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# Preliminary Design and Performance Verification of a Guided Entry Thruster System for Precision Landing on Mars

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## Abstract

As a vehicle enters an atmosphere, it interacts with the surrounding gas. The interaction produces aerodynamic forces and moments that act on the vehicle during entry, and in the process, reduce the vehicle internal energy to an acceptable value for the deployment of a decelerator. The RCS jets will interact with the aftbody flow too, inducing different interaction phenomena that may alter both aerodynamic characteristics and aerothermodynamic environment of the backshell of the capsule. Those interactions, in some cases, could counter the RCS control authority too.
The ESA study "Preliminary design and performance verification of critical elements for guided entry thrusters", performed by Thales Alenia Space Italia, CIRA and T4i, has the main goals to define the preliminary design of a RCS capable to control and guide a reference entry probe in the scope of the studied ESA Mars Precision Lander mission and to derive the requirements for a future test campaign in CIRA Scirocco PWT facility, to verify the performance of the designed system.
The present paper will describe:

- The preliminary design of a Guided Entry Thruster System for Precision Landing on Mars, including the trade-off between different layouts
- The setup of a test campaign in CIRA Scirocco facility to verify the performance of the designed system
- The design of the test article, including the test thruster system, and the setup of the Wind Tunnel Test campaign in CIRA SCIROCCO arc jet facility to verify the performance of the flight thruster system.

## 1. Introduction

ESA MREP-2 programme (Mars Robotic Exploration Preparation-2) has the objective to reinforce Europe's position in Mars robotic exploration and prepare for a European contribution to a future international Mars Sample Return (MSR) mission. One of the studied scenarios is based on a Mars Precision Landing (MPL) entry capsule that would carry and precisely land a Sample Fetching Rover (SFR) on the Mars Surface, close to assets already present. The SFR will pick-up a sample cached by a previous mission and deliver it to a Mars Ascent Vehicle (MAV) for the first stage of the journey back to Earth.
To achieve this aim the MPL will need to have quite demanding landing accuracy requirements (<10 km at 3s), that could be satisfied by means of a guided entry: thanks to an appropriate CoG offset, the capsule can flight in the Mars atmosphere with an angle of attack sufficient to generate a lift force, that can be modulated by means of dedicated attitude manoeuvres along the trajectory, performed by thrusters.

The study presented in this paper, has the overall goal to de-risk critical aspects for the design, development and use of entry thrusters for entry guidance into Mars atmosphere.
The activity has been split into 3 main phases characterized by the following main objectives:

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1. Design preliminarily a RCS capable to control and guide a reference entry probe of the ESA's Mars Precision Lander mission.
2. Derive the requirements for a test campaign in CIRA Scirocco facility to verify the performance of the designed system.
3. Manufacture a representative test article and prepare and upgrade Scirocco facility and measurement techniques to perform the test campaign.

## 1.1 MarsPlay Reference Mission

ESA/TAS-I Mars PLAY was an Optional segment in the frame of the MSR: it carries and precisely lands a Fetching Rover on the Mars Surface, to fetch the samples cached by the previous caching mission and return them to the MAV.
Mars Play mission and related scenario have been selected as reference ones for the current Study.

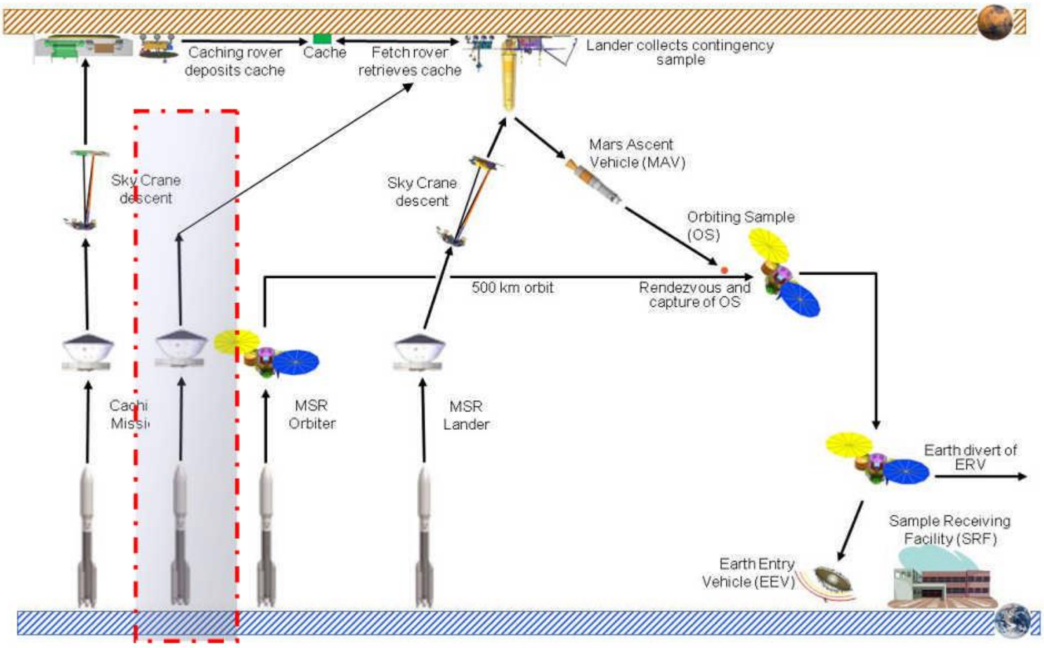


Figure 1: MPL Mission (Red Box) as Optional Segment of the MSR mission

In MarsPlay, thanks to an appropriate offset of the Center of Gravity, the capsule can fly in the Mars atmosphere with an angle of attack sufficient to generate a lift force that can be modulated by means of dedicated attitude manoeuvres along the trajectory, performed by thrusters.
The Lift is used to actively compensate the position dispersion: to perform the GNC task, the capsule would rely on a Reaction Control System (RCS) able to command and control torques along roll axis, while leaving sufficient manoeuvrability to pitch and yaw axes.

