Radiation-Shapes-Thermal Protection Investigations

for High Speed Earth Re-entry

RASTAS SPEAR : Radiation-Shapes-Thermal Protection Investigations for High Speed Earth Re-entry

10th International Planetary Probe Workshop
June 17-21, 2013 - San Jose (CA, USA)
Session 8B: Cross-Cutting Technologies III: TPS Technologies

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The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 241992

Overview

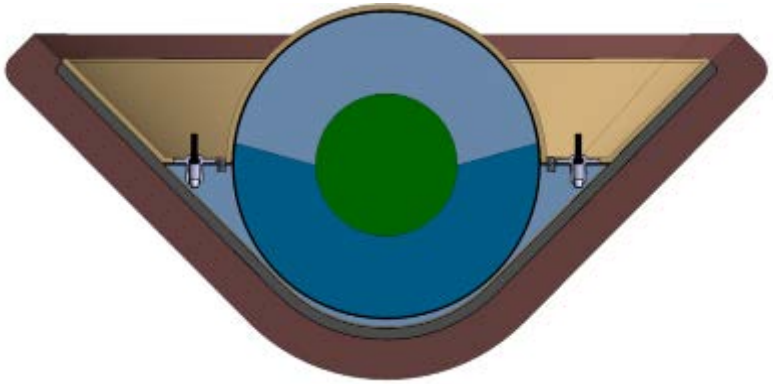
- Introduction
  - Objectives
  - WBS
- Overview of technical activities
  - Review of System Requirements
  - Ground Facilities Improvement
  - Key Technologies for High Speed Entry
  - Ablation – flight mechanics coupling assessment
  - Gas-surface interactions modeling
- Next Steps / Conclusion

General Objective

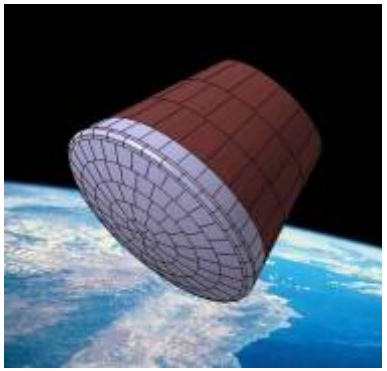
- Sample Return Missions : an important step for Solar System Exploration
  - After collecting samples, any return mission will end by high-speed re-entry in Earth's atmosphere.
  - This requires strong technological bases and a good understanding of the environment encountered during the Earth re-entry.

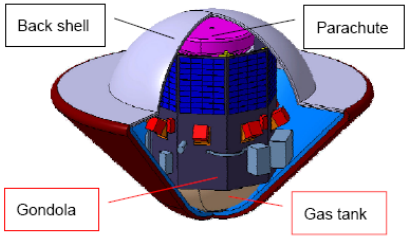
- Investment in high speed re-entry technology development is thus appropriate today
- to enable future planetary exploration missions in the coming decades.
  - Phobos Sample Return, Marco Polo, …, Mars Sample Return

→ Rastas Spear project
  - to increase Europe's knowledge in high speed re-entry vehicle technology



Main focus : Sample Return Capsule





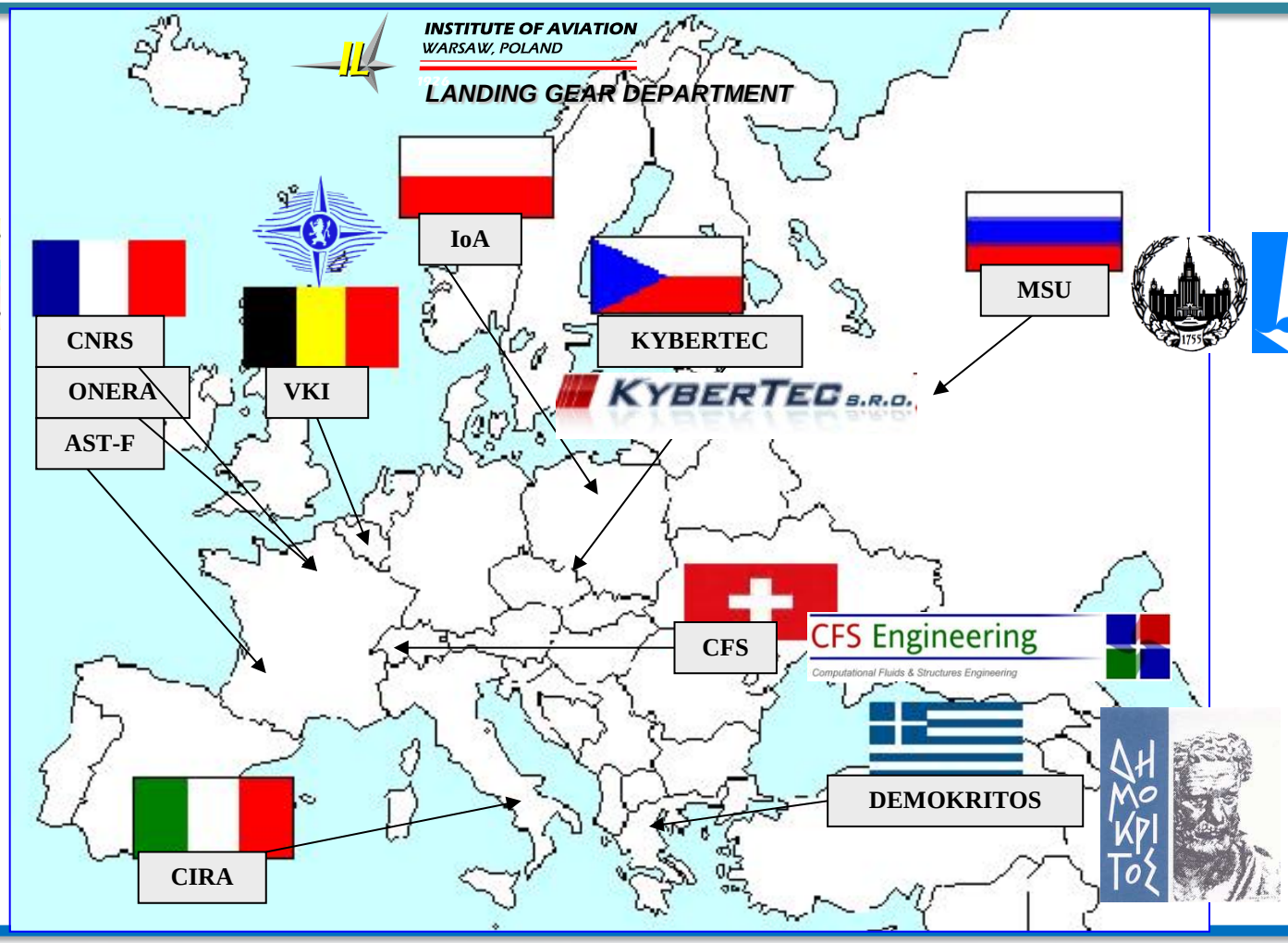
Other potential applications : ARV, Venus

