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FINAL TEST CAMPAIGN ON FLUIDIC MOCK-UP FOR EXOMARS EDM PROPULSION DESIGN VALIDATION (WITH HYDRAZINE)

F. Laverty	**Thales Alenia Space (France)**
G. Lubrano	Thales Alenia Space (France)
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A. Iffly	Thales Alenia Space (France)
P. Garçon	Thales Alenia Space (France)

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Thales Alenia Space, Cannes, France
fanny.laverty@thalesaleniaspace.com

ABSTRACT

In the frame of the development of the new complex propulsion subsystem for the Entry, Descent & Landing Demonstrator Module (EDM) of the Exomars Mission, a fluidic test campaign in three big steps was rolled-out. It was composed of two sessions of tests in water (Hydraulic Mock-Up #1 and #2 – HMU#1 & HMU#2) and one session of tests in hydrazine (Firing Development Model – FDM).

The first test campaign (HMU#1) was held on a reduced flight-like mock-up and it was composed of priming and pressure drop tests in water. Its successful completion allowed to conclude on several design trade-offs and to improve the subsystem fluidic numerical models. The results were presented at the Space Propulsion 2012.

The second campaign (HMU#2) was held on a flight-like mock-up representing the final subsystem design and including the pressurant and the propellant stages. It was divided into three parts covering the propulsion operation cycle: priming, pressurization and firing (with water). Its successful completion allowed to fully validate the final subsystem design and to correlate the associated fluidic numerical models. The results were presented at the Space Propulsion 2014.

Finally the third campaign (FDM) was held on the same flight-like mock-up refurbished with complete engines. It was composed of real flight sequences with different firing profiles (priming > pressurization > firing) and was performed with the flight fluids (helium and hydrazine). Its successful completion allowed to confirm the good performance of the propulsion subsystem with flight like sequence and fluids: hydrazine priming of the engines lines through a dedicated calibrated orifice, pressurization and engines firing performances versus the feeding system.

The article focuses on the third campaign. It first details the proceedings and the results of the tests and then presents the numerical correlation work (using EcosimPro software and the European Space Propulsion System Simulation library – ESPSS).

Exomars and the ESPSS library are programs of the European Space Agency (ESA). EcosimPro is a simulation tool developed by Empresarios Agrupados International.

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1. INTRODUCTION

Exomars Entry, Descent & Landing Demonstrator Module (EDM) will validate key technologies for Mars exploration, and will land a science payload on the planet Mars. Therefore it is equipped with a propulsion subsystem designed to decelerate the final descent onto the Mars surface before final touch down [3] [5] [6].

This propulsion subsystem is a hydrazine monopropellant subsystem that operates in regulated pressure mode. It is composed of a single pressurization assembly regulating the pressure of three independent propellant assemblies (Figure 1). Each propellant assembly contains a cluster of thrusters composed of three 400 N engines.

For the development of this new complex propulsion subsystem, a wide validation plan was necessary to study in detail the fluidic phenomena and to correlate the numerical models [4].

The design validation plan of the EDM Propulsion subsystem is composed of three major test steps:

- HMU#1, priming and pressure drop tests in water (this activity took place in 2011 and was presented in a previous paper at the Space Propulsion 2012 [1]),
- HMU#2, priming / pressurization / firing tests in helium and water (this activity took place in 2013 and was presented in a previous paper at the Space Propulsion 2014 [2]),
- FDM, priming / pressurization / firing tests in helium and hydrazine (this activity took place in 2015 and is presented in the present paper).

The paper presents the FDM activity: mock-up, test sequence, results, correlation and conclusions.

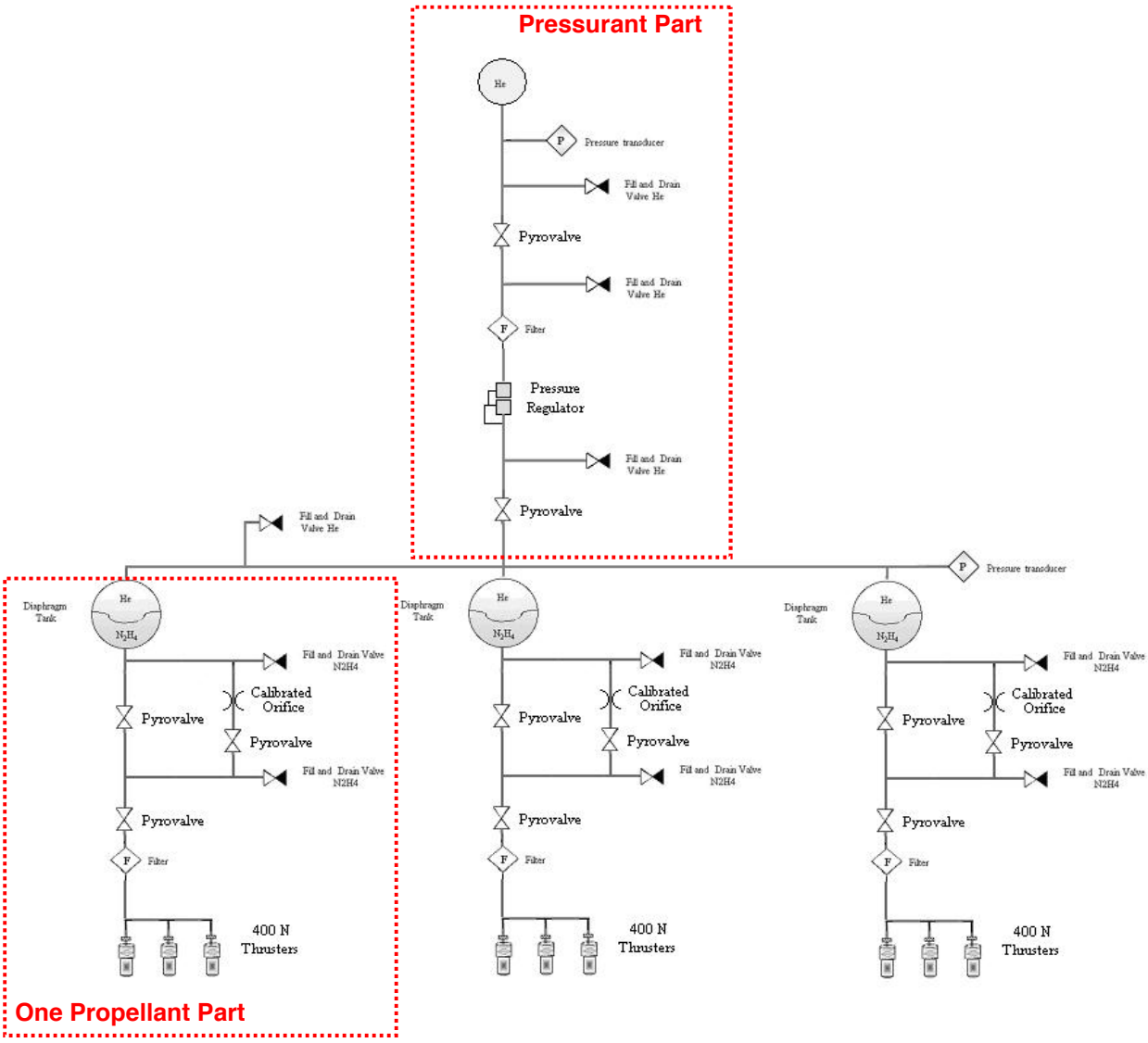

Figure 1: EXOMARS RCS Propulsion Subsystem Schematic

2. FIRING DEVELOPMENT MODEL (FDM) PRESENTATION

HMU#1 test campaign focused on the design validation of the propellant lines [1]. When the propulsion subsystem design was defined [6], HMU#2 test campaign was carried out in order to test the complete flight sequence on a representative mock-up of the propulsion subsystem in helium and water. Finally, the same test campaign was carried out with the same mock-up and with flight engines and flight fluids (helium and hydrazine) in order to validate the engines firing performances versus the feeding system.

FDM mock-up was therefore as representative as possible of the flight model. It was installed and tested in a closed test cell to impose Martian atmospheric conditions to operate the engines in flight conditions.

Figure 2 shows a picture of the complete mock-up.

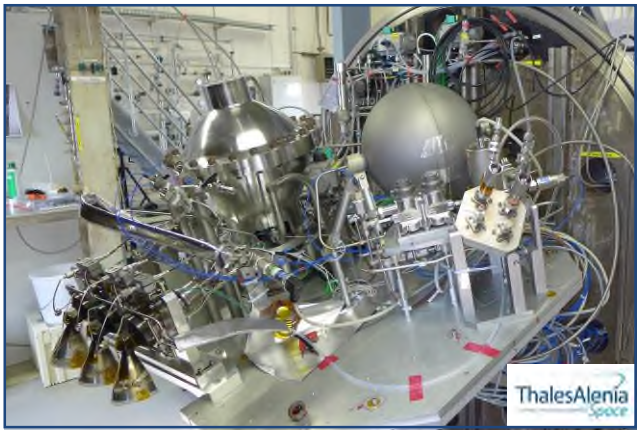

Figure 2: FDM Mock-Up

FDM mock-up was composed of the pressurant part and of one propellant part (see details on Figure 1). The two other propellant parts were replaced with an equivalent ullage volume for priming and pressurization tests and with a continuous outgoing helium mass flow for firing tests.

