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Engineering validation model for the Exomars bi-propellant propulsion subsystem

S. Pavón(1), V. Tregubow(1), M. Peukert(1), R. Lescouzères(1)

(1) OHB-System AG, Universitätsallee 27-29, 28359 Bremen, Germany, www.ohb-system.de
e-mail: samantha.pavon@ohb-system.de, Phone:+49-421-2020-9934

ABSTRACT

The Exomars mission is an ESA led scientific mission to Mars. Its goal is to launch, in 2016, a composite spacecraft including an orbiter and a demonstration descent and landing module. The orbiter will carry scientific payload which will analyze the Martian atmosphere composition. The objective of the landing module is to validate the landing scenario for the second part of the Exomars mission, foreseen to land rovers on Mars in 2018.

Due to program constraints, a new cost- and schedule-optimized validation method for the propulsion subsystem had to be developed and is presented here.

The paper outlines the new validation approach, stressing the efficient interaction between validation by test and by analysis, which permits to comply with the stringent Exomars program constraints. The test setups are presented and their representativeness, as compared to the PFM, is justified and discussed in details. Test conditions are also defined thoroughly, based on the real Exomars mission scenario, initial PFM numerical analysis and the state of the art.

INTRODUCTION

The propulsion subsystem of the Exomars orbiter is a bi-propellant pressure-regulated system, using MON and MMH as propellants and helium as pressurant gas. High thrust manoeuvers are performed by a 400N main engine (ME). In addition to that, 20 reaction control thrusters (RCTs) with 10 N thrust each, are used for orbit correction manoeuvers, station keeping and support to the main engine during high impulse manoeuvers. Ten of the RCTs are nominal, backed-up by 10 redundant thrusters.

Figure 1 shows a schematic of the Exomars propulsion subsystem as accommodated on the spacecraft. The detailed flow schematic of the subsystem is presented in Figure 2.