Introduction /Acknowledgement

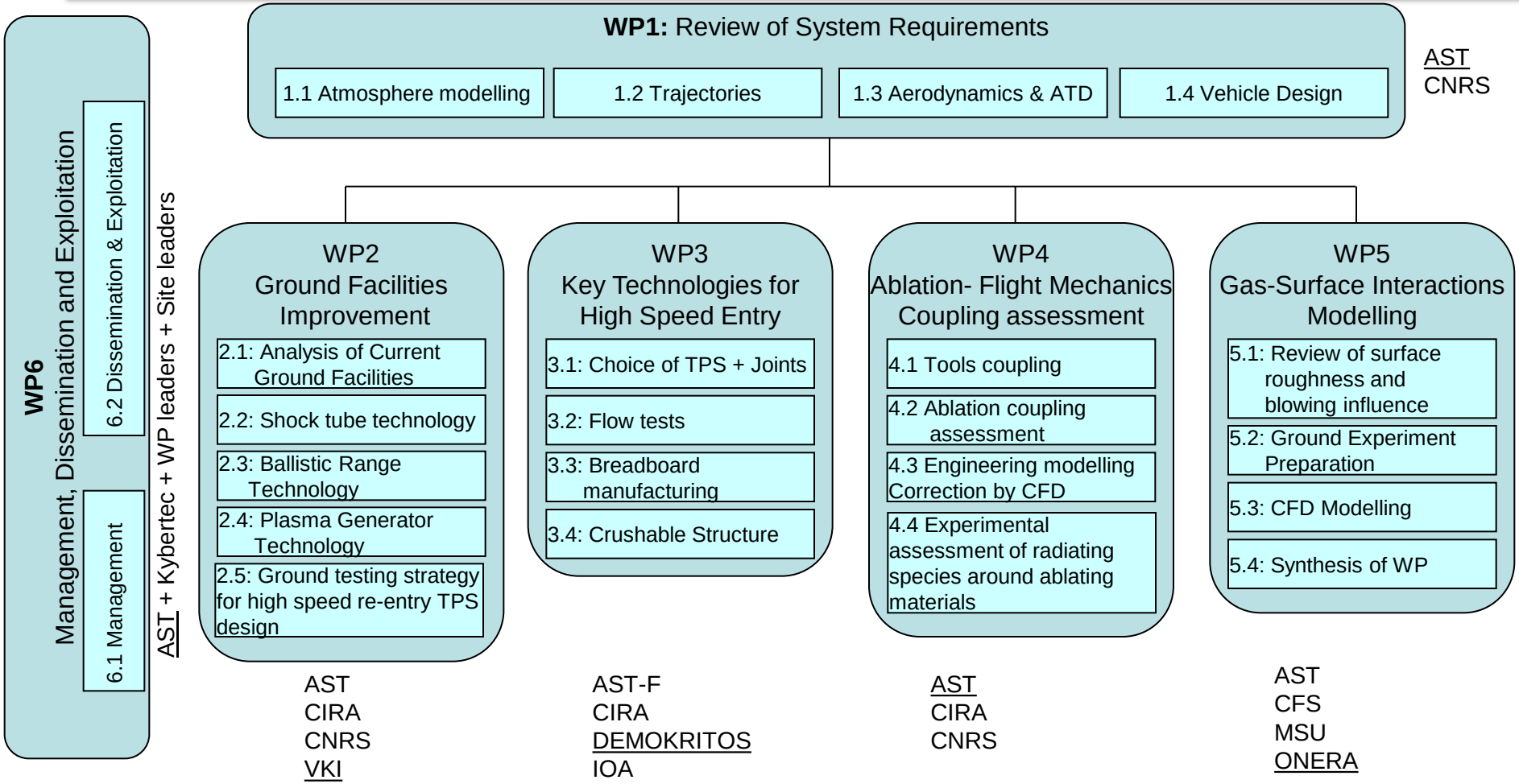
- In the frame of EC FP7 second call
  - Activity 9.2 – strengthening of space foundations / research to support space science exploration
  - SPA.2009.2.1.01 Space Exploration
- Duration
  - Sep 2010 – Apr 2013 (*)
    (*) after 6-month extension
- Status :
  - Team composed of 10 partners
  - Astrium is the coordinator
- Budget
  - total : 2.3 M€
  - including 1.6 M€ EU grant
- More at www.rastas-spear.eu

SEVENTH FRAMEWORK PROGRAMME

10 partners from 8 European countries



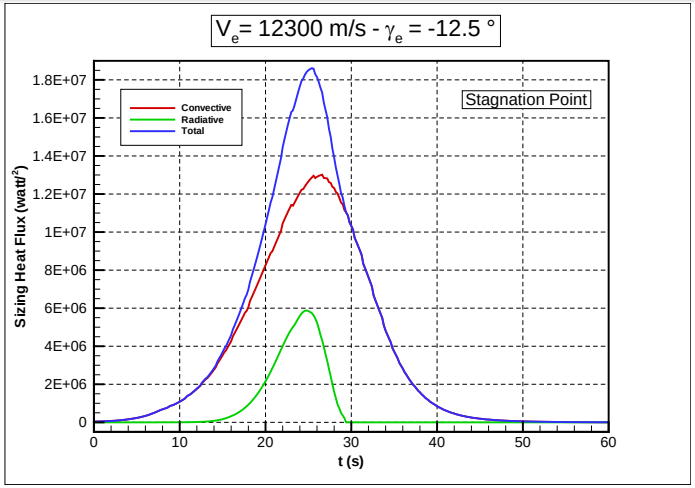
WBS


WP6
Management, Dissemination and Exploitation
6.1 Management
6.2 Dissemination & Exploitation
AST + Kybertec + WP leaders + Site leaders
WP1: Review of System Requirements
1.1 Atmosphere modelling
1.2 Trajectories
1.3 Aerodynamics & ATD
1.4 Vehicle Design
AST
CNRS
WP2
Ground Facilities Improvement
2.1: Analysis of Current Ground Facilities
2.2: Shock tube technology
2.3: Ballistic Range Technology
2.4: Plasma Generator Technology
2.5: Ground testing strategy for high speed re-entry TPS design
AST
CIRA
CNRS
VKI
WP3
Key Technologies for High Speed Entry
3.1: Choice of TPS + Joints
3.2: Flow tests
3.3: Breadboard manufacturing
3.4: Crushable Structure
AST-F
CIRA
DEMOKRITOS
IOA
WP4
Ablation- Flight Mechanics Coupling assessment
4.1 Tools coupling
4.2 Ablation coupling assessment
4.3 Engineering modelling Correction by CFD
4.4 Experimental assessment of radiating species around ablating materials
AST
CIRA
CNRS
WP5
Gas-Surface Interactions Modelling
5.1: Review of surface roughness and blowing influence
5.2: Ground Experiment Preparation
5.3: CFD Modelling
5.4: Synthesis of WP
AST
CFS
MSU
ONERA

WP 1 results: Review of System Requirements

- WP 1.1: Atmosphere modelling
  - Atmosphere compositions for Earth and Venus,
- WP 1.2: Trajectories
  - Identification of generic aeroshapes with respect to candidate exploration missions.
    - Investigation focused on Earth entry,
  - Flight domain determined with constraints on:
    - max heat flux, max heat load, max g-load
- WP 1.3: Aerodynamics & Aerothermodynamics
  - Convective and radiative heat flux
- WP 1.4: Vehicle design
  - Preliminary design of the generic capsule, and determination of TPS thickness
    - Definition of the Mass Centering and Inertia (MCI)
  - Preliminary TPS related requirements for other WP : surface recession, mass loss, temperature evolution, gas flow rate,…

