

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

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ABSTRACT / INTRODUCTION:

An important step for Space Exploration activities and for a more accurate knowledge of the Earth, universe and environment is to develop the capability to send vehicles into space, which collect and return to Earth samples from solar system bodies. To return these samples, any mission will end by high-speed re-entry in the 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 Exploration missions such as Mars Sample Return. Rastas Spear project started in September 2010, with the main objective to increase Europe's knowledge in high speed re-entry vehicle technology to allow for planetary exploration missions in the coming decades.

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

The project's main objective can be sub-divided into sub-objectives as follows:

- **OBJ1:** To better understand phenomena during high speed re-entry, enabling more precise Capsule sizing and reduced margins,
- **OBJ2:** To identify the ground facility needs for simulation,
- **OBJ3:** To master heat shield manufacturing techniques and demonstrate heat shield capabilities.
- **OBJ4:** To master damping at ground impact and flight mechanics and thus ensure a safe return of the samples.

This study is carried out by a consortium of 10 European companies and institutes: VKI (B), Kybertec (Cz), Demokritos (Gr), IoA (PI), CIRA (I), CFS (CH), MSU (Ru), CNRS and ONERA (F), and coordinated by Astrium (F).

The aim of this paper is to present the organisation, objectives and main actions proposed in the RASTAS SPEAR project, to enlarge the basic capabilities on some specific topics such as:

- Aeroshape stability
- High speed aerothermal environment
- Sub-system / equipment : Thermal protection, Crushable material

1 - SCOPE

1.1 - PROJECT OVERVIEW

This project is being funded from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 241992. It was approved within EC FP7 second call, as part of the following topics:

- Activity 9.2 – strengthening of space foundations / research to support space science exploration
- SPA.2009.2.1.01 Space Exploration

This 26 month project started in September 2010, and it is scheduled to be completed at the end of October 2012. The total budget is about 2.3 M€, including about 1.6 M€ grant from the European Commission.

The team is composed of 10 partners from 8 European Countries (see Table 1), Astrium being the coordinator.

More information can be found on the project website at www.rastas-spear.eu

Partner	Country
ASTRIUM-ST SAS	France
CIRA : Centro Italiano Ricerche Aerospaziali	Italy
CFS Engineering	Switzerland
NCSR Demokritos	Greece
CNRS	France
IoA : Institute of Aviation	Poland
KYBERTEC	Czech Republic
MSU : Lomonosov Moscow State University	Russia
ONERA : Office National d'Etudes et de Recherches Aéropatiales	France
VKI : Von Karman Institute for Fluid Dynamics	Belgium

Table 1 Partners involved in Rastas Spear project

1.2 - MOTIVATION FOR RASTAS SPEAR PROJECT

As mentioned in the introduction, Sample Return Missions are considered as an important step for Solar System Exploration. Some essential technical aspects are reminded below:

- After collecting samples, any return mission will end by high-speed re-entry in the Earth's atmosphere.
- This requires strong technological bases and a good understanding of the environment encountered during the Earth re-entry.

It was therefore deemed paramount to invest today in high speed re-entry technology development, in order to increase Europe's knowledge in such re-entry vehicle technology and hence pave the way for future planetary exploration missions in the coming decades.

- Mars Sample Return, Marco Polo...

Eventual attractive spinoff is also kept in mind for other potential applications with high speed atmospheric entry:

- ISS return (ARV), Venus Exploration (EVE-VEP)

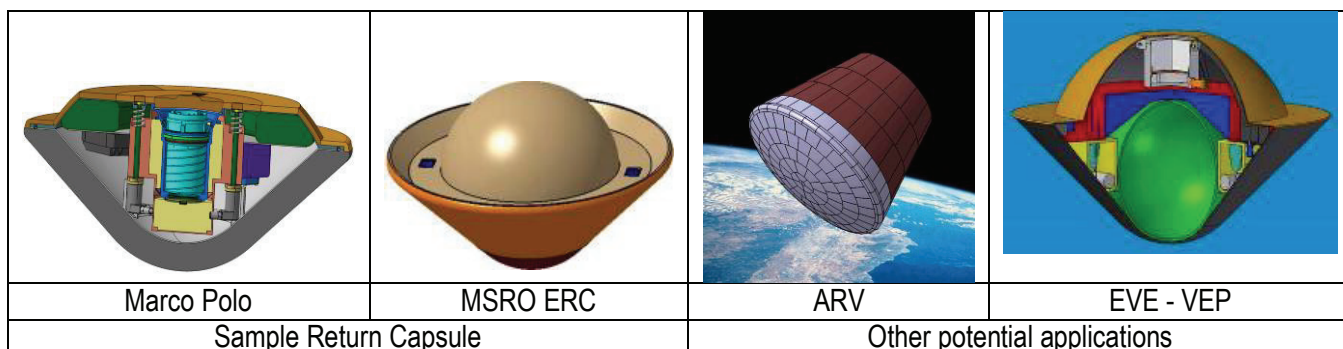


Figure 1: Future European atmospheric entry missions with high speed entry

1.3 - TECHNICAL ORGANISATION

In order to achieve the project goal, the main objective is derived in sub-objectives as follows and adequately split in 6 Work Packages (see Figure 2) that address these different sub-objectives:

- **OBJ1 (WP1, WP2, WP4 + WP5):** To better understand phenomena during high speed re-entry enabling more precise Capsule sizing and reduced margins.
- **OBJ2 (WP2) :**To identify the ground facility needs for simulation
- **OBJ3 (WP3):** To master heat shield manufacturing techniques and demonstrate heat shield capabilities.
- **OBJ4 (WP3+WP4) :** To master damping at ground impact and flight mechanics and thus ensure a safe return of the samples

WP1 was completed during the first quarter of the project, and defined the required inputs towards the four other technical WP, which are conducted as parallel and quite independent tasks.