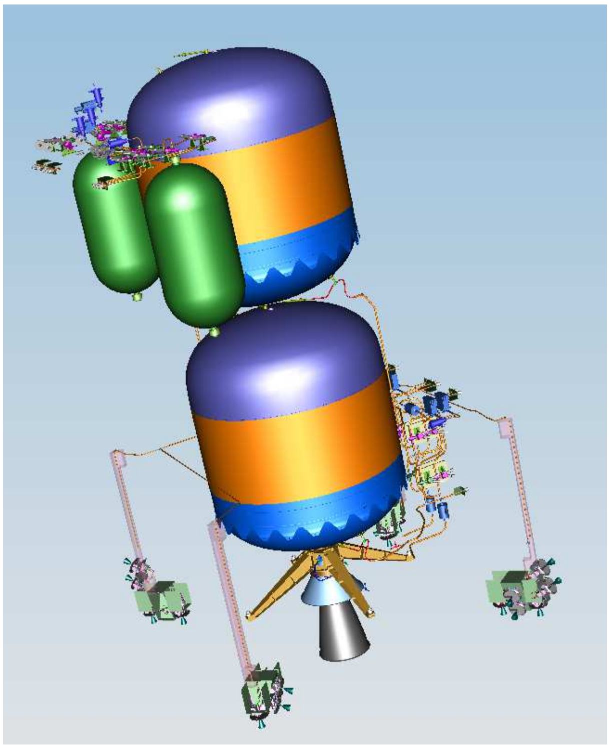


Figure 1: Overview of the Exomars PFM propulsion subsystem

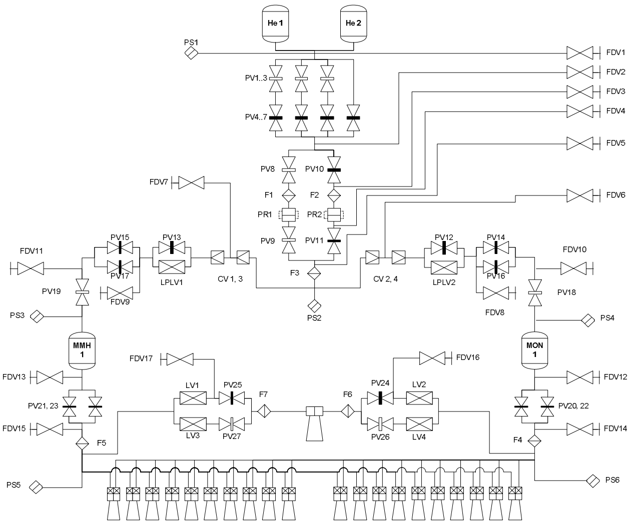


Figure 2: Flow schematic of the ExoMars propulsion subsystem

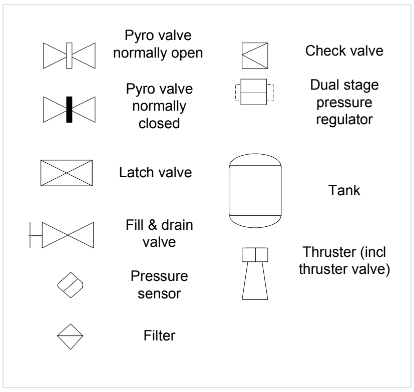


Figure 3: Legend for the flow schematic of Figure 2

Helium is stored in two 90 L tanks, and routed to the propellant tanks through the pressurant control assembly (PCA). The main PCA components are the pressure regulator (redounded), which allows to control the propellant tank pressures during long manoeuvers, and 2 sets of check valves, one on each branch (MON an MMH), to avoid propellant vapors to come into contact and cause unwanted chemical reaction in the PCA. The pyro-valves and latch valves are here to comply with the relatively complex mission operation scenario and consequent reliability requirements.

Propellant tanks are 1210 L each and feed the main engine and RCTs through the propellant isolation assembly (PIA). The main component of the PIA is the latch valve on the main engine branch, which isolates the main engine from the propellant, on ground and between manoeuvers. Closing of the latch valve provides the capability for main engine valve venting and flushing of the line between the latch valve itself and the main engine valve. This can reduce the contact duration between the engine valves and the propellant, and minimize the probability of swelling of Teflon parts in the engine valves.

As shown in Figure 1, the helium tanks and the PCA are accommodated at the top of the spacecraft, and the PIA, main engine and RCTs at the bottom of the spacecraft. MMH tank is at the top and MON tank at the bottom.

VALIDATION APPROACH

The Exomars program schedule asks for an unconventional repartition of system and subsystem phasing. Where conventional programs run in a relatively linear separation of design and manufacturing phases, Exomars requires high parallelization of system and subsystem (even component) design, manufacturing and qualification. Examples come up where subsystem manufacturing has to start before system final design freeze.

In order to comply with these stringent cost and schedule optimization requirements, the validation approach shown in Figure 4 has been developed. Green boxes differentiate between the Exomars propulsion protoflight model (PFM) and the Engineering Validation Model (EVM) test rig. Orange boxes highlight the validation steps. Blue boxes show the information flow between the PFM and EVM, and finally white boxes are steps in the PFM or EVM timelines.

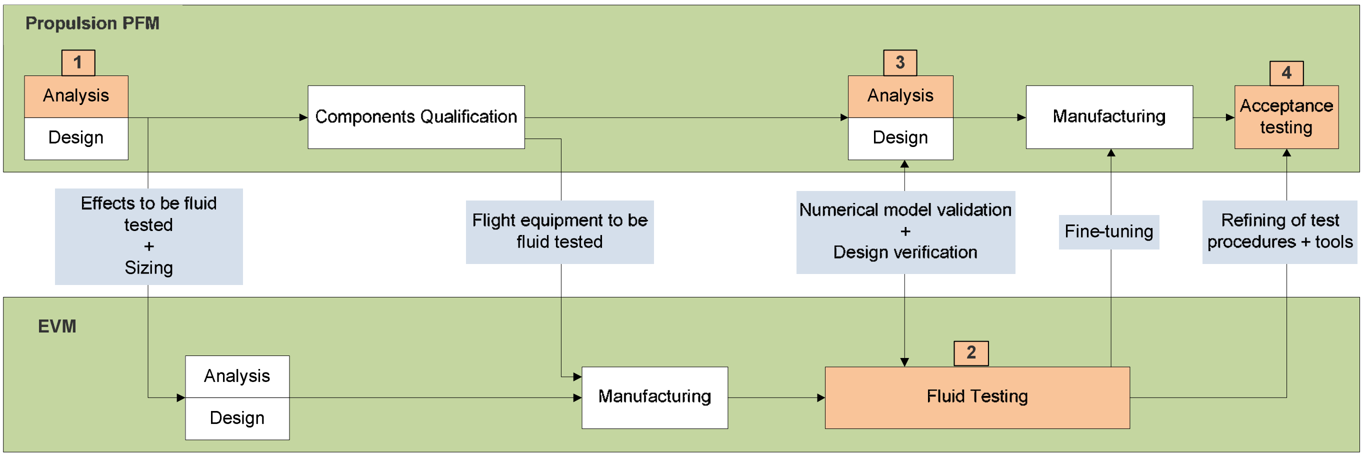


Figure 4: Verification logic for the Exomars propulsion subsystem

First, numerical analysis of the PFM propulsion subsystem is performed, using the real Exomars mission scenario. The model can however not accurately predict complex transient effects, one of the most critical being line priming with propellants. These effects depend on several parameters and are still difficult to simulate with sufficient confidence level. Moreover, data from the scientific state of the art is very scarce, due to safety issues related to propellant handling and the related costs. Finally, in-house heritage does not cover this area yet. This therefore justifies the need for a test validation of transient effects in the Exomars propulsion subsystem.

