JOINT DEVELOPMENT TESTING OF THE INTEGRATED GATEWAY-ESPRIT BIPROPELLANT REFUELLING SYSTEM

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Sebastian Hill (1), Andrew Hughes (1), Giancarlo Wellons(1), Laura Hoyland(1)

Brandie Rhodes (2), Adela Han (2), Brian Lusby (2), Pooja Desai (2), Chris Radke (2)

Olivier Zagoni (3)

Marco Leonardi (4)

(1) Thales Alenia Space UK, Harwell, United Kingdom, Email: sebastian.hill@thalesaleniaspace.com
andrew.hughes@thalesaleniaspace.com
(2) NASA - Johnson Space Centre, Houston, USA, Email: brandie.l.rhodes@nasa.gov,
christopher.d.radke@nasa.gov
(3) Thales Alenia Space France, Cannes, France, Email: olivier.zagoni@thalesaleniaspace.com
(4) ESA-ESTEC, Noordwijk, Netherlands, Email: marco.leonardi@esa,int

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ABSTRACT:

The Gateway is an upcoming long term lunar exploration program to be completed by NASA in partnership with ESA and other US and international partners. The system design of the Gateway contains both a high performance Xenon based Solar Electric Propulsion system, as well as a bi-propellant attitude control system. Both propulsion systems are designed for on-orbit refuelling to enable long life performance of the Gateway. The ESPRIT-RM is a module which will expand the pressurized volume of Gateway, while also providing refuelling capability for both the Xenon and Bipropellant propulsion systems, therefore extending the Gateway life on orbit.

As part of the Gateway bi-propellant refuelling system development, a simplified fluidic breadboard system was created to evaluate system performance and response using simulant fluids. The test plan includes verification activities with simulant (water, HFE-7100) to verify joined subsystem behaviour in the critical operations, including propellant transfer demonstration between modules, transient tests and venting tests. Integrated testing will occur at TASUK in collaboration with NASA to support joint verification activities to de-risk the major functions of the ESPRIT Bipropellant Transfer Subsystem (BTS) and the overall CONOPS of the refuelling of the Gateway chemical propulsion system. Initially collected test data at NASA is presented and has shown the architected system performance is closing initial design assumptions, but much forward work is identified to continue to characterize and develop the system.

NOMENCLATURE AND SYMBOLS

1. INTRODUCTION

Gateway will be an orbiting lunar outpost supporting the long-term human return to the surface of the Moon and providing a staging point for deep space exploration. It is a critical component to NASA’s Artemis program.

The first two modules of Gateway, to be launched as part of Artemis III, will be the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO). Together these are referred to as the Co-manifested Vehicle (CMV). The PPE features a high performance, 60-kilowatt xenon-based solar electric propulsion system and a higher-thrust bi-propellant chemical propulsion system. This propulsion package will provide attitude control and orbital transfer capability for Gateway. HALO will be the be initial crew quarters for visiting astronauts and will have several docking ports for visiting vehicles and future modules.

A rendering of Gateway including elements from multiple international partners is shown in Figure 1 PPE can be seen on the far left connected to HALO, while the ESPRIT-RM is located on the northern leftmost radial port.

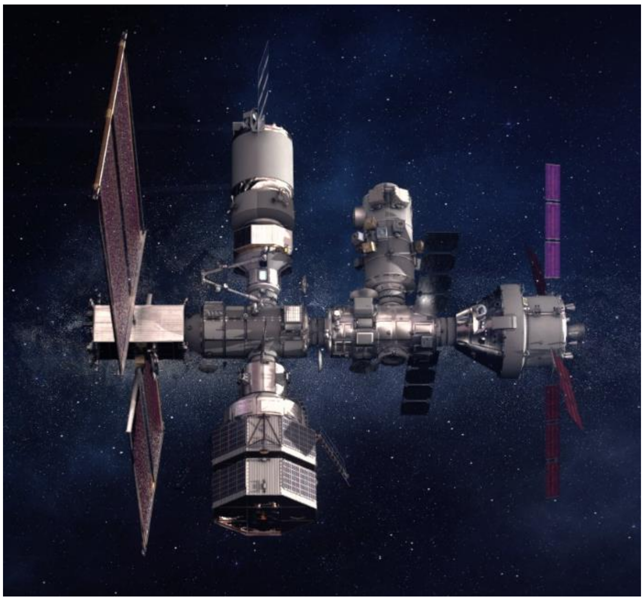


Figure 1: A rendering of Gateway, including elements from international partners (Credit: NASA/Alberto Bertolin).

1.1. Lunar Gateway Refuelling

Both the chemical and electrical propulsion systems of Gateway are designed to be refuellable. Propellant and pressurant will be provided by the ESA European System Providing Infrastructure and Telecommunications – Refueller Module (ESPRIT-RM), which will be launched as part of Artemis V. Xenon, monomethylhydrazine (MMH), and mixed oxides of nitrogen (MON-3) will all be transferred from ESPRIT-RM through HALO to PPE. Figure 2 shows a very simplified illustration of the transfer path for the bipropellant system.

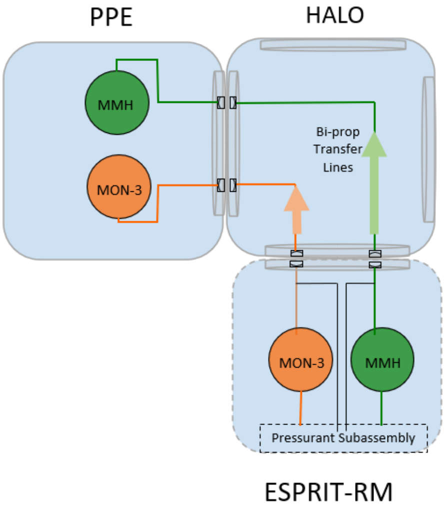


Figure 2: Simplified illustration of bipropellant transfer path

1.2. ESPRIT Module

The ESPRIT-RM is a major European contribution to the Gateway. The module is planned to dock into the NASA-led HALO module via an International Berthing and Docking Mechanism (IBDM). Refuelling fluidic interfaces are located externally along the ring of the IBDM.

