Space Propulsion Conference 2014, SP2014_ 2968951

Propulsion System Development and Verification Activities for the 2016 ExoMars Trace Gas Orbiter

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Abstract

The ESA-led EXOMARS 2016 mission requires for its Trace Gas Orbiter (TGO) a challenging propulsion subsystem. The TGO Reaction Control System (RCS), which is currently in final integration, shall provide the thrust to the spacecraft for all initial trajectory corrections, Deep Space Manoeuvres (DSM) during the cruise phase to Mars and also the high thrust necessary for the final Mars Orbit Insertion manoeuvre (MOI). Subsequently, it shall perform 3-axis attitude control of the TGO once in orbit around Mars for the remainder of its seven year lifetime.

The selected RCS is a helium-pressurised bi-propellant propulsion system utilising monomethylhydrazine (MMH) as the fuel and mixed oxides of nitrogen (MON-1) as the oxidiser. The architecture is derived from previous flight proven European applications however the detailed layout is unique and driven by the specific configuration of the TGO spacecraft and the redundancy needs of the Exomars 2016 mission.

All RCS architecture and engineering activities have been performed by OHB-System (including all subsystem analyses), whilst Airbus Defence and Space (Airbus DS) has responsibility for the mechanical configuration, procurement and manufacturing of equipment, integration and acceptance test to ensure that the system requirements defined by TAS-F are satisfied. The subsystem test programme has been defined by OHB-System and performed by Airbus DS at the Airbus DS, OHB-System and TAS facilities. Out of the 92 components comprising the flight RCS, 67 are manufactured by Airbus DS including all tanks and thrusters.

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1 Introduction

The ExoMars programme, established by the European Space Agency (ESA), is a scientific mission to Mars. The main target is to investigate the Martian environment and to demonstrate new technologies paving the way for a future Mars Rover Mission in 2018 and potential Mars sample return mission in the 2020's [1].

The first mission, scheduled to be launched beginning of 2016, consists of a so called Trace Gas Orbiter (TGO) and an Entry, Descent and Landing demonstrator Module (EDM). While the Orbiter (TGO) will carry scientific instruments to detect and study atmospheric trace gases, such as methane [2], the EDM will contain sensors to evaluate the lander's performance as it descends, and additional sensors to study the environment at the landing site.

To fulfil the specific mission demands a challenging propulsion subsystem has been developed for the TGO module, which is currently in final integration (see Figure 1-1). The Reaction Control System (RCS) shall provide the thrust to the spacecraft for all initial trajectory corrections, Deep Space Manoeuvres (DSM) during the cruise phase to Mars and also the high thrust necessary for the final Mars Orbit Insertion manoeuvre (MOI). Subsequently, it shall perform 3-axis attitude control of the TGO once in orbit around Mars for the remainder of its seven year lifetime.

The main ExoMars TGO propulsion subsystem specifics are (for a detailed description refer to [3]):

- Several pressurisations,
- Cruise duration,
- Long burn duration for the Mars Orbit Insertion,
- Aerobraking in Mars atmosphere,
- Lessons learnt from Mars Observer [4].

This paper presents an overview of the specific propulsion subsystem architecture developed by OHB-System and the technical solutions derived. Furthermore, the extensive qualification activities performed on component level to satisfy the ExoMars TGO mission specific requirements will be summarized. These includes for example:

- Successful component qualification, namely:
  - He latch valve usage in reverse flow direction
  - Verification of main engine for long single burn and long duration operation
  - Delta qualification of the pyro valve and propellant latch valve for the ExoMars application
- Leak test measurement at higher pressures as nominal acceptance test for Check valve and Helium filter
- Development of the integration concept by using dedicated jigs and tools for a flexible work-share between the differing integration sites and responsible companies

Finally, the integration and acceptance status of the RCS is presented.

Figure 1-1: ExoMars TGO during Integration at OHB

2 RCS Design Key Features

The selected RCS for the ExoMars TGO is a helium-pressurised bi-propellant propulsion system utilising monomethyl-hydrazine (MMH) as the fuel, mixed oxides of nitrogen (MON-1) as the oxidiser and helium as pressure gas. The architecture is derived from previous flight proven European applications however the detailed layout is unique and driven by the specific configuration of the TGO spacecraft and the redundancy needs of the ExoMars 2016 mission. A detailed flow schematic of the propulsion subsystem, which highlights the complexity, is shown in Figure 2-2.