The WP 6 consists of two main tasks for the whole duration of the project: the project management, and the coordination of internal and external communication.

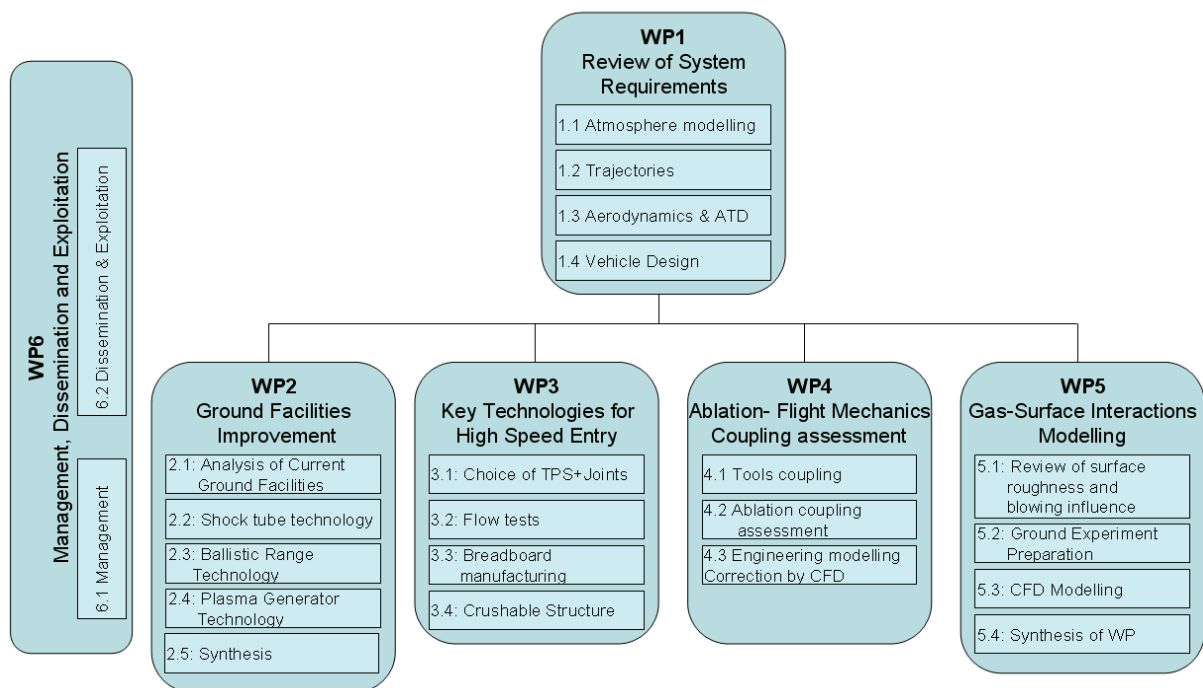


Figure 2: Project WBS

Table 2 below identifies the contributors and leader of each Work Package.

Work Packages titles	WP Participants and Leader
WP1 Review of System Requirements	AST, CNRS
WP2 Ground Facilities Improvement	AST, CIRA, CNRS, VKI
WP3 Key Technologies for High Speed Entry Mastering	AST-F, CIRA, DEMOKRITOS, IOA
WP4 Ablation-Flight mechanics coupling assessment	AST, CIRA, CNRS
WP5 Gas-Surface interactions modelling	AST, CFS, MSU, ONERA
WP6 Synthesis, Management & Coordination	AST + KYBERTEC, + WP leaders

Table 2 Work packages: titles, participants and leaders,

The following sections give a synthesis of the results of WP1, and an overview of the work proposed in other work packages.

WP1: REVIEW OF SYSTEM REQUIREMENTS

This WP deals with the definition of general system requirements for high-speed entry capsules and its main objective is thus to provide with general inputs for any other WP of the project. Among future exploration missions, capsules can experience high-speed entries when samples from any asteroids or planets (Mars Sample Return mission, Stardust, Japanese Hayabusa for instance) are brought back to Earth for instance or when they enter into any solar system Giant planets (Jupiter, Saturn, Uranus, Neptune) for atmosphere science investigation (US Galileo mission for instance).

This WP is divided into four sub-tasks presented hereafter:

The **WP1.1 – Atmosphere modelling** is dedicated to the definition of atmosphere data that are necessary to be identified for any entry vehicle. For Earth or Mars atmospheres, data are available and largely documented (CIRA 88, GRAM, Mars-GRAM, EMCD). For any other planets, it is worth reviewing the atmosphere models available on Venus ($V_e \sim 11.6$ km/s), Saturn, Jupiter, Uranus and Neptune ($V_e \sim 30-60$ km/s). This is particularly important for WP2 task where ground facilities will be identified with respect to the gas composition to be tested.