→ *See details on IPPW8 poster and paper*

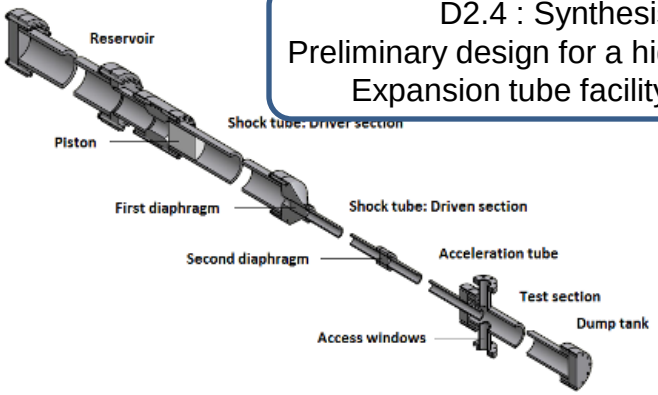


Sphere cone 45°
Diameter D =1100 mm
Nose radius Rn = 275 mm
Mass m = 46.6 kg

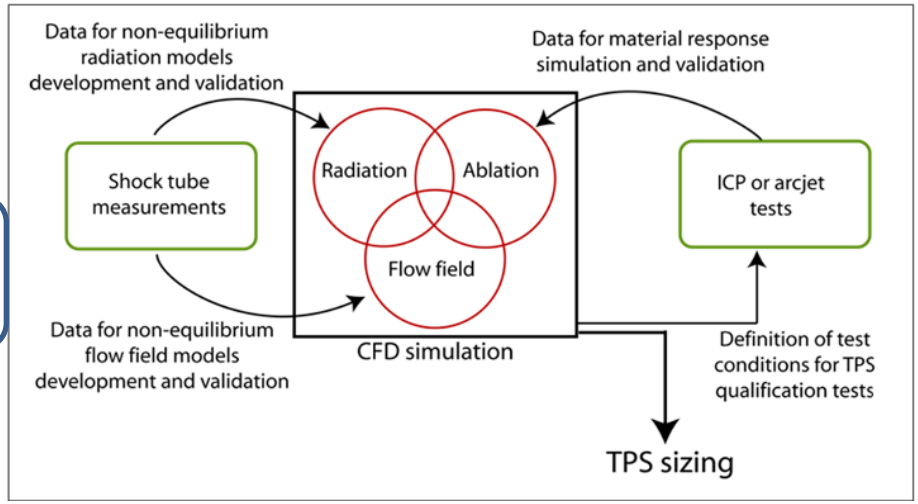
WP2: Ground Facilities Improvement

D2.1 : Review on High Enthalpy Facilities
Only few facilities (in blue) are able to duplicate super orbital reentry conditions

D2.4 : Synthesis
Preliminary design for a high Enthalpy Expansion tube facility : HEX



D2.5 Testing strategy for super-orbital reentry
The testing strategy involves hyper velocity facility together with plasma wind tunnel to develop radiation and GSI models to be coupled with CFD tools.



For more details, see IPPW9 presentation
Reports are also available on website
www.rastas-spear.eu

WP3: Key Technologies for High Speed Entry Choice of TPS + joints

WP3.1 : choice of TPS + joints

- Based on ASTERM material
- Elaboration of a relevant set of criteria
- Screening of adhesives
  - → 2 products compared with ref CV1142
- Elementary characterisation
  - (shear, bending, tensile)

WP3.3

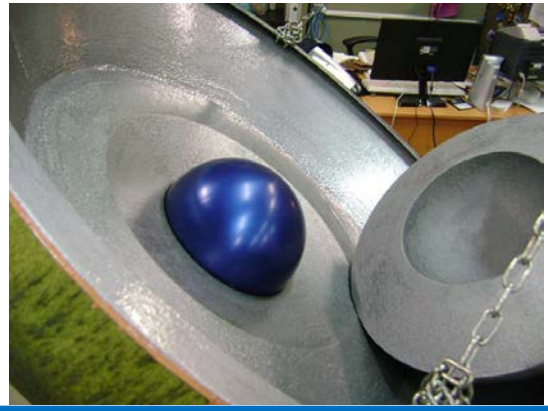
- Manufacturing of a demonstrator
  - Final diameter 92.5cm
  - Bonds and joints about 1-1.5mm max.
  - Outer surface finished in one operation
  - TPS thickness 56mm
- Manual methodology
  → low cost prototype
- Potential for further improvement, using greater precision tooling
- Capability for actual implementation, provided current dimensional tolerances are relaxed to some extent

Bending test

Shear test

Demonstrator with ASTERM TPS

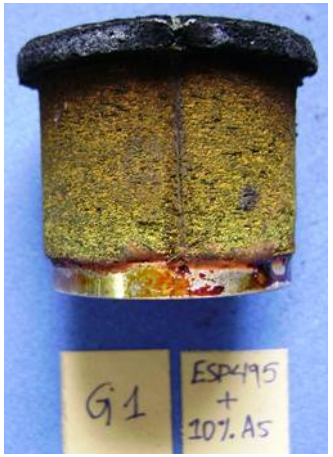
Crushable material insert and sample sphere



WP3: Key Technologies for High Speed Entry Choice of TPS + joints

WP3.2

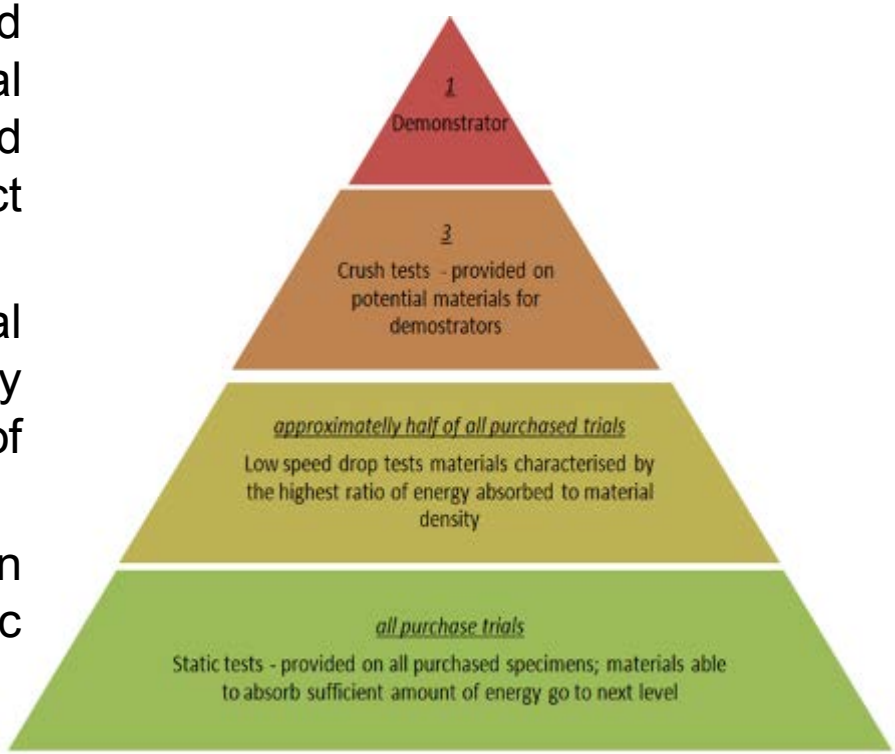
- Manufacturing of samples for testing on Scirocco
  - One test done, at 5 MW/m²
  - Then, campaign stopped due to unavailability of facility
- New test campaign had to be prepared on DLR L3K
  - 15 tests performed with various joint materials
  - Tests at 6 and 13.6 MW/m²
- Then analysis of the tests results
  - CV1142 and ESP495 display good erosion resistance at 6 MW/m²
  - At 13.6 MW/m², erosion becomes more important
  - Interest to add Asterm powder to the adhesive as reinforcement



For more details, see specific presentation at 7th ESA TPS Workshop

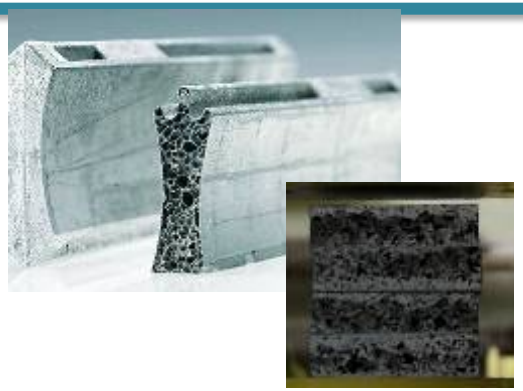
WP3.4. Crushable Structures General overview

- Main task of the research: developing methodology for selection and evaluation of energy absorbing material based on numerical simulations coupled with simple shape specimens impact tests
- Selection of energy absorbing material for max. deceleration approximately 2000 g, and a defined set of requirements
- Developed methodology based on complementary static and dynamic tests