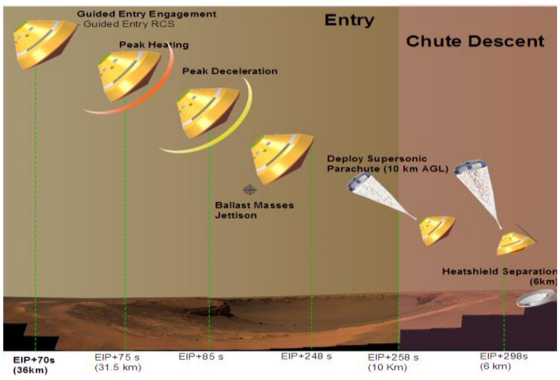


Figure 2: Entry and Chuted Descent Overview

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The following structure for the design of the Guided Entry G&C algorithms is considered:

1. A nominal Entry profile is available to the GNC at the separation: it includes the nominal bank profile with certain number of Bank Reversal Manoeuvres (BRMs).
2. The dispersion at the Entry Interface point (EI)P is tackled by a guidance algorithm which finds a bank angle profile that will make the capsule to reach the nominal Parachute Deployment Point (PDP) starting from the navigated EIP. This is achieved separating the longitudinal and the lateral motion and by iteratively solving optimal point-to-point control problems based on a linearized dynamics around the guidance trajectory.
3. Atmospheric and environmental dispersion are seen as external disturbances that stress the stability of the capsule. Guidance algorithm are written in order to relax the work-load of the CoM Control because it offers as output a better "natural Trajectory" i.e. a bank angle profile with bounded second derivative.

## 1.2 Aero RCS interaction

As a vehicle enters an atmosphere, it interacts with the surrounding gas. The interaction produces aerodynamic forces and moments that act on the vehicle during entry, and in the process, reduce the vehicle kinetic energy to an acceptable value for the deployment of a decelerator. The interactions between the vehicle and the surrounding flow occur during whole flight and in particular during the hypersonic and supersonic phase when the flow around the capsule is characterized by the presence of the bow shock ahead of the capsule, multiple expansion waves around the forebody shoulder, a massively separated wake flow field, and a complex recompression shock system behind the vehicle.

The RCS jets will interact with the aftbody flow, inducing different interaction phenomena, as shown in the following figures, where the impact on the base flowfield for different conditions (RCS off and RCS on with two thrust conditions) is shown

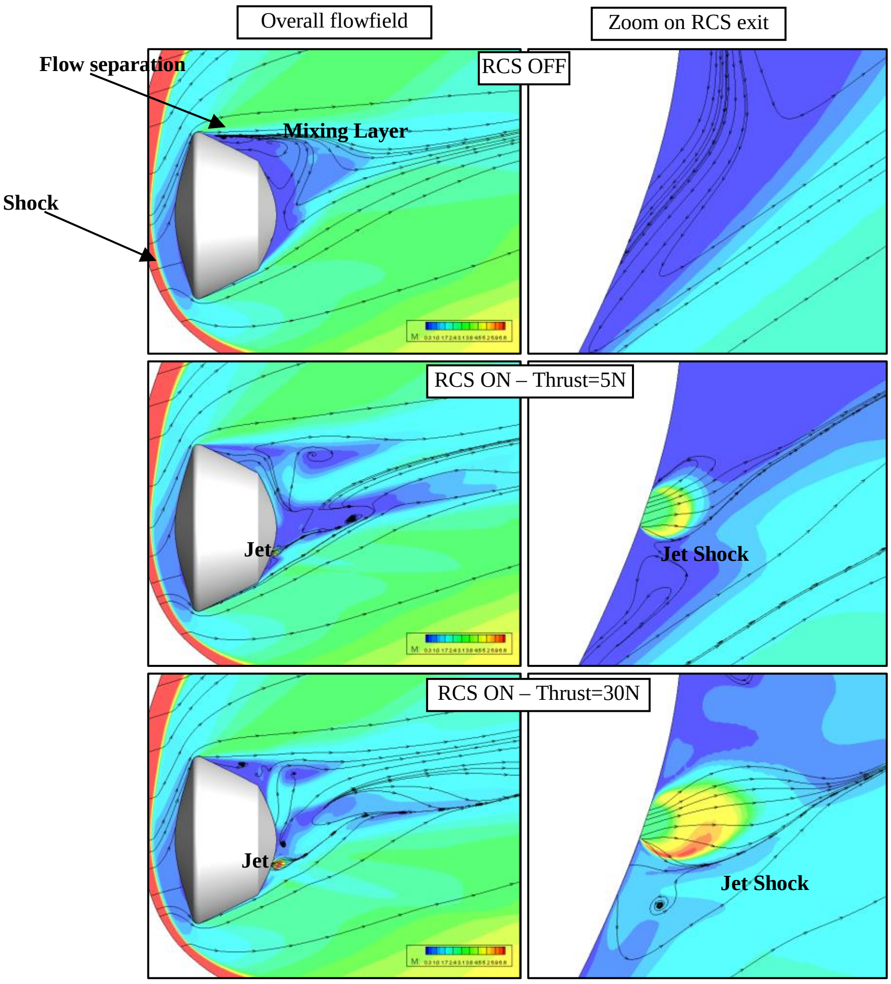


Figure 3: Hypersonic flowfield with RCS off and on – Slice along jet axis in WTT conditions ($M_\infty$ =6.9)

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These interactions may alter both aerodynamic characteristics and aerothermodynamic environment of the backshell of the capsule.
There are two main sources of RCS-Aero interaction:

- The under-expanded jet produces a change in near-exit flowfield, causing entrainment and reduction in pressure in the near field. If this jet impinges onto the surface, or collides with another jet, a local increase in surface pressure may result. This type of a near field interaction is relatively invariant with the trajectory condition, and is fairly easy to analyse.
- The jet influencing the rest of the capsule wake flowfield, causing global changes in the capsule pressure field. This change is much more complex and it depends on the flight condition.

The induced changes in the surface pressure distribution can produce moments on the capsule, which can interfere with the native authority of RCS.
In addition when RCS jets are activated their plumes could penetrate and disrupt the shear layer, which promotes increased mixing between the high enthalpy post-shock inviscid flow and the separated wake, inducing significant heat flux augmentation.