ESPRIT-RM provides four major functionalities:

- Bi-propellant and Xenon refuelling capabilities;
    - Propellant Refuelling from the ESPRIT-RM to the PPE of the Lunar Gateway will be provided to enable extension of the space station lifetime and excursions capabilities.
    - Additionally, the Bipropellant Transfer Subsystem (BTS) has the capability to transfer propellant from a Visiting Vehicle (VV) cargo ship to its own propellant tanks or straight to the PPE propellant tanks.
- Pressurized access between HALO and Visiting Vehicles for Crew and Cargo passage;
- External viewing capabilities of Moon, Earth and Gateway surroundings;
- Internal pressurized Logistics loading at launch (one-time).

ESPRIT-RM is led by ESA, with TASF as a prime contractor.

1.3. ESPRIT-BTS Subsystem

TASUK is responsible for the design and development of the BTS, which is one of the two refuelling subsystems on ESPRIT-RM, which provides refuelling functions to Gateway and the RCS located in PPE. The subsystem is capable of active gas-pressurised and blowdown transfer, as well as control of the maximum pressure differences between the BTS and the PPE or a tanker vehicle and the PPE. The BTS may modulate pressure difference as well as flow, by altering critical propellant flow paths between modules.

The BTS provides auxiliary functions to support propellant transfer between modules, with a high level of control and monitoring. These functions include:

- In-orbit leak checking of refuelling fluidic networks and refuelling couplings via helium pressure decay
- Priming control between modules
- Propellant Purging of tubing networks to

ensure minimised propellant hazards when crew is present
- Pressurant tank venting to control source pressure

A simplified architecture of the BTS is presented below highlighting the major fluidic assemblies with respect to the tanks and refuelling couplings.

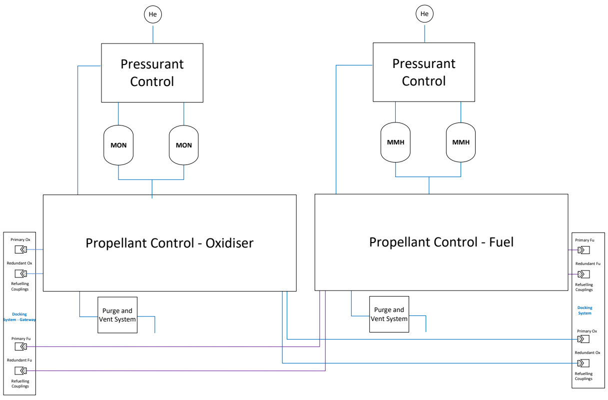


Figure 3: BTS Simplified Fluidic Architecture

The architecture of the BTS is based on largely qualified propulsion components, with developments needed for some components to adjust to the new refuelling context. The major developments on equipment level are:

- The propellant and pressurant flow control valves, due to the potential for backflow and changes of standard interfaces
- The propellant tanks, due to multiple in-orbit fill and drain/ pressure cycles

The BTS has a thorough development plan on the subsystem level with three major development stages, as well as on the equipment level.

To support PDR closure, a simulant based breadboard model is required to validate analysis and de-risk the subsystem major operations. This breadboard model also allows the investigation of worst case interface conditions coming from other connected systems which are undefined, such as the conceptual tanker visiting vehicle refuelling architecture.

A propellant development model is planned to support CDR and will act as a functional qualification model of the subsystem, which will be run with a much higher representativeness and design fidelity.

The third subsystem development activity is in the frame of the acceptance tests to ensure proper functionality and build quality of the flight system. The acceptance tests will support the successful delivery of the module.

2. JOINT TEST OBJECTIVES

Within the Gateway refuelling group, consisting of the major agencies (NASA and ESA) and the contractors developing the Gateway refuelling systems, a joint test campaign was developed to enhance what would have otherwise been a self-contained development campaign between TASUK, TASF and ESA for the BTS simulant model. The joint development effort includes breadboards built by both the TASUK and NASA teams, therefore allowing a high representativeness of all elements. The simulant development effort is designated **ERM-1** and is the first of the three major development activities for the BTS.

The joint development campaign has the following major goals:

1. Support L2 (Gateway) level risk reduction of refuelling operations
2. Calibrate numerical models for BTS analysis (via Ecosim)
3. Calibrate numerical model for L2 refueling analysis
4. To inform L2 level refuelling analyses
5. Inform, demonstrate and characterise propellant transfer operations
6. Characterise the fluidic behaviour of the refuelling flowpaths
7. Demonstrate and characterise critical transient operations, for example in priming or in the case of a refuelling pause.

Goals 2,4,5 and 6 are pursued for the value of all stakeholders, but will contribute to the derisking and closing the refuelling preliminary design for the BTS PDR.

The test objectives will be met in the joint setup by incorporating representative fluidic elements and setting up flight representative test conditions in terms of pressure, temperature and induced flowrates. Two simulants are used in the place of bipropellants to allows development testing:

- Water as a simulant for MMH (Fuel)
- HFE-7100 as a simulant for MON-3 (Oxidiser)

Water and HFE-7100 are common inert simulants for MMH and MON-3, respectively, due to their similar vapor pressure and density. Water will be the primary simulant used for test cases due to its low cost, where only selected cases will be with the HFE-7100 engineering fluid. Having a second simulant provides the advantage of another reference point in terms of calibrating analyses, as well as giving a good idea of the flow performance in flight of the MON-3 propellant transfer.

NASA has already conducted initial end-to-end development tests at their Energy Systems Test Area (ESTA) at Johnson Space Centre, where the BTS system has been represented with a simplified fluidic assembly based on initial assumptions. The ESTA test campaign is summarised in the following section.

