Centro Italiano Ricerche Aerospaziali

SPACE STRUCTURES: THE ROLE OF NEW MATERIALS AND INNOVATIVE STRUCTURES

Centro Italiano Ricerche Aerospaziali

13TH EASN INTERNATIONAL CONFERENCE ON INNOVATION IN AVIATION & SPACE FOR OPENING NEW HORIZONS

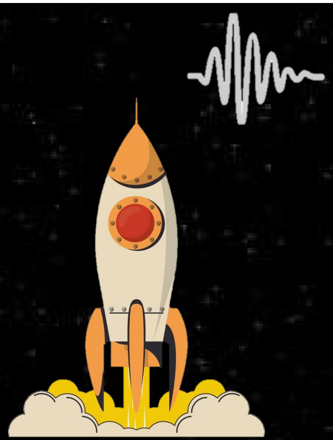
SALERNO

SEPTEMBER 5TH – 8TH, 2023

DR. STEFANIA CANTONI

CIRA - INFRASTRUCTURES DIRECTOR

LAUNCH, MISSION AND RE-ENTRY
MECHANICAL, THERMAL, AND RADIATION LOADS.



During the initial phases of a launch, high velocity gases are ejected from engine nozzles and reflected from the ground, creating turbulence in the surrounding air and inducing a vibratory response of the rocket structure.
Acoustic energy is the primary source of vibration input to a space launch vehicle. Acoustic vibration occurs over a broad frequency range **(30 Hz to 10000 Hz)**. **Overall Acoustic Sound Pressure Level ≥ 140 dB.**

During flight, the spacecraft is subjected to static and dynamic loads.
Such excitations may be of aerodynamic origin (e.g., wind, gusts, or buffeting at transonic velocity) or due to the propulsion systems.

Moreover pyrotechnic shock is associated with the firing of an explosive device, usually for the purpose of initiating or performing a mechanical action

(e.g., stage separation, fairing opening **2.000 g @1000 Hz)**

Last update 11 August 2023
36.500 space debris objects greater than 10 cm
1.000.000 space debris objects from greater than 1 cm to 10 cm
130 million space debris objects from greater than 1 mm to 1 cm

Spacecraft receive thermal energy from internal and external sources when they flight around the Earth

- Solar radiation (direct and reflected)
- Infrared radiation emitted by the Earth

This results for example in extreme temperatures from **-120 ° C to + 150 ° C.**

Spacecrafts have to withstand extreme aerothermodynamics heating when they re- enter the atmosphere.

Depending on the aerodynamic shapes and re-entry conditions temperature higher than 1300° C – 1700° C are experienced by external surfaces

THERMAL PROTECTION SYSTEM AND HOT STRUCTURES

SPACECRAFTS HAVE TO WITHSTAND EXTREME AEROTHERMODYNAMICS HEATING WHEN THEY RE- ENTER THE ATMOSPHERE.

DEPENDING ON THE AERODYNAMIC SHAPES AND RE-ENTRY CONDITIONS TEMPERATURE HIGHER THAN 1300° C- 1700° C ARE EXPERIENCED BY EXTERNAL SURFACES

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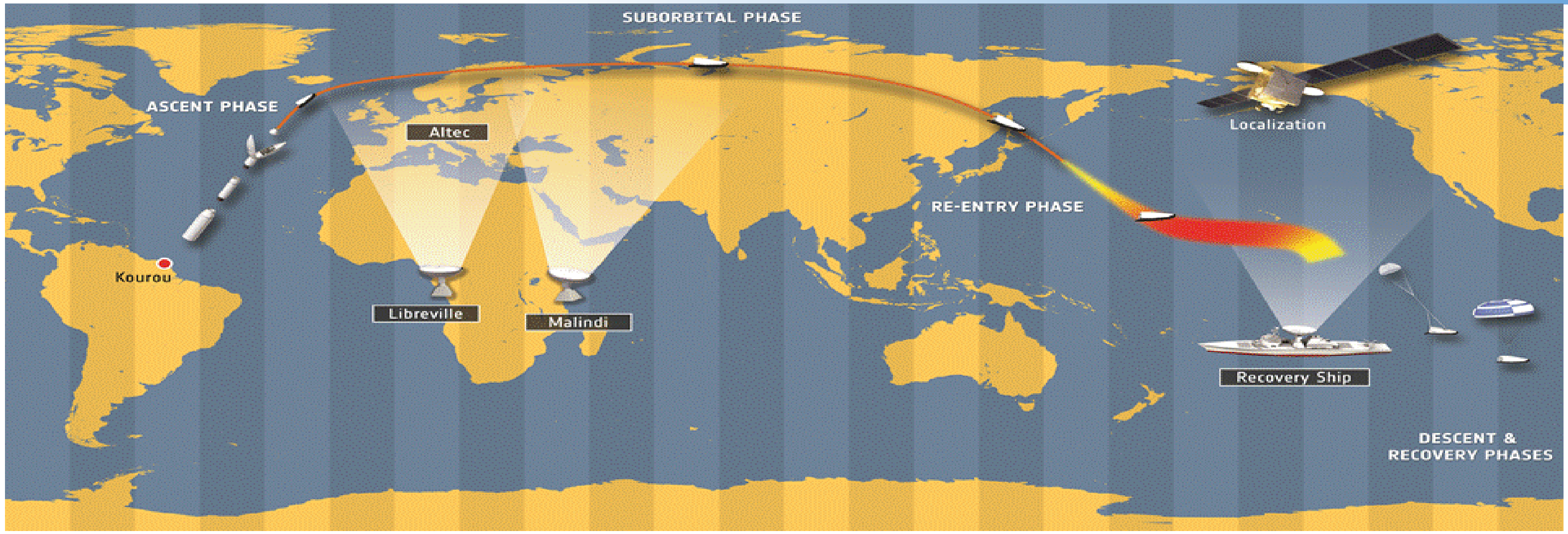
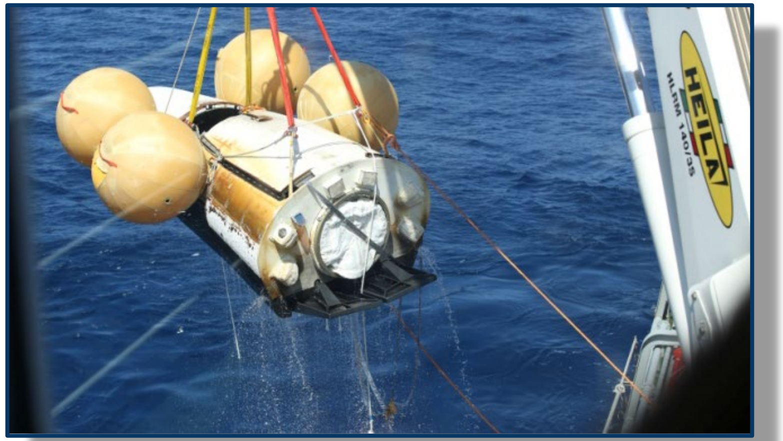
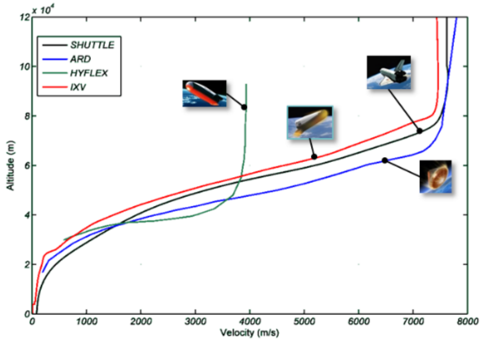
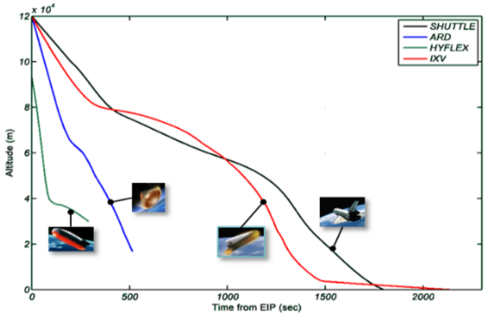
esa European Space Agency