The maximum aero RCS interaction is expected in correspondence of flight conditions where the maximum pressure the back side of the capsule is reached. Such a condition usually occurs in the hypersonic phase when the maximum freestream dynamic pressure is reached and in the supersonic phase. A good approximation to derive the base pressure from the flight reference condition is represented by Micheltree relation:

$$C_{p,b} = a_0 + \frac{a_1}{M_\infty} + \frac{a_2}{M_\infty^2} + \frac{a_3}{M_\infty^3} \tag{1}$$

$a_0 = 8.325E-3$, $a_1 = 1.1293E-1$, $a_2 = -1.801$ and $a_3 = 1.2885$

## 2. Preliminary Design of a Guided Entry Thruster System

The Study logic to consolidate preliminarily the flight Guided Entry Thruster (GET) system for the reference MarsPlay Mission is shown in Figure 4.

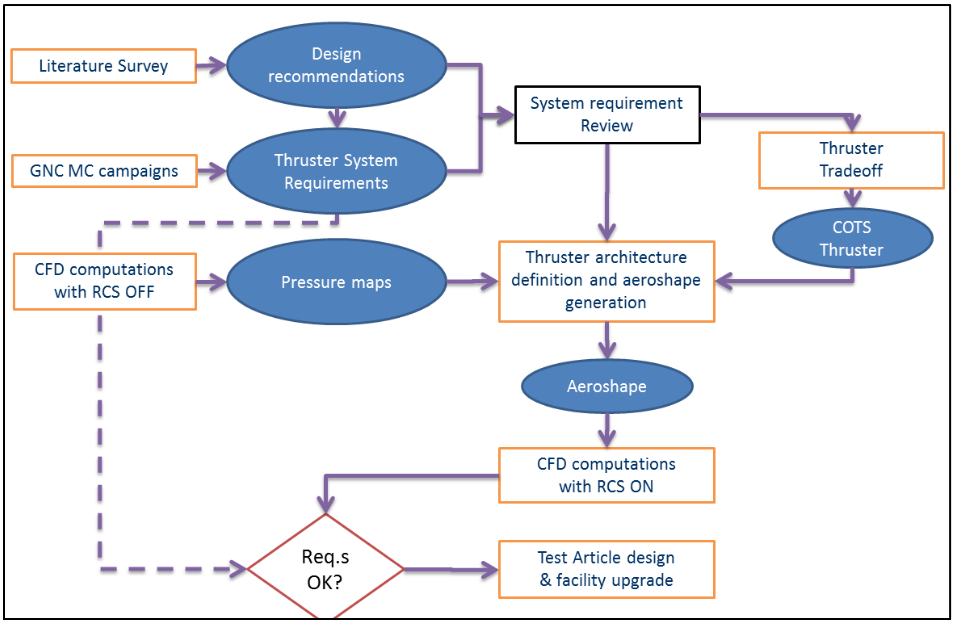


Figure 4: Study plan

It consists of the following main tasks:

- Definition of the Thruster System requirements

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Starting from Mars Play heritage and driven by the recommendations of a dedicated literature survey, all the Mars Play requirements, related to the GET system, have been revised and updated, with the support of several GNC Montecarlo campaigns.
A particular attention has been paid to the consolidation of:
  - Levels of the RCS thrust and torques compatible with MarsPlay GNC logic.
  - Maximum allowable Aero RCS interaction that the current GNC logic is able to manage without any significant loss of performances.

While the first objective has driven the subsequent thruster trade-off and layout optimization, the second one has fixed the requirements to be verified by CFD analyses.

- Definition of the GET System architecture
  On the basis of the identified requirements and with the support of dedicated CFD analyses with RCS Off, a trade-off has been performed to select both the GE thrusters and their configuration layout. The overall RCS architecture has been consolidated.
  The aeroshape of the selected configurations, including the thruster details, has been generated for the subsequent CFD analyses.
- Verification of RCS requirements by means of CFD analyses with RCS on.
  The main goal was to verify that the aero RCS interaction effects for the selected configuration are below the requirements on the maximum allowable RCS interaction effect.
- Design of the test article and identification of Scirocco facility upgrades.
  A scalability analysis has been performed to identify the main flight to ground correlation parameters for jet interaction.
  On the basis of the outcomes from this task, the WTT conditions have been identified as well as the test article requirements.
  A detailed design of the overall test article, including the thruster system too, has been finalized.

## 2.1 Definition of the thrusters system requirements

All Mars Play requirements have been revised, focusing the attention on the GET system; in particular the following requirements have been deeply investigated:

- Level of RCS thrust and torques
- Maximum allowable RCS interaction effects
- Selection of the most critical flight conditions

- **Level of RCS thrust and torques and RCS interaction effect**

In order to correctly assess the vehicle performances in case of actual aerodynamic interaction between the guided entry thrusters and the external flowfield, the original flight simulator, utilized in the frame of MarsPlay mission, has been modified introducing a disturbance model representing such interaction.
The modelling, derived from IXV experience, is quite similar to the one utilized on MSL program too.
During the re-entry phase, the RCS jets interact with the aft body flow, inducing different interaction phenomena. These interactions may alter both aerodynamic characteristics and aero thermodynamic environment of the backshell of the capsule, inducing changes in the surface pressure distribution that can produce additional moments on the capsule, which can interfere with the native authority of RCS.
Those additional RCS interaction moments can be represented as:

$$\tau_{int} = l_{ref} A_0 F_{RCS} \tag{2}$$

Where:
$\tau_{\mathrm{int}}$ = additional interaction RCS moments
$\mathrm{l_{ref}}$ = vehicle reference length
$F_{RCS}$ = vector of the forces commanded by each of the RCS jets:

$$F_{RCS} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \tag{3}$$

$A_0$ = matrix of non-dimensional interaction moments:

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$$A_0 = \begin{bmatrix} w_{p,1}R_{p,1} & w_{p,2}R_{p,2} & w_{p,3}R_{p,4} & w_{p,4}R_{p,4} \\ w_{q,1}R_{q,1} & w_{q,2}R_{q,2} & w_{q,3}R_{q,4} & w_{q,4}R_{q,4} \\ w_{r,1}R_{r,1} & w_{r,2}R_{r,2} & w_{r,3}R_{r,4} & w_{r,4}R_{r,4} \end{bmatrix} \tag{4}$$