The goals of FDM were to confirm the similarity of the results as compared to HMU#2, to validate the good performances of the design with the flight sequence and engines, and finally to correlate the final numerical models (EcosimPro & ESPSS) for further analyses.

FDM mock-up was used in one complete configuration allowing to perform the complete flight sequence for each test:

- Priming (representing the filling of propulsion lines with hydrazine after opening of pyrovalves): with closed engines valves and a dedicated rapid opening valve on the by-pass line,
- Pressurization (representing the initial pressurization of the propellant tanks): with closed engines valves and a dedicated rapid opening valve upstream the pressure regulator,
- Firing (representing the propulsion subsystem flight sequence with hydrazine): with flight-identical engines.

Each test case of the test campaign consequently included the three steps of the flight sequence:

- Priming (hydrazine),
- Pressurization (helium),
- Firing (helium & hydrazine).

For priming, only the flight scenario was tested.

For pressurization, two cases were tested: the nominal and the maximum propellant loading scenarios.

For firing, four cases were tested: two different flight sequences, the steady state firing case and an elementary firing case (to test the engine elementary opening/closing profiles).

Each run was performed twice to check reproducibility and discard any singular anomaly

The detailed tested cases are presented in Table 1.

Case	Helium Tank Pressure (bar abs)	Propellant Tank Hydrazine Filling (kg)	Propellant Tank Pressure (bar abs)	Engines Actuation Profile (*)
1	164.5	13.0	15.1	PFM1
2	164.5	13.0	15.1	PFM2
3	164.5	13.0	15.1	SSF
4	164.5	13.0	15.1	Elementary
5	164.5	15.4	15.1	SSF

Table 1: FDM Tests Cases

(*) The engines actuation profiles are the following:

- PMF1&2: flight Pulse Mode Firing profiles,
- SSF: Steady State Firing profile,
- Elementary: elementary engines opening and closing profiles.

3. TESTS RESULTS

The complete test campaign was successfully performed and the tests results were satisfactory. Indeed they showed:

- good consistency between the different sensors for a same test,
- good consistency between the different runs for a same test case,
- good consistency between the different cases,
- a consistent physical response for the different studied phenomena.

Examples of results are presented in the next figures. Figure 3 shows an example of priming fluid hammer (pressure evolution with time for the different dynamic pressure sensors). Figure 4 shows an example of pressure evolution with time in the tanks during pressurization and firing.

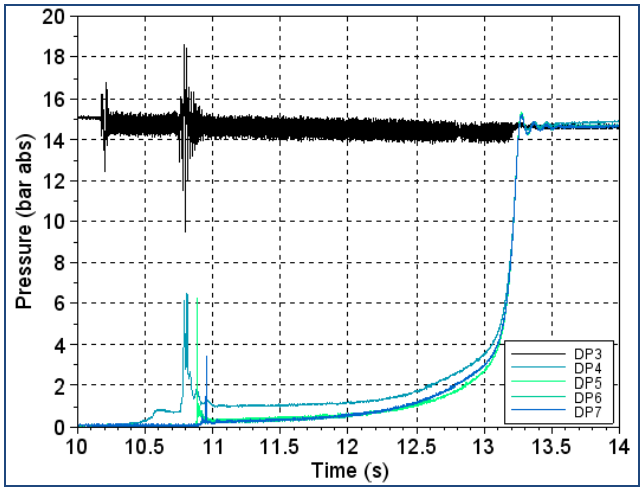

Figure 3: Priming Tests Result Example (Pressures in the subsystem – Case 1)

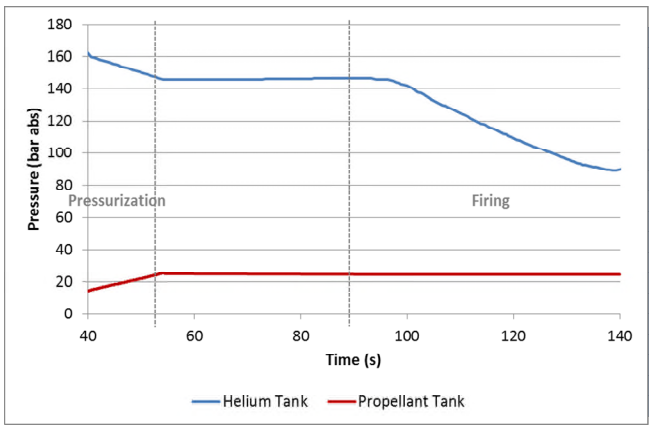

Figure 4: Pressurization / Firing Tests Result Example (Pressure in tanks – Case 1)

The tests allowed to draw interesting conclusions about the studied phenomena and to confirm the previous test campaign main results (HMU#2):

- Priming:

- The priming behavior in hydrazine is the same than in water, and in particular regarding the calibrated orifice damping effect.

- Pressurization:

- The pressure peaks at the Pressure Regulator inlet and outlet are very low.
- The temperatures are quite stable, most probably due to the shortness of the sequence and to the closed test cell.

- Firing:

- Again, the pressure peaks at the Pressure Regulator inlet and outlet are very low and the temperatures are quite stable, most probably due to the shortness of the sequence and to the closed test cell.
- Similarly to HMU#2, the maximum fluid hammer pressure peaks are obtained with the baseline pulse mode firing profile (most certainly due to cross-coupling effects) and are very dependent on the lines design at those high mass flow rates.
- Similarly to HMU#2, the propellant loading has no influence on the firing results.

4. CORRELATION OF NUMERICAL MODELS

The test results were correlated by numerical simulation with the software EcosimPro and the library ESPSS.

Three numerical models were built corresponding to each phase of the test sequence:

- Priming Model: modeling of the propellant part with closed thrusters,
- Pressurization Model: modeling of the pressurant part and of the propellant tanks ullage volumes,
- Firing Model: full modeling of the pressurant part and of the propellant part.

The numerical models were developed fully representative of the mock-up configuration, on the basis of the CAD model of the mock-up, of HMU#2 elementary pressure drop tests (conducted on THALES ALENIA SPACE internal designed tubing parts – tees, elbows, orifices) and of the acceptance test results of the equipments.

The test results were then directly compared to the simulation results. The correlation levels that were obtained are fairly good:

- Priming simulations:

The pressure peaks were correlated with a relative error inferior to 45% on the safe side (overestimation), which represents a good level for such phenomena (complex geometries and quasi-vacuum conditions) and is the same order of magnitude than HMU#2, showing a good accuracy of the model in hydrazine. Figure 5 shows the correlation level obtained on the different dynamic pressure sensors located at the end of lines (DP3 to DP5 are located at the Fill and Drain Valves inlets and DP6 & DP7 are located on the engines cluster).

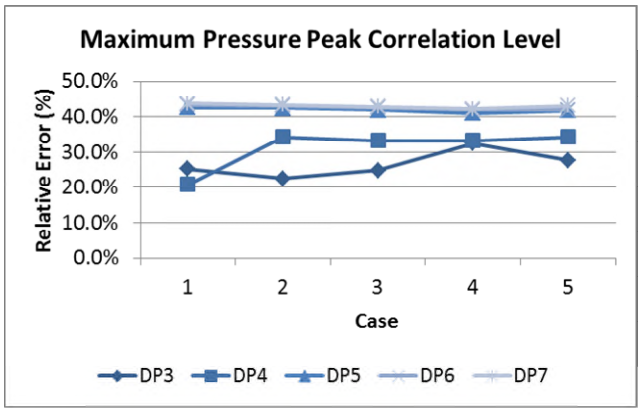

Figure 5: Priming Correlation Level (*)

(*) Relative Error = (Simulation – Test) / Simulation

- Pressurization simulations:

The final helium pressure was correlated with a relative error inferior to 4% on the safe side (underestimation), which represents a very good correlation level. Figure 6 shows the correlation level obtained on the helium tank static pressure sensor.

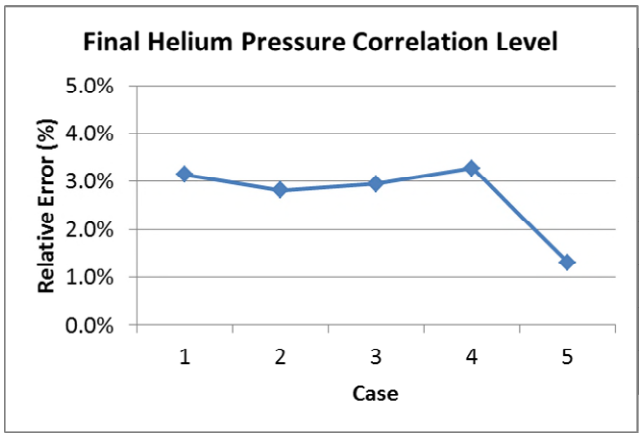

Figure 6: Pressurization Correlation Level (*)

(*) Relative Error = (Simulation – Test) / Simulation

- Firing simulations:

The helium and hydrazine consumptions were correlated with a relative error inferior to ±7%, which represents a good correlation level. The pressure drop between the tank and the cluster entrance in Steady State Firing was correlated with a relative error inferior to 27% on the safe side (overestimation), which represents a good correlation level. Figure 7 shows the correlation level obtained on the helium and hydrazine consumption.