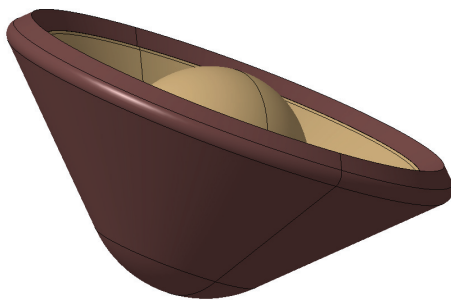
A Thermochemical model (kinetic model + thermal model) has thus been established as reference, with identification of all possible species and chemical reactions. It has been decided to focus on Atmosphere compositions for Earth and Venus, as shown in Table 3 below.

EARTH	VENUS
complete model based on N ₂ , O ₂ and Ar	model based on CO ₂ and N ₂ mixture
simplified model based only on N ₂ and O ₂	

Table 3 Thermochemical atmosphere models available for the project

The **WP1.2 – Trajectories** is dedicated to identification of generic aeroshapes with respect to candidate exploration missions, with focused attention towards Earth entry. Trajectories have been computed including usual design criteria and flight domain has been determined with classical constraints on several parameters (max heat flux, max heat load, max g-load,...) Particular attention however will be paid on sample return to Earth missions.

The main features of the selected shape are summarized on Figure 3, while Figure 4 shows the typical evolutions of some essential aerothermodynamic parameters.



Diameter $D = 1100$ mm
45° half cone angle (
Nose radius $R_n = 275$ mm ($R_n / D = 0.25$)
Shoulder radius $R_s = 27.5$ mm ($R_s / D = 0.025$)
G-load requirement 2000g on the sample canister at impact

Figure 3 : ERC Shape

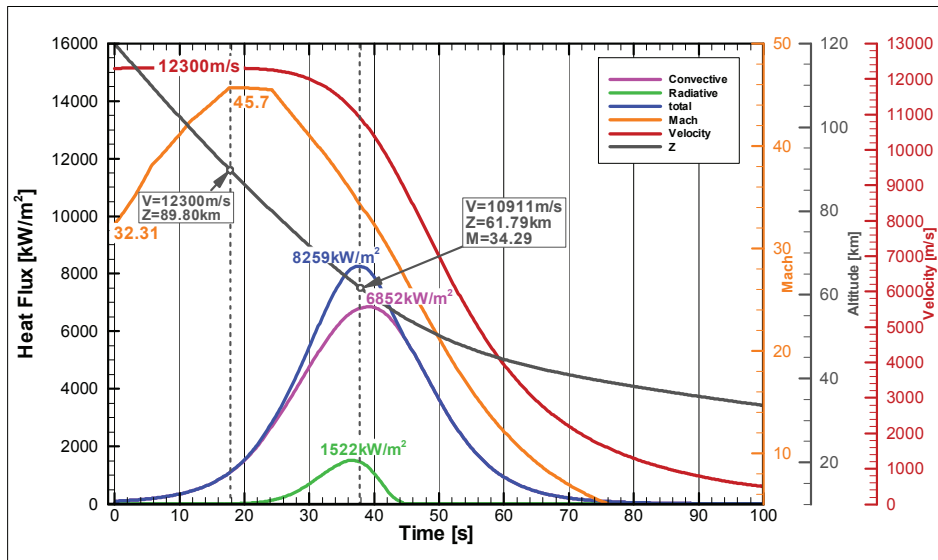
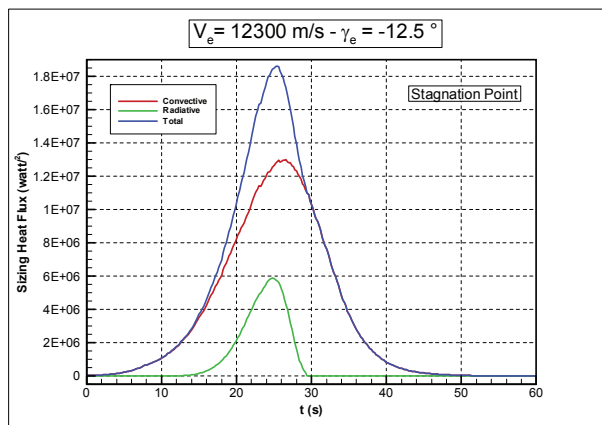
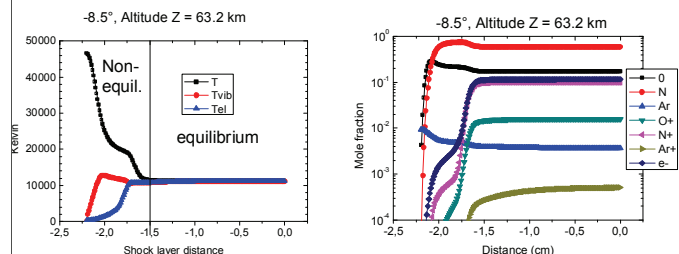


Figure 4: Heat Flux, Mach, Z, V vs. time for the FPAe=-8.5deg @120km trajectory

The **WP1.3 – Aerodynamics and Aerothermodynamics** deals with the aerodynamics and aerothermodynamics characterization of selected aeroshapes. Most of the data are derived from existing database available at Astrium-ST. Aerodynamics results are based on Newton preliminary analyses. Aerothermal environment has been determined using engineering methods for convective heating while radiative heating is based on shock-layer radiation computations with the radiation code SPECAIR of CNRS/Laboratoire EM2C.