For performance of the high thrust manoeuvres a 400N main engine ($\varepsilon = 330$) manufactured by Airbus DS is used. For performance of reaction and attitude control manoeuvres but also to support during MOI manoeuvres, twenty 10N thrusters (10 nominal and 10 backup thrusters) are integrated. Both thruster types exhibit an extensive qualification status ([7], [8]) and flight heritage on various geostationary and interplanetary missions (e.g. Alphabus, Spacebus, Rosetta, Mars Express, etc.).

As discussed by OHB-System in a previous paper [3], specifics of ExoMars lead to design characteristics that are not standard:

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- 3 stage pyro-ladder that allows having three pressurisations, i.e. repeated isolation of the pressurant tanks from the pressure regulated system (minimization of potential pressure increase due to internal leakage during long phases between two Main engine manoeuvres). This leads to have pyro valves normally open and closed seeing pressures up to 310 bar
- The Cruise duration imply having a Helium latch valves in order to have telemetry on the open/close status as the Check Valves are purely mechanical parts. The valve acts as third barrier in series as well. Reliability requirement implies parallel latch and pyrotechnic valve isolation. This leads to an unusual use of a standard component.
- The RCS conditions during Cruise imply having the Helium latch valves in reverse flow. This will provide a back relief function for the pressurized section downstream of the regulators during short operational periods (minimisation of maximum pressure caused for example by internal leakage). This leads to delta qualification of the Helium latch valve in reverse flow and leak tests at higher pressures than in usual acceptance test for other equipment
- The lessons learnt from Mars Observer [4] lead to a specific thermal design for the Pressure Control Assembly (PCA)

The RCS provides multiple levels of isolation and back relief functions to provide a high reliability whilst to cope with the stringent mission demands.

Due to the long and late firing for Mars Orbit Insertion, the trimming point of the 10N RCT have been set to an unconventional value of 17.6 bar. This leads to a minimal inlet pressure during operation of 11 bar instead of 10 bar. This is the consequence of the extensive operating box analysis done by OHB-System for both 10N RCT and 400N Main engine, see Figure 2-1 below.