Note: For firing correlation, only cases 1 to 3 were studied to correlate helium and hydrazine consumptions since the other cases were useless. These other cases were only tested to study different fluid hammer pressure peaks in flight conditions.

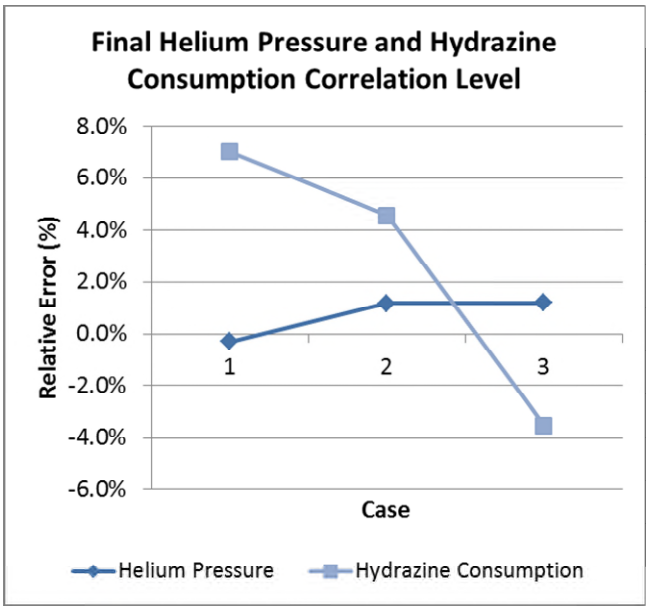

Figure 7: Firing Correlation Level (1) (*)

(*) Relative Error = (Simulation – Test) / Simulation

The correlation level concerning the firing pressure peaks due to the engines pulses was less accurate due to the lack of representativeness in the 400 N engine numerical model (accurate model not available to THALES ALENIA SPACE). Figure 8 shows the correlation level obtained on the different dynamic pressure sensors located at the end of lines (DP3 to DP5 are located at the Fill and Drain Valves inlets and DP6 & DP7 are located on the engines cluster).

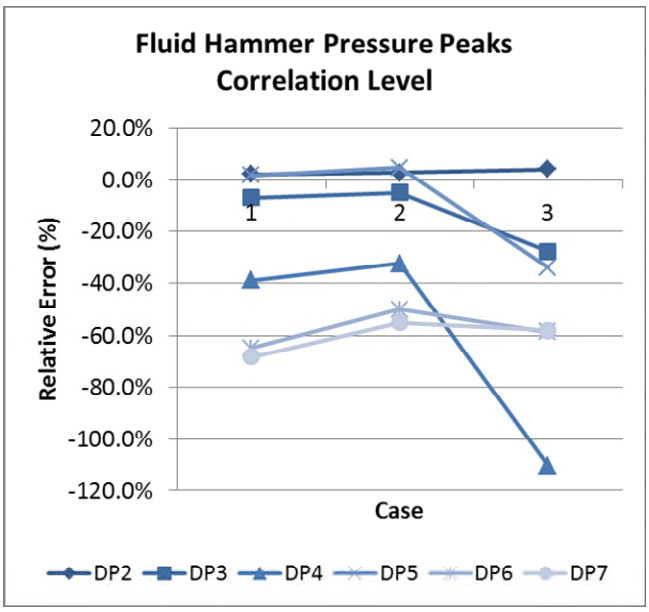

Figure 8: Firing Correlation Level (2) (*)

(*) Relative Error = (Simulation – Test) / Simulation

As stated after HMU#2 test campaign, the lesson learnt from the low correlation level on the firing fluid hammer phenomena is that despite the good analytical tools that are available these days, real testing is still an essential part of new complex propulsion subsystems development.

Note: Better correlation results were obtained by the engine manufacturer with a more detailed engine numerical model.

The good understanding and correlation of the numerical models allowed to validate the analyses that were performed using these models and to highlight the phenomena that had to be taken into account in addition to the analyses results (high cross-coupling pressure peaks during pulse mode firing).

5. CONCLUSION

In the challenging development of Exomars EDM propulsion subsystem, the third and final step of the validation plan – FDM test and correlation campaign – was successfully performed and the results were satisfying. The campaign objectives were fulfilled:

- similarity of the FDM results (hydrazine) with the HMU#2 results (water),
- good performance of the subsystem with the complete flight sequence, conditions and equipments,
- verification of the acceptable level of cross talk between the engines during firing due to the opening/closing cycles of the engines,
- good global correlation level with the fluidic numerical simulations.

The overall test campaign highlighted that:

- on one hand, it is important to conservatively predict and design a propulsion subsystem with a good level of confidence thanks to numerical tools,
- on the other hand, real testing allows to identify the fields in which the numerical tools are well correlated and the ones, more complex like fluids transients, in which there is still room for improvement.

Finally, this complete validation plan and associated correlation activities show Thales Alenia Space Cannes expertise in the simulation of complex propulsion systems.

6. ACKNOWLEDGMENT

The Exomars EDM team at Thales Alenia Space Cannes wishes to thank ESA for their support and advice all along the modeling and test activities.

7. SUMMARY

In the scope of Exomars EDM propulsion subsystem development [3] [5] [6], the design validation plan was composed of three fluidic test campaigns in order to help with design trade-offs, to validate performances of the subsystem and to correlate fluidic numerical models [4].

The first test campaign (HMU#1) was presented at the Space Propulsion 2012 [1].

The second test campaign (HMU#2) was presented Space Propulsion 2012 [2].

The third and final test campaign (FDM) was presented in this paper. It was composed of the same fluidic tests on the same flight representative mock-up as in the previous test campaign (HMU#2) but with flight fluids (helium and hydrazine) instead of simulation fluids (helium and water). The correlation of these tests showed a global good level: 45% on priming simulations (conservative side), 4% on pressurization simulations (conservative side), +/-7% on the firing simulations budgets (pressurant & propellant consumption) and 110% on the fluid hammer due to engines opening/closing cycles (not conservative). This last point was studied and understood and finally taken into account at equipments level.

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EXO | MARS
BY THALES ALENIA SPACE

WE LOOK AFTER THE EARTH BEAT

Final Test Campaign on Fluidic Mock-Up for EXOMARS EDM (with Hydrazine)

05/05/2016

Ref.: SP2016 – 3124632

F. LAVERTY

THALES ALENIA SPACE INTERNAL

ThalesAlenia Space
A Thales / Finmeccanica Company

83230910-DOC-TAS-FR-003

EXOMARS EDM (Entry, Descent & Landing Demonstrator Module)

Presentation

- Spacecraft designed to safely land a science payload on Mars
- Equipped with a hydrazine Monopropellant Propulsion Subsystem operating in regulated mode
- Composed of 1 Pressurant Part + 3 Propellant Parts (3*3*400N engines)

Propulsion Validation Plan

- Propulsion Subsystem with a complex and new geometry
- Wide validation plan necessary to study the fluidic phenomena and correlate the performance models
- 3 fluidic test campaigns on representative mock-ups

More information about EXM EDM in Presentation 3124683 (Session 36 – 4st May 2016 11h40)

