. G. Milassin, K. Heary, A. Polsak, A. Tighe, C.O.A. Semprimoschnig : "ESA's LEOX facility and introduction of an in-vacuum transfer mechanism". 14th International Symposium on Materials in the Space Environment, France, October 2018.
6. L. Cutrone, C. Purpura, G. Rufolo, M. De Stefano Fumo, A. Schettino: "Arc-jet Testing and Catalytic Model Development for the Ceramic Reinforced Composite Material of the Space Rider Body Flaps". 2nd International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions & Engineering (FAR), Heilbronn, Germany June 2022.
7. Putzar, R., Schäfer, F.: "Experimental space debris simulation at EMI's calibre 4 MM two-stage light gas gun". European Space Agency, (Special Publication) ESA SP. 672, 2009.
8. A. Scaccia, D. Galli, F. Caramelli, C. Cossu, G. Tumino: "The new European frontier of in-space Experimentation, Demonstration and Validation: Space Rider System". 72nd International Astrounatical Congress, Dubai, United Arab Emirates, October 2021.