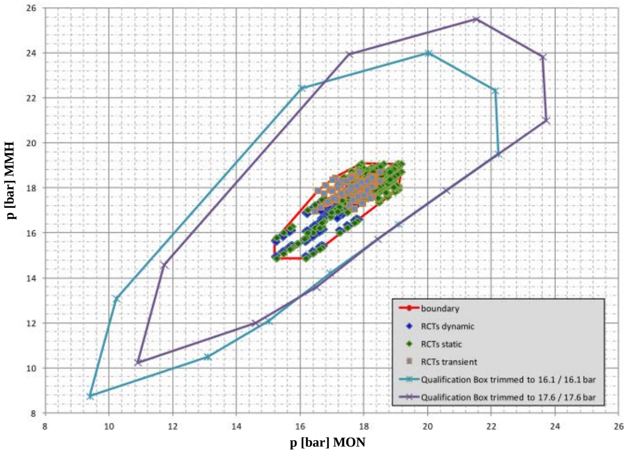

Figure 2-1: 10N RCT operating box

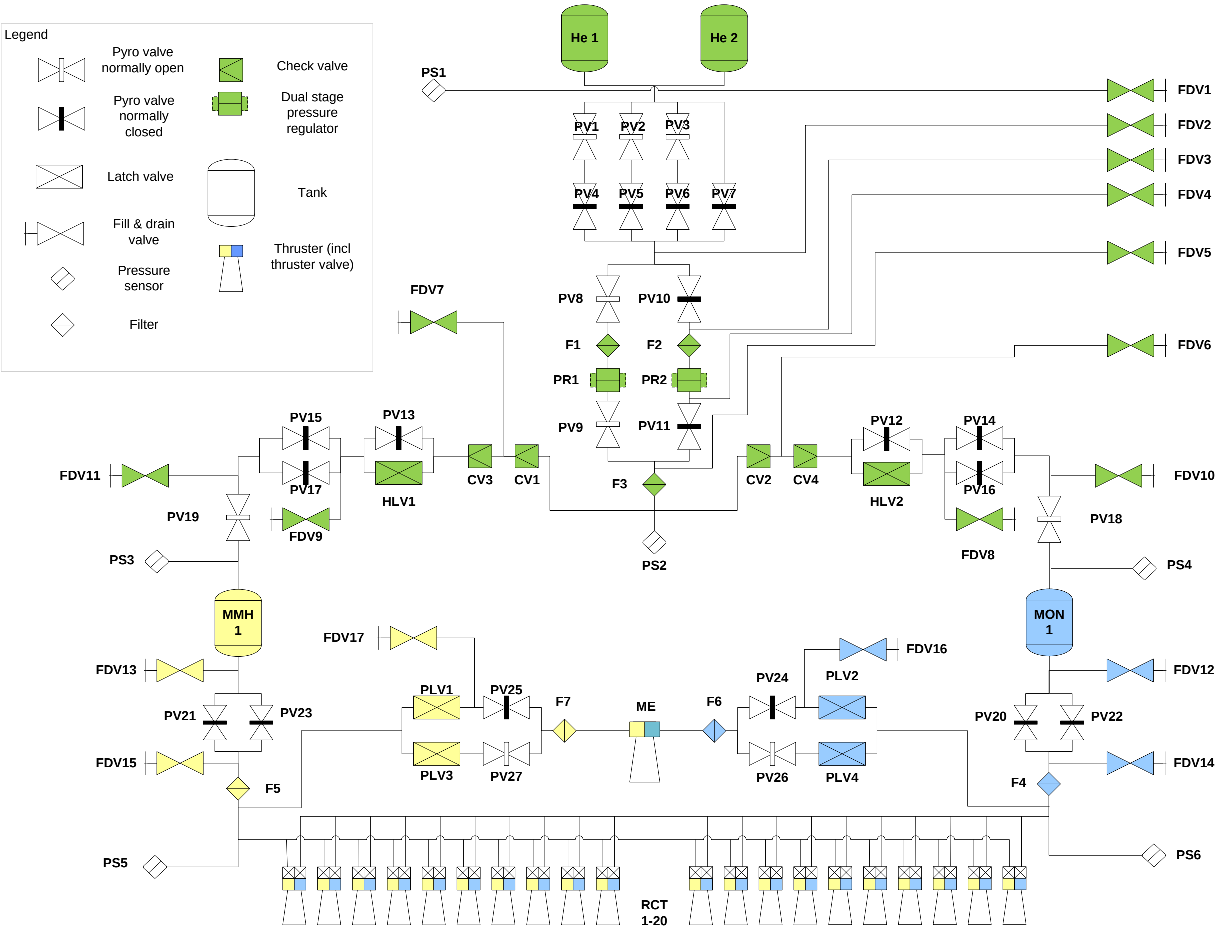

Figure 2-2: Flow Schematic of the ExoMars propulsion sub system (refer to [3] for further details)

3 Equipment Verification and Qualification Activities

For economic reasons mainly off-the shelf equipment were selected for the ExoMars RCS. However, with respect to the non-standard features, several delta qualification and additional verifications were necessary.

3.1 Long Single burn duration of 400N Main Engine

The 400N engine S400-15 ($\varepsilon = 330$) is a derivative of the S400-12 engine ($\varepsilon = 220$) and is typically used as main engine for apogee boost manoeuvres (ABMs) of GEO satellites, for circularization of the transfer orbit. For interplanetary mission, the main task is to provide the braking impulse for orbit insertion, or performance of certain manoeuvres during cruise and orbit phases. This has been successfully demonstrated in the frame of Venus Express and Mars Express mission which were using the S400-12 engine, the predecessor of the S400-15.

Figure 3-1: 400N thruster module assembly (S400-15)

Depending on the individual mission planning long single burns, to provide the required impulse change, can last up to 100-150 minutes. Typically for verification a qualification test is required. However, due to facility limitations (supply tank capacity of steam generator) of the German Aerospace Centre (DLR) in Lampoldshausen, only 120 minutes vacuum phase with parallel operation of the S400-15 engine can be realised. The engine itself is of course not limited to this operating time.

For verification of the defined requirement a detailed assessment of already performed long single burns has been done as well as a detailed review of existing flight data:

- Two qualification programs were run with the S400-15 qualification engine, the first in 2004 and the second one in 2008/2009 as part of a customer specific delta qualification. In total a cumulated burn time of >470min has been successfully demonstrated on the qualification unit.
- Chamber pressure and temperatures measured during qualification show fully stable behaviour during long time burns. Also after adjustment to an extreme run point (here for demonstration of margin vs. extreme temperature conditions), stable conditions were quickly achieved on throat and chamber.