Contributions to the radiative flux of the equilibrium and nonequilibrium zones



- Nonequilibrium zone produces less than 19% of the radiative flux
- Less than 8% between -2.2 and -1.7 cm.



Figure 5: Determination of convective and radiative environment

The **WP 1.4 – Vehicle design** aimed at a preliminary design of the generic capsule (see Figure 6), including the determination of TPS thickness, in order to define the Mass Centering and Inertia (MCI) for the given architecture. Preliminary requirements related to TPS for other WP have also been established thanks to 1 or 2D thermal models of the capsule: surface recession, mass loss, temperature evolution, gas flow rate,...

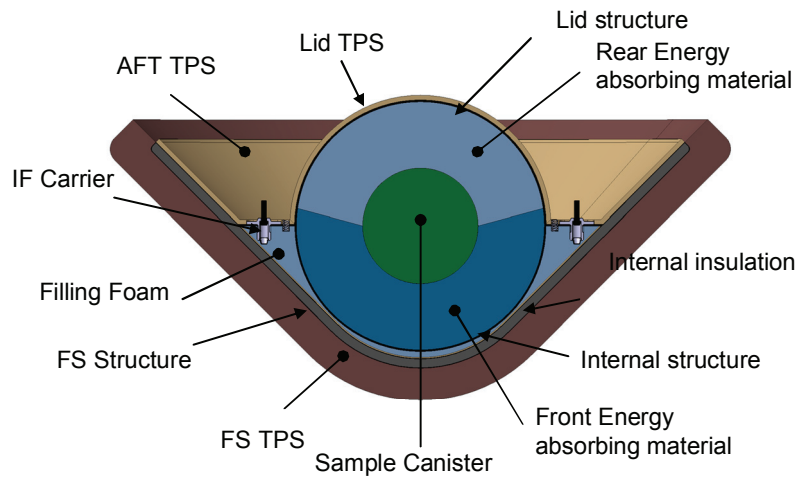


Figure 6 : preliminary ERC design

WP2: GROUND FACILITIES IMPROVEMENT

The general objective of this WP is to identify the ground experimental needs for characterization and qualification of high speed Earth entry capsules. Starting from an investigation of the physical phenomena involved in the range of operation of the different hypersonic facilities (shock tube, ballistic range, plasma wind tunnel), it will lead to the review of the current capabilities and limitations in Europe for high speed re-entry simulations.

This analysis should also address the operational principles of such facilities with their testing methodology, as well as the measurement techniques equipment dedicated to the testing conditions definition.

As shown on Figure 7, two types of ground based facilities are involved to reproduce the typical flight environment:

- **Shock tube/ Shock tunnels** duplicate the **shock layer** and generate database for the **radiation features**
- **Plasma wind tunnels** duplicate the boundary layer around the vehicle and allow **TPS qualification**

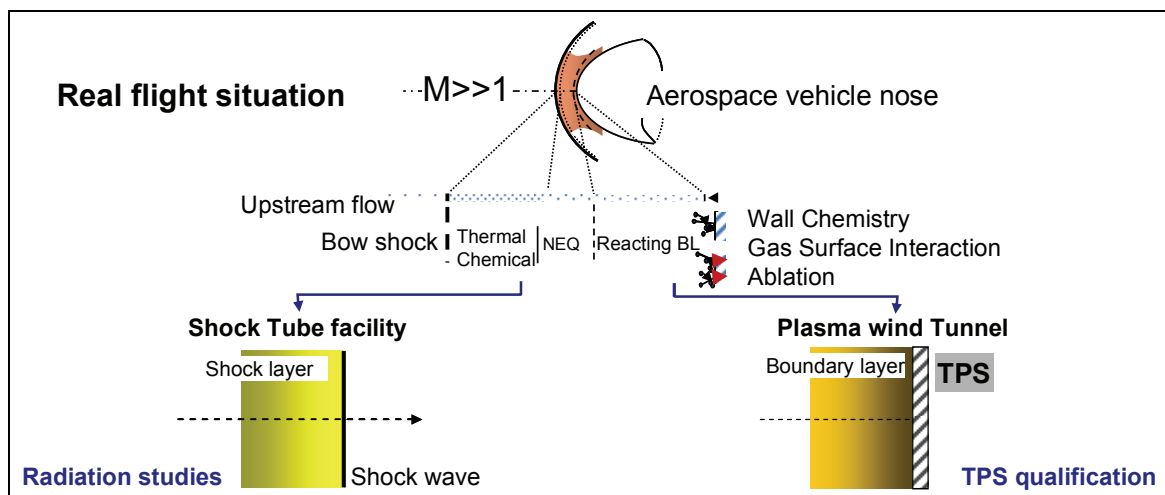


Figure 7 : ground testing strategy for hypersonic entry simulation

WP2 is organized on four WorkPackage activities. WP2.1 will provide a selected review of the most relevant facilities existing worldwide specific to high speed re-entry simulation. WP2.2 will address the operation and related equipment of shock tube type facilities allowing the generation of radiation databases. WP2.3 will focus on plasma wind tunnels dedicated to TPS testing and qualification from which gas-surface interaction could be characterized. A global synthesis report will be elaborated in WP2.4. On top of the review, recommendations will be expressed for required performances of test facilities and associated methodologies to be used in characterisation and qualification of high speed Earth atmosphere entry capsules. Finally, a preliminary definition of a **hyper-velocity facility** dedicated to super orbital re-entry investigations will be proposed.