The second step in the validation logic is the manufacturing and testing of the hardware model, so-called Engineering Validation Model (EVM). The PFM analysis is used as input to size the test rig. As will be discussed later in this paper, some parts of the EVM will require the use of flight hardware is order to ensure the model is as representative as possible. This is a second input from the PFM to the EVM definition. The EVM will test of transient flow phenomena, both in the PCA and in the PIA, as described in details in the following chapters.

The EVM test results will be used to validate and improve the numerical model of the PFM. It will also provide test data that will be a direct input to the fine-tuning of the design (and manufacturing) of the PFM (step 3). As shown in Figure 4, EVM testing has to run in parallel with detailed PFM analysis and design and PFM manufacturing, due to Exomars Schedule constraints.

Finally, the PFM subsystem including possible minor modifications is acceptance tested (step 4). Moreover, EVM testing will provide a basis for the refinement of test procedures and tools needed on the PFM.

Steps 1 and 2 are detailed in the following chapters.

PFM NUMERICAL ANALYSIS AND EXPERIMENTAL STATE OF THE ART

In the first step of PFM analysis and design, steady state flow effects have been calculated numerically with a commercial tool (EcoSimPro). These include pressure drop analysis in the complete propulsion subsystem (PCA and PIA), maximum expected operating pressure (MEOP) analysis, engine operation envelope analysis, internal leak analysis, gauging and residual analysis. In addition to that, an assessment has been performed, to test the suitability of this numerical model to simulate transient effects. Propellant priming and water hammer are shown below as examples.

Table 1 compares priming calculation using EcoSimPro on a simple setup (calibration setup) taken from the literature [4], with test data from the same reference. Results show a relatively good correlation for water, but a large deviation (43%) for calculations with MMH and with NTO (20%).

Fluid 1	Fluid 2	Calculated P priming [MPa]	Measured P priming [MPa]	Δ [%]
real H2O	perfect N2	312,9	289	8,3
real H2O	perfect N2	312,9	289	8,3
real H2O	perfect N2	297,08	289	2,8
real MMH	perfect N2	360	252	42,9
real NTO	perfect N2	301,4	252	19,6
real MMH	perfect N2	8,08	6,4	26,3

Table 1: Comparison of pressure peak values calculated using the numerical model and extracted from literature on priming tests [4]

In the same way, Table 2 compares water hammer calculation using EcoSimPro on a simple setup (calibration setup) taken from [1], with test data from the same reference. Results show deviations up to 65 % for calculations with MMH.

Fluid 1	Fluid 2	Pipe type	P initial Fluid 2	Calculated P water hammer [MPa]	Measured P water hammer [MPa]	Δ [%]
real MMH	perfect N2	straight pipe	0.001	40,9	30,1	35,9
real MMH	perfect N2	straight pipe	0.434	2,66	2,4	10,8
real MMH	perfect N2	bend pipe	0.001	45,9	27,9	64,5
real MMH	perfect N2	bend pipe	0.001	44,9	28,9	55,4
real MMH	perfect N2	bend pipe	0,1	7,9	6,1	29,5
real MMH	perfect N2	bend pipe	0,1	8,08	6,4	26,3

Table 2: Comparison of pressure peak values calculated using the numerical model and extracted from literature on water hammer tests [1]

In both cases calculated values overestimate measured values. This problem has been reported in several studies (e.g. [3]). Indeed, today's numerical models are based on current knowledge of propellant properties, which is not complete. This is mainly due to high cost of propellant testing (due to safety issues) and thus reduced test opportunities. Numerical models therefore still poorly represent complex physic-chemical phenomena in propellants. This justifies the need for propellant testing of the Exomars subsystem, since no heritage is available yet in-house on priming on water hammer.

In order to extract reliable guidelines for EVM sizing and test definition, test data has been extracted from one of the only sources available in the open literature [1] on priming with propellants and is shortly summarized in Figure 5.

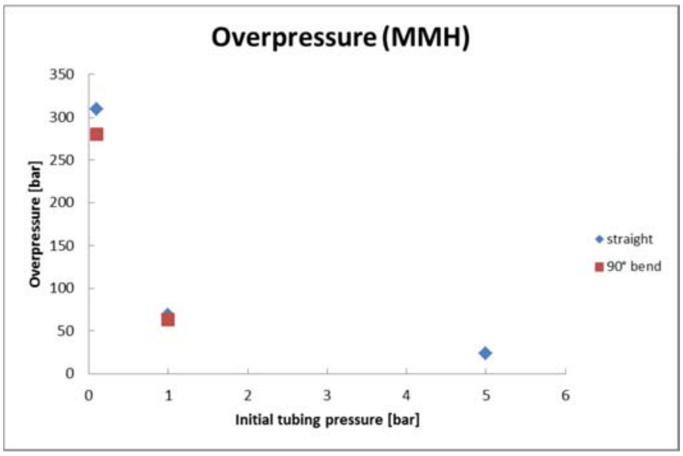


Figure 5: Priming measurements with MMH, extracted from [1]

Figure 5 shows that:

- Increasing the initial gas pressure in the line reduced the amplitude of the priming peak.
- Bends reduce the priming overpressure.