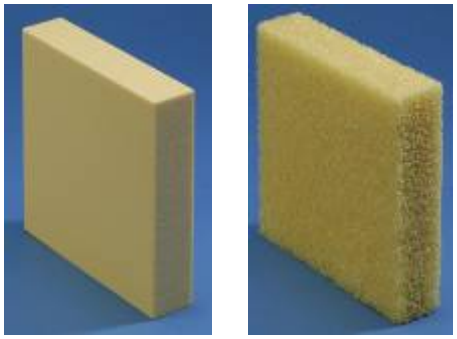


WP3.4. Crushable Structures Material screening (examples)

Soft PU foam with Al coating ; 30-40 kg/m3

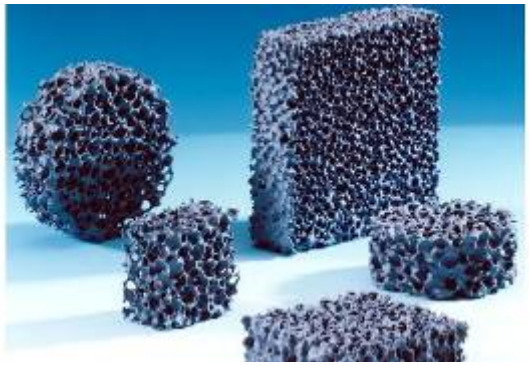


Metallic foam/ hard ALSi alloy ; 500 kg/m3



Solid / cellular PU foam 85 to 280 kg/m3

Metallic foam/ hard ALCaTi alloy 250 kg/m3



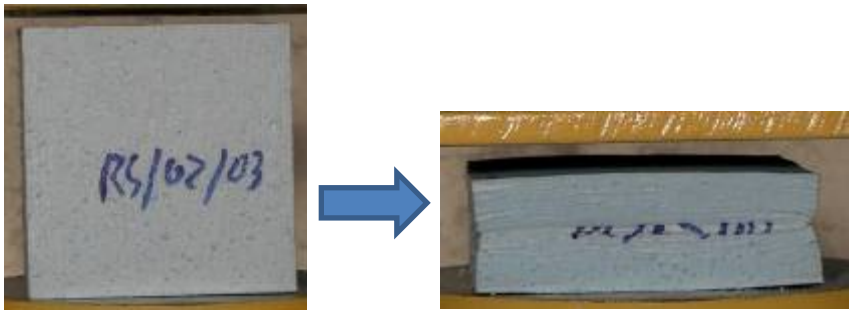
Ceramic foam 400-500 kg/m3

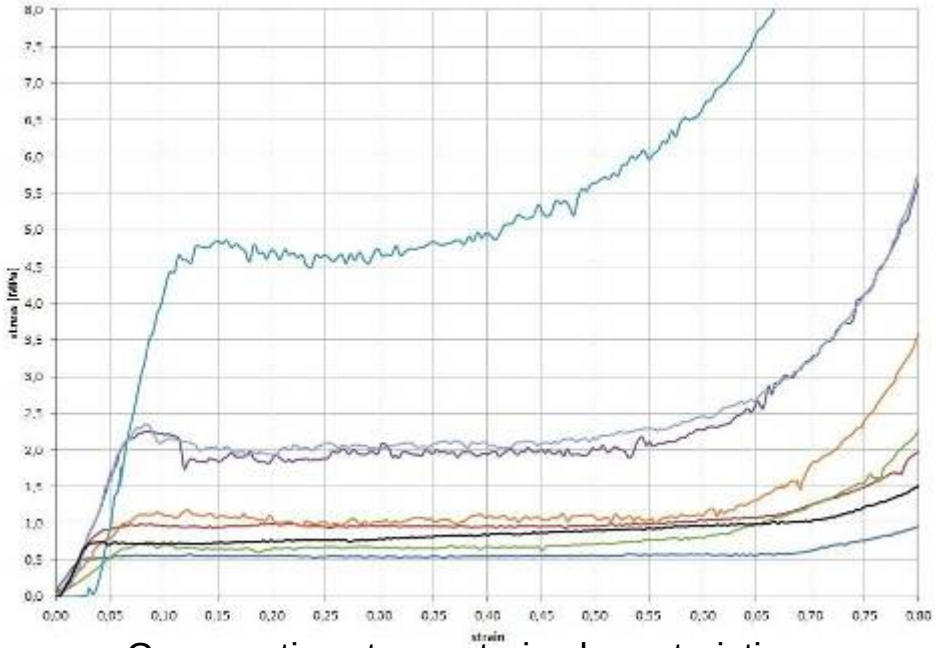
Polymeric foam/ medium Extruded Polystyrene (XPS) 45 kg/m3

WP3.4. Crushable Structures Static tests

- Static tests on cubic samples 100 x 100 x 100 mm
- Determination of stress-strain characteristics

→ static experimental data then used as inputs for dynamic numerical simulations

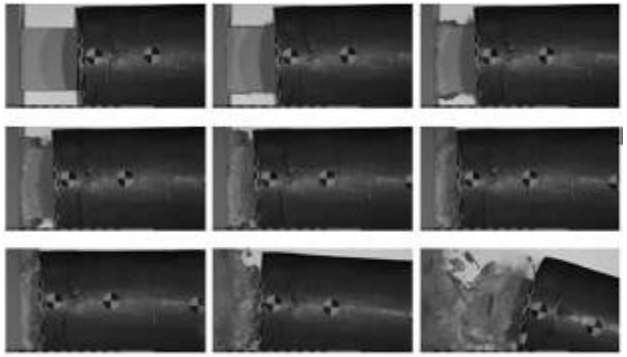


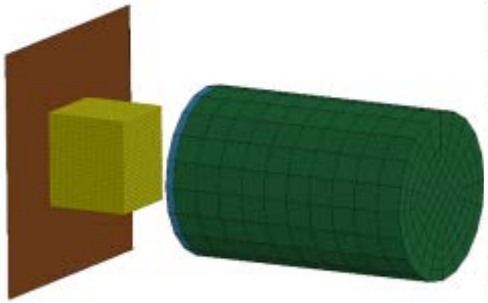


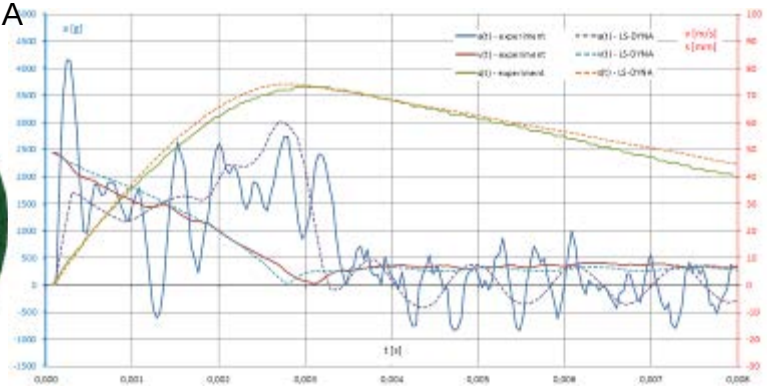
Comparative stress-strain characteristics determined for various materials

WP3.4. Crushable Structures High Speed Tests

- Air canon calibration and testing using 1.6 kg bullet
- Cubic samples 100 x 100 x 100 mm
- Selected impact velocity at 45 m/s
- First-stage high-speed camera tests for finding optimal experiment setup
- Final calibration for impact tests (high-speed camera settings, lighting, position etc.)
- Image analysis using TEMA motion → position vs time
- Improved numerical SPH and FEM LS-DYNA model for testing crushable foam materials
- Good correlation between numerical and experiment data numerical SPH and FEM LS-DYNA