INITIAL BREADOARD TESTING AT NASA

The CMV breadboard fluid emulator was built to support integrated Gateway refueling testing with the ESA ERM developmental testbed, referred to as ERM-1. The combination of the ERM-1 and the CMV breadboard will create a powerful early developmental tool to understand the fluid dynamics of on-orbit Gateway refueling, while saving cost and time by using representative commercial-off-the-shelf (COTS) components.

Prior to integrated testing at TAS-UK, the CMV breadboard was tested at Johnson Space Center with a simplified version of the ERM to validate the design and component selection. The experimental data from that campaign is highlighted here and was used for numerical model validation and provided the opportunity for early program risk reduction. Areas of concern that were targeted in this campaign included excessive pressure transients during vacuum priming and refueling pauses.

3.2 Experimental setup

An image and a reduced schematic of the CMV breadboard is shown in Figure 4 and Figure ***5***, respectively. Components that are not necessary to communicate primary results have been removed. In the schematic, water flows right to left, starting at the ERM tank. The system tees in the PPE element with one leg going to the PPE tank and one going to the venting valve, SV-905. Refueling is completed through a pressure-differential process, where the ERM tank is pressurized with helium higher than the pressure within the PPE tank thus initiating and sustaining flow. The vent valve is used to purge liquid out of the system post refueling.

Figure 4: JSC Breadboard test set up

Subscale tanks with sight glasses were used to represent the ERM and PPE propellant tanks. Hand valves were used to fill the ERM tank with water, pressurize the tank with helium, and control flow to the vacuum and purge systems. Fast-acting solenoid valves were used to represent flight valves and emulate their opening and closing response times. COTS filters with similar size and pressure drop characteristics as the flight components were used throughout the experimental apparatus at flight locations. The pressure drop for flight components that could not be fully represented in this developmental test was captured by using square-edge orifices. The size and length of tubing was flight representative. Pressure and temperature sensors were added in key locations to characterize both transient and steady state behavior.