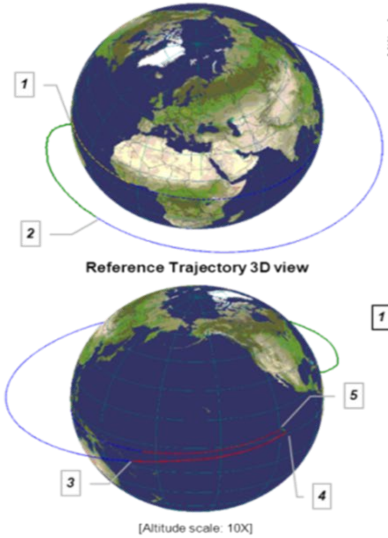
IXV Mission

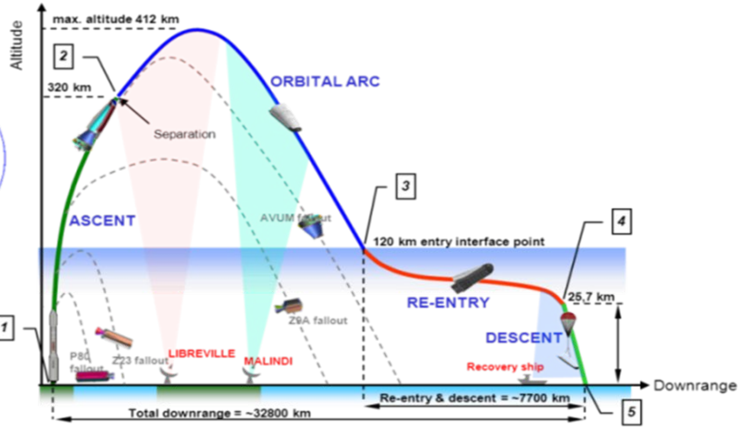












Reference Timeline

1 – Lift off	T = 0 [s]	⇒	*Ascent segment*	*966 [s]*
2 – Separation	T = 966 [s]	⇒	*Orbital segment*	*2891 [s]*
3 – Entry gate	T = 3857 [s]	⇒	*Re-entry segment*	*1323 [s]*
4 – Descent gate	T = 5180 [s]	⇒	*Descent segment*	*881 [s]*
5 – Splashdown	T = 6061 [s]			

The IXV mission was successfully performed on the **11th of February 2015**, with all flight hardware and all flight data successfully recovered, through flight segment telemetry transmission and ground segment acquisition, and on- board recording, with the confirmation that the flight data is complete and consistent among the various sources.

- ✓ Overall flight of approximately **25.000** km
- ✓ **8.000** km in hot atmospheric re-entry environment with automatic guidance
- ✓ Starting from an orbital velocity of ~7.5 km/sec (Mach=27),
- ✓ Concluding with precision landing.

CIRA
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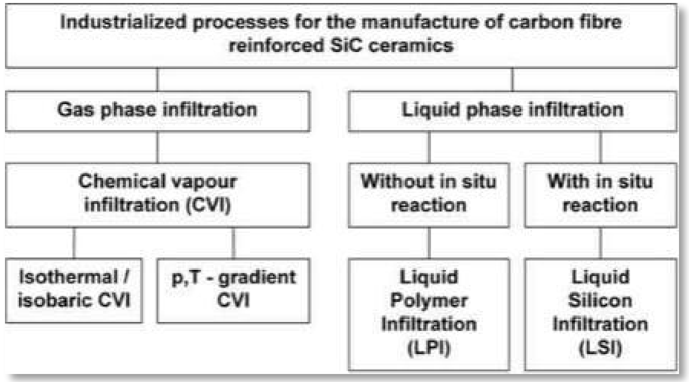
IXV (Exhibition in Caserta Royal Palace, June-July 2015)

Ceramic Matrix Composites (CMCs)

- A very low expansion at high temperatures of above 1000 ° C,
- A high resistance to
  - abrasion
  - corrosion and
  - thermo-shocks
- Light-weight with only 2,3 – 2,5 g/cm^3 vs. Al with 2,7 g/cm^3 or Steel with ~8 g/cm^3
- Excellent tensile, shear and bending strength
- High ductility



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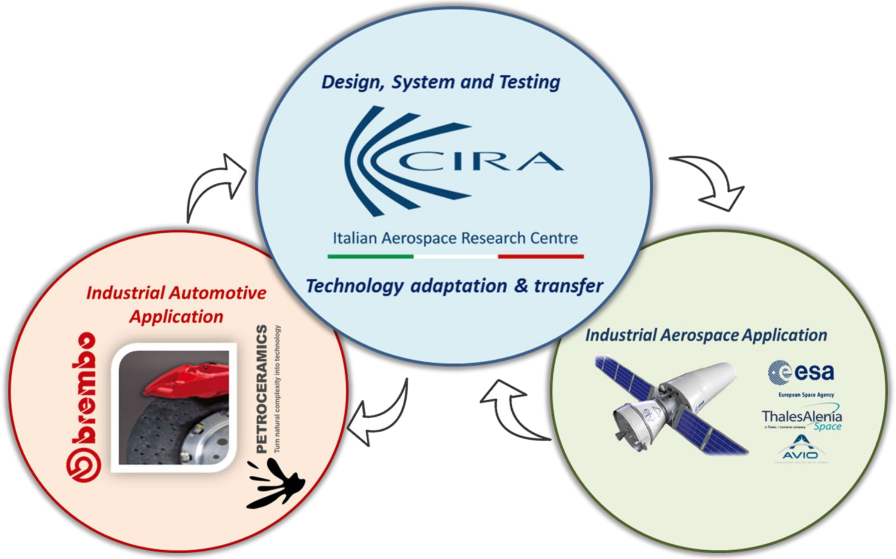
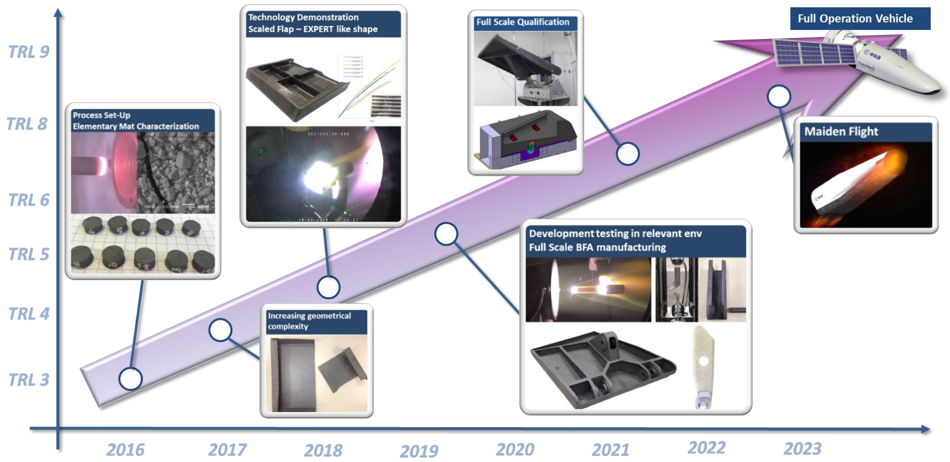
ISiComp ®
Carbon fiber reinforced silicon carbide - Ceramic Matrix Composite

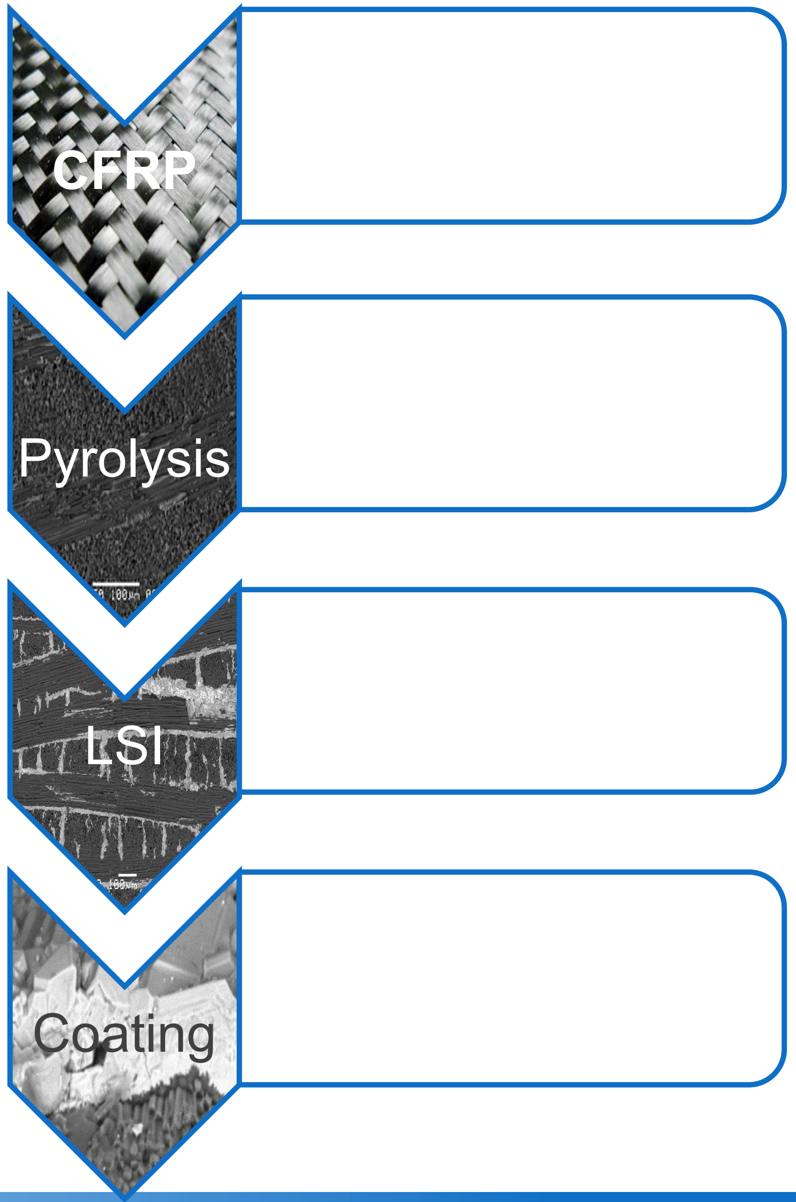
ISiComp®

ISiComp® Mean Properties		Value
Tensile Strength, MPa		142
Young Modulus, GPa		60
Compressive Strength, Mpa		266
Flexural Strength, Mpa		200
ILSS, MPa		36
Density, kg/m^3		1900
CTE, 1/K x 10^{-6}	INP	2
@1000° C	TTT	7
Thermal Cond., W/m K	INP	16
@1000° C	TTT	8
Specific Heat, J/kg K @1000° C		1600