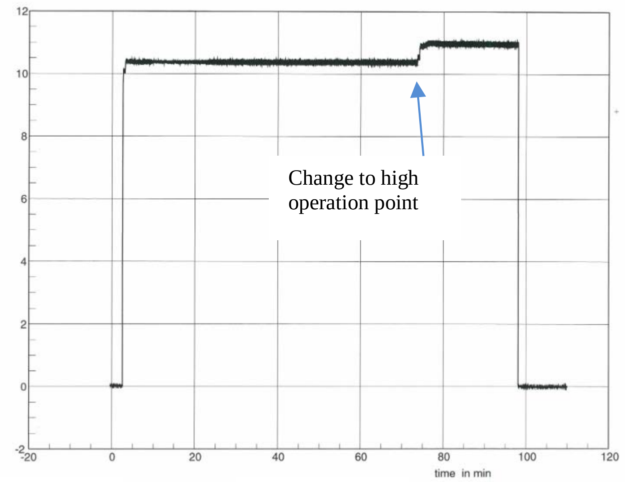

Figure 3-2: S400-15 chamber pressure measured during initial qualification

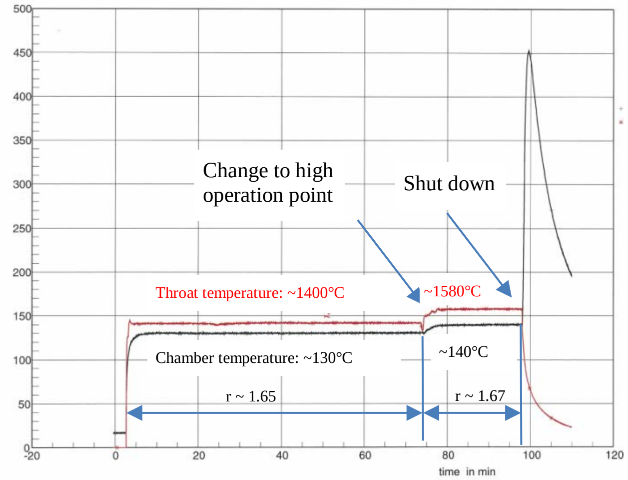

Figure 3-3: S400-15 chamber and throat temperature measured during initial qualification

- Outstanding flight history of Airbus DS 400N thruster family (S400-12 and S400-15) without failure or malfunction. More than 40 missions were successfully flown and in all missions the required performance was provided. Several missions had single burn times exceeding the vacuum tests on ground level during qualification. Longest single burns ranging up to >140 min and total burn times up to >280 min were successfully demonstrated in orbit

Operated at nominal inlet conditions no limitation is seen for single burn durations within the total cumulated burn time demonstrated during qualification. Although individual qualification burns were shorter, the thermal cycling imposed by splitting the total burn time into many single burns is judged more demanding to the engine hardware than a long single burn of same duration at stable conditions.

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3.2 Shock qualification of NO type PV in actuated condition

Pyrovalves are used to definitely open or close a fluid / gas flow path. The valve mechanism is driven by activation of a pyrotechnical charge. By design, these valves can only be actuated once. They are distinguished between normally closed (NC) and normally open (NO) type pyrovalves. While NC type pyrovalves provide a leak tight barrier prior actuation, NO type ones will provide it after actuation. On the ExoMars TGO pyrovalves manufactured by Airbus DS will be used, which can rely on an extensive qualification and flight heritage [5].

During the initial qualification review only one requirement related to the environmental loads was found, which was not yet covered by previous qualification campaigns. Typically, the driving environmental vibration and shock loads are of external nature, induced during launch and separation of the spacecraft from the launcher. At this stage the spacecraft itself is in its (non-activated) flight condition. Due to the specific ExoMars TGO RCS design, which includes a pyro-ladder (see Figure 3-4), shock loads created during actuation of a pyrovalve can be imposed on already actuated ones. Therefore, it was deemed necessary to demonstrate and verify the capability of a Normally Open (NO) and Normally closed (NC) type pyrovalve to withstand a certain shock load in actuated condition without any impact e.g. on the leak tightness capability.

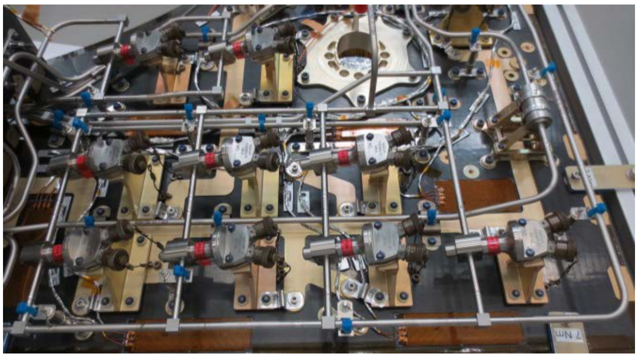

Figure 3-4: Pyrovalve-ladder on ExoMars TGO Pressure Control Assembly (PCA)

For NC type pyrovalves post actuation shock loads were already successfully demonstrated, hence a delta qualification demand was identified for the NO type pyrovalves only.

The main risk on actuated NO pyrovalves is that the punch, which sheared a weakened section during actuation, gets loosened and will no longer provide a tight barrier against internal leakage.