In addition to that, it is shown in [2] that:

- Increasing the initial gas pressure in the line increases the propagation time of the pressure peak and the time between the first peak and consequent secondary peaks.
- Increasing the pressure in the propellant tank increases the pressure surge and that modifying the tank pressure has a stronger effect than modifying the pipe pressure.

Finally, [3] also shows that:

- Increasing the length of the pipe increases the amplitude of the pressure peak.

EVM TEST SETUPS

Most of the objectives of the EVM have been mentioned in the precedent chapters in the frame of the PFM validation sequence. The EVM will allow the fulfillment of additional secondary objectives, namely regarding operation of the subsystem and off-design features. The complete list is summarized below:

Primary objectives

1) Validation of the numerical model to be used for predictions on the PFM:
    - PCA: pressure drop, interaction of the pressure regulator with check valves, cross-talk between the two sets of check valves (MON and MMH side).
    - PIA: pressure drop, priming, water hammer.
2) Verification of individual components:
    - Behavior of the pressure regulator.

Secondary objectives

3) Development and validation of test procedures to be used on the PFM.
4) Validation of subsystem operation strategies to be used on PFM.
5) Identification of marginal design features.

In order to optimize the EVM schedule, EVM test setup is split in two parts: the PCA part (Figure 6) and the PIA part (Figure 7). In this way, manufacturing and testing of one part can be parallelized with the manufacturing and testing of the other part. This strategy does not affect the test objectives in any way. Indeed, the large volume of the propellant tanks filled either with gas or liquid will damp the transients from the gas or propellant side. The propagation of these effects from PCA to PIA or inversely is therefore negligible. In both set-ups, only the nominal flow path is represented.

The PCA part test campaign will be split in 5 sub-campaigns, each addressing specific objectives as described in Table 3. Test procedures for each sub-campaign are discussed in the next chapter.

PCA test campaign obectives	
PCA-1	Characterize pressure regulator behavior
PCA-2	Study interaction between PR and CV
PCA-3	Study cross talk between sets of check valves
	Measure steady-state pressure drop
PCA-4	Test operation sequences
PCA-5	Identify marginal design features

Table 3: Objectives of the EVM PCA test setup

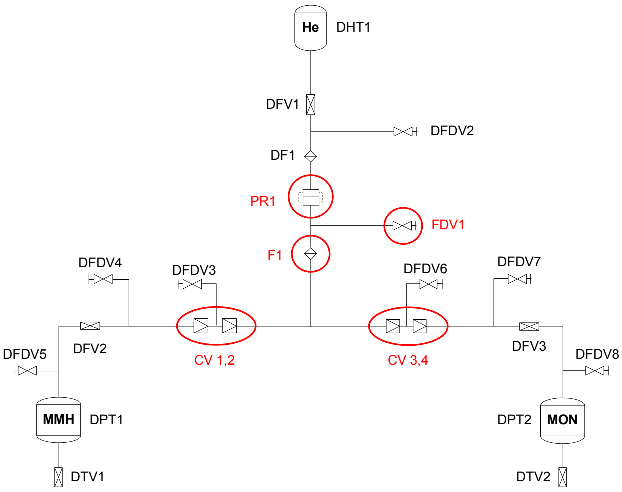


Figure 6: Flow schematic for the EVM PCA test setup

Figure 6 shows the flow schematic of the PCA set-up. Flight hardware is highlighted with red circles. The following equipment will be flight-like: the pressure regulator (PR1), the fill and drain valve (FDV) after the pressure regulator, the helium filter (F1), and the check valves (CV 1-4). Indeed, pressure regulator testing and its interaction with check valves is a primary objective. Also, no dummy equipment is available that can simulate the behavior of the helium filter and the check valves in a sufficiently representative way. The flight FDV is introduced in order to simulate the tests performed on the PFM regulator as close as possible. All PFM pyrovalves are replaced by dummy fast valves (DFV) with fast opening times (<2ms). If flight pyrovalves were used, they would have to be replaced after each test and this would imply considerable and unnecessary cost and time.

Tubing is flight hardware in order to have the best possible representativeness for the propagation of pressure waves in the systems and validate tubing design. Lengths, diameter, wall thickness, number of bends, radius and angle of bends will be the same as for the PFM, but relative angles between 2 bends will be modified in order to accommodate the tubing in 2D and simplify the setup.