$w_{i,j}$ = non-dimensional torques
with *i=p,q,r j=1,2,3,4*

$$w_{i,j} = \frac{a_{i,j} l_{i,j}}{l_{ref}} \tag{5}$$

$l_{i,j}$ = moment arms, depending on thruster location and orientation
$a_{i,j}$ = interaction magnitudes
$R_{i,j}$ = dispersion variables

In the selected modelling:

- the dispersion variables, $R_{p,j}$, $R_{q,j}$ and $R_{r,j}$ are selected randomly with a Gaussian distribution and mean value of zero;
- the values of the interaction magnitudes $a_{i,j}$ are constant, invariant with Mach number, backshell pressure, angle-of-attack and sideslip. They represent an estimated 3σ limit on the magnitude of the interactions.

In order to assess the maximum allowable interaction magnitude values and the nominal RCS thrust, several simulations have been performed.

As first step, in order to have a sensitivity on the vehicle behaviour, simulations without any RCS interaction (i.e. baseline of MarsPlay study) and with the maximum RCS interaction have been performed, considering both pulsed and throttable thrusters.
All the design variables (i.e. atmosphere, AEDB, etc.) were set at their nominal values while for the RCS interaction the main assumptions were the following:

$$R_{i,j} = \pm 1$$

$$F_{RCS} = 200\ N \text{ and } 300\ \text{N}$$

$$[a_{i,j}] = \begin{bmatrix} 0.2 & 0.2 & 0.2 & 0.2 \\ 0.4 & 0.4 & 0.4 & 0.4 \\ 0.4 & 0.4 & 0.4 & 0.4 \end{bmatrix} \text{(MSL heritage)} \tag{6}$$

On the basis of the results of this first simulation campaign and considering the state of the art of the thruster technology too, pulsed thrusters were selected as baseline.

In a second step of the study, some complementary analyses have been performed by means of Montecarlo campaigns (all design parameters, including $R_i j$ too, are varied randomly) to consolidate the above mentioned requirements.
Finally, to support the thruster layout definition, other MC campaigns have been preliminary performed to compare the selected thruster layout, as detailed in § 2.2.

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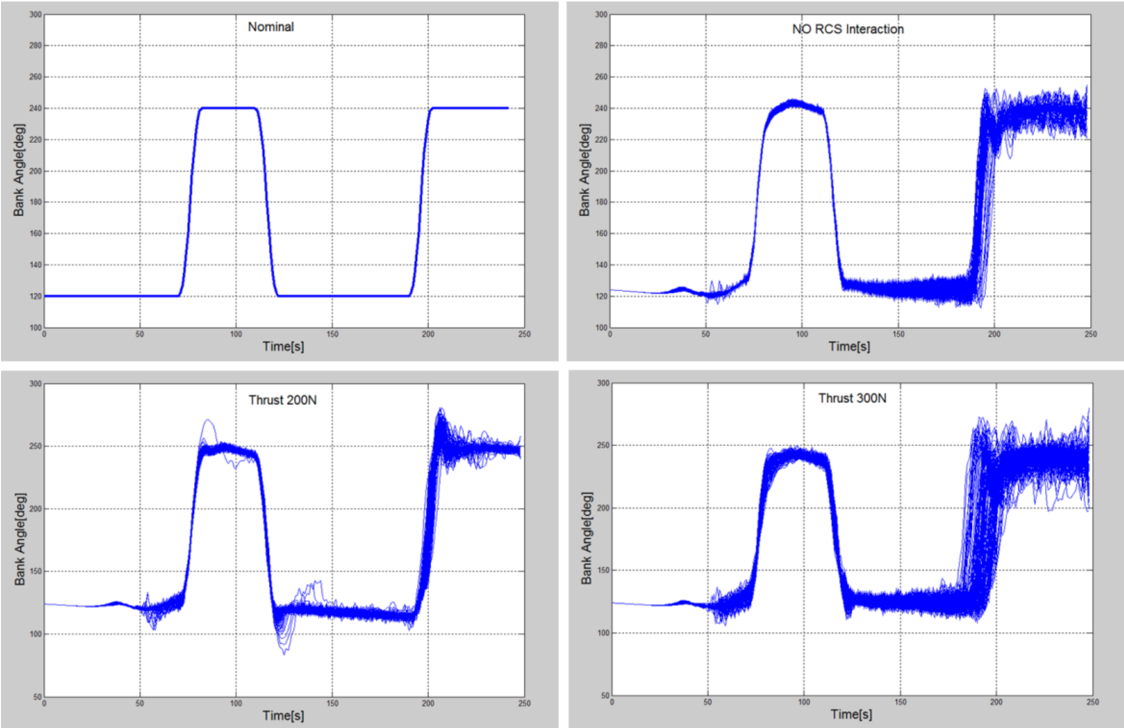

Figure 5: Bank angle vs. time for the selected configuration

On the basis of the performed analyses, the following requirements have been consolidated:

- The Guided Entry controlled phase is performed by using 2x4x200N pulsed thrusters mounted on the Backshell (4 redundant thrusters are considered).
- The level of required torques around the three axes have been defined.
- The maximum aero RCS interaction is the one reported in equation (6)

- **Selection of the most critical flight conditions**

Applying Metcheltree correlation (equation 1) to MarsPlay reference trajectory, the most critical flight conditions have been identified (Figure 6): $p_{inf}$ is the freestream pressure, $q_{inf}$ is the freestream dynamic pressure, $p_{base}$ is the estimated pressure on the base of the vehicle
It can be seen that the most critical points for the RCS interaction are:

- Point 2, at the end of the BRM #1: maximum pressure on the base
- Point 6, at the end of the BRM #3: maximum pressure on the base in supersonic regime with RCS activated.

For the selected flight conditions, dedicated CFD analyses with RCS off have been performed to compute the pressure distribution on the vehicle.