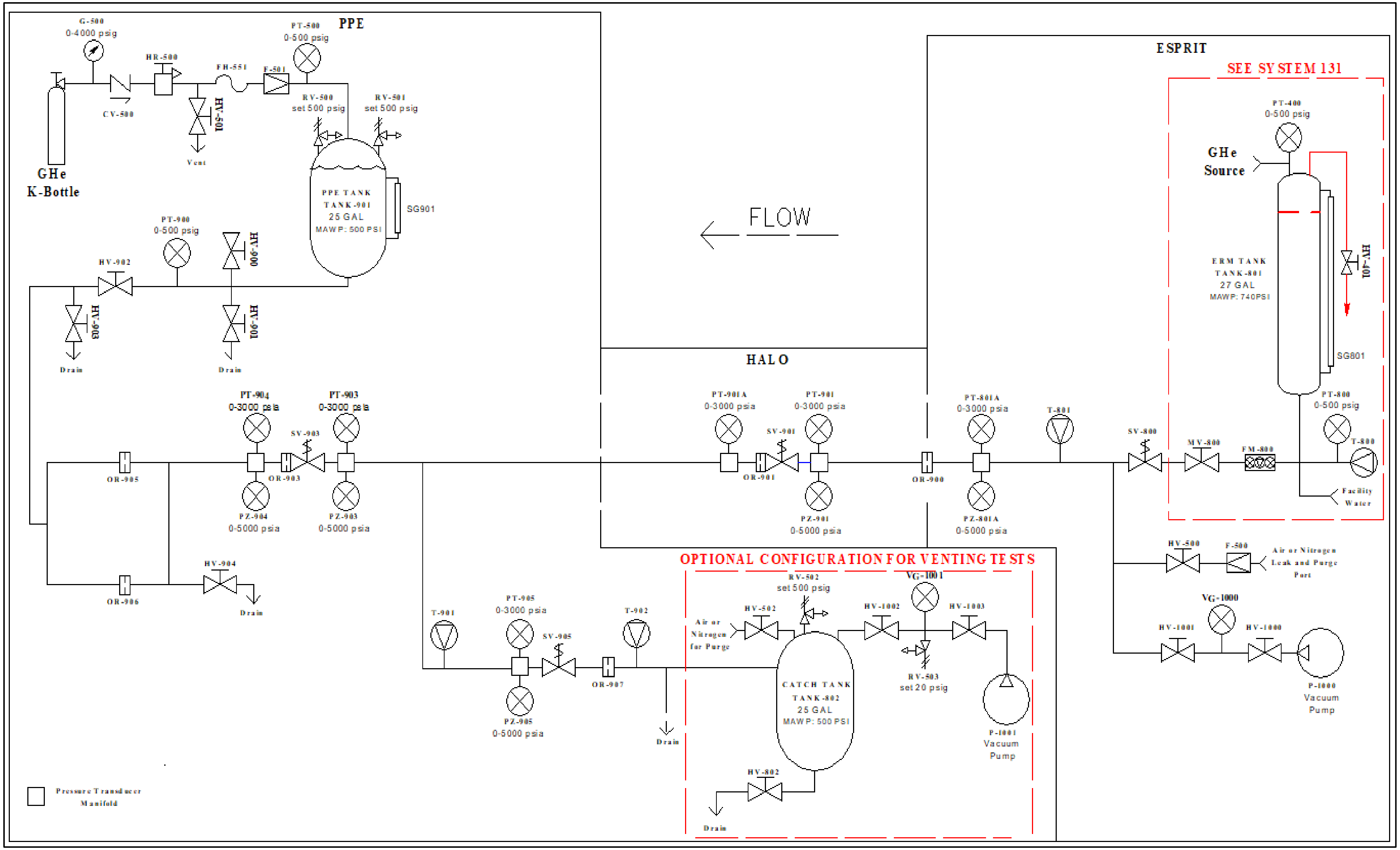


Figure 5: JSC test campaign reduced schematic

The pressure and temperature sensors were not sized or placed in the experimental setup to emulate flight, but instead were placed at locations expected to experience the most substantial water hammer events. In the schematic, the designation PT is used for strain gage pressure transducers and PZ is used for piezo electric sensors. Their pressure range is provided below the component number. In many locations, particularly upstream a solenoid valve, a manifold with both a Taber model 2911 strain gage pressure transducer and a PCB Piezotronics model 113B22 piezoelectric sensor were used to capture the dynamic water hammer event to provide two sets of high speed pressure transient data. The Taber model 2911 PTs also were used to characterize the steady state behavior. PCB Piezotronics model 113B22 piezoelectric sensors (PZ) were used to capture the dynamic water hammer events in their entirety with a rise time of less than 1 µs (repeatability within 0.1% full scale).

All testing at JSC was performed with water, however all components were selected to also be compatible with HFE-7100 for integrated testing in the UK.

The overall data acquisition and control structure is shown in Figure 6. Data could be recorded at 1 Hz and/or 10 kHz depending on the needs of the specific test. High speed data collection was limited to the highly dynamic water hammer events due to the immense file sizes. Control was provided by a LABVIEW graphical user interface (GUI) with a visual schematic with indicators for all instrumentation and on/off buttons for all solenoid valves. The GUI also featured warnings for max file size and solenoid valve overheating conditions.

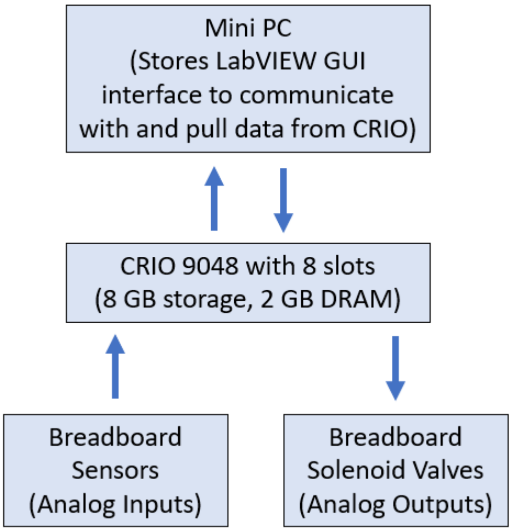


Figure 6: JSC testing DAQ structure

3.3 Test description and results

3.3.1 Propellant priming

The propellant lines between ESPRIT and PPE in flight will be at vacuum prior to the refueling operation. In order to begin refueling those lines must be hard-filled with liquid; this is done through a process called vacuum priming. The initial valve within ESPRIT is opened allowing liquid to flow into the vacuum-evacuated lines up to the next valve in the system causing a highly dynamic, water hammer event. That water hammer is caused by the rapid change in velocity and fluid momentum of the liquid at the dead end, causing a potentially damaging spike in pressure.

Due to the nature of Gateway, priming was broken into two stages. Stage one was from the ESPRIT valve to the closed HALO valve. Stage 2 was from the HALO valve to the closed PPE tank valve and the PPE vent valve. In stage 2, there is a split in the priming flow to the two dead ends. The PPE tank does not experience the large water hammer spikes like the valves due to the substantial ullage volume and therefore was not characterized in these tests. Tests were performed for both priming stages with ERM tank pressures at 1.4 ± 0.1 bar, 2.4 ± 0.1 bar, 3.5 ± 0.3 bar, and 6.9 ± 0.7 bar. All tests were performed twice to ensure repeatability. Vacuum levels prior to test were verified to be below 2.7 E-3 bar. Vacuum levels throughout the test were verified to be under 6.7 E-3 bar based on a characterization of reverse leakage by performing an isolated pressure rise test before running the priming test. Extensive testing was performed before the priming test series to ensure no water vapor remained in the lines and the system's reverse leak rate was acceptable.

Figure 7 shows an example data set from the upstream HALO pressure sensor suite during a stage 1 priming event with the ERM tank set at 3.5 bar. The data shows a pressure peak of 12.3 bar for the PT and 12.8 bar for PZ sensor as the liquid slams the HALO valve. In general, higher transient peak pressure is detected on PZ compare to PT because of the faster response time of the PZ. Therefore, the PZ provides more reliable data during this high transient but needs the PT for steady state reference and calibration. The discrepancies of the peak pressures between the PT and PZ were observed to be increasing as the ΔP from the source to the system increase.

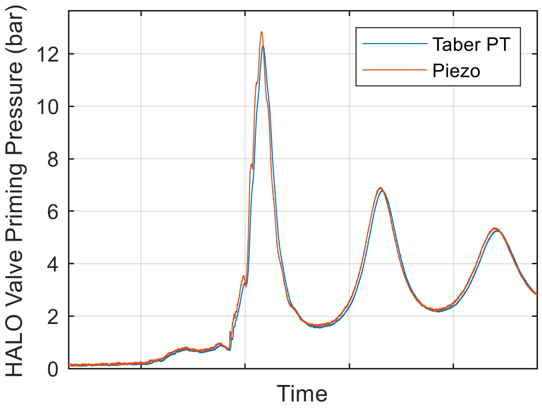


Figure 7: Stage 1 Priming Transient Pressure with 3.5 bar ERM Tank.

Figure 8 provides a summary of HALO valve peak pressures during stage 1 priming captured from PZ for the various test cases. For the maximum ERM tank pressure condition tested, 6.9 bar, there is a peak pressure 3.5 times the priming pressure during the water hammer event.