For verification of the required post actuation shock spectrum (Table 1) a pyrovalve was selected, which was previously actuated at low temperature by a single undercharged cartridge (80% of the nominal charge). In terms of available energy, this unit represents worst case configuration with regard to the punch penetration. Moreover, this unit has already passed an extensive destructive lot acceptance test (DLAT) including pre actuation vibration and shock testing.

Frequency [Hz]	Level [g]
100	64
900	2.000
6.700	2.000
10.000	6.300

Table 1: Shock environment for actuated PVs

Within the frame of the delta qualification campaign the following main results were obtained:

- Successful demonstration of required post actuation shock spectrum (Table 1) in all axes during three consecutive tests as required per ECSS. The applied shock spectrum was even higher than required, which demonstrated the robustness of the Airbus DS PV design.

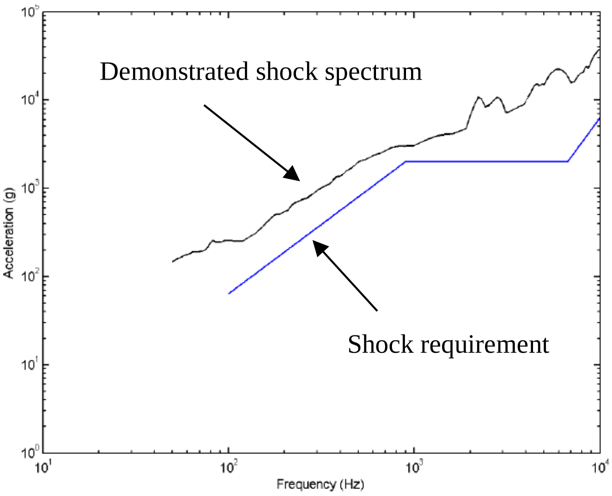

Figure 3-5: Demonstrated shock spectrum measured in PV punch axis

- No change of punch position was noticed during x-ray inspection performed after shock test
- Structural robustness was successfully demonstrated during a post shock proof pressure test at 465 bar for 5 min. After the pyrovalve was already actuated, the proof pressure was applied on each side of the tube individually.
- No degradation of internal leakage observed at a differential pressure of 387.5 bar, when measured from PV inlet to outlet (respectively vice versa). In addition, to check each individual barrier, a test port was installed.

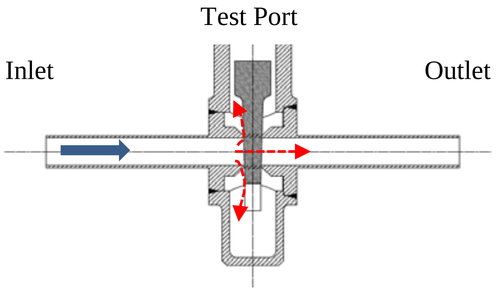

Figure 3-6: Potential leak paths on activated NO type PV

The delta qualification has been performed successfully on an actuated NO type (worst case) pyrovalve and demonstrated the robustness of the design. The obtained results are valid for all Airbus DS types of NO pyrovalves since the internal shearing section is identical. For further details of the PV qualification status refer to [5].

3.3 Propellant Latch Valve Surge and Water hammer

For isolation of the main engine especially during short cruise phases dedicated high flow propellant latch valves with a 3/8" interface are used. These units are procured as off-the shelf items from a US supplier. By review of the existing qualification it was noticed that the required surge and water hammer requirements as required by Airbus DS were not yet thoroughly demonstrated and verified. For this reason a delta qualification has been performed at Airbus DS premise on a representative test item. The main goals were to demonstrate:

- **Priming test with latch valve open:** The hydraulic shock on the inlet of the closed latch valve is typically related to the line priming of a liquid propulsion system, when normally closed pyros between propellant tank and closed latch valve are fired open. The propellant fills up the line and creates a priming shock at the end of the line.
- **Rapid through flow test:** This case is similar to the priming case above, except that the latch valve now is open when the pyro is fired. Thus, during line filling, the flow will pass the open latch valve and priming is done up to the main engine thruster valve. Since at this stage severe forces are applied on the latch valve seat, the main target is to test whether the latch valve will stay open or not. Based on the test results, the RCS level priming sequence can be finally selected.
- **Re-priming test:** The re-priming is related to the filling of the line downstream of the latch valve, where the line upstream of the latch valve is already filled. The re-priming is initiated by opening of the latch valve. The re-priming can be the second step of the feed line priming, where in the first step the upstream line was primed up to the closed latch valve. The re-priming can also be necessary in a later mission phase (all lines already filled with propellant), when for some reason the latch valve had to be closed and the line between latch valve and thrusters had to be drained. The difference between the re-priming as a second step of the initial priming and the re-priming during a later mission phase will normally be the tank pressure, which will very likely be higher in the latter case.
- **Valve closure test at 0,1 kg/s flow rate:** The closing of the latch valve under flow of propellant can occur when the latch valve is commanded closed during main engine operation. The latch valve commanding can be unintentionally (degraded AOCS) or intentionally (e.g. nominal thruster shut down does not work then shut down must be performed by closing of latch valve).