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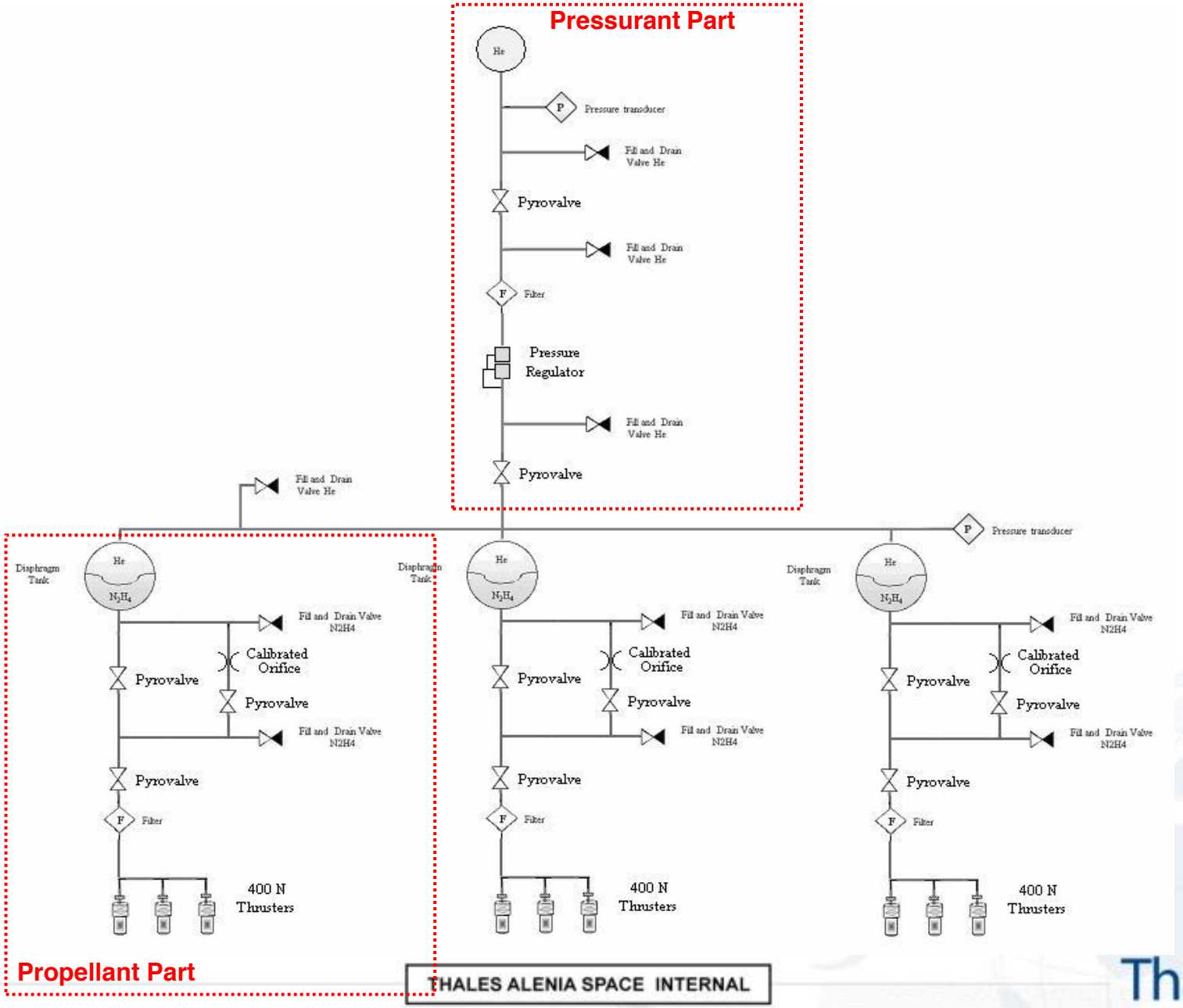
Introduction (3)



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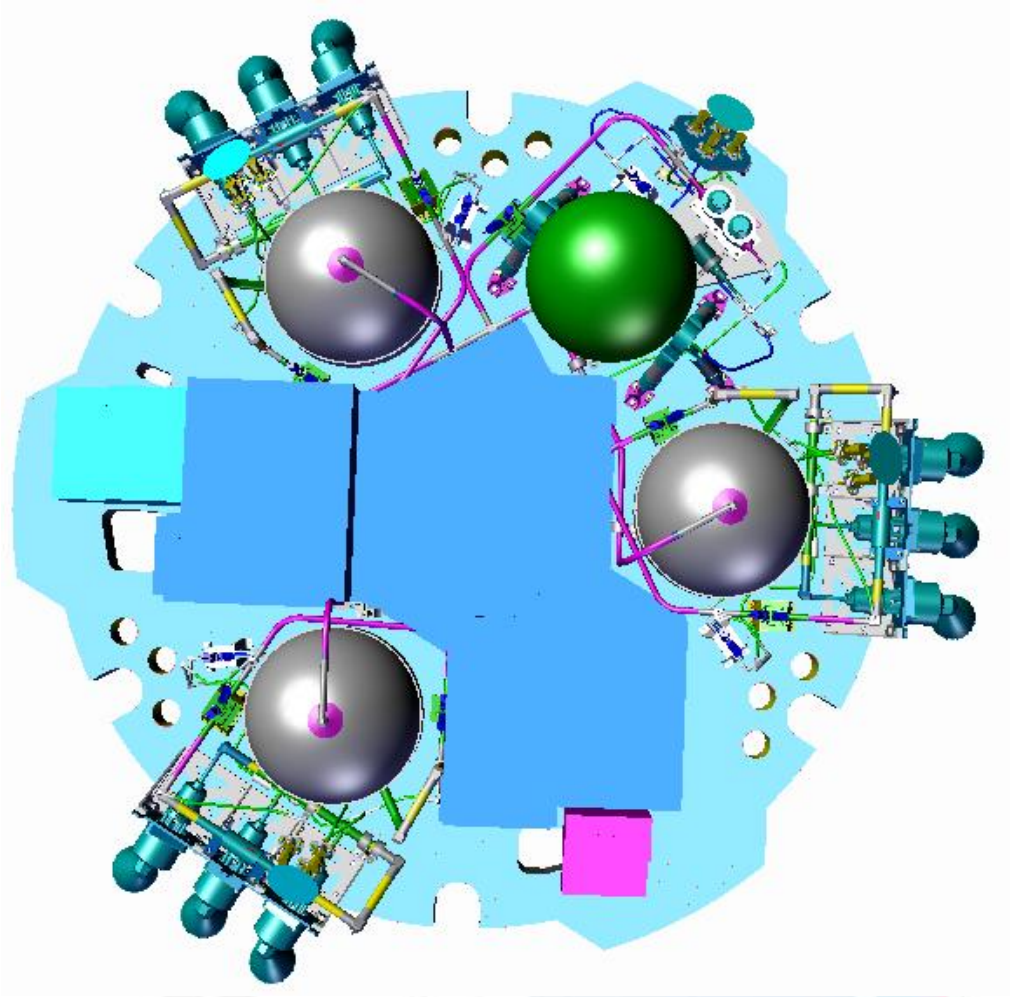
Presentation Plan

- 1/ Propulsion Validation Plan
- 2/ FDM
  - Mock-Up
  - Configuration & Test Plan
  - Tests Results
- 3/ Correlation of Numerical Models
  - Mock-Up Numerical Models
  - Correlation Process
  - Correlation Results
  - Conclusion on correlations
- 4/ Conclusion & Summary

Exomars Propulsion Subsystem



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1/ Propulsion Validation Plan

- Propulsion Validation Plan => 3 Fluidic Test Campaigns:
  - HMU#1: fluidic tests on the propellant lines (presented in Bordeaux at SP2012 – ref. 2355818)
    - priming / pressure drop with water
  - HMU#2: complete flight sequence tests on a representative mock-up of the whole subsystem (presented in Cologne at SP2014 – ref. 2967994)
    - priming / pressurization / firing with water
  - FDM: complete flight sequence tests on a representative mock-up of the whole subsystem with flight engines and hydrazine
    - priming / pressurization / firing with hydrazine

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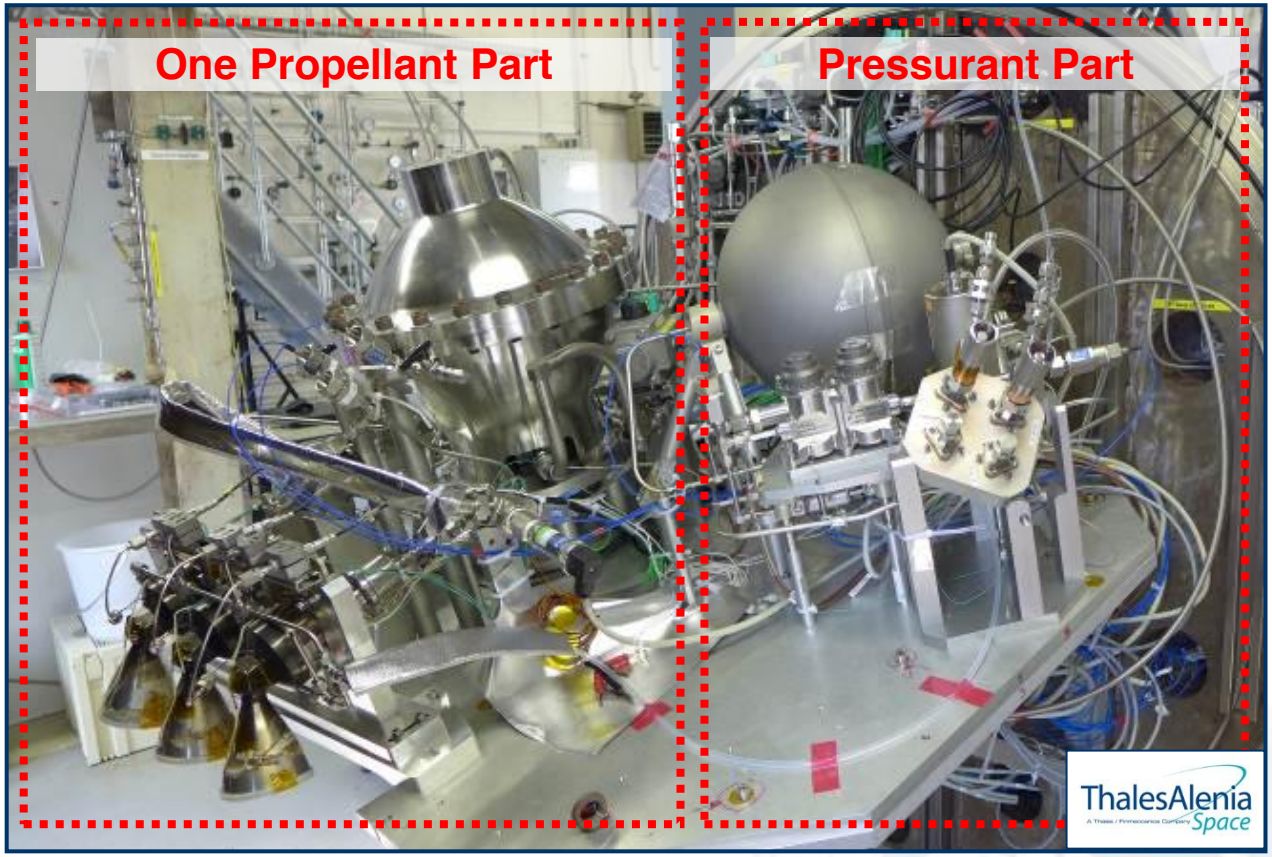
2/ FDM (1)