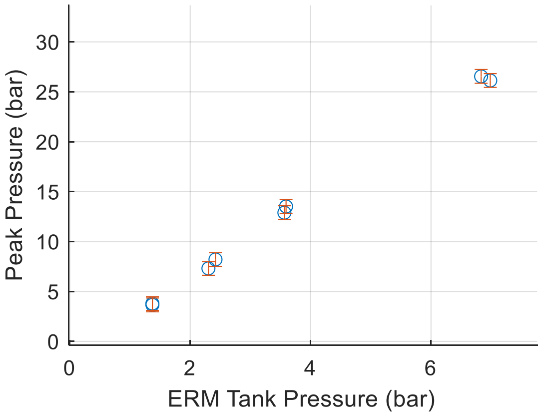


Figure 8: Stage 1 priming test summary

Stage 2 priming results in less aggressive peak pressures at the two dead-end PPE valves. The vent valve sees higher pressures and an example of the PT trace is shown in Figure 9. A summary plot of the peak pressures at the PPE tank and vent valve during second stage priming is shown in Figure 10.

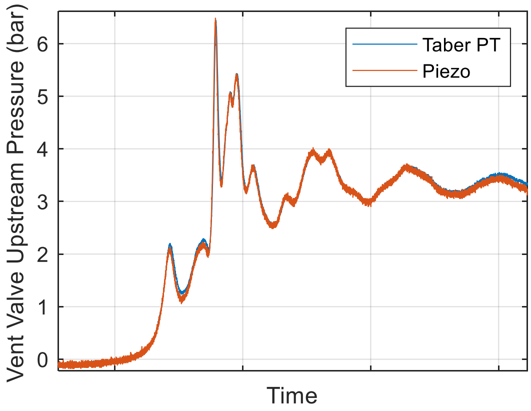


Figure 9: Stage 2 Priming Transient Pressure with 3.5 bar ERM Tank.

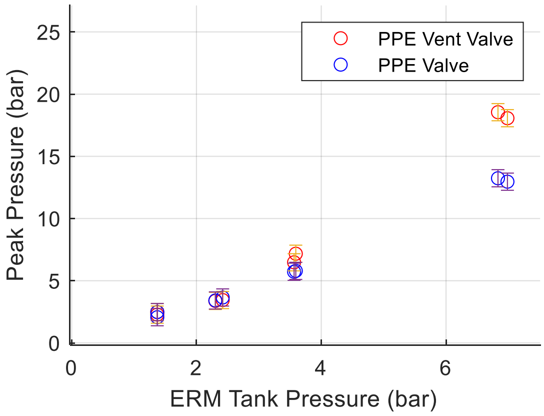


Figure 10: Stage 2 priming test summary

3.3.2 Refuelling pause

Once the system is primed and the final PPE tank valve is open, steady pressure-differential fed refueling begins. However, it is important to be able to stop the refueling process by closing the valves. This could be necessary due to an emergency or just nominal operations for a pause or end of transfer. The closing of a fast-acting valve causes a water hammer transient and can also damage components.

To simulate a refueling pause or stop, a flow of water in the test setup is established via a pressure differential between the ERM and PPE tanks. The PPE vent valve remained closed for this test series. Tests were performed with differential pressures of approximately 0.7 bar, 1.4 bar, 3.5 bar, 5.5 bar, and 7.6 bar. For each flow condition the HALO valve and the PPE tank valve were closed to capture the pressure transients associated with each.

Figure 11 shows an example pressure transient seen at the HALO valve when it is closed at the 7.6 bar differential flow case. The y-axis has been normalized to the pressure seen by the valve prior to closing. The closure results in a massive upstream pressure spike, 4.2 times the initial steady state pressure, endured by the valve. Downstream of the valve, there is a suction effect prior to the spike, as seen in Figure 12. Closure of the PPE valve resulted in similar, albeit lower, pressure spikes. Summary results of refueling pause test series for the HALO and PPE tank valve are shown in Figure 13Figure 14.

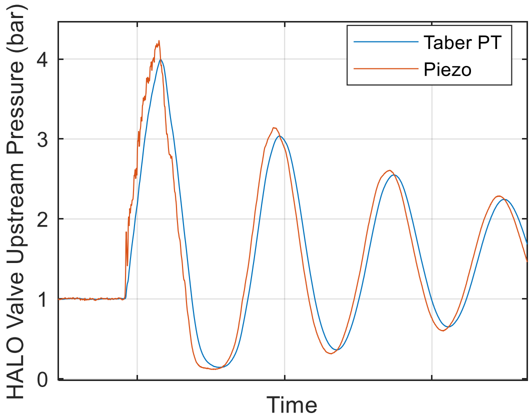


Figure 11: Upstream Transient Pressure, HALO valve closure during refueling with ERM/PPE differential pressure of 7.6 bar.

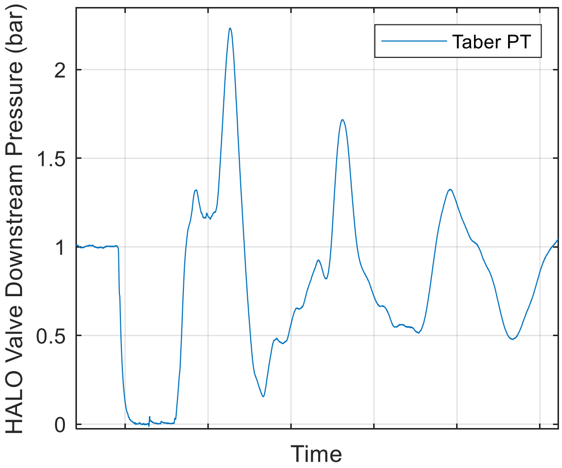


Figure 12: Downstream Transient Pressure, HALO valve closure during refueling with an ERM/PPE differential of 7.6 bar.