WP3: KEY TECHNOLOGIES FOR HIGH SPEED ENTRY MASTERING

Work Package 3 is led by Demokritos and deals with the technologies that need to be developed for the ERC. Specifically, the main objectives of WP3 will be to investigate and develop new and innovative methods, materials and systems for joining the ablative blocks together and to the substructure, to produce a complete Thermal Protection System (TPS) for sample-return missions. Another topic is also considered, related to the crushable material which would absorb the impact forces during the probe's landing on Earth.

WP3 is further subdivided into 4 sub-work-packages whose objectives and tasks are as follows:

WP3.1 - Choice of TPS + joints is being carried out by Demokritos in collaboration with ASTRIUM-F and deals with the identification and development of novel joining and bonding materials for the special ablative tiles and blocks, as identified in WP1. The material for the TPS tiles ("ASTERM") will be manufactured by ASTRIUM-F and the choice of compatible and reliable materials for their bonding is crucial to the success of the TPS. During high-speed re-entry, the generation of gaps and recesses between the ablation blocks can cause run-away ablation leading to potentially catastrophic damage of the protective layer. Many different combinations of materials will be developed and tested for this purpose and a small number will be selected for plasma flow testing. An important consideration will be the development of relatively simple and inexpensive processing and manufacturing methods. Figure 8 below shows a flow chart of the work being carried out.

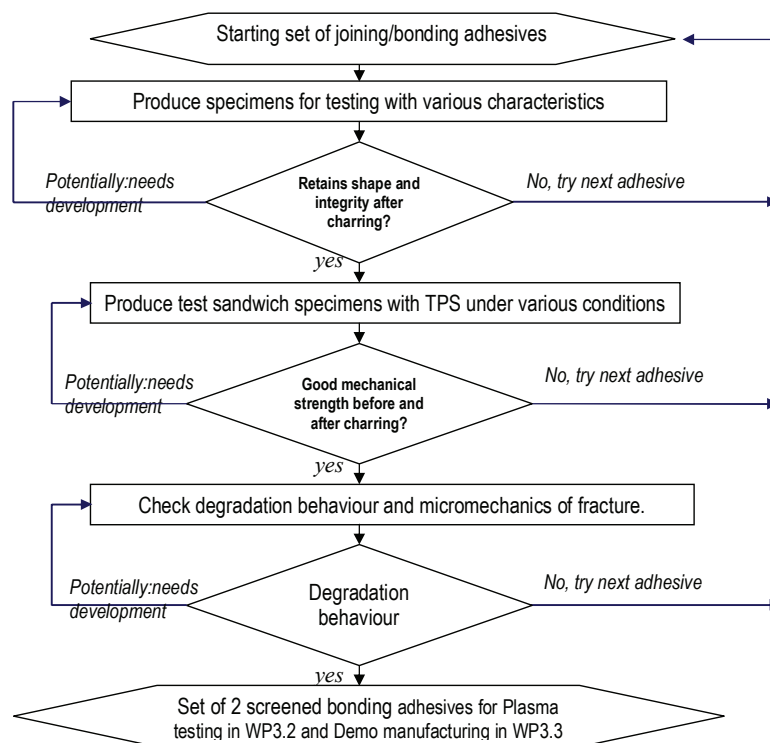


Figure 8 : The flow chart for WP3.1

WP3.2 - Flow tests will take input from WP3.1 and WP1 to design and carry out plasma-jet flow experiments to be carried out by CIRA using the "Scirocco" facility (see Figure 9) of a number of material combinations at heat flux levels up to about 15MW/m² under sample-return mission conditions. Iteration with WP3.1 will thus enable the selection of the best possible material combination.

WP3.3 - Breadboard Manufacturing will then use the results from WP3.1 and WP3.2 to design and manufacture a Demonstrator representative of a TPS shield for a sample-return mission, to demonstrate the feasibility and efficacy of the use of the materials and manufacturing method developed.

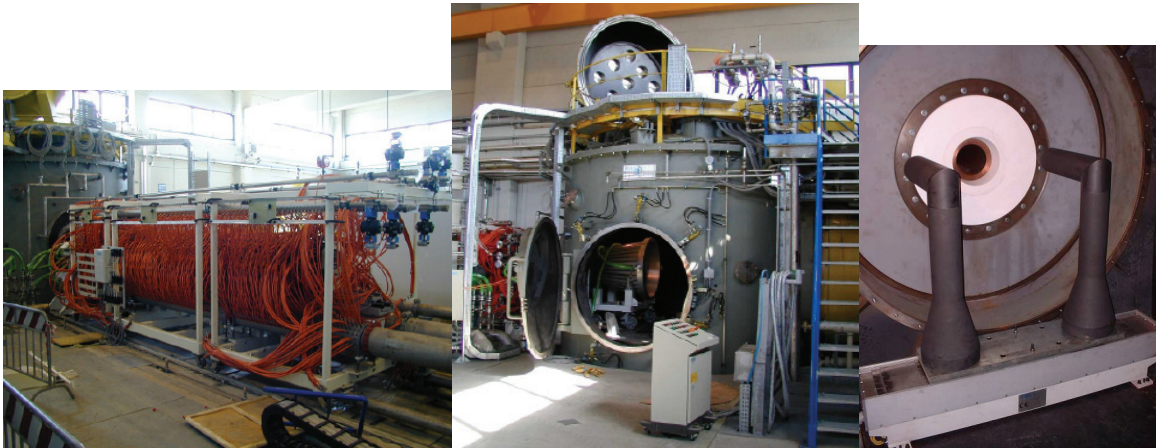


Figure 9 : The SCIROCCO facility at CIRA to be used for WP3.2

Finally, **WP3.4 - crushable structure** is being carried out by Institute of Aviation, Poland. It will run parallel to other activities but will not be strictly dependent to other members of package tasks.