Material properties	Unit	XB	XT
Manufacturer	–	DLR	DLR
Fiber reinforcement	–	Fabric	Fabric
Density	gcm^{-3}	1.9	1.92
Open porosity	%	3.5	3.7
Young's modulus*	GPa	60	100
Flexural strength	MPa	160	300
Tensile strength	MPa	80	190

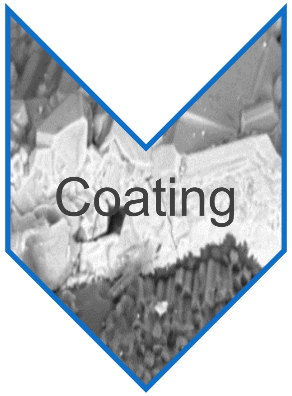






OXIDATION PROTECTIVE COATING

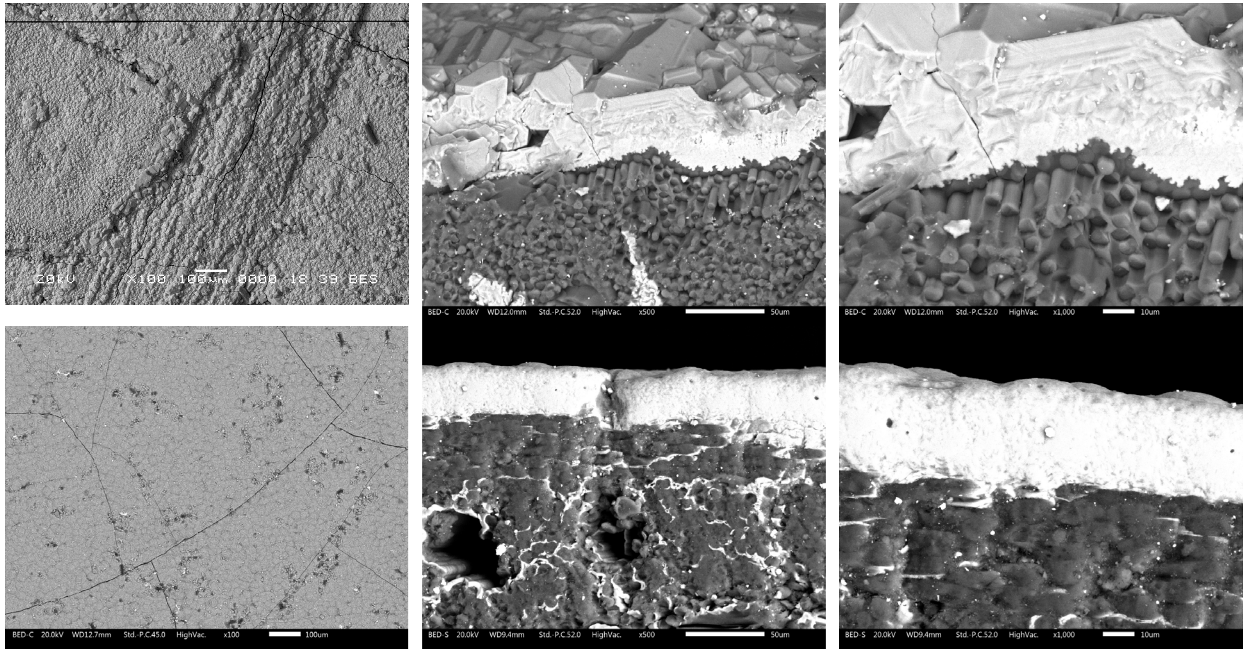
- THE SiC COATING CAN BE APPLIED BY THE CHEMICAL REACTION BETWEEN SILICON VAPORS AND THE FREE CARBON AVAILABLE ON THE CMC SURFACE