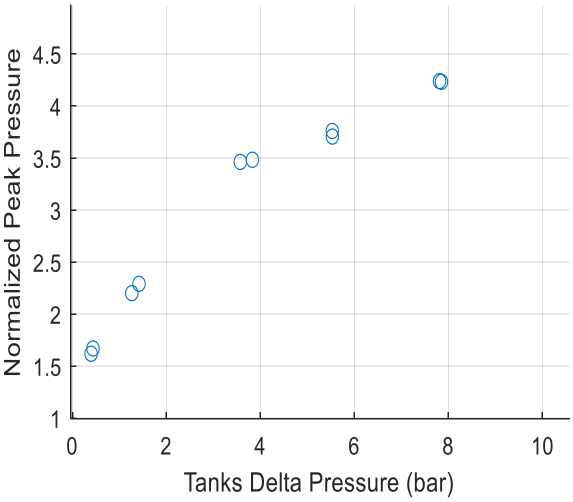


Figure 13: Refueling pause, HALO closure summary

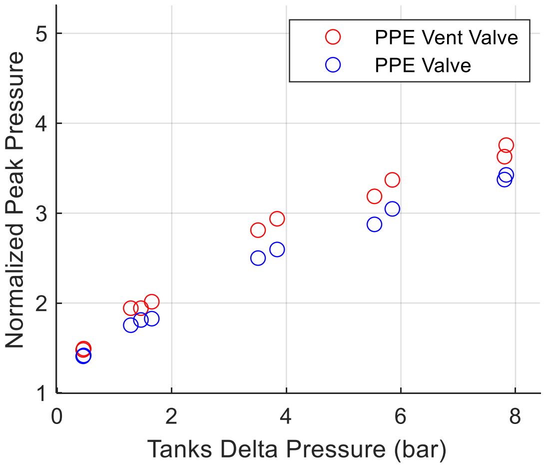


Figure 14: Refueling Pause, PPE Closure Summary at PPE Valve

3.3.4 JSC test campaign conclusions

Prior to initiating the breadboard test campaign, early numerical modelling indicated a substantial risk of transient pressures exceeding system design pressures during refuelling operations, especially during the initial vacuum priming sequence.

NASA breadboard test data allowed for the grounding of those numerical models with actual data and better defined the risks due to pressure transients. Vacuum priming proved to be more benign than initial models indicated, where on the other hand, transients during a refueling pause or emergency stop were more dramatic than anticipated. These data provided important background for the early development of concept of operations, fault detection and response, and informed the creation of additional verification models and test activities. Furthermore, the data and lessons-learned in this campaign on experimental set up, operation, testing, and model validation provided valuable input to develop the NASA + ESA joint breadboarding verification test plan.

Due to major differences in this initial NASA test schematic, the results presented in this section will vary from those collected in the full integrated campaign with ERM-1. That testing will provide a more holistic and representative view of Gateway refuelling fluidic behaviour.

3. ERM-1 JOINT TEST SETUP

Following the preliminary test campaign carried out at Johnson Space Centre. The PPE breadboard model was brought to TASUK premises to be integrated with the TASUK ESPRIT and VV breadboards. Figure 15 gives a block diagram of the joint test setup.

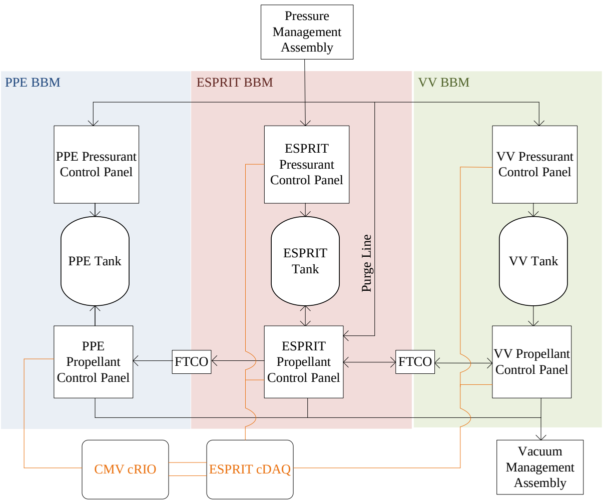


Figure 15: ERM-1 joint test setup block diagram

The ESPRIT and VV breadboards are composed of COTS products, chosen to be a representative to flight system equipment as practically possible.

The setup allows for demonstration of operations, primarily propellant transfer from the ESPRIT to PPE tank. The setup also allows demonstration of propellant transfer from the VV tank to ESPRIT and from the VV tank directly to the PPE tank. Although, neither of these extensions are currently planned, the ESPRIT refuelling module must be capable of receiving propellant from a visiting vehicle and facilitate the direct transfer of propellant from the VV to PPE.

Although the direction of propellant transfer will only occur in the direction from VV to ESPRIT to PPE, the system priming will always occur from ESPRIT, outward towards PPE and VV.

Subscale tanks used to represent the ESPRIT and VV tanks. Those tanks were placed on scales, shown in Figure 16. to accurately measure the mass of simulant in the tank through a propellant transfer test. A mass flow meter is installed on the fluidic panels as shown in to measure flowrate between tanks, shown in ***Figure 1***Figure 17.

Figure 16: Fluidic Network and Tanks Configuration

Figure 17: ESPRIT and VV BBM Fluidic Panels with Mass Flow Meter (right)

Pressure transducers from Keller (PA33X and PAA33X) and from RS (797-5030 and 797-4961) are distributed in key locations throughout the breadboard to determine steady state and slow changing pressures. High frequency pressure transducers from Kistler (4260A) will be placed in areas of interest for pressure peaks.

Typical distributions of pressure transducers, temperature sensors, flow meters and scales are described in more detail in Section 4, however, the full schematic and of the breadboard cannot be given in this paper.

4. JOINT BREADBOARDING VERIFICATION TEST PLAN

5.1 Transient tests

5.1.1 Priming tests

Priming tests are a critical component of the campaign to validate that pressure peaks caused by water hammer are kept within acceptable limits to avoid structural failure.