On the high pressure side (upstream of the pressure regulator), a dummy fast valve (DFV1) and a dummy filter are used. Since this part is relatively static, apart from the pressure regulator inlet, dummies can be used to replace pyros and filters. The tubing is flight like, representing the shortest path from the PFM helium tank to the PFM pressure regulator PR1 and therefore the expected worst case regarding interaction of the PR with the upstream volume. Dead tubing volumes between the PFM normally closed pyro-valve and the PFM pressure regulator are also included (namely the FDV2 line).The effect of the dead volumes between the helium tank and the pyrovalve are considered negligible.

On the low pressure side (downstream of the pressure regulator), the behavior of the flow will be highly dynamic, including check valve-check valve interactions, in the same branch and in different branches, as well as check valve-pressure regulator interactions. Since inter-branch interactions (MON and MMH sides) are to be investigated, the two branches have to be represented. The branches go all the way to the propellant tank dummies. Propellant tank volume needs to be represented since its volume is large compared to the tubing volume and will introduce considerable damping of the pressure waves in the gas system. The fluid will be simulant since only the gas volume is relevant here. Throttle valves at the exit of the tanks will permit to regulate simulant evacuation and thus variation of gas volume in the tank. PFM latch valves have been removed since they can easily be accounted for in the pressure drop tests and they do not introduce relevant transient effects in the system considering how they will be operated. Dead tubing volumes are all represented in the low pressure side.

Static and dynamic pressures will be measured along the two paths, together with temperatures in order to fully determine the thermodynamic state of the fluid at each measurement point. Accelerometers will be accommodated on the pressure regulator and the check valves.

The PIA part test campaign will be split in 3 sub-campaigns, each addressing specific objectives as described in Table 4. Test procedures for each sub-campaign are discussed in the next chapter.

PIA test campaign obectives	
PIA-1	Study priming of PIA
PIA-2	Measure steady state pressure drop + flow rate
	Study water hammer propagation
PIA-3	Identify marginal design features

Table 4: Objectives of the EVM PIA test setup

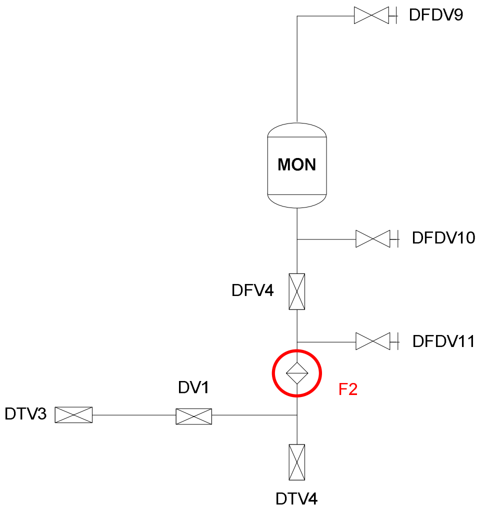


Figure 7: Flow schematic for the EVM PIA test setup

Figure 7 shows the flow schematic of the PIA set-up. Two PIA set-ups will be built, one for the MON side and on for the MMH side. Indeed, if the same set-up was used for testing with MON and MMH, decontamination would have to be performed in between, which would actually represent more effort than building a second setup. In addition to that, tubing paths are different on the MON and MMH side on the PFM. As for the PCA, flight hardware is highlighted with red circles, in this case only the filter. The filter is the critical component of the PIA. Indeed, it is the first component that will be on the “primed”, i.e. hit by the pressure surge when the pyrovalve downstream of the propellant tank is opened. The shock is expected to relatively high since the filter is a highly damping component. All the other components are dummy since they can be represented in a way close enough to the flight equipment to comply with the test objectives.

The main engine line is represented, as well as one of the RCT lines. Ideally, all the RCT lines should be represented in order to investigate the effects of the reflection of pressure in one line on the other lines. However, in a cost-reduction effort, the PIA test setup had to be reduced to a single RCT line. The longest RCT line will be represented, following the guideline from [3] as presented in the previous chapter, in order to measure the worst case pressure surges. Other RCTs will be represented as a volume branching out from the one RCT line represented, in a similar way as RCT lines branch out on the PFM. On the main engine line, the latch valve is represented too, since the operation sequences are not yet frozen on this part of the PFM. Test will provide guidelines how to operate the latch valve during priming.

To avoid introducing parasitic additional pressure due to gravity effects (hydrostatic pressures in vertical fluid columns), the setup will be designed in a 2D plane. This is also meant to avoid effects of trapped gas bubbles that can be compressed and can thus damp pressure waves in the liquid.

As for the PCA, static and dynamic pressures will be measured along the main engine and RCT paths, together with temperatures in order to fully determine the thermodynamic state of the fluid at each measurement point. An accelerometer will be accommodated on the filter.