Surface | Cross section | Cross section

v-Si reactive coating applied on ISiComp®

SiC-CVI coating applied on Cf-SiC obtained by SiC CVI

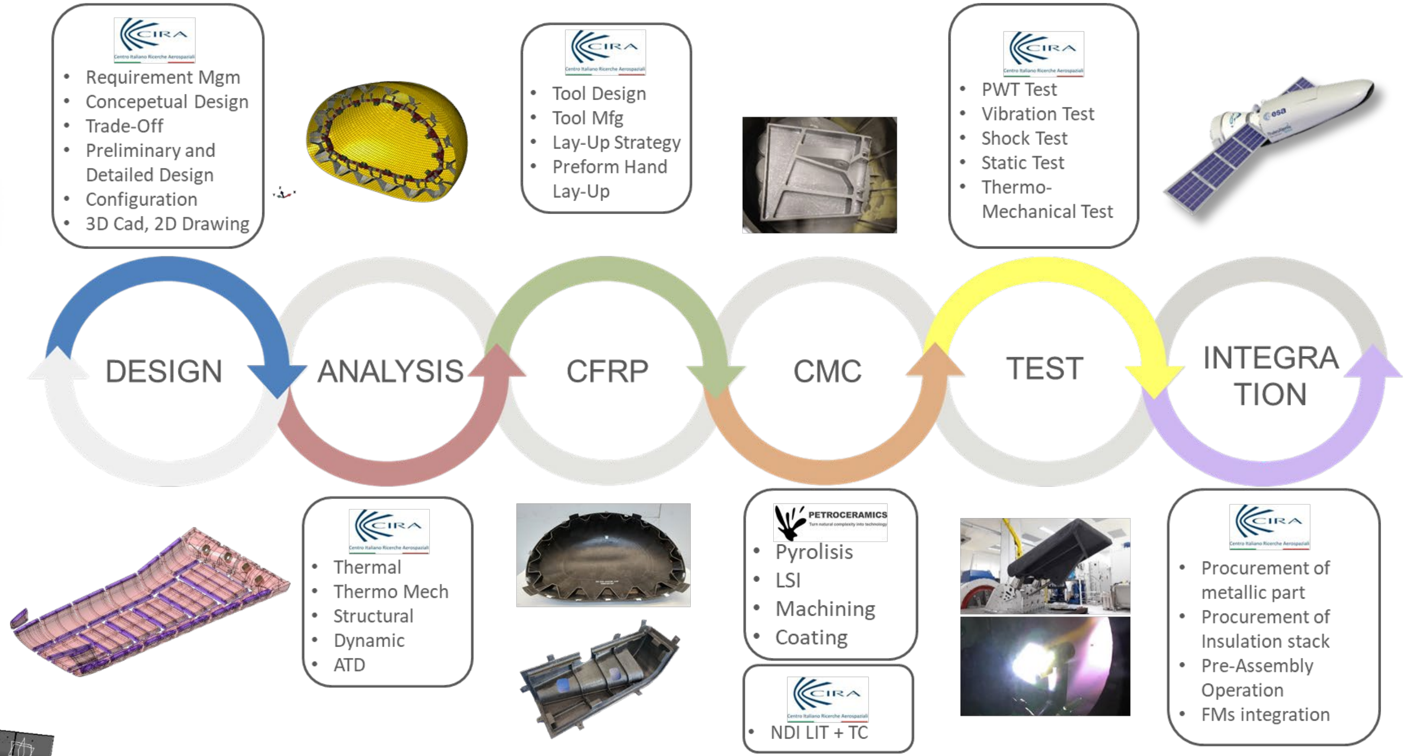


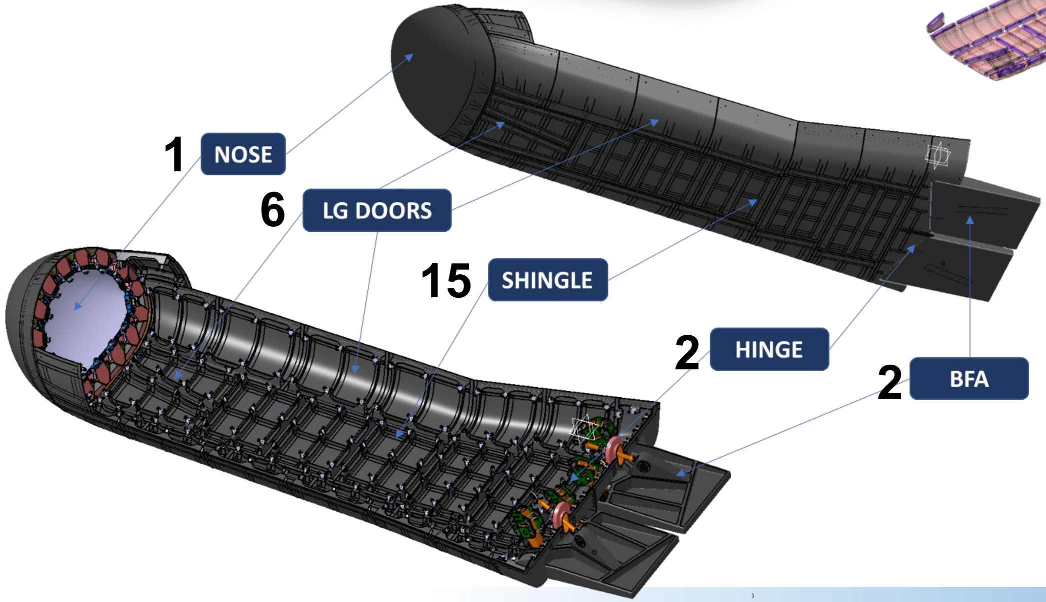
Dendritic interface

Sharp interface

REUSABILITY

Space Rider TPS: from Design to Flight





DESIGN DRIVER

- **REUSABILITY:** Survive 6 times to harsh re-entry environment without degradation (Tmax≈1650° C)
- REUSABILITY: Survive to 2 months (x6) orbital environement (ATOx, Tcycling)
- Need for minimum and fast refurbishement operations
- Be cost effective for commercial exploitation

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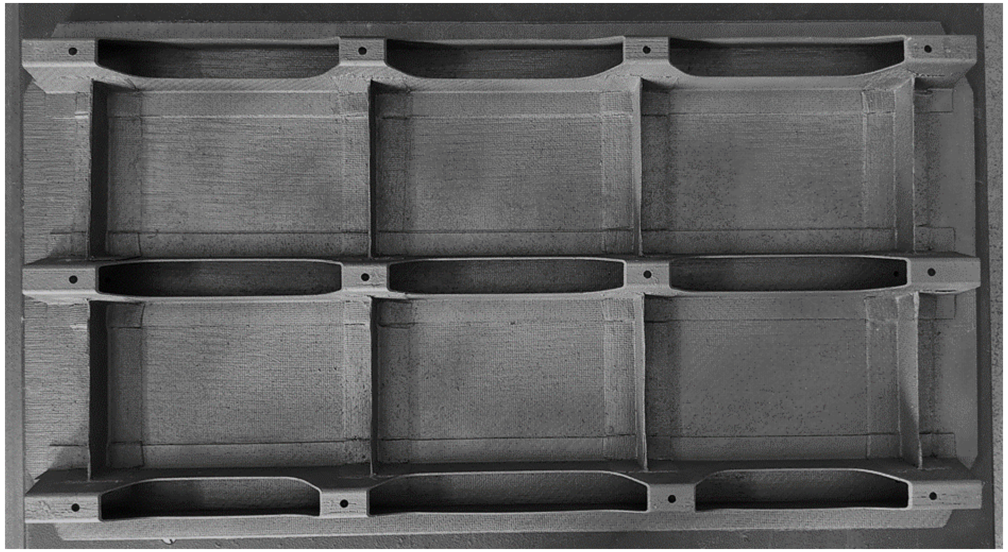
TPS Engineering Models

Body Flap

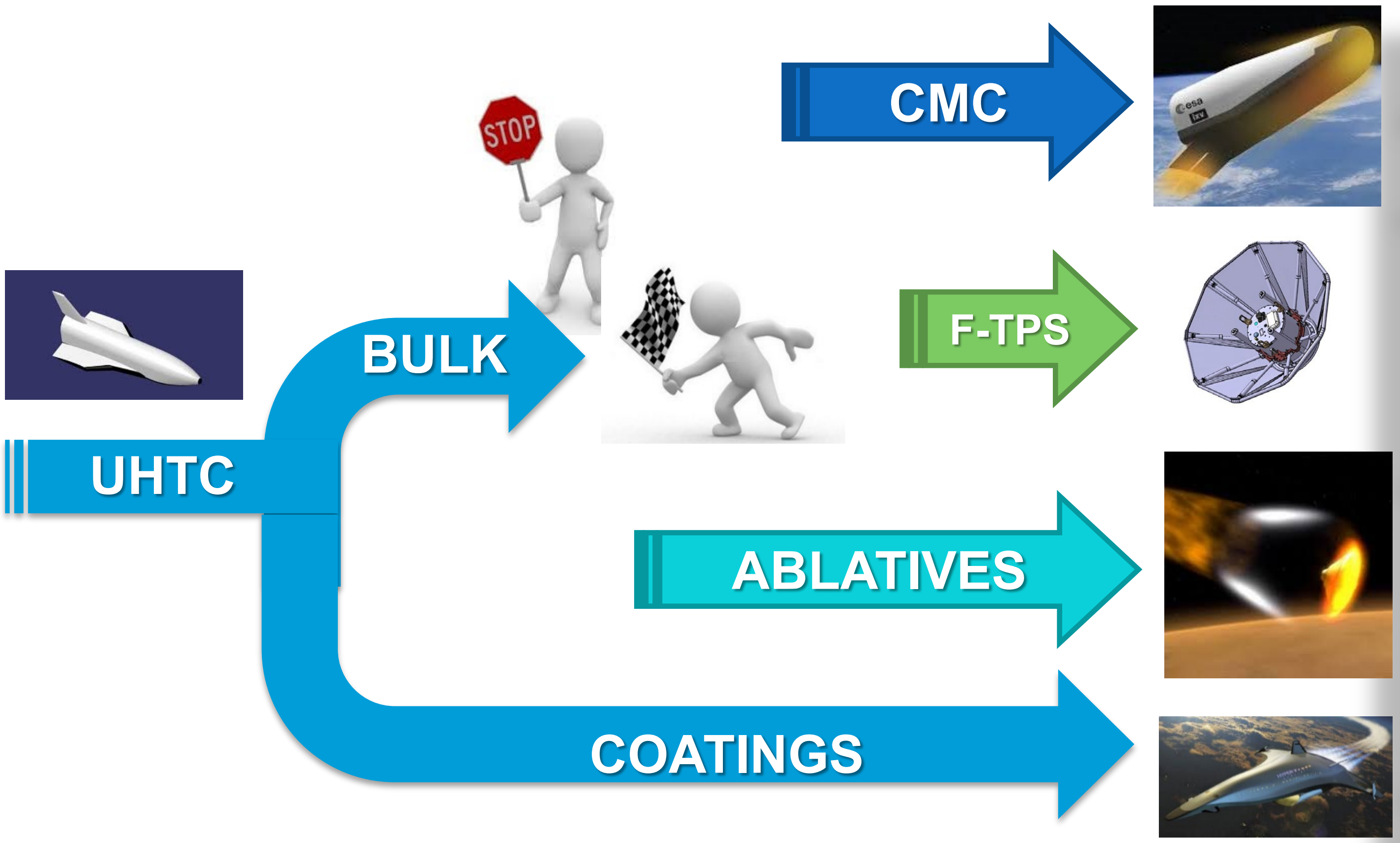
Hinge TPS



Shingle

Nose

WHICH KIND OF MATERIAL?