An example of the equipment setup for the priming tests is given in Figure 18.

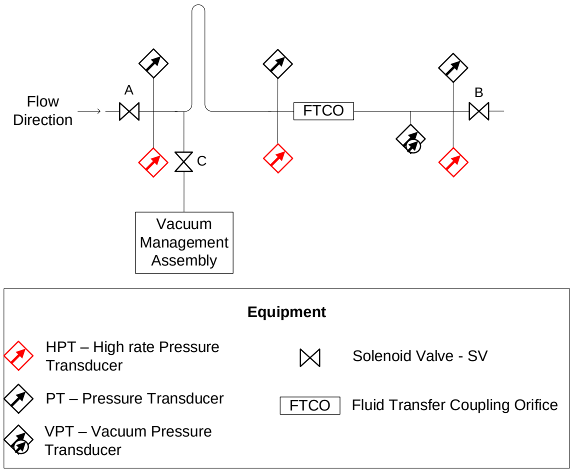


Figure 18: Example equipment setup for priming test

All priming tests in the campaign will conducted with a tubing line at vacuum pressure of less than 10 mbar. To achieve this, a vacuum will be drawn from near the line inlet. The pressure will be measured by a piezo vacuum transducer at the opposite end of the line. This ensures the worst case (highest pressure) initial condition is measured. This is critical as the liquid entering line can mix with the residual gas, forming a vapour cushion which effects the evolution of the first pressure peak [1].

5.1.2 Refuelling Pause Tests

If an anomaly occurs during propellant transfer, a refuelling pause could be initiated. In this instance, a solenoid valve on the propellant line would close. This would result in an initial pressure peak at the solenoid valve inlet and pressure trough at the solenoid valve outlet. Both of these artefacts will be captured by high frequency pressure transducers at the inlet and outlet of the valve, as shown in Figure 19.

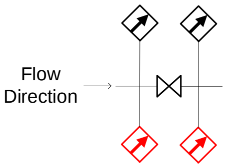


Figure 19: Example critical equipment setup for refuelling pause tests

5.2 Characterisation tests

5.2.1 Liquid flow path characterisations

The ESPRIT propellant control panel contains multiple flow paths to provide operational flexibility. Each flow path from ESPRIT to PPE and VV to ESPRIT must be characterised. The key equipments for the ESPRIT-PPE and VV-PPE characterisations are given in Figure 20 and Figure 21 respectively.

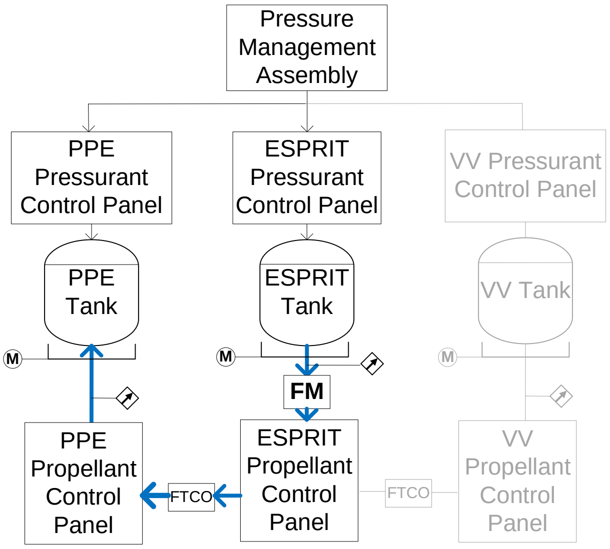


Figure 20: Simplified equipment setup for ESPRIT-PPE propellant transfer

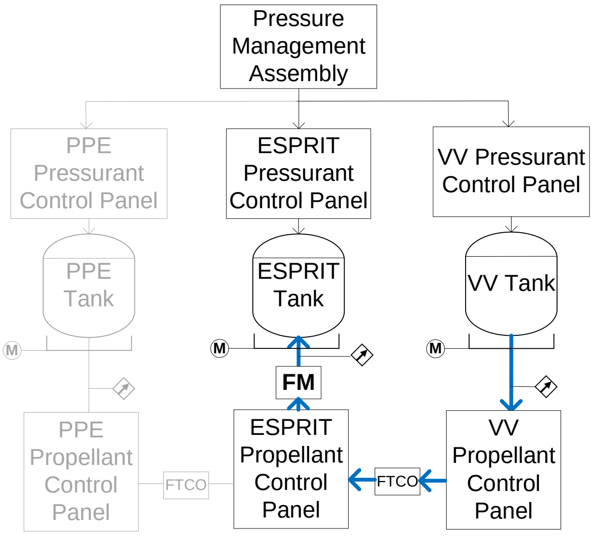


Figure 21: Simplified equipment setup for liquid flow path characterisations and VV-ESPRIT propellant transfer

In each case a pressure difference across two propellant tanks is set by the Pressure Management Assembly and measured by the pressure transducers immediately downstream of the tanks. The flow path is opened and the mass flow is measured by a mass flow meter. Intermediate static pressures will measure by standard rate pressure transducers in various locations of all propellant control panels at 1 Hz. The integral of the mass flow data will be compared to the data recorded from the tank scales. The pressure differential across the tanks will be plotted against the mass flow rate to show the mass flow characteristics of each flow path.

5.2.2 Tank gas pressure evolution characterisations

During propellant transfer from ESPRIT to PPE, the ESPRIT propellant tank will be repressurised to achieve the mass transfer objective. In this test, helium will flow from the pressure management assembly through the ESPRIT Pressurant Control Panel to the ESPRIT tank. To facilitate the controlled repressurisation of the ESPRIT tank, a needle valve is used upstream of the tank.