EVM TEST DEFINITION

The test campaigns have been defined in a way so as to minimize testing time without affecting test objectives. Indeed, the main driver of the EVM test campaign is the cost of using and occupying the test facility, which is directly proportional to number of days it is booked for. This translates into choosing which test can be made simultaneously during the same campaign, but also how to build the setups in order to make the minimum of changes on the set-up during the campaign.

Additional constraints include lead times for the flight components, performing potentially destructive tests at the end of the test series, and of course safety with propellant handling.

The first test sub-campaign performed on the PCA, PCA-1, is described in Table 5. The objective of the test is recalled, the study of the pressure regulator behavior, and the typical test procedure is given, with the operation of the different valves. Finally, test variables are given, in this case the initial helium tank pressure, 310 bar and 207.3 bar, corresponding to the helium pressures on the PFM at the beginning of the mission and just before the Mars Orbit Insertion (MOI) manoeuver, which is the longest manoeuver of the Exomars mission, using the main engine and 4 to 6 RCTs. In addition to that, two pressure regulator settings will be investigated, regulator opened or closed before opening DFV1. This is not yet definitively set for the PFM. The PFM setting will depend on the results of this test. There will be therefore 4 sets of initial test conditions, and each test will be repeated 3 times on average to test reproducibility, that is 12 runs in total for the PCA-1 campaign.

The objective of this campaign requires the isolation of the pressure regulator from the rest of the system in order to measure the pressure variations coming from the regulator only, without the influence of the check valves. For this purpose, the test will be performed during integration of the PCA set-up, i.e. when the setup is not yet complete and does not include the check valves yet, as pictured in Figure 8. This option has been preferred over the one where additional isolation valves are introduced in the complete set-up, because it avoids introducing parasitic effects from valves, which do not exist on the PFM.

PCA-1		
Objectives	**Characterize pressure regulator behavior**	
Test procedure	**DFV1**	opens
		MEASUREMENT
	FDV 1	throttle valve connected to FDV3 opens to simulate flow rate
		MEASUREMENT
	FDV 1	throttle valve connected to FDV3
		END
Test variables and range	**Initial tank pressure**	310 bar (before 1st pressurization)
		207.3 bar (before 3rd pressurization)
	Procedure	PR initially open or PR initially closed (only at 310 bar)

Table 5: PCA-1 test definition

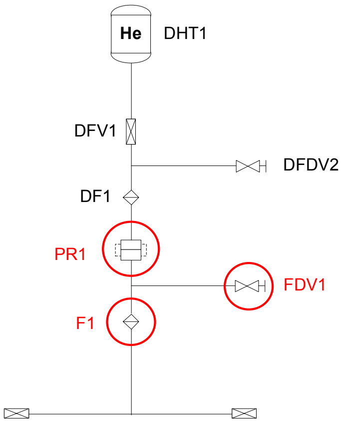


Figure 8: Flow schematic for the EVM PCA-1 test setup

In the same way, the campaign PCA-2 which aims at testing the interaction between the regulator and the check valves, will be performed at the stage of the integration shown in Figure 9 where only one branch with check valves is represented, i.e. the regulator-check valve interaction is isolated from the check valve-check valve interaction. The same helium tank initial pressures as for PCA-1 will be tested, 310 bar and 207.3 bar. Here only 2 sets of initial conditions apply, with a 3x repetition, i.e. 6 runs of the test.

PCA-2		
Objectives	Study interaction between PR and CV	
Test procedure	DFV1	opens
	DFV2	opens
		MEASUREMENT
	DTV1	opens to simulate corresponding manoeuver flow rate
		MEASUREMENT
	DTV1	closes
		END
Test variables and range	Initial tank pressure	310 bar (before 1st pressurization)
		207.3 bar (before 3rd pressurization)

Table 6: PCA-2 test definition

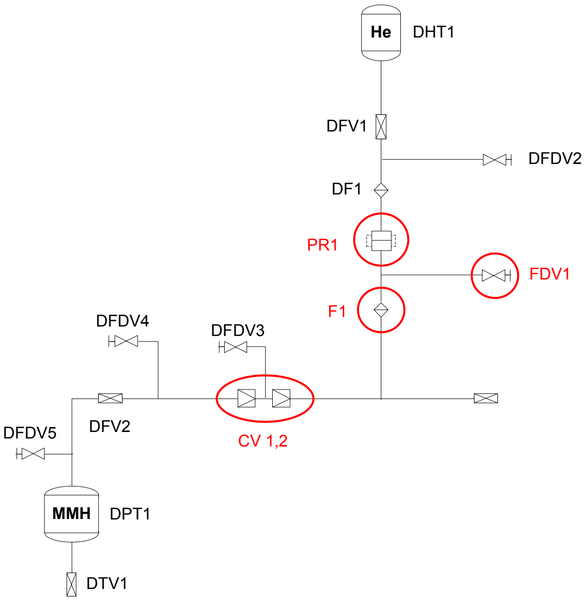


Figure 9: Flow schematic for the EVM PCA-2 test setup

The complete PCA test set-up will then be used for the PCA-3 test series that will include the regulator branch and both check valve branches to measure pressure transients when all the PCA components interact. The results from this campaign will be compared to the PCA-1 and PCA-2 results, so as to evaluate the contribution of each component the pressure transients in the PCA and understand the interaction between all components. Additionally, the steady-state pressure drop will be measured to validate the PFM calculations. The initial helium tanks pressures will be the same as for the PCA-1 and PCA-2 campaigns. Here again there are only 2 sets of initial conditions, so 6 runs of the test including reproducibility tests.