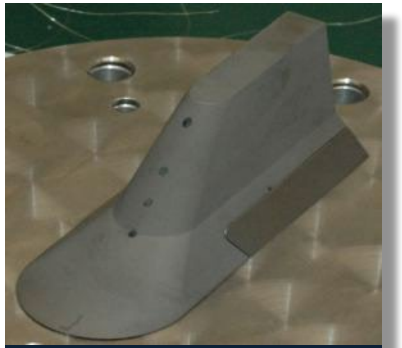
- CMCs (C/C, C/SiC, SiC/SiC, Ox/Ox) AND LOW COST PROCESS

+ GRADIENT INSULATORS

- PICA LIKE (GREEN) ABLATORS FOR INTERPLANETARY MISSIONS AND REUSABLE SYSTEMS

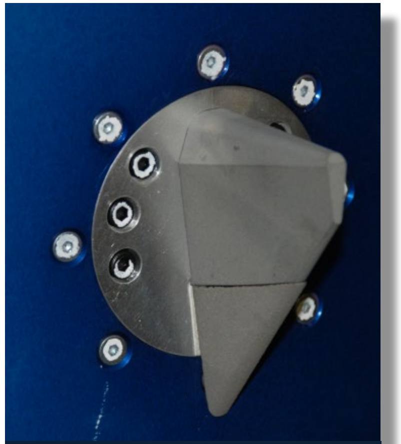
- METAL OR C/SIC WITH ENHANCED OXIDATION RESISTANCE CAPABILITIES TROUGH AD HOC DEVELOPED UHTC COATINGS TO IMPROVE REUSABILITY CHARACTERISTICS

MASSIVE UHTC

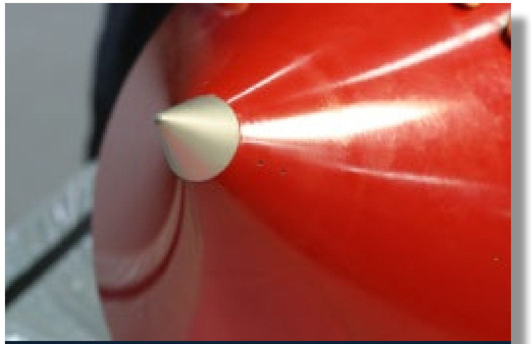


EXPERT: MASSIVE UHTC ; UHTC-METAL I/F

ASA
WLE Demonstrator made of CMC coated with UHTC



SCRAMSPACE
metal UHTC coated, massive UHTC



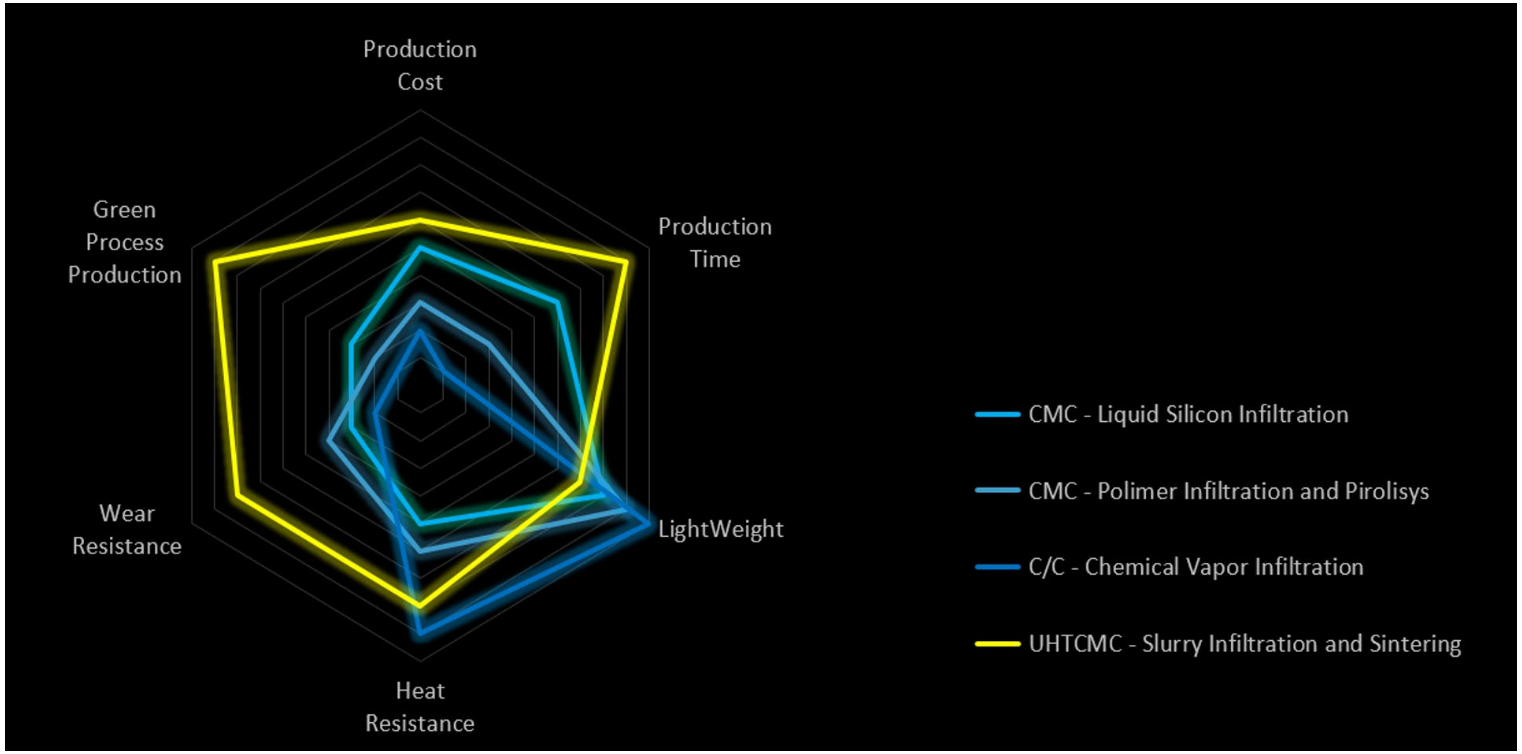
SHARK
Structural aerodynamic profile made of massive UHTC

UHTC COATING ON METALLIC AND CMC SUBSTRATE

...UHTCCMC coming soon

Ultra High Temperature Ceramic Material: Past, Present, Future

UHTCCMC is an innovative class of materials which combine the superior erosion/ablation resistance of Ultra-high temperature ceramics (UHTCs) at extreme hot and harsh environments and advantages of current ceramic matrix composites (CMCs) such as toughness, thermal shock resistance and damage tolerance.



Courtesy by K3RX

Compared to C/C and C/SiC
- High ablation resistance
- High erosion resistance
- High electrical conductivity
- Low porosity

Compared to refractory metals
- Lightweight (1/5 of tungsten)
- High heat resistance
- Low thermal expansion
- Excellent resistance to chemicals

Compared to graphite
- High strength and rigidity
- High ablation resistance
- High erosion resistance

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NEW STRUCTURES TO REDUCE WEIGHT

Design ...new paradigm

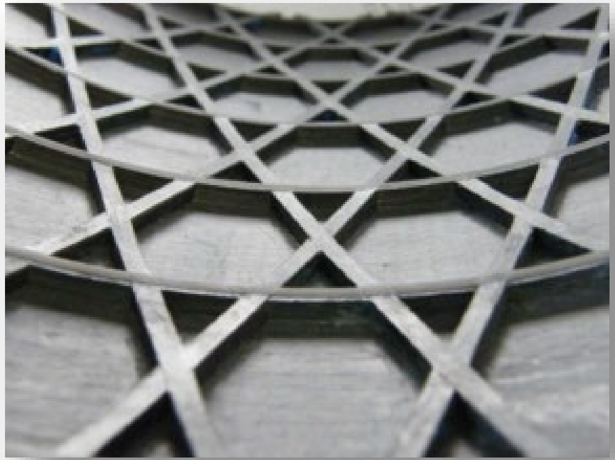
……..from early aluminum alloys 1940s (7075) to Boeing 787 composite fuselage

The classical design paradigm

A BASIC LOAD-CARRYING SHELL REINFORCED BY FRAMES AND LONGERONS IN THE BODIES, AND A SKIN-STRINGER CONSTRUCTION SUPPORTED BY SPARS AND RIBS IN THE SURFACES

REMOVING THE IDEA OF COMPOSITE AS BLACK ALUMINUM WITH DEDICATED DESIGN APPROACHES AND COMPLETELY AUTOMATED PROCESS

AN ISOGRID IS A TYPE OF PARTIALLY HOLLOWED-OUT STRUCTURE FORMED USUALLY FROM A SINGLE METAL PLATE (OR FACE SHEET) WITH TRIANGULAR INTEGRAL STIFFENING RIBS (OFTEN CALLED STRINGERS)



COMPOSITE ANISOGRID CONCEPT MADE OF UNIDIRECTIONAL RIBS

……..from UK Wellington bombers in World War II to 2/3 VEGA C composite anisogrid interstage

A new design paradigm

Design ...new paradigm

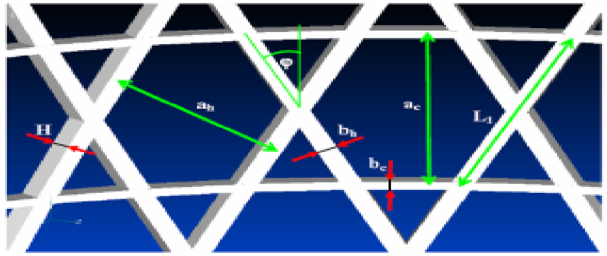
- The theoretical structural efficiency of lattice shells under heavy axially compressive/bending loads is higher than equivalent layered shells