Mock-Up

- Flight like subsystem and equipments

- Pressurant part
  + 1 propellant part
  + 1 dummy assembly representing the 2 other propellant parts (ullage volume & outgoing mass flow)



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Configuration & Test Plan (1)

- One single configuration with the complete sequence tested for all cases:

Priming
Representing the filling of propulsion lines with hydrazine after opening of pyrovalves

+

Pressurization
Representing the initial pressurization of the propellant tanks

+

Firing
Representing the propulsion subsystem flight sequence

Case	Helium Tank Pressure (bar abs)	Propellant Tank Hydrazine Filling (kg)	Propellant Tank Pressure (bar abs)	Engines Actuation Profile (*)
1	164.5	13.0	15.1	PFM1
2	164.5	13.0	15.1	PFM2
3	164.5	13.0	15.1	SSF
4	164.5	13.0	15.1	Elementary
5	164.5	15.4	15.1	SSF

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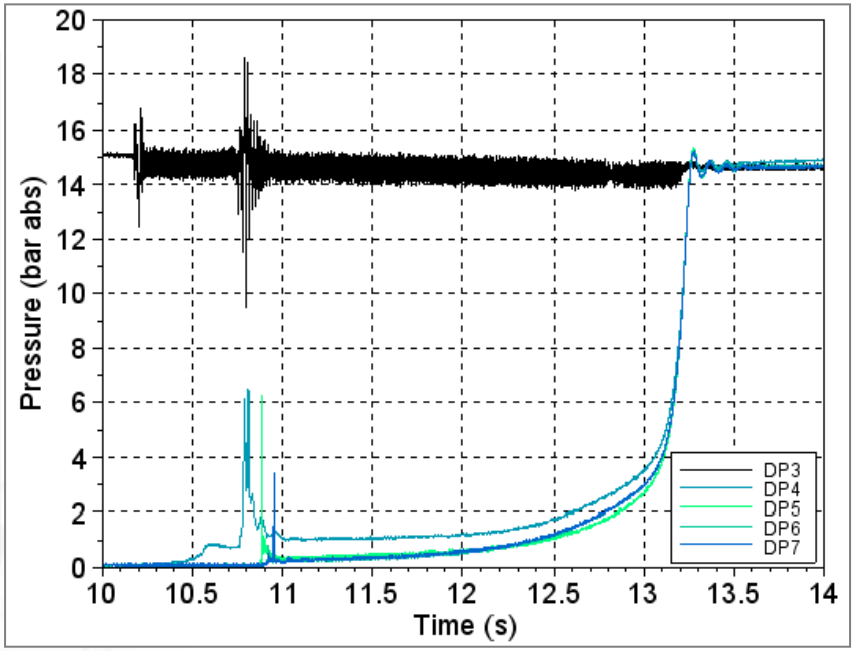
Tests Results (1)

- Test campaign successfully performed with coherent results:
  - Between sensors / runs / test cases
  - Regarding studied fluidic phenomena

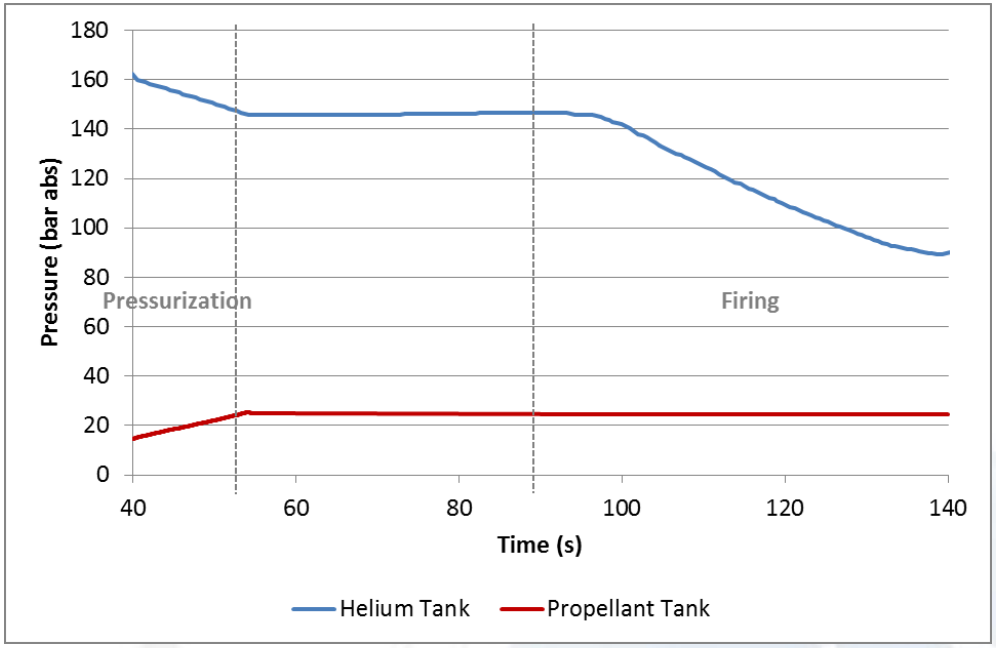
EXAMPLE

PRIMING



PRESSU

FIRING



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Tests Results (2)

Main interesting conclusions

- Priming:
  - Confirmation that the behavior in hydrazine is identical to the behavior in water (HMU#2), in particular regarding the calibrated orifice
- Pressurization:
  - Confirmation that the pressure peaks at the pressure regulator inlet and outlet are very low
- Firing:
  - Confirmation that the maximum fluid hammer pressure peaks are obtained in Pulse Mode Firing, due to cross-coupling effects
  - Validation of the good performance of the engines versus the feeding system

=> Flight Sequence validated from Priming to Pressurization and Firing

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Mock-Up Numerical Models

- 3 numerical models to study the 3 test phases
- Built with the following rules:
  - Tubing routing based on CAD model
  - Tubing singularities models based on elementary pressure drop tests performed during HMU#2 Test Campaign
  - Test equipments parameters based on equipments calibration data
  - Flight equipments parameters based on equipments acceptance test results

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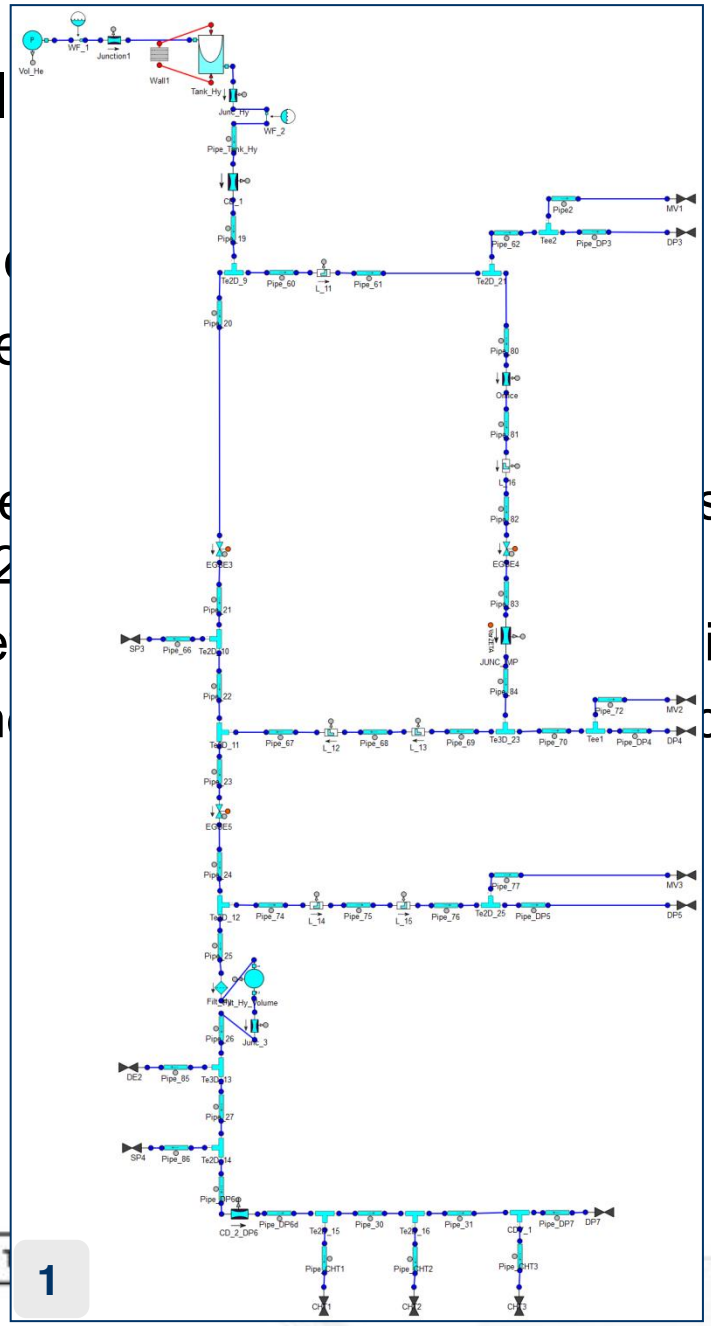
3/ Correlation of Numerical Models (1)