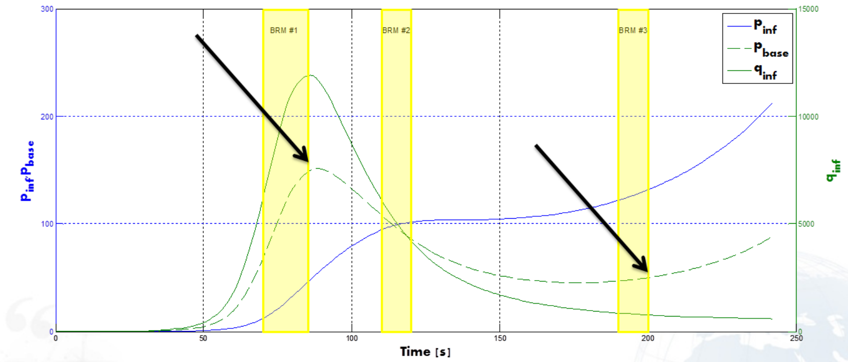

Figure 6: Reference trajectory - Pressures evolution

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## 2.2 Thruster trade-off and Thruster system architecture consolidation

Once the requirements have been consolidated, a trade-off has been performed to identify on one hand the COTS Guided Entry thrusters and on the other hand to optimize their location and orientation.
A large number of different configurations have been analysed, focusing on:

- Avoid plume impingement on zones with high moment arms, in line of principle, although the whole effect must take into account the command effectiveness, too.
  Moment arms distributions have been generated and analyzed (Figure 7).
  On the basis of that recommendation it is better to put the thruster in the circumferential zone located in the middle of the rearmost cone.
- To orient the trhusters towards the back:
  - To avoid/minimize plume impingement on the back shield
  - To direct jets with the oncoming flow, avoiding transverse injection

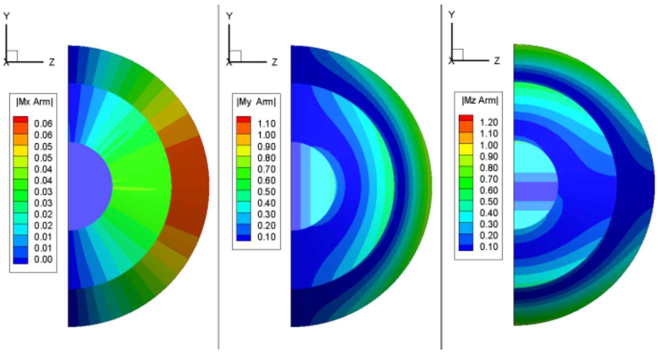


Figure 7: Moment arms distributions

Some of the configurations, analysed with TAS-I TIM code, are shown in Figure 8. Three main parameters have been considered: torque interaction effect, maximum contaminant mas flux, maximum impingement heat flux.
As a result of the trade-off, Aerojet MR-107N has been selected and the thrusters' location and orientation have been consolidated.

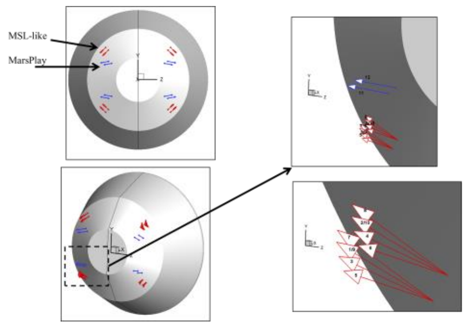


Figure 8: layout configurations

Following Mars Play heritage, a unified propulsion system integrating both Power Descent (PD) and Guided Entry (GE) RCS has been set up:

- four 200 N thrusters (plus four for redundancy) units each including single seat flow control valve and TCA temperature sensor;
- four 2500 N thruster units, each including single seat (TBC) control valve;
- three elastomeric diaphragm propellant tank for the storage and the supply of the hydrazine;
- one COPV pressurant tank for storage and supply of Helium;
- one internal redundant pressure regulator (PR);

The schematic of the RCS system is shown in Figure 9. It can be subdivided in two sections:

- Pressurized section
  The system is pressurized: a helium tank provides the require pressure to the three propellant tanks through a pressure regulator (with internal redundancy), to guarantee a constant thruster inlet pressure.

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Downstream the Helium Tank and two redundant NCPV provide the safety isolation from the propellant tanks during Launch phase.
High Pressure Filter is needed to stop impurities before the passage into the pressure regulator.

- Engine Feeding section
  The system provides thruster for power descendent and attitude control; the initialization of the system is provided through priming branch after hydrazine tanks.
  The attitude system is divided into two branches, complying with the single failure tolerance requirement.
  A LV is installed upstream each of the thrusters branch for isolation purposes.
  The redundancy at the Thruster descent Branch is defined at FCV level for the failure open mode, putting two FCV in parallel upstream each engine.