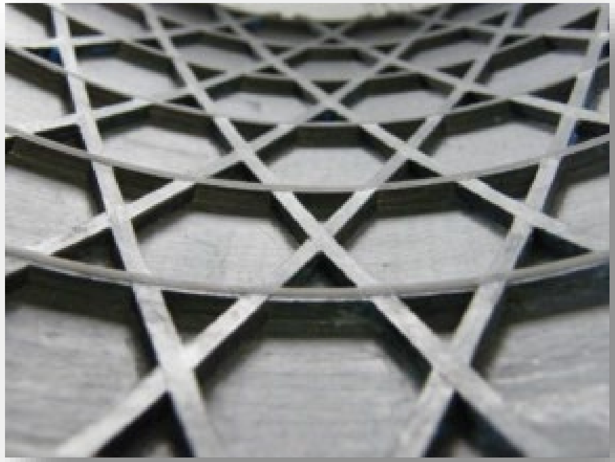
- Orthotropic elastic properties are demonstrated to increase the weight efficiency with respect to the Isotropic ones under specific stiffness, strength, and buckling constraints

- The helical ribs sustain compression, inducing a circumferential tension in the hoop ribs (skin), producing an effect similar to the action of internal pressure

- This "pressure" stabilizes the circular form, reduces the shell sensitivity to shape imperfections and increases the critical load

Composite Anisogrid concept made of unidirectional ribs is a perfect combination of such theoretical pros

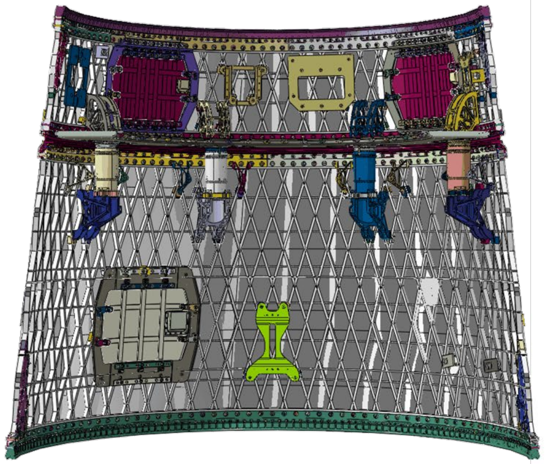
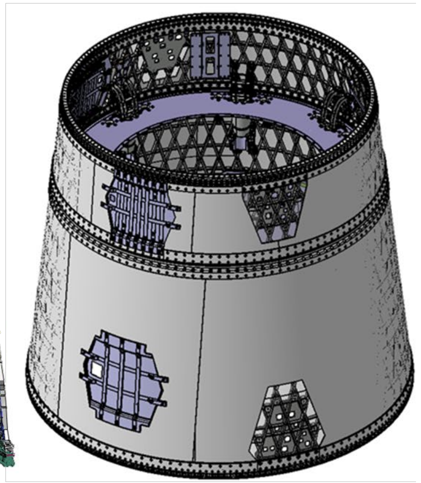




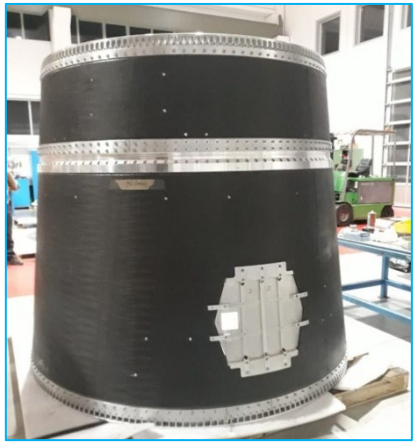
Composite Anisogrid concept made of unidirectional ribs

A new design paradigm

In highly loaded cases the grid structure exhibits a weight reduction up to 20% less than sandwich, 40-60 % wrt to metal - Results : **Limit Load 750 KN with a mass of ~ 250 kg of composite structures**

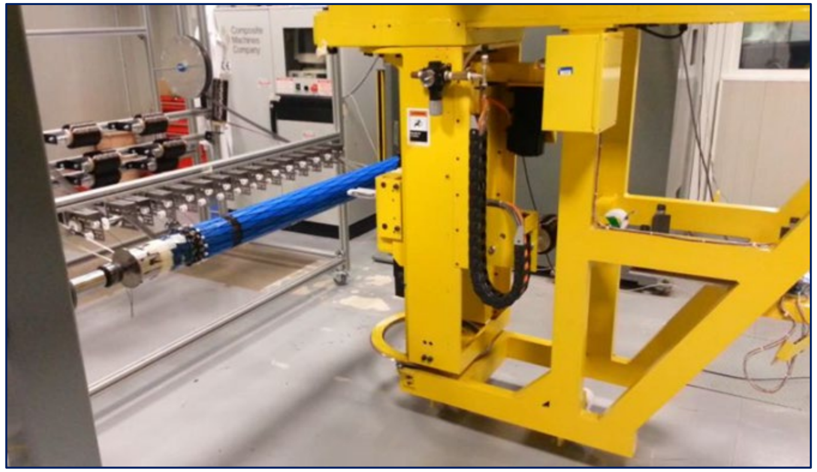


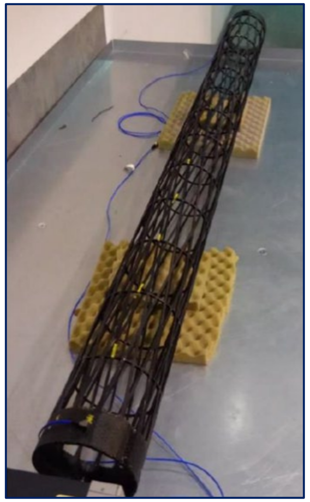


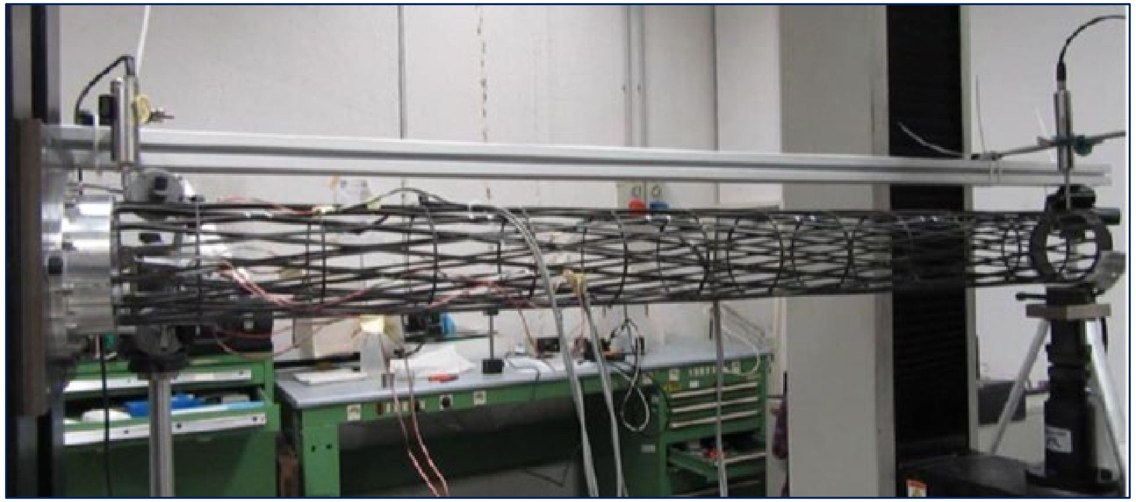
BOOM FOR A LARGE DEPLOYABLE SATELLITE ANTENNA

DESIGN DRIVERS: THE FIRST FUNDAMENTAL FREQUENCY AND THE THERMAL STABILITY (-180°C÷180°C)

MASS < 0.5 KG/M







MASS = 0.5 KG/M

RADIUS AND LENGTH= 60 MM AND 1500 MM

FIRST NATURAL FREQUENCY REQUIREMENTS 1,7HZ ACHIEVED

THERMAL STABILITY, MAX TIP DEFLECTION 0.15 MM ACHIEVED

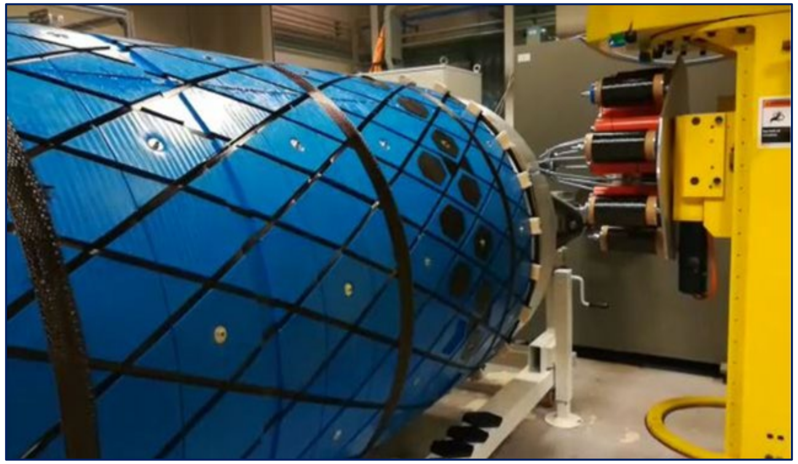
CTE (CFRP ONLY): NEAR ZERO με/ ° C, ACHIEVED