Main objectives of WP3.4 are:

- Propose a suitable impact absorbing material for RASTAS SPEAR project for use in sample-return re-entry vehicles. Investigations are being carried out about state of knowledge, technology readiness and commercial applications of this type of materials. Any modifications in its structure (made by purpose by IoA) should not be excluded.
 - This prospective will rely on a set of requirements established in WP1 : lightweight material, good energy absorber during crush, quasi isotropic, thermally stable and insulator, compatible with vacuum, reproducible manufacturing process
- Provide numerical simulation, calculations and analysis, which will lead to right choice of crushable structure. Create a mathematical model to picture the phenomenon.
- Do the laboratory test to reflect the semi-real conditions of work in ambient, high and low temperatures.
- Select the final material and provide the method and material for assembly on demonstrator.

In order to confirm properties of selected materials the laboratory verification tests must be provided. For this purposes a crush stand designed in Landing Gear Department usually used for tests of airplane and car gears, will be suitably modified to perform desired crush tests. Ensuing step test are presented on Figure 10.

In the first phase all purchased materials will be tested, to verify the assumptions made before the test. In drop test phase quantitative analysis will be provided. Three materials with the best ratio will undergo to the last phase. Crush test will select the most suitable material.

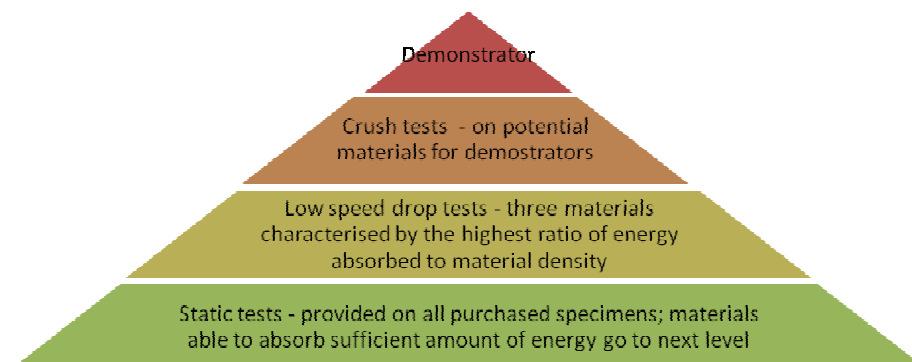


Figure 10 : Graduation of test phase

With the outline of the preliminary data, it can be stated that three main groups of materials (PU foams, Metallic foams, Phenolic and ceramic microspheres) present potential interest to be used as lightweight crushable structure.

WP4: ABLATION-FLIGHT MECHANICS COUPLING ASSESSMENT

The main objective of this WP is to assess the impact of massive ablation on aerodynamic performances and stability along the entry trajectory path. High TPS recession might occur during high-speed entries and it is necessary to identify what recession level could be tolerated with respect to capsule aerodynamic performances and stability requirements. It is necessary to use an approach that couples aeroshape aerodynamic, trajectory and stability, aerothermal environment, TPS material thermal response and recession determination resulting in aeroshape modification. Criteria for maximum recession requirements will be related to usual landing accuracy, g-loads, heating and incidence profile issues.

This WP is divided into three sub-tasks presented hereafter:

The **WP4.1 – Tools coupling** is dedicated to the implementation of coupled analyses tool. Here, existing methodology developed at Astrium-ST will be used. Some adaptations are however required to account for high-speed entry specificities, namely high recession rates and radiative heating. The analysis tools that are coupled (Ablation and TPS thermal response, Aerodynamic and Aerothermodynamic Environment, Trajectory) are mainly engineering tools that require to be corrected by more detailed analyses to be performed in WP 4.3.

The **WP4.2 – Ablation coupling assessment** has two main objectives. The first one is of course to evaluate the influence of the coupling strategy on the results. Then the main goal is the identification and the definition of surface recession or aeroshape change rates requirements that the TPS material must fulfil. These requirements will be used in WP3 tasks.

The **WP4.3 – Engineering modelling correction by CFD** is dedicated to detailed CFD support to WP4.1. The following items should be considered:

- Non-equilibrium radiation,
- Mass blowing influence on convection and radiation,
- Aeroshape change aerodynamics and aerothermodynamics

Flow-field computations will be performed by CIRA while radiation will be analyzed by CNRS. Engineering models will be up-dated/corrected and implemented in the coupled analysis tools by AST in WP4.1. The global work logic is presented hereafter:

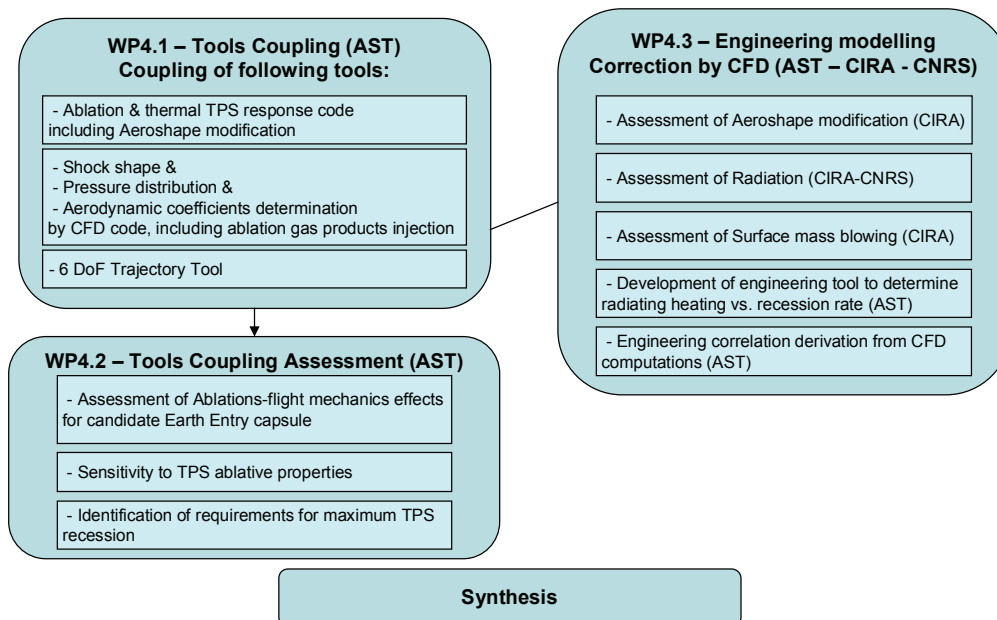


Figure 11 : Detailed activities of WP4: Ablation-Flight mechanics coupling assessment

WP5 GAS-SURFACE INTERACTIONS MODELLING

TPS material degradation results in rough surfaces, which may dramatically enhance the turbulent heating. In case of high gas surface blowing due to massive ablation, blowing might encompass roughness-induced over-heating. General objective of this WP is to analyse in detail the coupling between surface roughness and blowing and identify possible margins saving. Thus the aim is to reproduce in a cold wind tunnel - i.e. a WT in which the air is heated just sufficiently to avoid its liquefaction - the effect of roughness and blowing and to perform associated calculations in order to analyse the experimental results.

The task is divided in four sub-tasks. The WP 5.1 is relative to review of surface roughness and blowing. The WP 5.2 is devoted to ground experiment preparation and tests analyses including Euler+Boundary-layer. The WP 5.3 addresses engineering models assessment. Then a synthesis of the results constitutes the sub-task WP 5.4.

The **WP 5.1: bibliographical review** is mainly carried out by Astrium and Lomonosov MSU, also including Onera with a bibliographical review performed about surface roughness effects. MSU added a part about blowing. One interest is that the Russian publications are relatively unknown by other partners from E.U. This work has already been achieved and was very useful to determine the conditions of the experimental work.

The critical analysis from real flight has been carried out by Astrium. The Table 4 present the mass-flow rate calculated on the maximum heat-flux trajectory for three different altitudes, $(\rho V)_{\infty}$ being the mass-flow determined for the free stream conditions and m the mass of gas ejected from the wall by pyrolysis and ablation. The altitude $Z=52\text{km}$ corresponds to the maximum reduced mass flow rate which occurs in turbulent regime.

Z(km)	52	46	36.2
$m/(\rho V)_{\infty}$	0.012	0.005	0.0012

Table 4 Estimated mass flow rate on reentry trajectory

Considering the maximum $(\rho V)_{\infty} \sim 320 \text{ kg/m}^2/\text{sec}$ to be applied for ground tests, it was derived from this analysis that it is required to reproduce maximum mass-flow rates up to $3.8 \text{ kg/m}^2/\text{s}$ in the experiments.

In **WP 5.2: ground experiment preparation**, a series of ground tests will be performed, with the objective to qualify the wall heat-flux with different roughness and blowing rates.

The Onera blow down wind tunnel R2Ch will be used with the Mach 5 nozzle (exit diameter: 326 mm). The stagnation conditions will be: p_{st} : from $5 \cdot 10^5 \text{ Pa}$ to $50 \cdot 10^5 \text{ Pa}$ and $T_{st} = 650 \text{ K}$. These conditions lead to an unit Reynolds number from $4.25 \cdot 10^6$ to $42.5 \cdot 10^6$.

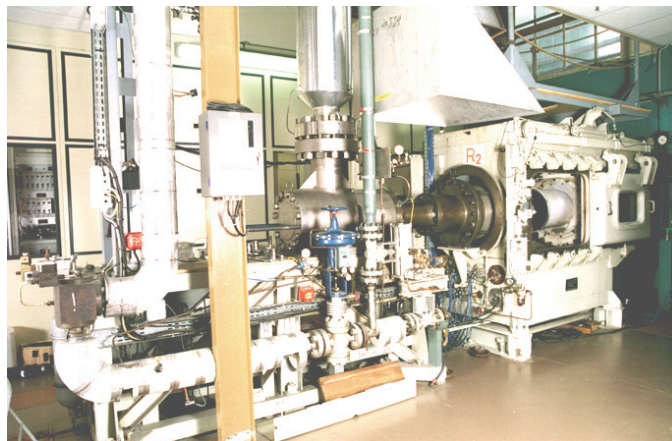


Figure 12 : Onera blow down wind tunnel R2Ch

The model that will be used is a flat plate with a sharp leading edge, already available from a prior test campaign at 0° incidence. The set-up will be improved in order to test the plate also at the incidence 10° . This model is constituted with ceramics inserts with a porosity of about 48 %.