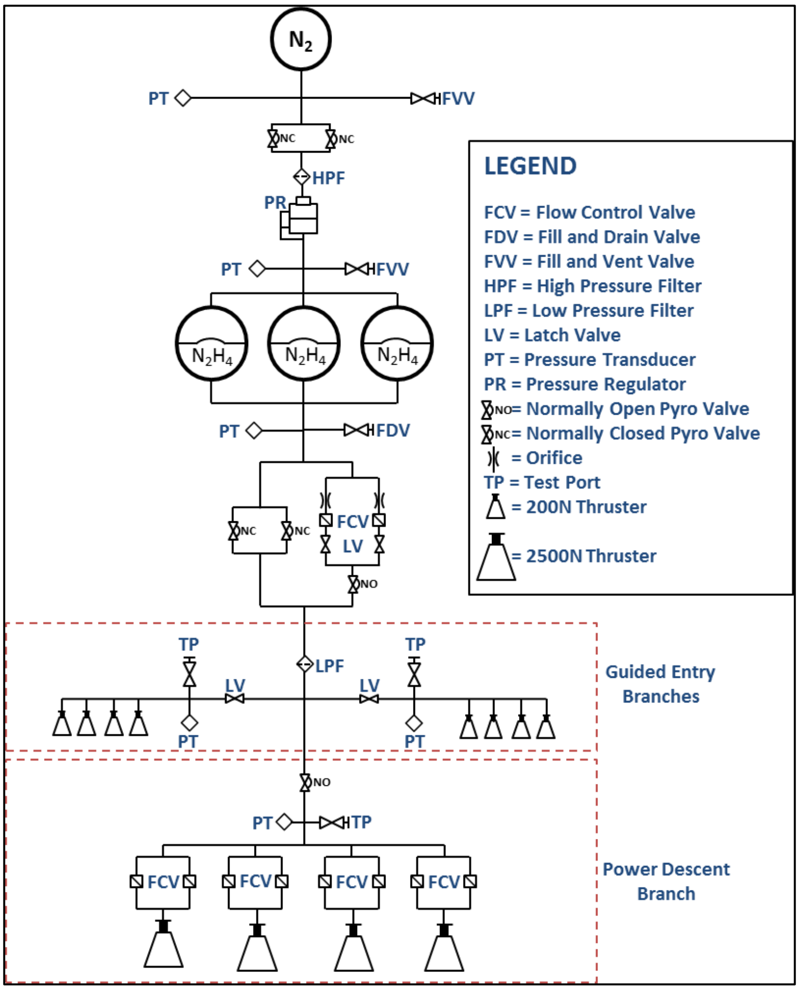

Figure 9: RCS System Schematic

## 2.3 Verification by CFD analyses

An extended CFD analysis campaign has been conducted by CIRA and TAS-I, with a twofold main objective:

- To verify that the experienced aero RCS interaction, in terms of disturbance torques induced by the RCS activation, is below the requirements (equation 6).
- To verify that the local heat flux augmentation is not significant.

While TAS-I have carried out the computations with the commercial code Metacomp CFD++®, CIRA have used FLUENT® for flight cases and the in-house NExT code for wind tunnel conditions
In TAS-I computations the Martian atmosphere has been simulated by 6 species (O, CO, C, O2, C2, CO2) with 27 reaction, while in CIRA ones it’s a mixture with 9 species (Ar, CO2, N2, O2, CO, NO, N, O, C).

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As experienced in MSL too ([5], [6]), a good compromise between accuracy of the results and computational effort is reached modelling only the exit plane of the thrusters as boundary inlet and applying on it the conditions computed by CEA code.
All the three flight conditions, corresponding to the three BRMs have been analyzed:

- BRM #1 in high hypersonic regime at Mach 20.23.
- BRM #2 in low hypersonic regime at Mach 7.28.
- BRM #3 in supersonic regime at Mach 2.87.

No impacts in terms of heat flux augmentation have observed and the aero RCS interaction is in all the cases well below the requirements (equation 6):

- the effects on roll moment are negligible both for TAS-I and CIRA computations (max 3 Nm wrt req. ±33).
- the effects on yaw moment are negligible (max 8 Nm wrt. req. ±74)
- the effects on pitch moment are higher (max 11 Nm wrt req. +48/-59).

As expected, the RCS interaction is higher in correspondence of BRM #1: maximum pressure in the base flow.
As example, the pressure distribution on the back shield for the cases examined by TAS-I at BRM #1 is shown in figure 10.