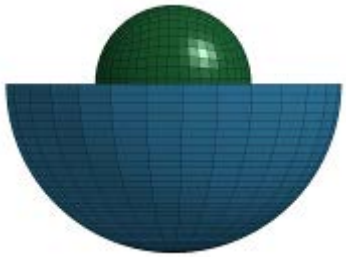


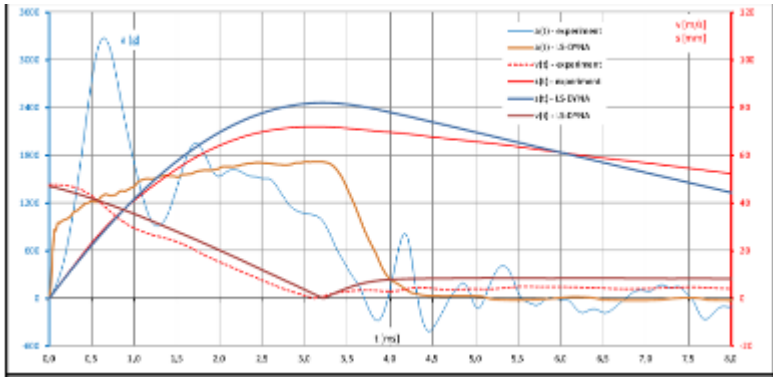


Comparison of experiment and numerical data for SR10 material

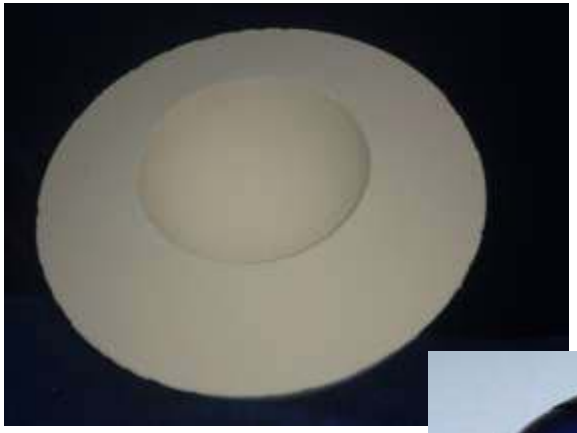
WP3.4. Crushable Structures High Speed Tests – full scale

- Full-scale impact test of chosen material for:
  - bullet mass m=5 [kg]
  - impact velocity v= 45 [m/s]
  - material thickness t = 0.115 [m]
- Test data analysis and excellent comparison with numerical simulation





WP3.4. Crushable Structures Conclusions



- Efficient methodology based on a two-step experimental approach
- Numerical simulation using static tests results giving good correlation between static and dynamic simulations
  - Validity demonstrated for PU foams – other types of materials should be verified
  - It is possible numerically to simulate various geometries based only on static test results
- High speed camera and picture analysis software works perfectly with project application
- After setup pneumatic cannon test procedure allows to perform 10 – 12 tests per day – efficient methodology
  - Using pneumatic cannon for dynamic test gives important energy differences with small velocity variation
- Finally, delivery of a representative breadboard to be integrated within the technological demonstrator

WP4: Ablation – flight mechanics coupling assessment Work logic

For more details, see specific presentation at 7th ESA TPS Workshop

Based on WP1 results as inputs : flight environment, vehicle configuration

WP4.1 – Tools Coupling (AST)
Coupling of following tools:

- Ablation & thermal TPS response code including Aeroshape modification
- Shock shape & - Pressure distribution & - Aerodynamic coefficients determination by CFD code, including ablation gas products injection
- 6 DoF Trajectory Tool

WP4.2 – Tools Coupling Assessment (AST)

- Assessment of Ablations-flight mechanics effects for candidate Earth Entry capsule
- Sensitivity to TPS ablative properties
- Identification of requirements for maximum TPS recession

WP4.3 – Engineering modelling
Correction by CFD (AST – CIRA - CNRS)

- Assessment of Aeroshape modification (CIRA)
- Assessment of Radiation (CIRA-CNRS)
- Assessment of Surface mass blowing (CIRA)
- Development of engineering tool to determine radiating heating vs. recession rate (AST)
- Engineering correlation derivation from CFD computations (AST)

WP4.4 – Experimental assessment of radiating species around ablating materials (CNRS)

Synthesis (AST)

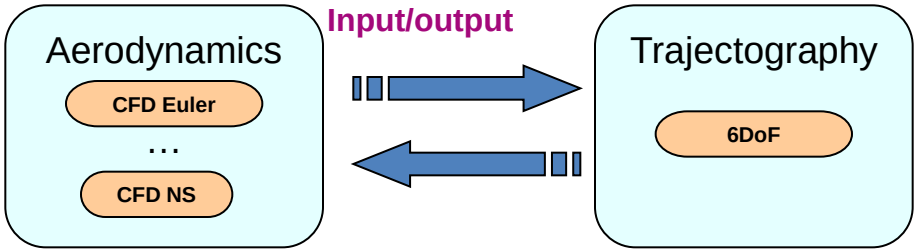
WP 4.1 – Tools coupling

Main Objectives

- To assess impact of massive ablation on aerodynamic performances and stability along the entry trajectory path.
- To elaborate and validate a coupled engineering tool

Main requirements:

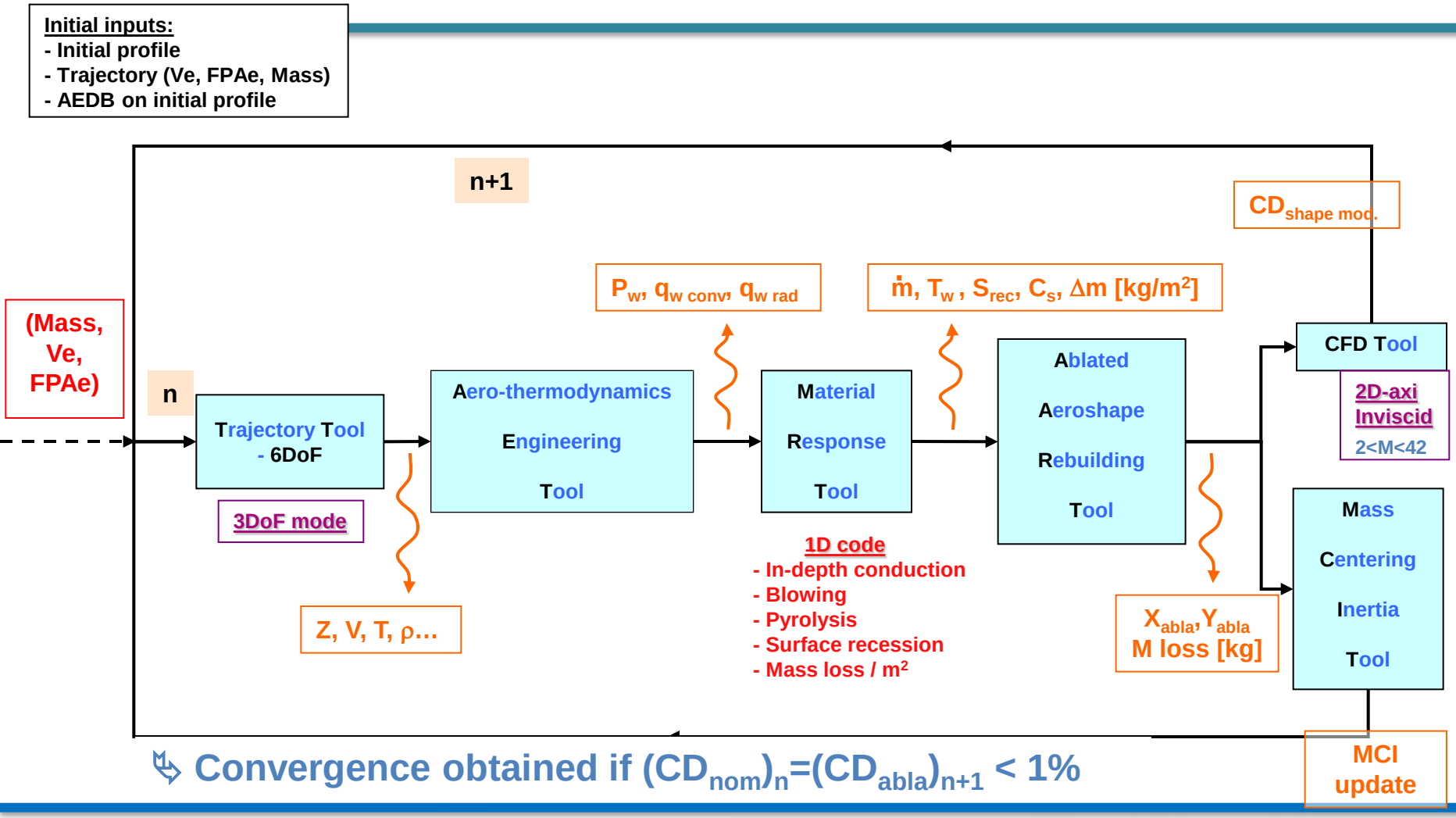
- Modular tool:



↳ **To permit easily the change of module (software) inside a functional class**

- Robustness:
  - ↳ **High requirement of robustness is needed for high speed entry**
- Evolutionary tool:
  - ↳ **Basic requirement for software**
- To perform a complete trajectory within 12 CPU hours
  - ↳ **To keep the Engineering tool spirit**

WP 4.1 – Tools coupling



↳ Convergence obtained if $(CD_{nom})_n=(CD_{abla})_{n+1} < 1\%$

WP 4.2 – Ablation coupling assessment

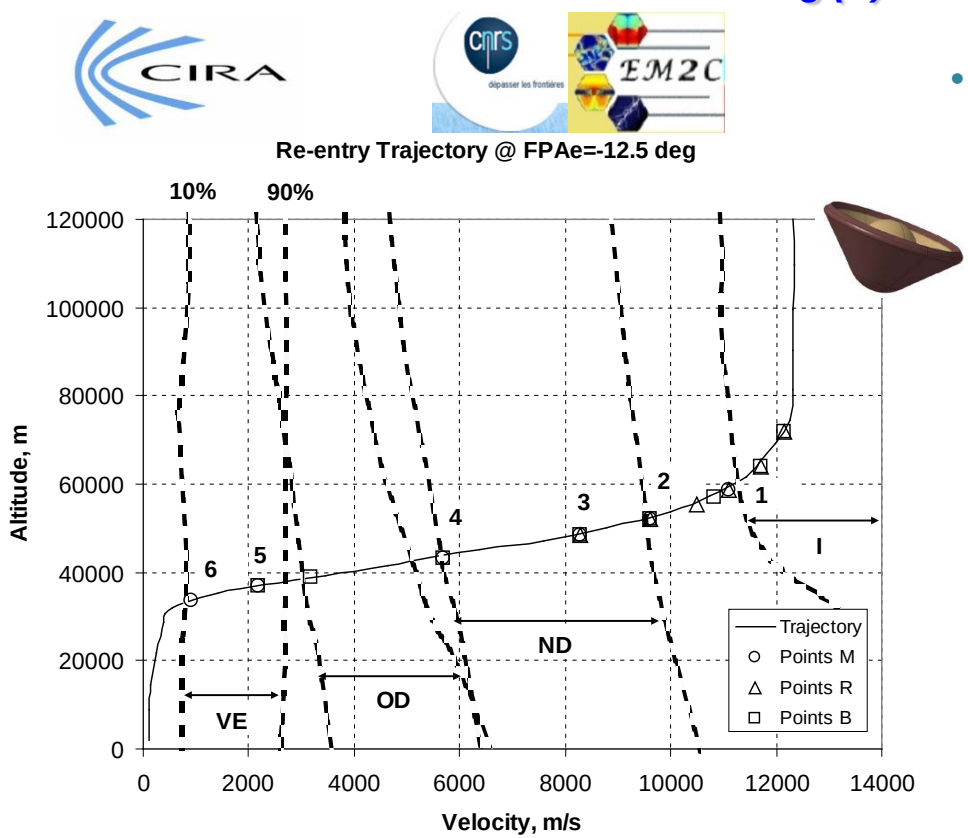
- Trajectory analysis – Summary

Parameters	Effects compared with nominal case	Maximum levels difference	% vs nominal case	Criticality
Velocity	⇘	50 ⇔ 75m/s	~1 %	Low
Mach	⇘	0.15 ⇔ 0.25	~1 %	Low
Deceleration	⇗	-0.5⇔1g	1 % ⇔ 1.5 %	Low
Dynamic pressure	⇘	0.9⇔1.3kPa	3 % ⇔ 3.5 %	Medium
Stagnation pressure	⇘	2⇔3kPa	2.5 % ⇔ 4 %	Medium
Heat Fluxes	⇘	<100W/m^2	~0 %	Negligible
Heat Load	⇘	1.5⇔2.5MJ/m^2	1 % ⇔ 2 %	Medium
Range	⇘	0.8⇔1.4km	~0.3 %	Low

Assessment of tools coupling:
On the considered Rastas Spear trajectories (12.3 km/s), the aeroshape modification due to ablation is limited, and hence a low influence is observed on trajectory, heat fluxes and MCI

WP4.3 – Engineering Modelling Correction by CFD

Task # 1: Assessment of aeroshape modification (M)
Task # 2: Assessment of Radiation Coupling (R)
Task # 3: Assessment of Surface Mass Blowing (B)



- Complex CFD analyses were run to assess these various aspects
  - Not all results were satisfactory, and consolidation is required for several points
- Aerodynamic coefficient
  - CFD computations show that current correlations are valid (to be consolidated for high velocities)

Convective heat flux

- Correlations used for coupling tool are kept by conservatism
- No firm trend may be derived from current CFD computations, which require further consolidation

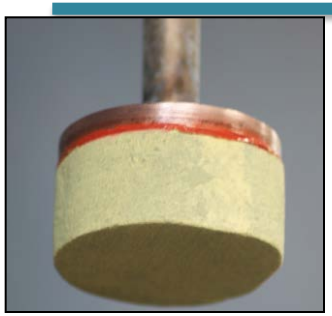
Radiative heat flux

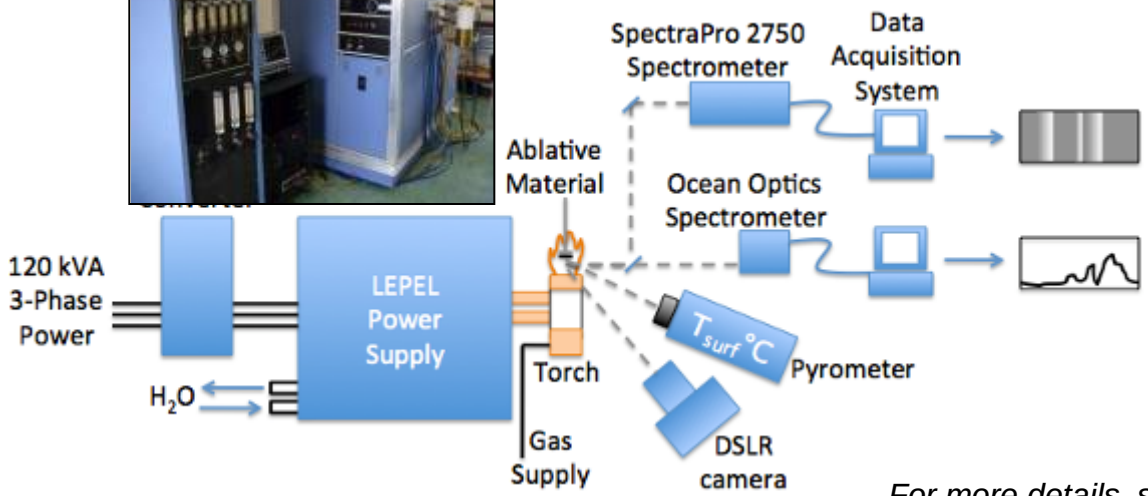
- Correlation can be updated (confirmed reduction of shock stand-off distance on stagnation line)
- Anticipated reduction of level of radiative heat flux
- To be extended for a larger range of entry velocities