Three roughnesses will be tested: a smooth one, which is the reference case without roughness (r_1) and two roughness r_2 and r_3 of respectively $100 \mu\text{m}$ and $300 \mu\text{m}$. The Figure 13 presents the shape of the roughness, the ratio k/b being equal to 1, which characterizes a 45° angle for the pyramid.

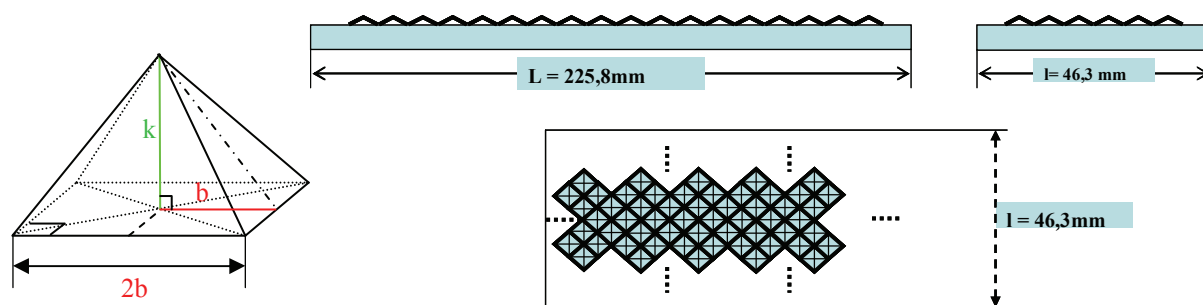


Figure 13 : roughness distribution on the test sample

These pyramids will be joined and in staggered rows. The Table 5 gives the reduced roughness height h_s^+ for the two cases and for two stagnation pressure. This choice will permit to test a wide range of h_s^+ from 20 to 500.

r (μm)	h_s^+ ($P_i=5b$)	h_s^+ ($P_i=50b$)
$r_2 = 100$	20.1	169.2
$r_3 = 300$	60.3	507.6

Table 5 reduced roughness height h_s^+

Also three mass flow rates will be tested (m_1, m_2, m_3) :

- m_1 being the minimal flow rate $m_1 = 0$, i.e. without mass flow rate
- m_3 being the maximal flow rate and m_2 being equal to $m_3/2$.

Some tests have already been performed to check the possibility to reach the mass-flow rates $m_3 = 3.8 \text{ kg/m}^2/\text{s}$ determined according to the real flight (WP 5.1).

For all the aerodynamic configurations, Schlieren photographs and heat-flux cartography obtained with an infrared camera will be produced. Tests analyses including Euler + Boundary-layer will be performed, in order to achieve a proper restitution of the experimental results.

The **WP 5.3 - CFD Modelling** concerns the Models Implementation. Most promising models tested in WP 5.2 will be pre-selected for implementation in CFD carrier code. The rebuilding of the wind tunnel tests will be performed by CFS and MSU.

The critical analysis of the models and the propositions for improvements will be performed by MSU in OPENFOAM. The CFD simulations for candidate earth entry vehicles will be carried out by CFS in the Navier-Stokes Multi- Blocks [NSMB] solver.

NEXT STEPS

All the requirements established within WP1 were consolidated early 2011. There is a significant amount of activity to be performed during the following months, with a lot of results expected during the third quarter 2011 (see Table 6).

WP 2	<ul style="list-style-type: none"> • Review and description of dedicated shock tube and plasma facilities • First design of hyper-velocity facility to simulate high speed Earth re-entry.
WP 3	<ul style="list-style-type: none"> • Complete bibliographic review on joints and bonding materials and systems • Screening and testing of crushable materials • Preparation of arc jet tests in Scirocco
WP 4	<ul style="list-style-type: none"> • Flow computations with and without ablation products • Preparation of tools for coupling
WP 5	<ul style="list-style-type: none"> • Completion of bibliographic review • Preparation and performance of ground experiments

Table 6 Synthesis of main results expected in 2011

CONCLUSION

Rastas Spear is a typical R&D project, which is carried out thanks to the funding of European Community Framework Programme n°7 (FP7).

The main objectives are to increase the European TRL of

- Key technologies (Thermal Protection System, Crushable Structure)
- Ground test facilities to be used for simulation of high speed entry
- Methodologies and tools to address flight mechanics, and flow / material interaction, while considering coupling effects

The project is now on-track, and the overall framework of the study has been defined

- All requirements have been established with focus on passive Earth Return Capsule

Completion of overall project objectives is anticipated to be reached in Fall 2012.

For more information, the project website www.rastas-spear.eu will be updated during the whole project.

ABBREVIATIONS

ATD	AeroThermoDynamics
ARV	Advanced Return Vehicle
ERC	Earth Return Capsule
EVE	European Venus Explorer
DEAM	Development of European Ablative Material
MREP	Mars Robotic Exploration Preparation
MSR	Mars Sample Return
MSRO	Mars Sample Return Orbiter
TP - TPS	Thermal Protection - Thermal Protection System
TRL	Technology Readiness Level
TRP	Technological Research Programme (ESA)
VEP	Venus Entry Probe
WT-WTT	Wind Tunnel - Wind Tunnel Test