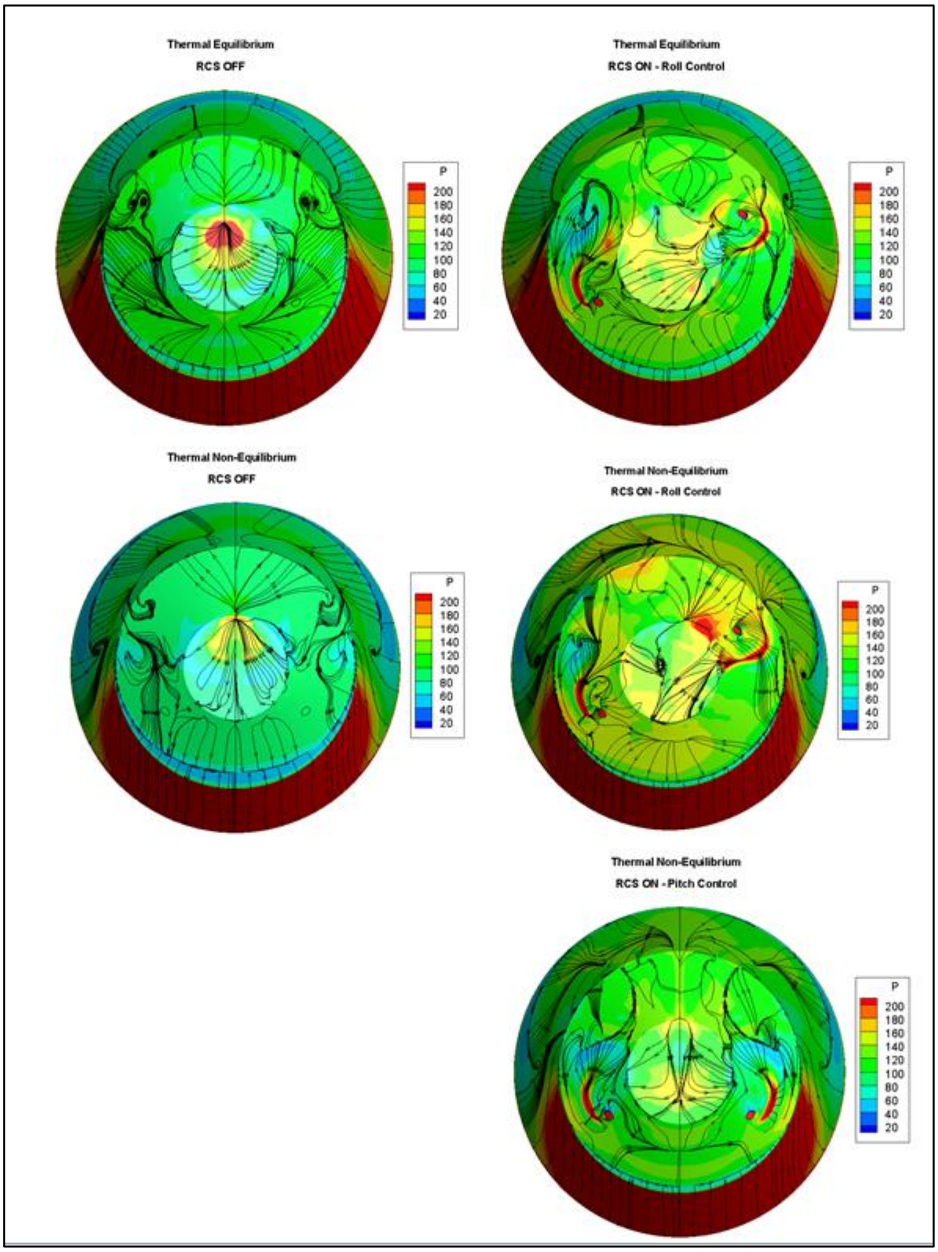


Figure 10: TAS-I BRM #1 - Pressure distributions back shield

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## 3. Test article design and facility upgrade

Even if the geometry of the thruster plume is cited by Pindzola [32] as one of the most important parameters for simulation in ground test facilities, in a general case of a plume interacting with a wake of a blunt capsule the plume shape may not be as critical a parameter, as it is for a rocket.
Testing of RCS in ground facilities requires duplication of a number of relevant physical scales.
External flow would typically require the replication of the free-stream Mach and Reynolds numbers, enthalpy, momentum thickness Reynolds number, especially if this is an aeroheating test. Comparable properties of the gas mixture are also desired.
In addition to that, the nozzles and nozzle flow should be scaled appropriately. Scaling parameters, presented by Pindzola [32] for this problem result in the attempt to match momentum and pressure ratio.

- Momentum ratio

$$\left[\frac{Q_{exit}A_{exit}}{Q_{\infty}A_{ref}}\right]_{Test} = \left[\frac{Q_{exit}A_{exit}}{Q_{\infty}A_{ref}}\right]_{Flight}$$

- Pressure ratio

$$\left[\frac{P_{localflow}}{P_{jet,exit}}\right]_{Test} = \left[\frac{P_{localflow}}{P_{jet,exit}}\right]_{Flight}$$

The setup of the WTT conditions and of the test thruster system requirements has been a step by step procedure:

**Test article scaling.**
The reference Mars Play entry probe (see Fig. 11 left) is scaled to a ground test article suited for SCIROCCO, in order to reproduce on ground the jet interaction found in hypersonic flight conditions.
To this scope the ground test article keeps the same shape of the entry probe but with dimensions reduced by a factor of 1/6.125.
The front diameter of the ground test article is scaled from 2940 mm of the entry probe to 480 mm (see Fig. 11 right) in order to allow the testing with smaller SCIROCCO nozzle C (900 mm exit diameter) candidate for testing with the highest possible base pressure. The Angle of Attack of the ground test article is 17°, the same of BRM #1 end of reference flight mission

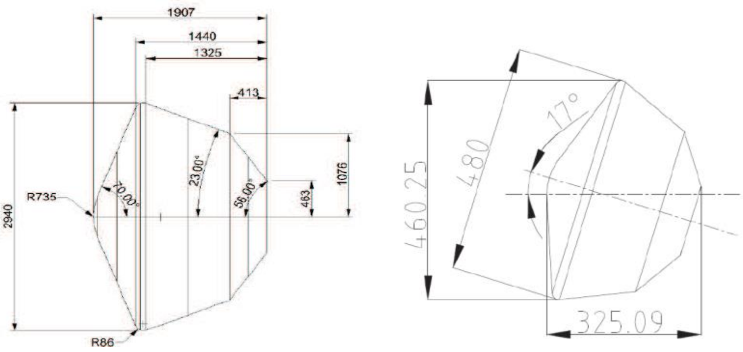


Figure 11: Reference MarsPlay entry probe vs. SCIROCCO test article

**WTT condition**
Two different Scirocco test conditions have been set up:

- Test condition 1, designed to be representative of the flight condition BRM #2 end in terms of freestream Mach number (7.28) and pressure on the base flow (80 Pa).
- Test condition 2, designed to be representative of the flight condition BRM #1 end in terms of pressure on the base flow (150 Pa); a higher RCS interaction is expected. The free stream Mach is 6.9.

To support the definition of the PWT conditions, a dedicated CFD campaign has been performed, by means of 2D axisymmetric computations Scirocco nozzle, to derive the free stream condition (see Fig. 12) and 3D computations

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with RCS Off to check the pressure level on the base of the vehicle (see Fig. 12) and to assess the heat flux distribution on the test article too.

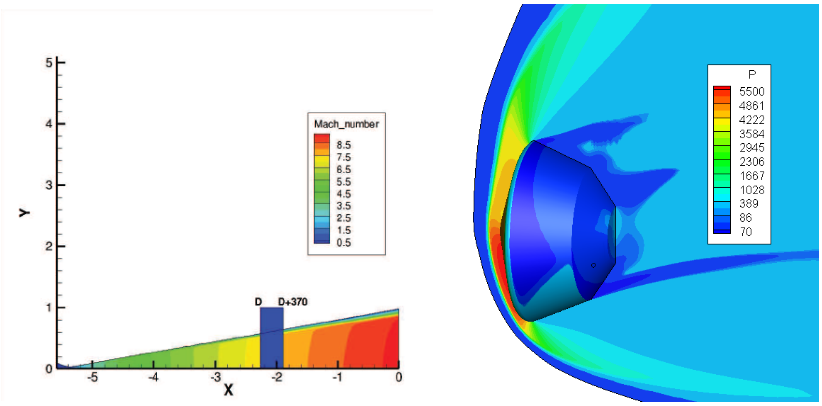



Figure 12: Scirocco nozzle iso-Mach contour (left) – Test pressure distribution (right) – condition Test 1

**Test Thruster system requirements**

The performances required by the test thruster system, have been setup in order to match the flight momentum ratio of both BRMs #2 and #1. An additional requirement on the exit area dimension (1/6.125 of the flight unit) has been imposed too.

Since the expected RCS interaction is low, the possibility to increase the momentum ratio has been taken into account too: even if such a condition is not representative of any flight conditions, it could be useful to obtain significant experimental data useful for the CFD code validation.