For verification a dedicated test setup as shown in Figure 3-7 has been built-up in a laboratory at Airbus DS facility Lampoldshausen. All tests were performed with deionized water which was supplied by a large water tank, pressurized to the required level. Downstream of the water tank, adequate feed lines were installed. Supported by analysis, the length of the feed lines was selected such that the flow had sufficient time to develop before the priming front reached the test item. Whenever necessary, the setup was adjusted to represent worst case conditions. To initiate the flow for priming and through flow a fast acting latch valve (EV) was used.

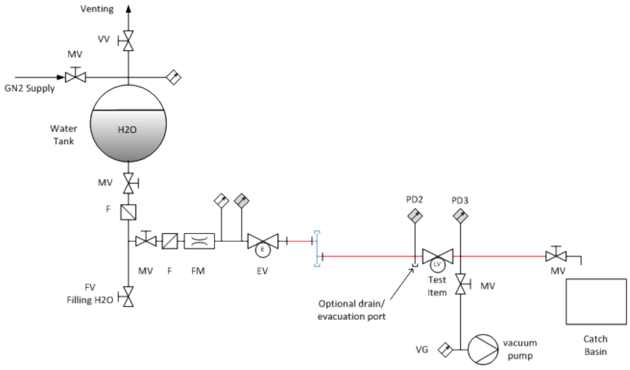

Figure 3-7: Test Setup during surge and water hammer verification test of propellant latch valve

Different test campaigns were performed in order to satisfy and demonstrate the different demands as discussed above. For verification, that the test item was not damaged or its performance degraded, intermediate health checks were performed (functional and electrical checks).

The following test results were achieved:

- Successful demonstration of a priming peak of 100bar at the valve inlet, no degradation observed during follow-on functional tests (see Figure 3-8).

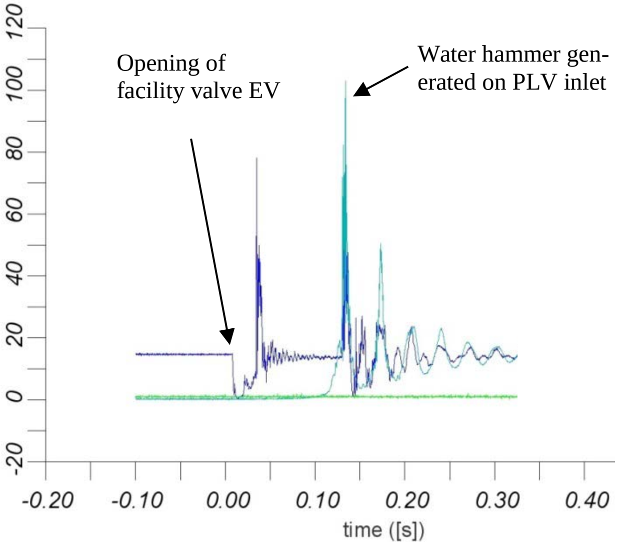

Figure 3-8: Priming peak demonstrated on propellant latch valve inlet (valve closed)

- Reliable opening (re-priming test) under differential pressure successfully demonstrated. The Water hammer created downstream of the PLV was within the expectations and in line with the equipment limitations (see Figure 3-9).

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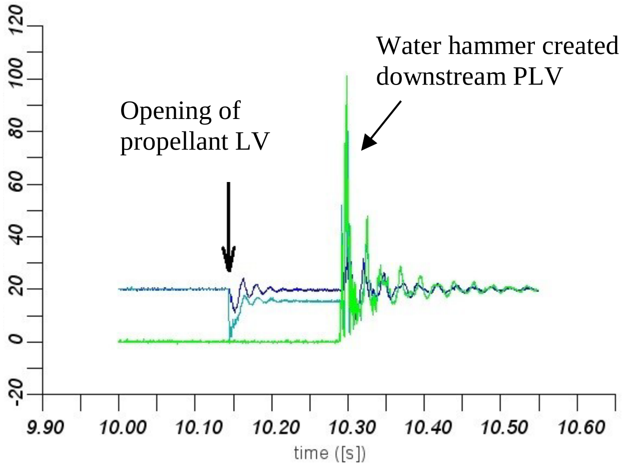