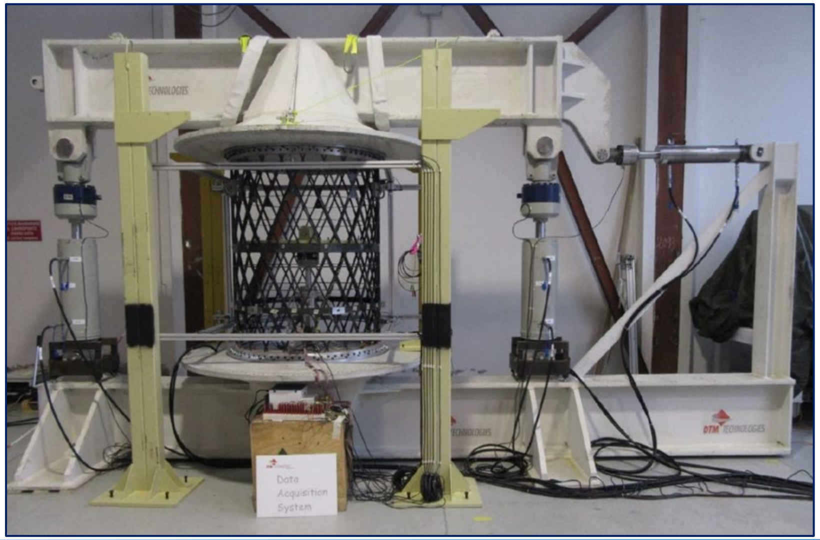
Central Tube of a Satellite Structure

Central Tube for a medium class Satellite

Design dominated by the global stiffness properties of the shell other than by the strength

Mass < 17 Kg/m



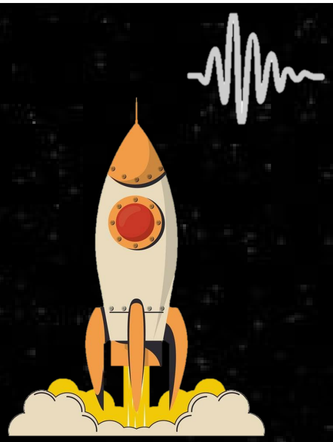


Weight: 14 kg/m, achieved

Radius 1194 mm and Length= 1500 mm

Load and stiffness requirements achieved

QUALIFICATION BEFORE FLIGHT



DURING THE INITIAL PHASES OF A LAUNCH, HIGH VELOCITY GASES ARE EJECTED FROM ENGINE NOZZLES AND REFLECTED FROM THE GROUND, CREATING TURBULENCE IN THE SURROUNDING AIR AND INDUCING A VIBRATORY RESPONSE OF THE ROCKET STRUCTURE.
ACOUSTIC ENERGY IS THE PRIMARY SOURCE OF VIBRATION INPUT TO A SPACE LAUNCH VEHICLE. ACOUSTIC VIBRATION OCCURS OVER A BROAD FREQUENCY RANGE **(30 HZ TO 10000 HZ)**. **OVERALL ACOUSTIC SOUND PRESSURE LEVEL ≥ 140 DB.**

DURING FLIGHT, THE SPACECRAFT IS SUBJECTED TO STATIC AND DYNAMIC LOADS.
SUCH EXCITATIONS MAY BE OF AERODYNAMIC ORIGIN (E.G., WIND, GUSTS, OR BUFFETING AT TRANS…IC VELOCITY) OR DUE TO THE PROPULSION SYS…

MOREOVER PYROTECHNIC SH… THE FIRING OF AN EX… FOR THE PURPOSE … ORMING A MECHANI…

…ATION, FAIRING OPENING **2.000**

…PDATE 11 AUGUST 2023
…CE DEBRIS OBJECTS GREATER THAN 10 CM
…ACE DEBRIS OBJECTS FROM GREATER THAN 1 CM TO 10 CM
…LLION SPACE DEBRIS OBJECTS FROM GREATER THAN 1 MM TO 1 CM

SPACECRAFT RECEIVE THERMAL ENERGY FR… INTERNAL AND EXTERNAL SOURCES WHEN THE… FLIGHT AROUND THE EARTH

- SOLAR RADIATION (DIRECT AND REFLECTED)
- INFRARED RADIATION EMITTED BY THE EARTH

THIS RESULTS FOR EXAMPLE IN EXTREME TEMPERATURES FROM **-120 ° C TO + 150 ° C.**

SPACECRAFTS HAVE TO WITHSTAND EXTREME AEROTHERMODYNAMICS HEATING WHEN THEY RE- ENTER THE ATMOSPHERE.

DEPENDING ON THE AERODYNAMIC SHAPES AND RE-ENTRY CONDITIONS TEMPERATURE HIGHER THAN 1300° C – 1700° C ARE EXPERIENCED BY EXTERNAL SURFACES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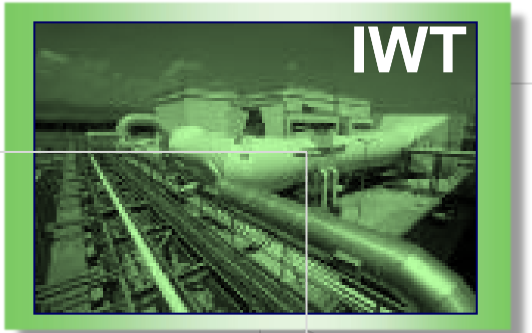
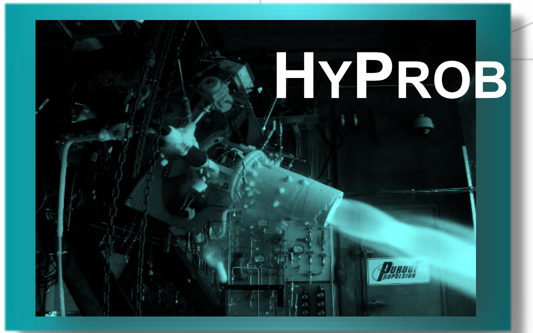
A PLACE WHERE SPACE IS ON GROUND

Main Research and Qualification Infrastructures

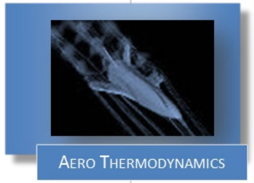
Feel Integrate Experiment

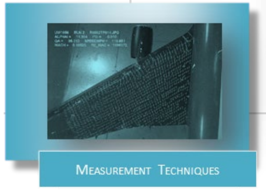


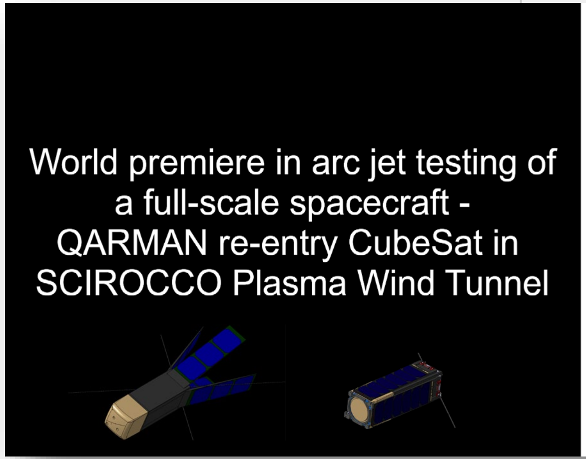


Next Is Coming…

PWT – Plasma Wind Tunnel







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von KARMAN INSTITUTE FOR FLUID DYNAMICS

esa

Goal: Improve safety of re-entry space vehicles

Use: Design and test thermal protection systems for space vehicles

- Operative since: 2002
- Testing fluid: AIR
- Max speed: up to Mach 12
- Stagnation temperature: ~ 10.000 ° C
- Max test durations: < 25 minutes
- Nozzle exit diameter: 2.0 m
- Nominal dimension of test specimen: 0.6 m
- Max power of arc heater: 70 MW

NASA, esa, NASDA National Space Development Agency of Japan, ThalesAlenia Space, Snecma Moteurs groupe snecma, DLR, agenzia spaziale italiana, AERO SEKUR, ISRO Indian Space Research Organisation, ALI