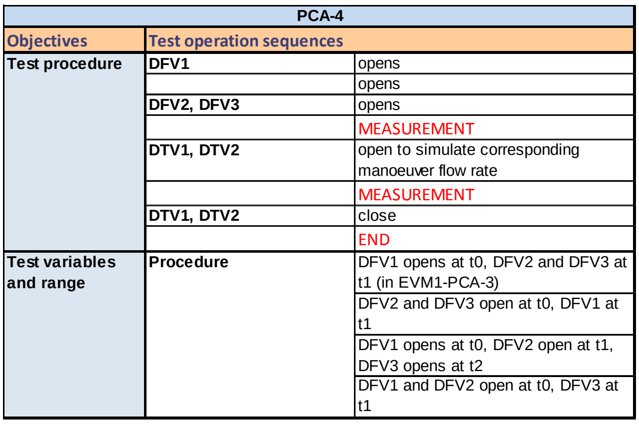
PCA-3		
Objectives	Study cross talk between sets of check valves	
	Measure steady-state pressure drop	
Test procedure	DFV1	opens
	DFV2	opens
	DFV3	opens
		MEASUREMENT
	DTV1, DTV2	open to simulate corresponding manoeuver flow rate
		MEASUREMENT
	DTV1, DTV2	close
		END
Test variables and range	Initial tank pressure	310 bar (before 1st pressurization)
		207.3 bar (before 3rd pressurization)

Table 7: PCA-3 test definition

After the component interactions have been addressed, the different possible operation sequences have to be tested in order to assess which one minimizes the transients in the system and thus induces the less fatigue on components. This will be done with campaign PCA-4.

The four sequences that will be tested are presented in Table 8. In the first scenario, the valve upstream of the pressure regulator is opened first, and in a second step the valves to the MON and MMH tanks are opened simultaneously. In the second scenario, the inverse is done, MON and MMH valves simultaneously first, and then only the valve upstream of the regulator. The third scenario opens all valves at different times, starting from one of the propellant branches, then the other, and finally the regulator branch. And finally the PR branch and one of the propellant branches are opened simultaneously, and then only the second propellant branch.

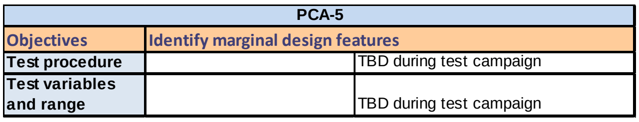
The best scenario is expected to be scenario 2, in terms of minimization of transients. Indeed, in this case, the biggest volume is available downstream of the regulator before its opening (including tank volume). So damping of the transients near the check valves is maximized. In addition to that, the branches are opened sequentially, which is expected to reduce cross-talk at the time of opening. However, the other cases have to be investigated as well, in case additional subsystem or system-level constraints rise later for the PFM that will require operating certain valves simultaneously or in a certain sequence.



PCA-4		
Objectives	Test operation sequences	
Test procedure	**DFV1**	opens
		opens
	DFV2, DFV3	opens
		MEASUREMENT
	DTV1, DTV2	open to simulate corresponding manoeuver flow rate
		MEASUREMENT
	DTV1, DTV2	close
		END
Test variables and range	**Procedure**	DFV1 opens at t0, DFV2 and DFV3 at t1 (in EVM1-PCA-3)
		DFV2 and DFV3 open at t0, DFV1 at t1
		DFV1 opens at t0, DFV2 open at t1, DFV3 opens at t2
		DFV1 and DFV2 open at t0, DFV3 at t1

Table 8: PCA-4 test definition

Finally, one last measurement series is foreseen in order to test any unexpected behavior that might come up during campaigns PCA-1 to PCA-4. This is the purpose of the PCA-5 campaign (Table 9). This test campaign is also a place holder for potential additional tests in case a change in the PFM design occurs in parallel that needs to be tested. This is a good example of the pragmatic solutions that have to be found as a consequence of the PFM and EVM schedules running in a highly parallelized schedule-optimized way.