- Mock-Up Numerical Model
  - 3 numerical models to stu
  - Built with the following rule
    - Tubing routing based on
    - Tubing singularities mode sure drop tests performed during HMU#2
    - Test equipments parame ibration data
    - Flight equipments param cceptance test results

1/ Priming Model



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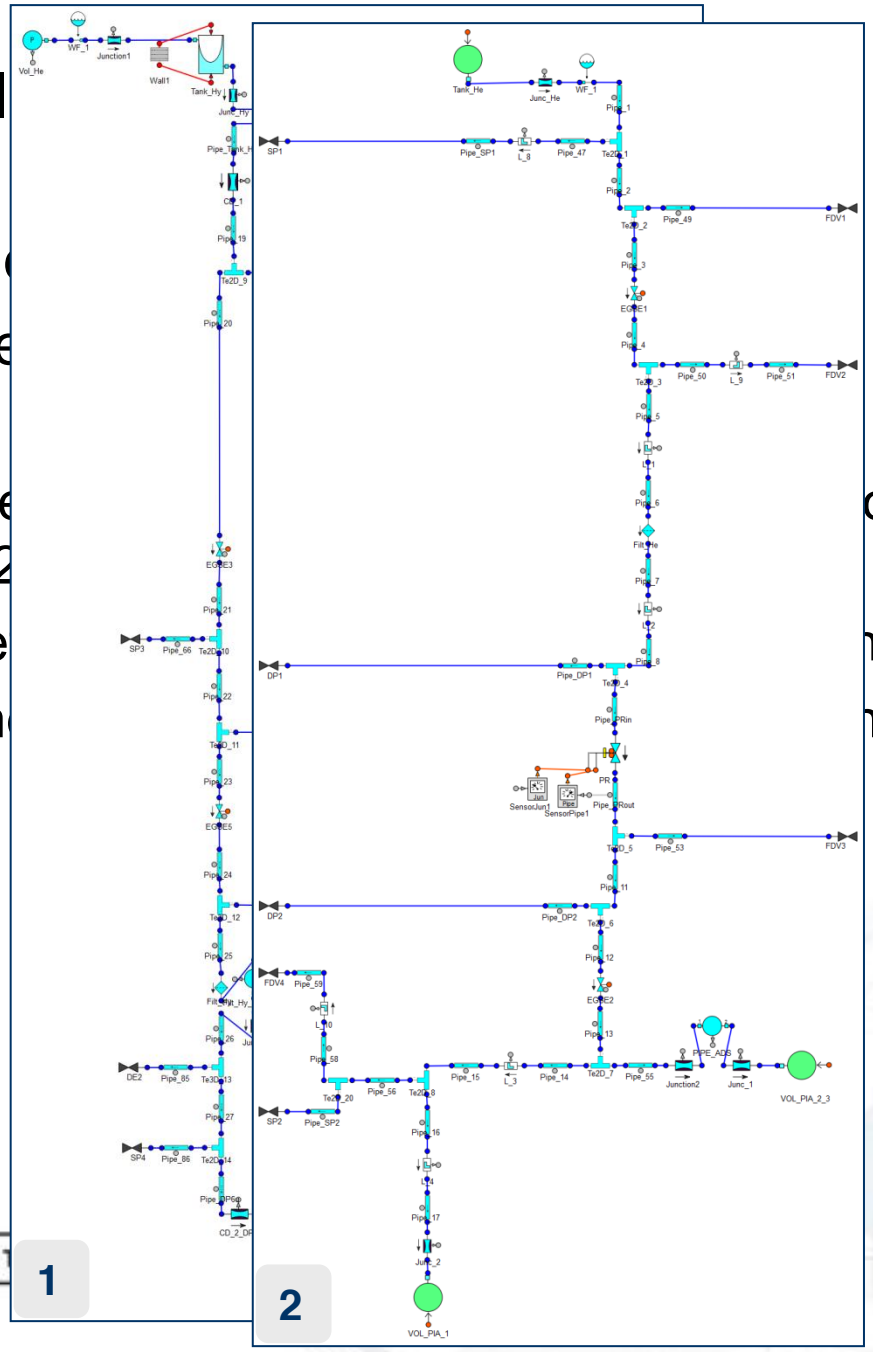
3/ Correlation of Numerical Models (1)

- Mock-Up Numerical Model
  - 3 numerical models to stu
  - Built with the following rule
    - Tubing routing based on
    - Tubing singularities mode op tests performed during HMU#2
    - Test equipments parame n data
    - Flight equipments param nce test results

1/ Priming Model

2/ Pressurization Model



3/ Correlation of Numerical Models (1)

- Mock-Up Numerical Mod
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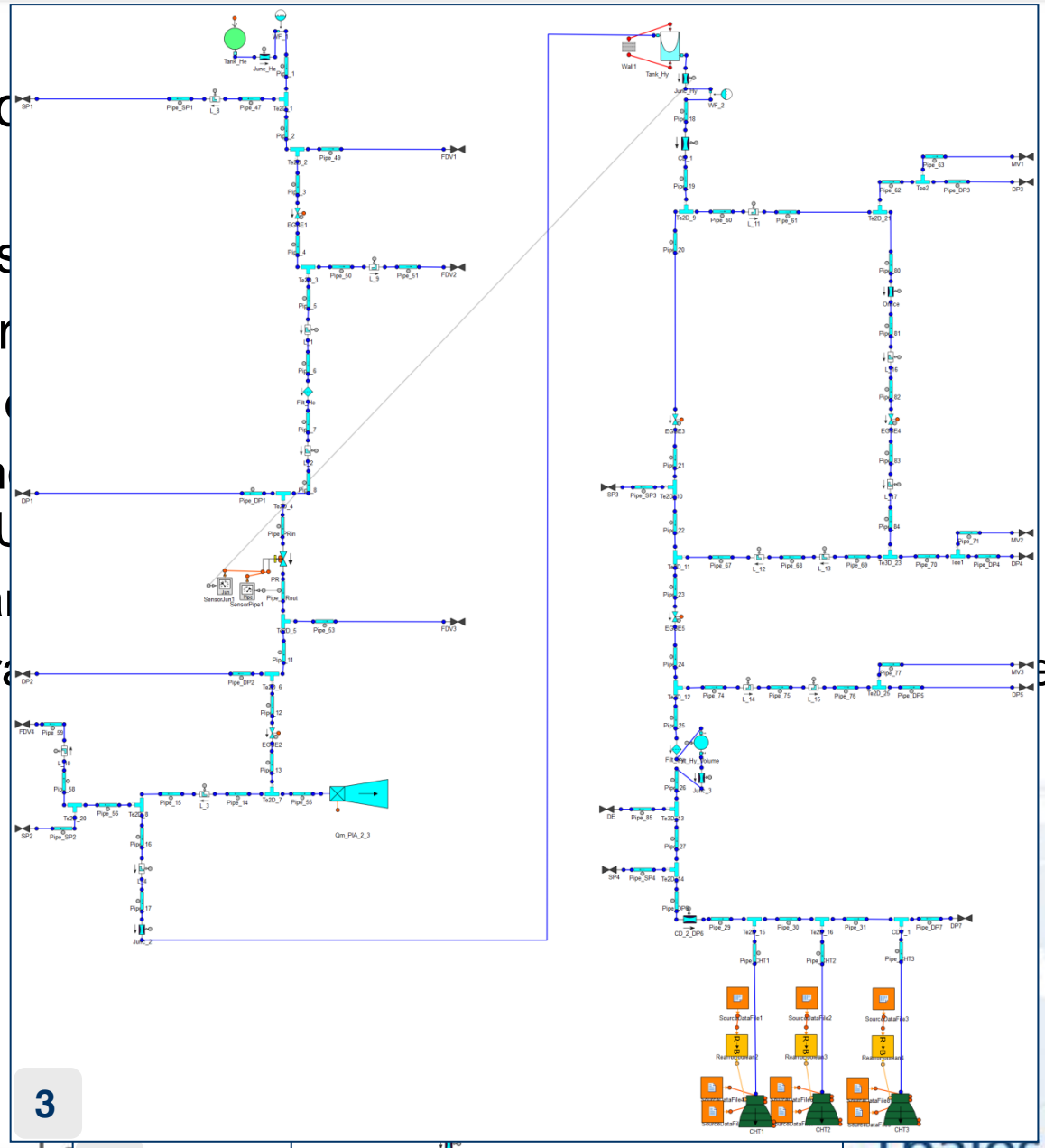
    - Tubing singularities m performed during HMU
    - Test equipments para
    - Flight equipments para esults