Synthesis

- Tools coupling:
  - A first version of the coupling tool is available and has been used for assessment tasks in WP4.2 activities
  - All the requirements are completed
  - Further work needed on following points
    - The aeroshape modification in Transsonic/Subsonic domain cannot be taken into account in this version ⇨ the use of NS computations seems to be the best way ⇨ strong investment on mesh activities, CPU time⇗ and impact on robustness
    - Rarefied domain must be examined
- Assessment of tools coupling:
  - Low influence observed on considered trajectories
  - High interest to evaluate the tool for more severe trajectories

WP4.4 – Experimental assessment of radiating species around ablating materials





- RF plasma torch facility and associated optical diagnostics implemented at CNRS
- Designed to support cylindrical ablator coupon (ASTERM, CBCF, ...) in the plasma stream
  - Water-cooled sting holds a 5 mm thick, 40 mm diameter copper disk
- Two surface T° measurements and two spectrometers
  - Acton SpectraPro 2750
  - OceanOptics USB2000+
- Material temperature and species concentration profiles have been measured in the boundary layer, showing spallated particles, sodium emission, plasma recombination
- Fully operational facility ready for more testing
  - Higher power and heat flux
  - Search for more species (C,C2, C3)

For more details, see specific presentation at 7th ESA TPS Workshop

WP5: Gas-surface interactions modeling

- WP 5.1 Review of surface roughness
  - Bibliography about roughness and blowing (Onera/MSU)
  - Turbulence model recommendations (MSU/Onera)
  - Critical analysis from real flight (Astrium/MSU)
- WP 5.2 Ground experiment
  - Tests in Mach 5 blow down wind tunnel (Onera)
  - Test analyses (Euler + boundary layer)

→ **Next slides**

- WP 5.3 CFD modeling
  - Implementation of turbulence models on rough surface (from WP5.1)
  - WTT reconstruction and validation
  - Earth re-entry vehicle computation
- WP 5.4 Synthesis

For more details, see specific presentation at 7th ESA TPS Workshop

WP5: Gas-surface interactions modeling
Experiments in the blow down wind tunnel R2Ch

- **Test Objective** : qualification of the wall heat-flux with roughness effects and different blowing rates
- Performance of 31 runs with various test conditions
  - without blowing (reference case)
  - with a moderate blowing (0,6 kg/m²/s)
  - with a maximal blowing (1,2 kg/m²/s)
  - On smooth or rough samples
- **Wind tunnel characteristics :**
  - Mach 5 nozzle with an
  - exit diameter : 326 mm
  - p_{st} : from 7 10^5 Pa to 50 10^5 Pa ; T_{st} = 650 K
  - Re (L=1 m) = from 5.95 10^6 to 42.5 10^6

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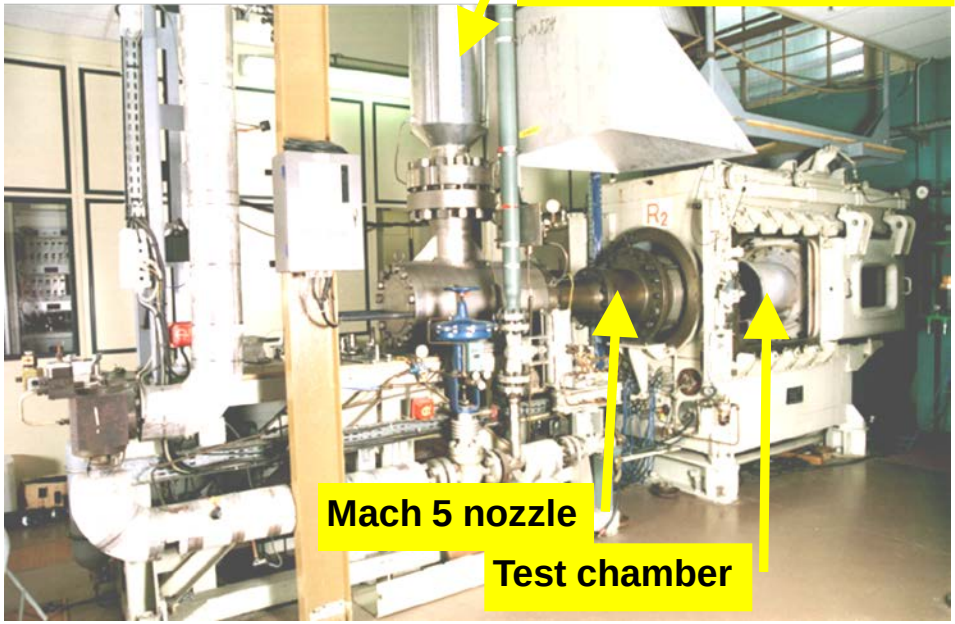

WP5: Gas-surface interactions modeling
Experiments in the blow down wind tunnel R2Ch

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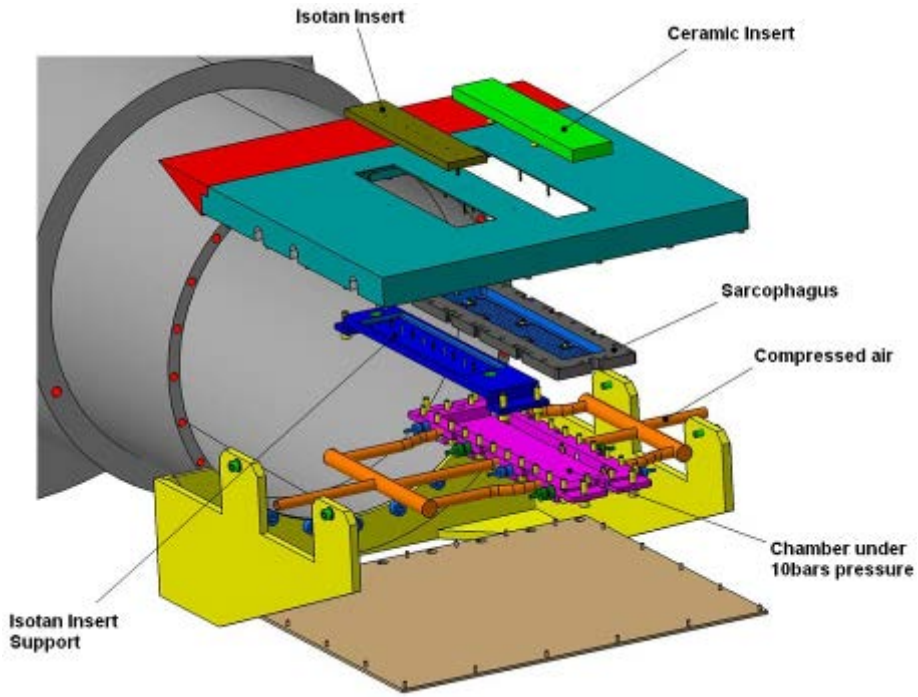
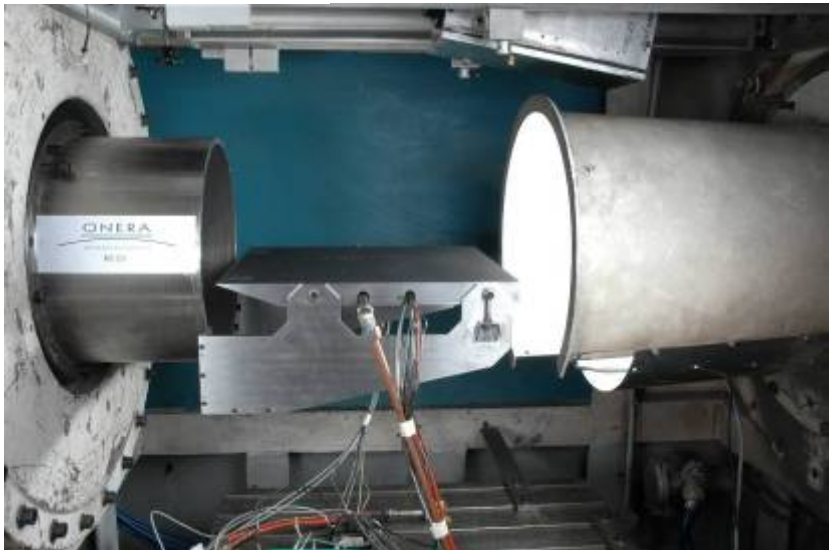
Exploded view of the test set-up