Figure 3-9: Re-priming demonstrated on propellant latch valve (dynamic pressure measured at different positions)

- Reliable valve closure at a flow rate of 0.1 kg/s H2O demonstrated.
- Rapid through flow performed to simulate priming up to the main engine thruster valve. During the second test an unintended de-latching was observed which created an internal water hammer significantly greater than the qualified level. Target of the rapid through flow test was to identify any limitation which might be imposed by the RCS priming sequence. This has been successfully demonstrated; even with the consequence that priming through the open valve is not recommended.
- All intermediate health checks were successfully performed , no degradation of valve performance and leak tightness observed

By performance of the delta qualification all main test objectives were met. The required water hammer as well as reliable opening and closing has been successfully demonstrated. The obtained test results showed a very good robustness of the propellant latch valve with respect to dynamic hydraulic loads.

3.4 10N Thruster Priming Levels

For verification of the ExoMars TGO propulsion system a detailed EcoSim analysis has been performed by OHB [3], which has been initially validated by an engineering validation model (EVM). Especially since the model cannot accurately predict complex transient effects like line priming and water hammer effects, tests on a representative setup are deemed necessary. Obtained results of these tests are presented in a dedicated paper [9].

The Airbus DS 10N thruster (S10-18) was selected based on it flight heritage and qualification status with respect to the ExoMars functional and performance needs. However, based on the findings made during the delta qualification of the propellant latch valves (see §3.3), the priming sequence of the RCS had to be adapted. This change imposed some higher constraints on the RCT flow control valve with regard to expected water hammer levels, which were observed during EVM testing. Detailed analysis performed by OHB showed, that levels up to 140 bar could occur at worst case conditions which exceed the current qualification. To cover model uncertainties and demonstrate margin a delta qualification was necessary.

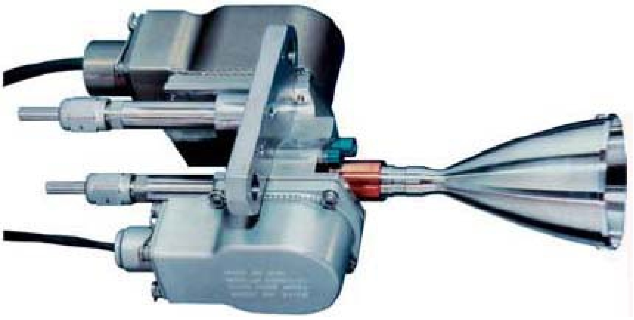

Figure 3-10: 10N thruster (S10-18) equipped with double seat valve (bi-stable latching and mono stable thruster valve)

The test objective was to demonstrate the valves capability to withstand three times a water hammer of ≥ 160bar at the valve inlet. Chamber and nozzle were not attached to the valve since they have no effect on priming and water hammer. Testing was performed on one side of the bipropellant valve only, which represents the flight case. For realisation two test campaigns were performed, one with the inlet latch valve closed and a second one with the inlet latch valve open. Functional tests were performed prior and after priming test for verification of the valve performance.

The priming verification tests were performed on representative setup which is shown in Figure 3-11 with water as test medium. The tubing lengths were adapted in order to achieve a developed flow. Prior test the complete compartment up to the test item has been evacuated to a level < 5mbar. Once achieved a fast actuation valve (EV) was actuated to release the flow. This simulated the priming on spacecraft level by actuation of a pyrovalve. Pre-tests were performed in advance to adjust the tank pressure in order to achieve a water hammer of ≥ 160 bar at the valve inlet.

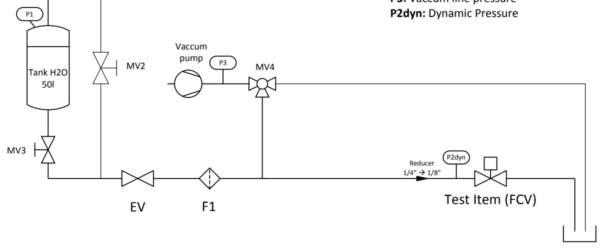

Figure 3-11: Test Setup during priming test of 10N Flow Control Valve

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The following test results were obtained during delta qualification of the 10N thruster flow control valve:

- Successful demonstration of three priming peaks ≥ 160 bar at the FCV inlet. Measured peaks were repeatable at the same inlet conditions.
- Tests performed with inlet latch valve in closed and in open condition. The resulting water hammer measured at the FCV inlet with the latch valve in open position was significantly lower (~100bar). This is mainly linked to the slow-down of the flow rate, when passing the inlet valve seat and filling of the interseat volume between bi-stable latch valve and monostable thruster valve. Hence, due to the reduced flow rate, the created water hammer is lower.
- Follow-on functional tests including electrical checks and leakage measurements performed successfully, no degradation of valve performance observed.