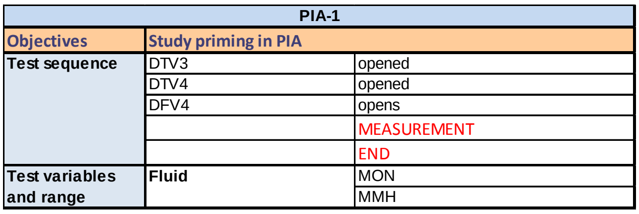
PCA-5		
Objectives	Identify marginal design features	
Test procedure		TBD during test campaign
Test variables and range		TBD during test campaign

Table 9: PCA-5 test definition

The PIA campaign will start with the priming test series PIA-1. It has been decided to start with these tests so that at least one test will be performed with a never wetted system as will be the case on the PFM. Since every test condition is run three times generally, the 2 re-runs of the priming tests will be with previous wetting. It is not expected that this has a strong influence on the results, but this sequence will permit to determine if pre-wetting is really negligible.

The test is not expected to be destructive, for the flight filter at least, following the preliminary analysis with EcoSimPro that predicts a pressure peak lower than what can be sustained by the filter, as specified by the filter manufacturer. This is bearing in mind that numerical estimations predict higher peaks than real peaks for propellants. A high pressure peak might appear at the RCT valve dummies, but these are replaceable at low cost and replacement time.

As discussed before and indicated in Table 10, two dedicated test setups are built for MON and for MMH respectively. SO there will be 3 runs for each setup, to check for the reproducibility.



PIA-1		
Objectives	Study priming in PIA	
Test sequence	DTV3	opened
	DTV4	opened
	DFV4	opens
		MEASUREMENT
		END
Test variables and range	**Fluid**	MON
		MMH

Table 10: PIA-1 test definition

The measurements performed next will aim at studying the water hammer effect in the PIA, due to the closing of the main engine valves principally. At the same time, the steady state pressure drop will be measured. As given by Table 12, different mass flow rates will be tested, which correspond to different operation cases of the main engine and RCTs on the PFM.

The first scenario presented simulates the orbit correction and attitude control manoeuvers, where only RCTs are used. In this case, the represented line will be open, and the volume representing the desired number of remaining RCTs lines will be open too. Water hammer will be generated by the one represented RCT line. In scenario two, both the main engine and RCT lines are open, in order to simulate the MOI manoeuver typically. In this case the main water hammer contribution will come from the main engine valve closing (DTV3 on the EVM setup). However, in order to test the worst case, both the main engine and RCT valves will be closed simultaneously. Finally, the case with only the main engine line open will be simulated as well, even if this will rarely be the case during the mission. This is performed in order to be able to decouple the contributions from each line in the results with both lines open.

PIA-2		
Objectives	**Measure steady state pressure drop + flow rate**	
	Study water hammer propagation	
Test sequence	DTV3	opened, mass flow rate equiv. to 1 RCT
	DTV4	closed
	DFV4	opens
		MEASUREMENT
	DTV3	closes
		MEASUREMENT
		END
Test variables and range	**Fluid**	Water
		MON
		MMH
	Mass flow rates	DTV1 flow rate for x RCTs, DTV2 closed (TBD depending on mission configurations)
		DTV1 flow rate for x RCTs, DTV2 flow rate for main engine
		DTV1 closed, DTV2 flow rate for main engine

Table 11: PIA-2 test definition

Finally, a last measurement set is conducted for unexpected effects that could come up during the precedent series. At the time of the EVM test schedule definition, the PFM design was not frozen yet and the latch valve on the main engine line was still an option, Afterwards, the latch valve was introduced in the baseline design, requiring additional water hammer tests. These tests will be introduced here. They will help determine which sequence is the best for opening and closing the main engine valve and the propellant line latch valve.

Again, this shows the high level of schedule optimization (parallelization), and the consequent need of new ways to implement the interaction between flight models and test models.

Test campaign EVM1-PIA-3		
Objectives	**Identify marginal design features**	
Test 1		TBD during test campaign
Test variables and range		TBD during test campaign

Table 12: PIA-3 test definition

CONCLUSION

The verification strategy of the Exomars propulsion subsystem has been newly developed specifically in response to the demanding program requirements in terms of cost and schedule, calling for high level of subsystem verification methodology. The very close dependency between the flight model (PFM) and the test model (EVM) is highlighted. This interaction will take place throughout the complete ground lifetime of the propulsion subsystem.

This PFM-EVM dependency is further illustrated in details through the presentation of the numerical model and its limitations and through the definition of the EVM test objectives and test procedures. The PFM and EVM must both be designed in a way flexible enough so that design changes implied by the other can be included at a later stage. This is the case for the test procedures as well.

As this paper is being written, the EVM design is being frozen and analysis and design on the PFM is at an advanced stage but still allowing for potential modifications that could be implied by EVM results. The next step is the manufacturing of the EVM starting of the test campaigns.

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