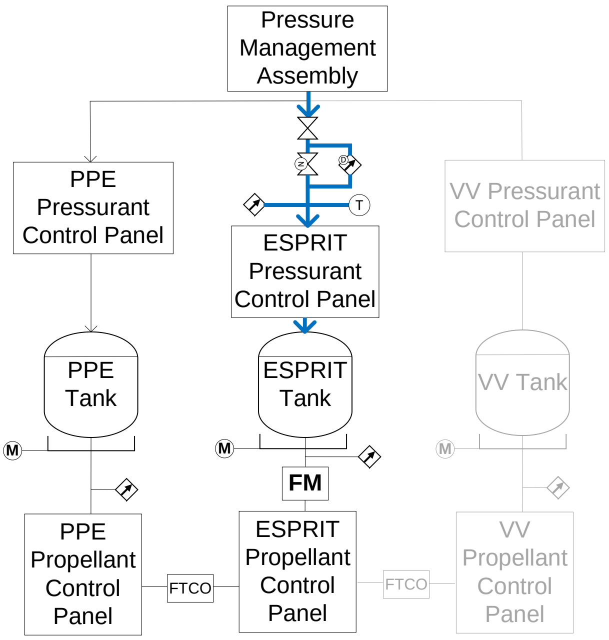


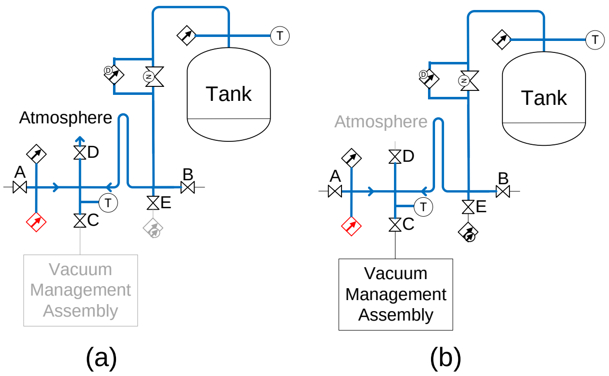
Figure 22: Simplified equipment setup for tank gas pressure evolution characteristics

The needle valve will be set prior to the characterisation to conform to system requirements.

The static pressure and temperature will be measured at a frequency of 1 Hz to verify that repressurisation occurs with time limits specified in system requirements. The differential pressure will also be measured across the needle valve to characterise the restriction required in the flight system.

5.2.3 Tubing venting characterisation

The objective of this test is to characterise the venting of a helium filled tubing section to vacuum. Due to challenges in maintaining vacuum conditions during a vent, this test will be carried out in two stages, as shown in Figure 23. This figure shows and example equipment setup for tubing venting characterisation.



(a) (b)

Figure 23: Simplified equipment setup for tubing venting characterisation test: (a) configuration when ptubing >1 barG, (b) configuration<1 barG

In the first stage, shown in Figure 23(a), valves A,B,C and E will closed and valve D will be open. This isolates Vacuum Management Assembly and Vacuum Pressure Transducer (VPT) whilst the line vents to atmosphere through valve D. During the choked flow phase of this vent, the results are expected to be representative however, the data from the unchoked flow will be discarded. Once the pressure in the tubing has reached atmospheric pressure, the second stage of the test will begin, shown in Figure 23(b). Valve D will be closed, isolating the tubing from atmosphere. Valves C and E will be opened and the tubing section will be exposed to vacuum conditions. It is expected that this characterisation of free molecular flow will be representative.

Static pressures will be measured at the positions given in Figure 23. The pressure will be recorded at 10 kHz in the first stage of the vent and at 1 Hz in the second stage. Temperature of the tank ullage and the vent outlet temperatures will be recorded at 1 kHz.

5.3 Operation Demonstration Tests

The operation demonstration tests will combine many of the previous tests to demonstrate a complete refuelling operation of PPE from ESPRIT and from VV to ESPRIT, as shown in Figure 20 and Figure 21 respectively.

5.3.1 ESPRIT-PPE refuelling

This test represents the baseline refuelling operation for ESPRIT. Firstly, the ESPRIT tank will be pressurised. A valve in the ESPRIT Propellant Management Assembly will then open, initiating a priming stage into the evacuated line between the ESPRIT and PPE BBMs. After the final stage of priming has been completed, a valve in the PPE Propellant Management Assembly will open, initiating simulant transfer. As the transfer progresses, the static pressure of the ESPRIT tank ullage will reduce. Predefined logic, based on the test defined in Section 5.2.2, will open and close the solenoid valve between the Pressure Management Assembly and the ESPRIT tank to repressurise the tank. The pressure band requirement will be based on the outcome of the previous test results.

5.3.2 VV-ESPRIT refuelling

This test will demonstrate the refuelling of ESPRIT from VV, as shown in Figure 21.
The ESPRIT and VV tanks will be pressurised by the Pressure Management Assembly to values defined in the system requirements. A valve in the ESPRIT Propellant Control Panel will open, initiating priming in the evacuated line between the ESPRIT and VV Propellant Control Panels. Once the priming is completed, a valve in the VV Propellant Control Panel will open initiating propellant transfer from VV to ESPRIT. The test will involve a single blowdown operation with no repressurisation the VV tank.

Static pressures throughout the system will be measured at 1 Hz for the duration of the demonstration. Static pressures in the key areas out lined in Figure 18. of the tubing line will be measured at 10 kHz during priming.

5. CONCLUSION

The simulant breadboarding campaigns on both the NASA and TASUK side have progressed to the point of being ready to link the systems in the fluids lab in TASUK. The joint test effort, will be able to build on the initial tests at NASA by investigating more flight relevant test cases with a highly representative fluidic architecture for the BTS. The preliminary data gathered by NASA with the setup at JSC-ESTA has already shown a good correlation with models developed and has shown potential worst case scenarios in terms of transient pressure peaks for waterhammer. In the scope of the joint ERM-1 development effort, the testing ahead will contribution to the closure of the verification goals of the simulant breadboarding campaign, with a highly representative setup.

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