Based on the performed delta qualification, the Airbus DS 10N thruster S10-18 has been successfully qualified for ExoMars needs in terms of expected water hammer peaks during RCS priming.

4 Subsystem / Project status

According to the RCS subsystem verification plan (see [6]), an Engineering Validation Model (EVM) representative of the flight model has been built and tested in Airbus DS premises using real propellants. The obtained EVM test results are presented in [9].

Transient behaviour of the propellant has been analysed based on above-mentioned ExoMars EVM test data and the analysis and correlation presented in [10] confirmed the RCS design.

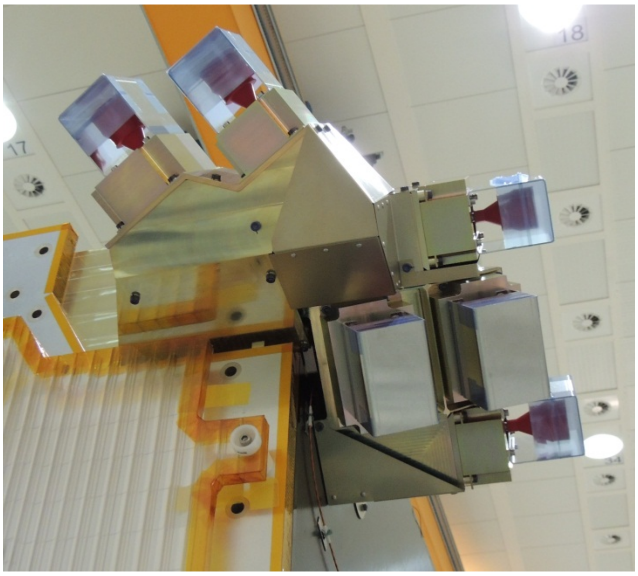

Figure 4-1: View on the RCT cluster with 6x 10N RCTs

As this paper is being written, integration of the RCS into the ExoMars TGO has been nearly completed. The last step was the integration of the RCT cluster (see Figure above). Except of the 400N main engine module, all components have been successfully acceptance tested and delta qualified when necessary. The 400N engine is currently in acceptance test at Airbus DS, integration on spacecraft level is foreseen by July 2014. No delta qualification is required for the Main Engine. In parallel to the last tests on equipment level, the acceptance test on RCS level has started. Meanwhile the complete PCA section as well as the helium and propellant tank section were successfully tested. On Propellant Isolation Assembly (PIA) level first verification tests were performed, indicating that the workmanship was successful. Final testing of the PIA section will be performed mid of 2014 following integration of the main engine module.

5 Summary and Conclusion

In order to cope with demanding ExoMars program requirements in terms of reliability, economic and schedule constraints, mostly off-the shelf equipment with extensive flight heritage has been selected for the RCS subsystem. With help of an equipment qualification status review, the individual qualification status of each component has been identified and compared to the ExoMars needs. With respect to the non-standard features of the propulsion subsystem a few delta qualifications were deemed necessary. Whenever appropriate this has been covered by a PFM approach while for some a dedicated delta qualification tests on separate units were performed.

The main test results achieved throughout the different delta qualifications performed are presented and summarized within this paper. All results were satisfactory and demonstrated the robustness of the selected hardware. It can be concluded that all ExoMars specific requirements were successfully verified at equipment level and the RCS subsystem design is considered acceptable for the 2016 mission.

As the first project, for which OHB-System is responsible for the propulsion engineering (e.g. analyses, design) and Airbus DS is responsible for the mechanical configuration, procurement and manufacturing of equipment, integration and acceptance test, the project status shows the capability of OHB-System and Airbus DS to handle these tasks for challenging missions. A major contributor to the successful project completion within very tight schedule constraints was the ability and willingness of both teams to cooperate closely. This is deemed to be a major success factor for executing projects within the highly distributed European industrial landscape.

6 Acknowledgments

The authors from OHB-System and Airbus DS acknowledge the close contact, good support and fruitful discussion with Thalès Alenia Space and ESA.

Furthermore we would like to thank the whole team and personnel from OHB-System, Airbus DS and their suppliers, who were involved in the ExoMars TGO RCS subsystem for design, analysis, manufacturing, integration and test.

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