GHIBLI – Small Plasma Wind Tunnel

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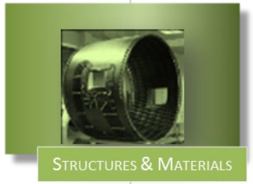
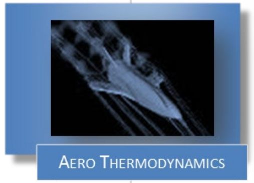
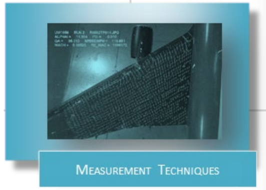
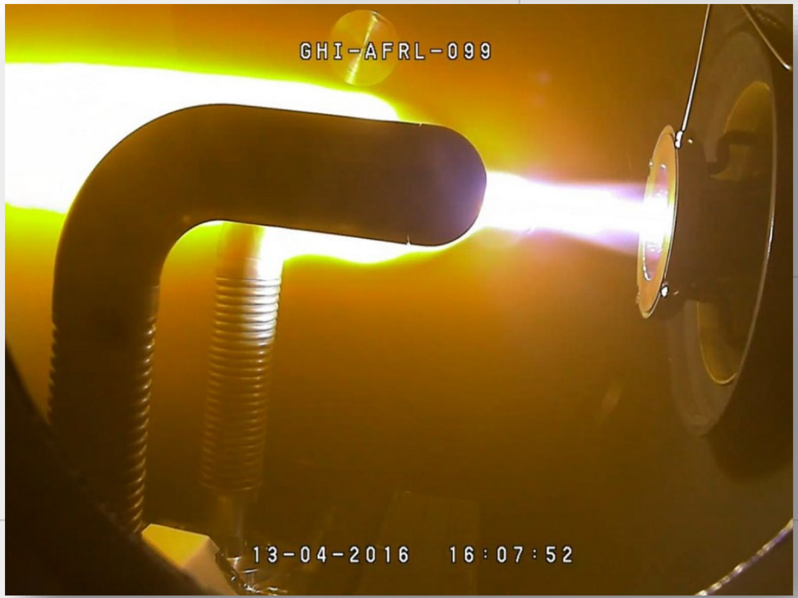








GOAL: IMPROVE SAFETY OF RE-ENTRY SPACE VEHICLES

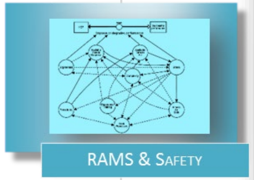
USE: DESIGN AND TEST SMALL SPECIMENS OF MATERIALS TO BE USED FOR THERMAL PROTECTION SYSTEMS OF SPACE VEHICLES

- TESTING FLUID: AIR (CO_2 IS UNDER DEVELOPMENT)
- MAX SPEED: UP TO MACH 10
- STAGNATION TEMPERATURE: ~ 10.000 ° C
- MAX TEST DURATIONS: < 25 MINUTES
- NOZZLE EXIT DIAMETER: 150 MM
- NOMINAL DIMENSION OF TEST SPECIMEN: 80 MM
- MAX POWER OF ARC HEATER: 2 MW

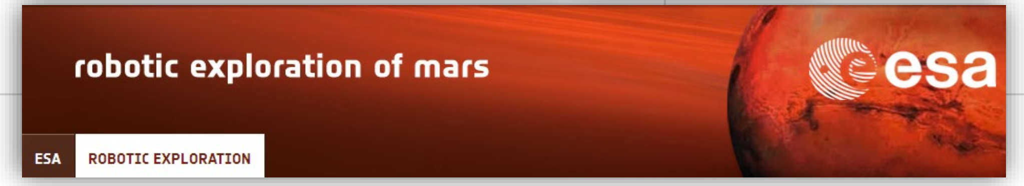
LISA – Crash Test Facility

Goal: Improve passenger/freight safety in case of crash on ground/sea

Use: Design and test aerospace structures and safety devices wrt crashworthiness



- Operational since 2003 (currently under maintenance and upgrading)
- Test article weight up to 10 ton
- Portal angle: 5 to 90 deg.
- Impact speed: up to 20 m/s
- Calibration and procedures: according to national standard defined by ENAC

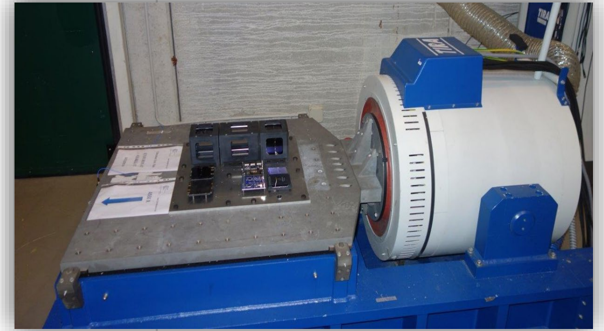
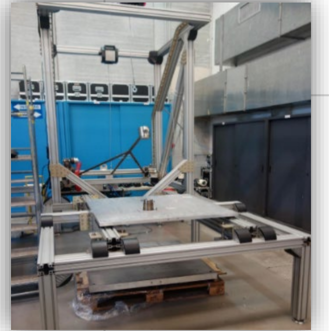


EXOMARS

Space Qualification Asset

Test & Qualify



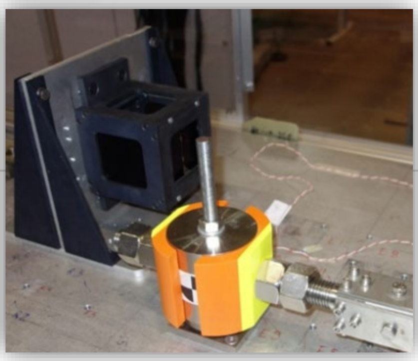



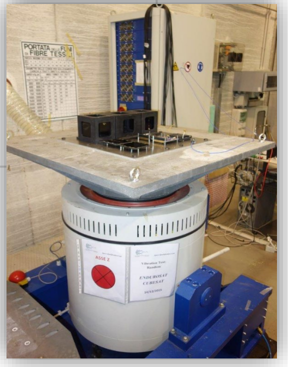
Standard ESA, ECSS-E-10-03C, MIL-STD-810G

Qualification capabilities for:

- Physical properties measurements
- Acceleration test
- Pyro-shock test
- Combined vibration, humidity, temperature and altitude test
- Environmental stress screening
- Thermal shock test, Thermal vacuum test
- Platform for measurement
- Vibration Table
- Mechanical Shock Test facility

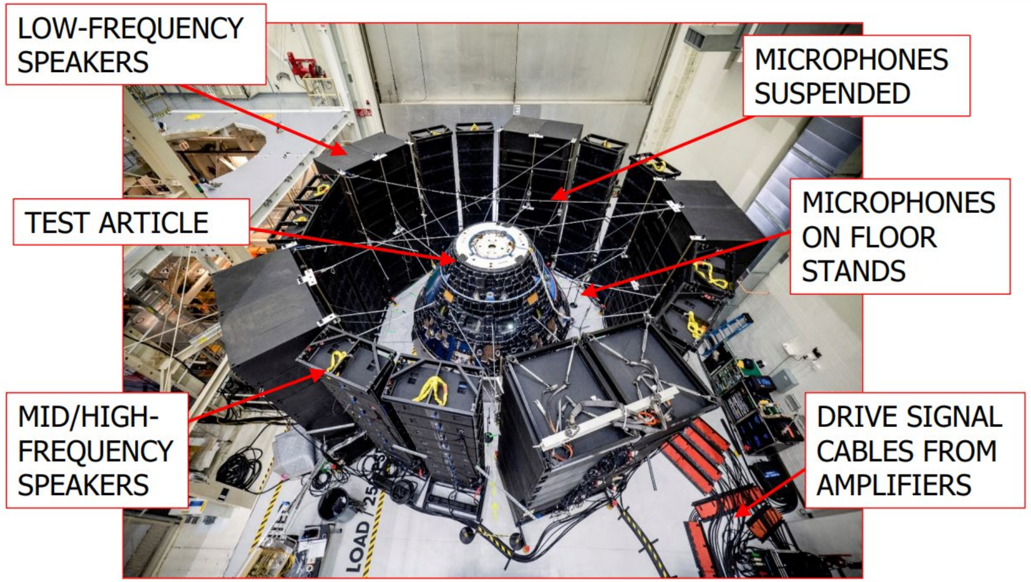




TEST & QUALIFY

DIRECT FIELD ACOUSTIC NOISE



Courtesy of MSI-DFAT

THE INNOVATIVE DFAN SYSTEM ALLOWS SPACE STRUCTURES TO BE QUALIFIED FOR ACOUSTIC LOADS AT LAUNCH BY SUBJECTING THEM TO ACOUSTIC WAVES GENERATED IN A DIRECT FIELD BY LOUDSPEAKER ARRAYS POSITIONED AROUND THE TEST ARTICLE, IN ORDER TO EXACTLY REPLICATE THE OPERATIONAL ACOUSTIC SPECTRUM

Courtesy of MSI-DFAT

……think different, use the material in the right way!

THANK YOU