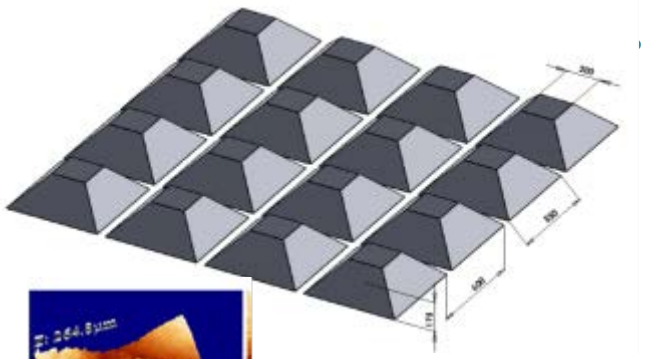


- **Model :** Flat plate with a sharp leading edge, already available from a prior test campaign

During tests :
- Heat flux measurements by infrared thermography,
- Schlieren photographs

WP5: Gas-surface interactions modeling

ONERA
THE FRENCH AEROSPACE LAB

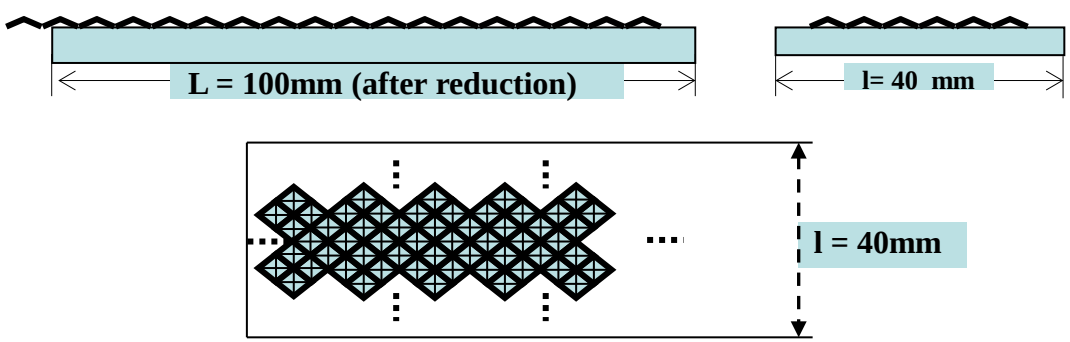


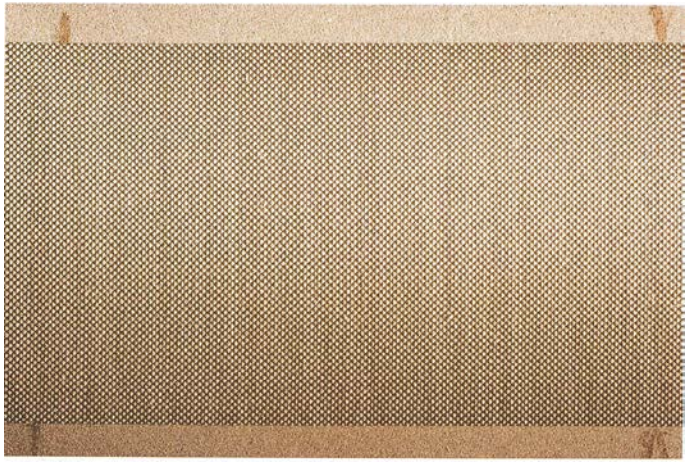
Two porous ceramic insert (porosity 48 %)

- without roughness

- with roughness r1 (pyramid height 176 ±34 µm)

- characteristics of the roughness : truncated pyramids (base ~550 µm) in staggered rows

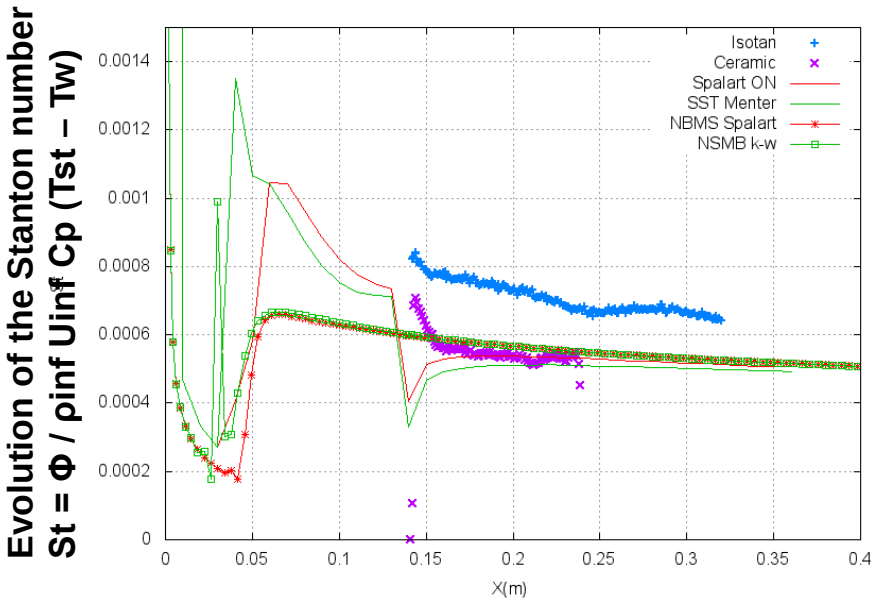




Top view of the rough insert

WP5: Gas-surface interactions modeling
WTT reconstruction and validation (CFD & BL)

Example of reconstruction
Run 3782: no blowing, no roughness



- Lot of valuable experimental data have been acquired
- Computations and comparison with the experimental data, after implementation of both roughness and blowing effects in different solvers.
- Good agreement between the different solvers
  - Boundary Layer Euler solver (ONERA)
  - NSMB - Navier-Stokes Multi-Blocks (CFS)
- No obvious best choice between Spalart and k-w models
- Wall blowing : Correct agreement of CFD simulations
  - Small blowing mass flow case well predicted by all models
  - Strong blowing mass flow case evidences the lack of a blowing correction for the Spalart and Allmaras model
- Wall roughness
  - Key issue: models predict heat flux increase, while experiment show heat flux decrease. Remains unexplained.
- Wall roughness + blowing cases are more complicated to simulate
  - Models which cannot account for wall blowing (Spalart, k-w) predict lower (too low?) levels

Conclusion

- Rastas Spear is a typical R&D project
  - Part of European Community Framework Programme n°7 (FP7)
- Well defined framework for the study
  - Focus on passive Earth Return Capsule
  - Target missions MarcoPolo-R, Phootprint, MSR…
- Successful achievement of the objective to increase the TRL of
  - Key technologies
  - Methodologies
- Completion of overall project objectives by end of April 2013
  - Finalization of the last actions and documents until end of study
- Highly valuable step towards an actual flight mission

Thank you for your attention

More at www.rastas-spear.eu

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