1/ Priming Model

2/ Pressurization Model

3/ Firing Model



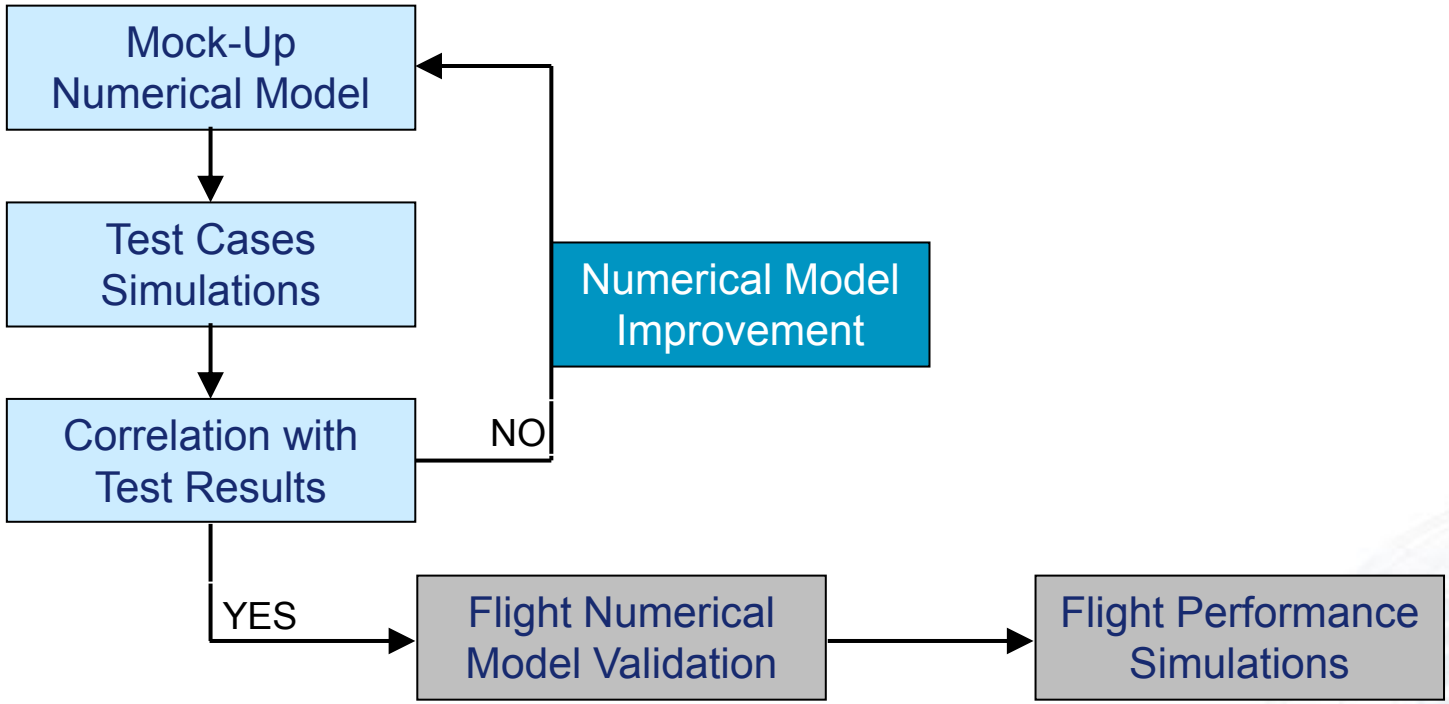
3

1

2

Correlation Process

- For each numerical model:



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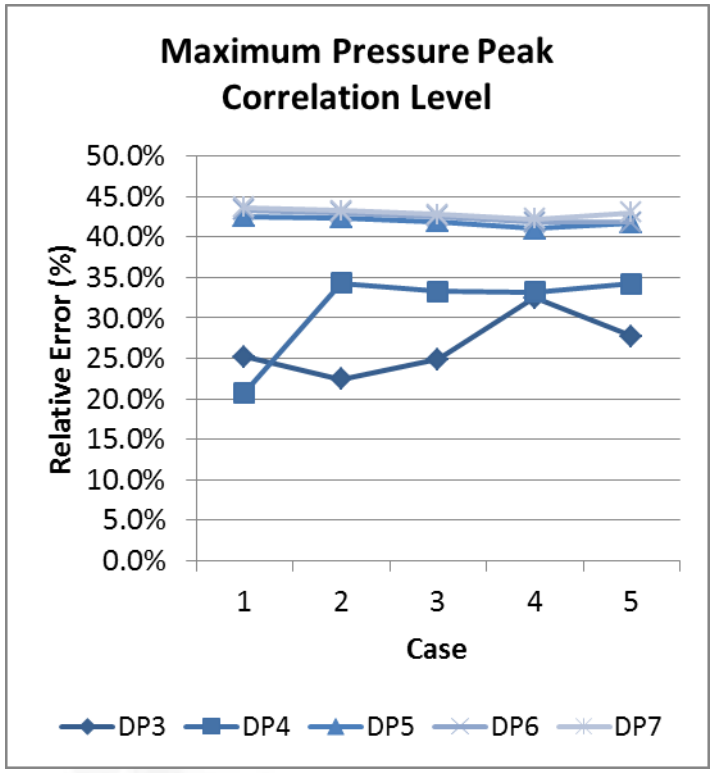
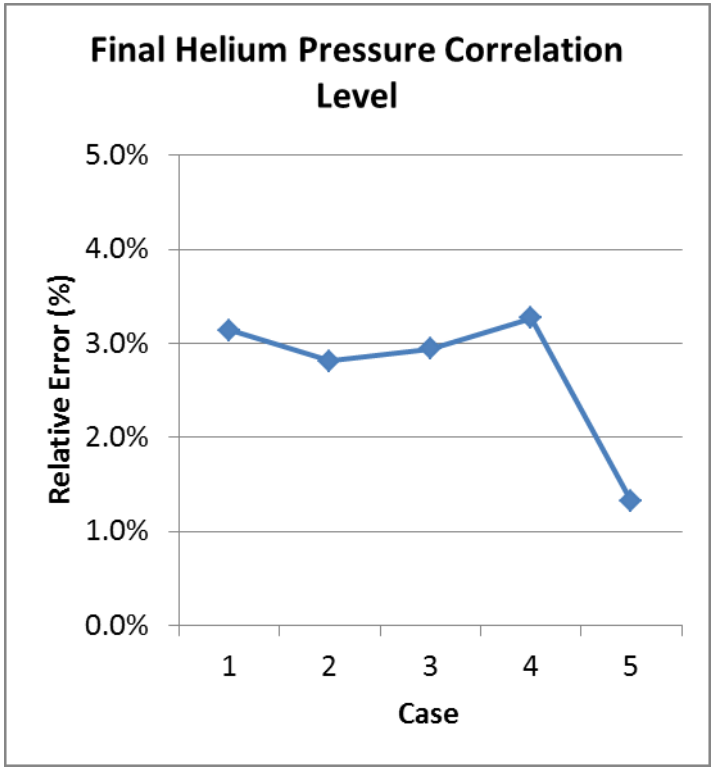
3/ Correlation of Numerical Models (3)

Correlation Results

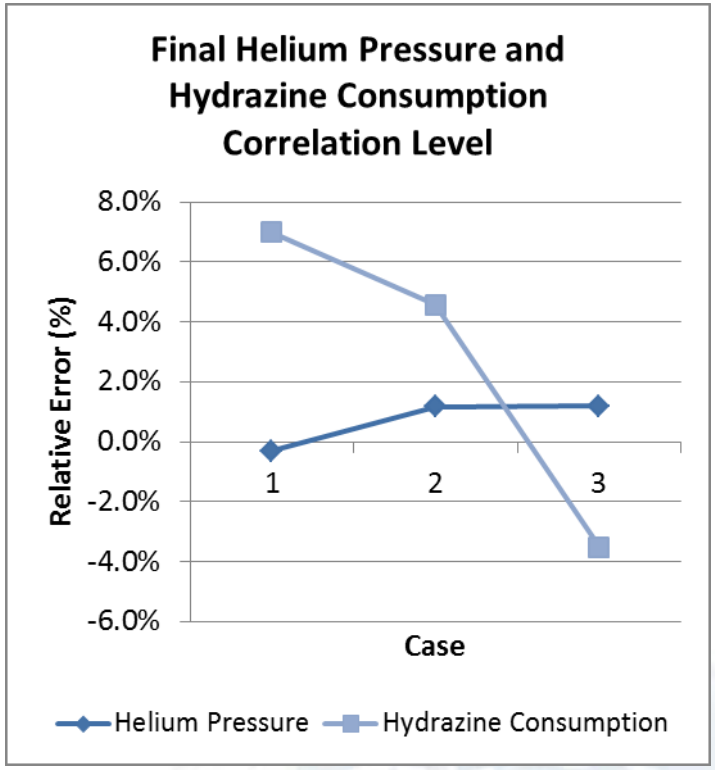
1/ Priming Model



2/ Pressurization Model



3/ Firing Model



DP3 to DP5 are located at the Fill and Drain Valves inlets and DP6 to DP7 are located on the engines cluster