The main characteristics of the selected test thruster is shown in the following table

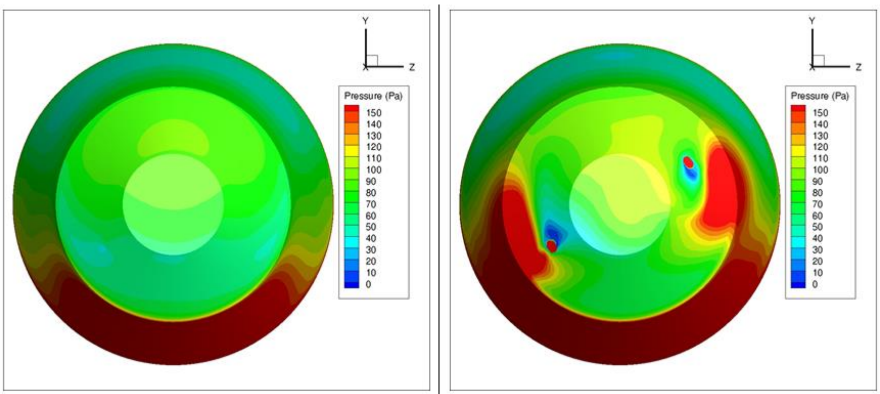
Table 1: Test thruster configuration

**Constraints**

1. Exit diameter = 10,38 mm
2. Exit Pressure = 3014 Pa
3. Force due to momentum: 5 N
4. Force range : 5 – 25 N
5. Ambient Pressure = 79 Pa

| Thrust (momentum) | Exit pressure | Chamber pressure | Mass flow rate | Mach | Texit |
|---|---|---|---|---|---|
| [N] | [Pa] | [bar] | [kg/s] | | [K] |
| 5 | 3014 | 3,22 | 0,00740 | 3,74 | 78,10 |
| 20 | 12008 | 12,91 | 0,0296 | | |
| 25 | 16742 | 18 | 0,0399 | | |

Additional 3D CFD analyses have been performed to assess the expected aero RCS interaction and pressure distribution on back side of the capsule, to support the design of the mechanical interface between the test article and the facility model support system and the layout definition of the pressure sensors.




RCS OFF RCS ON

Figure 13: Pressure distribution – WTT condition test 2

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**Test article design**

The design of the test article is still under finalization. In particular the definition of the mechanical interface between the probe and the model support system of Scirocco facility and the layout of all the pressure sensors that will be located mainly on the back side of the test article base are still to be consolidated.

The configuration of the overall test thruster system as well as its interfaces with the facility have been, indeed, consolidated. Due to volume constraints and safety issues, the overall test thruster set is divided in three main sections (see Fig. 14):

- Pressurant zone, including 6 tanks with N2+NO at 150 Bar
- Thrust regulation equipment, outside the test chamber, including all the regulation equipment
- Test thrusters + sensors and valves, inside the Probe test article, including two thrusters and related pressure and temperature sensors

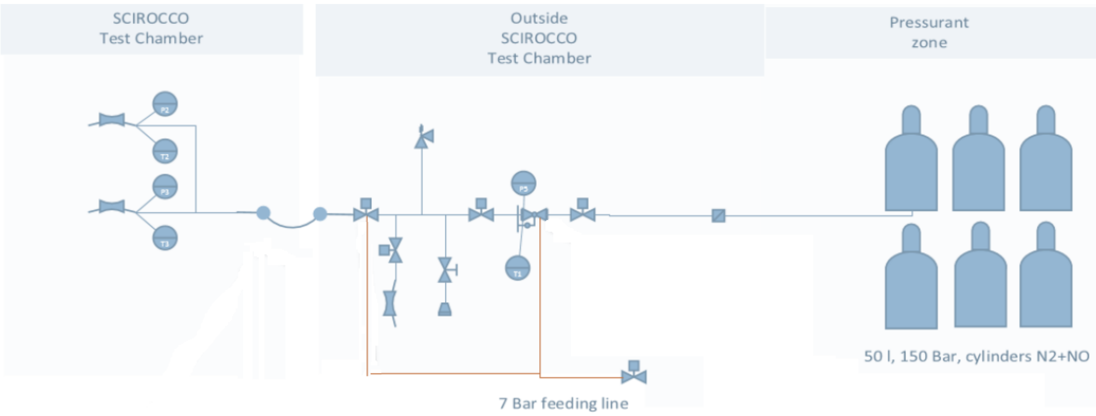


Figure 14: test thruster system

It is planned to install in the facility a Nitric Oxide Planar Laser Induced Fluorescence (NO PLIF) experiment The NO PLIF system uses an ultraviolet laser sheet to interrogate a slice in the flow containing seeded NO. This UV light sheet excited fluorescence from the seeded NO molecules. The fluorescence is detected by the high-speed PI-MAX II intensified CCD digital camera. The laser sheet could be swept through the flow, thereby visualizing different cross sections of the flow. In post-processing, these different spatial measurements could be recombined to show the three dimensional structure of the wake flow and RCS jets. Through modeling of the PLIF signal equation, computational flow images (CFI) were produced and directly compared to the qualitative PLIF data.

## 4. Conclusions

The study “Preliminary design and performance verification of critical elements for guided entry thrusters”, started in September 2016 and is still on going, with main aim goals to define the preliminary design of a RCS capable to control and guide a reference entry probe in the scope of the studied ESA Mars Precision Lander mission and to derive the requirements for a future test campaign in CIRA Scirocco PWT facility to verify the performance of the designed system.

The preliminary design of the flight thruster system architecture for the reference ESA/TAS-I Mars PLAY has been consolidated and the requirements for a test campaign in CIRA Scirocco facility have been derived.

The design of the complete WTT setup, including the test article and its thruster system, is going to be finalized.

The methodology to design a RCS capable to control and guide a reference entry probe has been successfully developed and implemented in the frame of this study.

The procurement of all the equipment, the manufacturing of the test article and the upgrade of Scirocco facility are planned to start after the project CDR (currently scheduled in September 2017).

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