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3/ Correlation of Numerical Models (3)

Correlation Results

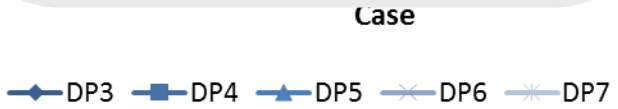
1/ Priming Model

Pressure Peaks

Global overestimation (conservative)

Relative Error < 45%

=> Good level for such highly intensive phenomena (complex geometries and vacuum conditions)



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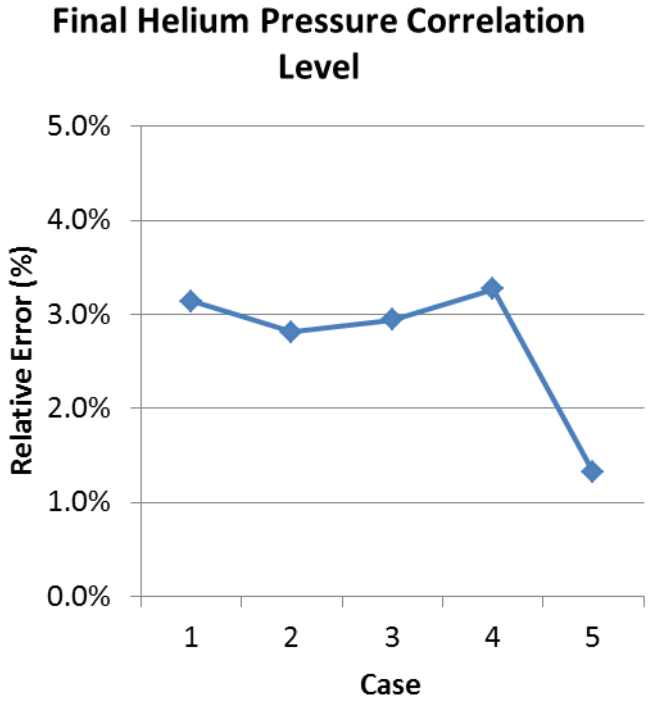

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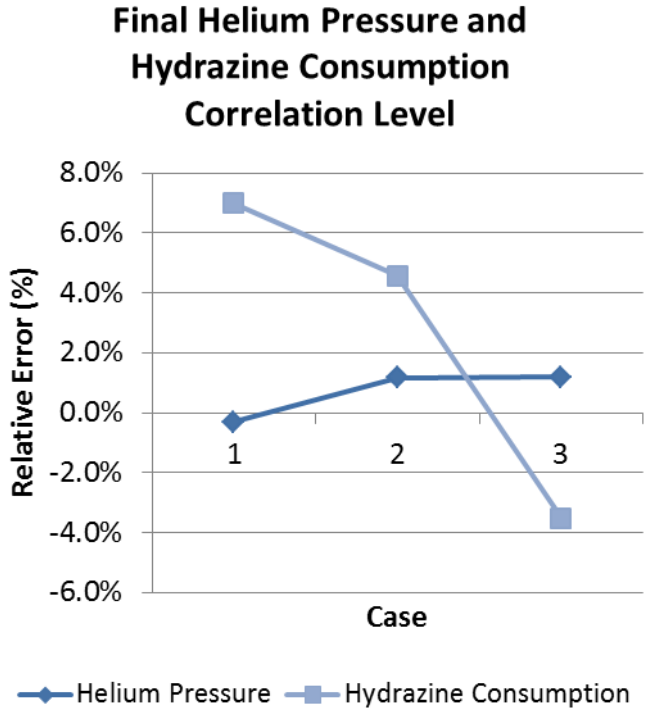

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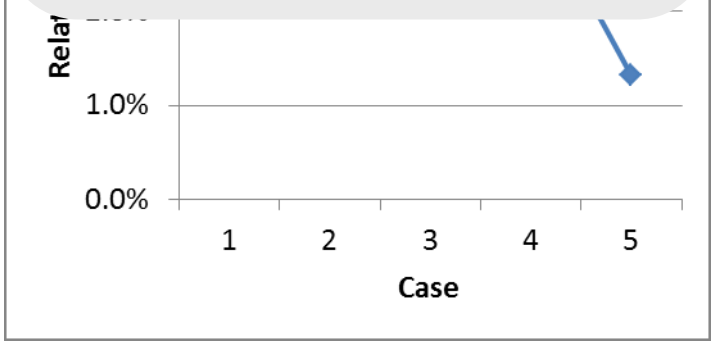
2/ Pressurization Model

Consumption

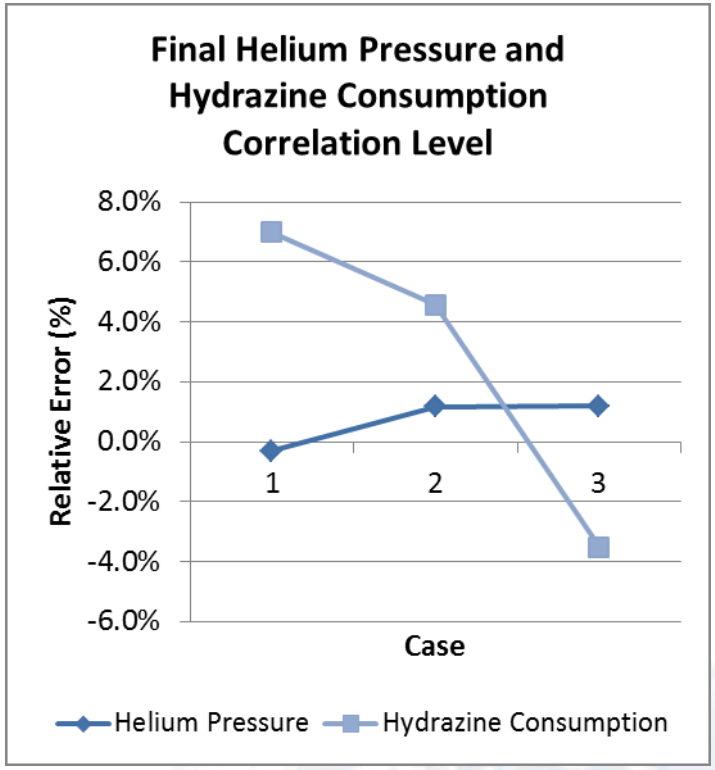
Global overestimation (conservative)

Relative Error < 4%

=> Very good level



3/ Firing Model



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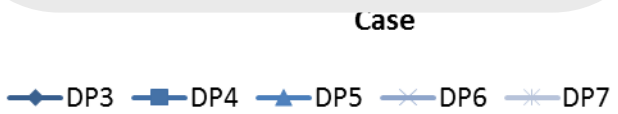

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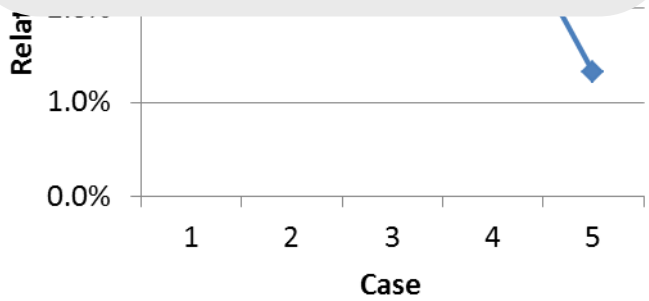

3/ Firing Model

Consumptions

Relative Error < ±7%

=> Very good level

Pressure Drop

Global overestimation (conservative)

Relative Error < 27%

=> Good level

Pressure Peaks

Global underestimation (not conservative)

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3/ Correlation of Numerical Models (3)

- Conclusion on correlations

  - Good overall correlation level
    - Except regarding firing fluid hammer peaks due to cross coupling between engines

    => Need for a better numerical model of the engines transient phases
  - Better understanding of the fluidic phenomena

=> Final improvements and validation of the numerical models used for the analysis of Propulsion Subsystem performance

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3/ Conclusion & Summary

- Exomars EDM Propulsion Subsystem = New challenging development
  - Validation plan with 3 fluidic test campaigns

- FDM = Final test campaign covering the complete flight sequence with flight media on flight representative mock-up
  => Successfully performed (priming / pressurization / firing in hydrazine)
  - Satisfying tests results (coherence with HMU#2 in water)
  - Good correlation level of the numerical models
  - Validation of engines performances versus feeding system
  - Confirmation of the complementarity between real testing and numerical simulations in the development of new complex propulsion subsystems

- Thales Alenia Space France Cannes Propulsion Team thanks ESA for its support in this activity.

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EXO | MARS
BY THALES ALENIA SPACE

WE LOOK AFTER THE EARTH BEAT

Thanks for listening

F. LAVERTY

05/05/2016
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