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# ANALYSIS AND VERIFICATION OF IN-ORBIT FUELLING SYSTEM DURING DEVELOPMENT AND BREADBOARD TESTING

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## ABSTRACT:

Space journeys are becoming increasingly ambitious over the years and an in-orbit fuelling station is becoming a necessity. The European System Providing Refuelling, Infrastructure and Telecommunications (ESPRIT) [1] is a module that will provide additional Xenon and chemical propellant capacity, additional communications equipment and an airlock for science packages led and funded by European Space Agency (ESA). During Phase A of the design process, the fuelling system architecture was consolidated and refined based on an advanced simulation of system flow properties. This paper discusses the simulation and the results obtained from the breadboard test campaign. The simulation is conducted using the EcosimPro (ESP) Software, tailored to simulate the actual flight configuration and parameters. The performance was first validated using existing data and simple test setups. The simulation was used to aid in the preliminary design processes. In order to verify the system simulation and calibrate its parameters, breadboard testing of essential aspects of the system were executed. The results obtained from the breadboard test campaign were used to adapt the behaviour of flight components in the analysis for the entire fuelling system. The breadboard tests also produced valuable information such as:

- Detailed hydraulic characterisation of the liquid side of the feed system, including steady state flow rate, steady state pressure drop;
- Transient phenomenon such as water hammer due to valve operation;
- Simulation of the priming process, shocks caused due to valve initiation with downstream vacuum;

## 1. MOTIVATION

The more demanding space missions get, the harder it is for current state-of-the-art propulsion technology to meet their requirements. Therefore, refuelling in space is becoming a more attractive solution. The ability to refuel in orbit paves the way for pioneering operations, with less volume taken up by propellant at the start of the mission can enable smaller launch vehicles or even using saved propellant budget to increase payload budgets.

In 2017 NASA (National Aeronautics and Space Administration) launched the Artemis program which intends to send the first woman and the next man to the moon. This program involves the collaboration of several international partners including ESA, JAXA (Japan Aerospace Exploration Agency) and CSA (Canadian Space Agency). The Lunar Gateway, part of the Artemis program and originally known as the Deep Space Gateway, is expected to heavily contribute to NASA’s vision. ESPRIT is one of the many modules that will form the Lunar Gateway. It is the module which will enable in-orbit fuelling to occur.

ESPRIT tanks will refuel the Power and Propulsion Element (PPE) where the electrical and chemical propulsion are based. At the time this study was conducted, hydrazine was the propellant under consideration. The hydrazine transfer from ESPRIT to PPE was enabled by a fluidic connector between the 2 modules. An additional fluidic connector facilitated the transfer of propellant from a third vehicle to ESPRIT tanks.

To support the development of the Hydrazine Transfer System (HTS), a Breadboard Model (BBM) test campaign was carried out. The main objectives of the test were to:

- Demonstrate the primary functions and flow paths of the system in the mission representative order.
- Characterize pressure peak behaviour and confirm safety in case of water hammer events due to priming and valve actuations.
- Characterize performance regarding system refuelling goals such as assessing pressure drops for desired mass flow rates; assessing the representativeness of the BBM architecture and working media for the HTS and its intended components and flow paths.

## 2. TEST SETUP

The test setup was designed to be as representative of the flight layout as possible, taking into account this is an early stage of the program and final design was not complete.

In order to reduce the risk of the BBM tests, the ground testing used de-ionized water instead of Hydrazine. This is widely accepted in the industry as densities are similar and a correlation of properties between the two can be found in various papers along with other Hydrazine based results ([2], [3], [4] and [5]).

The Nitrogen pressurant was controlled by a manual regulator.

A simplified BBM layout was created to represent the proposed flight layout:

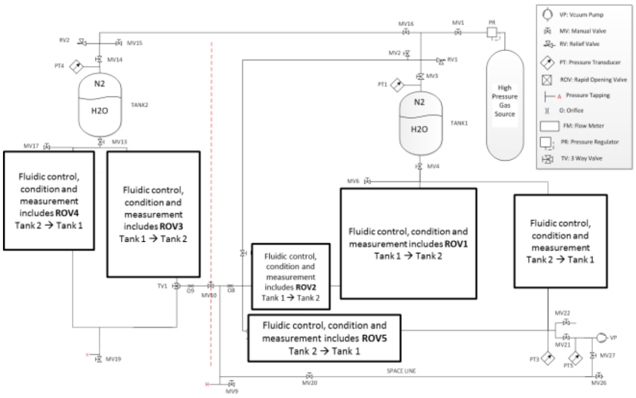

Figure 1. BBM layout

The BBM was designed to include filters and orifices in different sizes, representative of flight hardware in terms of minimum cross section area and pressure drop:

- Flight level filtration.
- Latch valves.
- Pyrovalves.
- Pressure peak reduction orifice.
- Pressure Transducer (PT)

All the BBM pipework length and bending angles were carefully measured in order to enable a more true to life analysis and were based on current knowledge of the tubing routes between the modules.

For more details on the different components on the BBM refer to section 4.1.

The orifices used were sized from a preliminary analysis model which used heritage proprietary data to predict the fluidic behaviour for the different operational cases. The orifices were sized to enable strict control and a benign environment for the subsystem components which would see multiple priming events throughout the ESPRIT lifetime.

## 3. TESTS

The test campaign was divided into three separate activities, representative of the operations expected to take place in the ESPRIT module:

- Initialisation
- Refuelling (flow from Tank 1 to Tank 2 – see Figure 3) representing fuel transfer from ESPRIT to PPE.
- Refilling (flow from Tank 2 to Tank 1 – see Figure 4) representing fuel transfer from tanker to ESPRIT.

Initialisation: This activity reflects the events that will occur after launch of the ESPRIT module. The tests were carried out to:

- Reflect priming before the transfer of fuel from ESPRIT to PPE;
- Investigate the extent of water hammering effects on pressure peaks.
- Assess several different initialisation strategies.

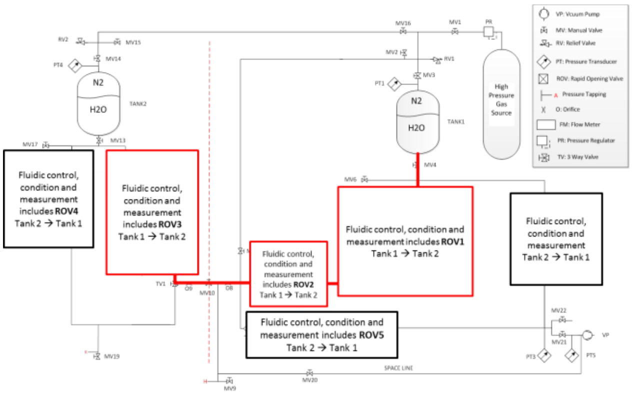

Figure 2. BBM Initialisation Path

Refuelling: This activity represents the transfer of hydrazine from the ESPRIT tank to PPE tank. The tests were carried out to:

- Observe pressure equalisation from an

initial and uncontrolled delta pressure between the tanks;
- Observe resultant pressure drops across the representative HTS by achieving predetermined mass flow rates in a pressure regulated flow.

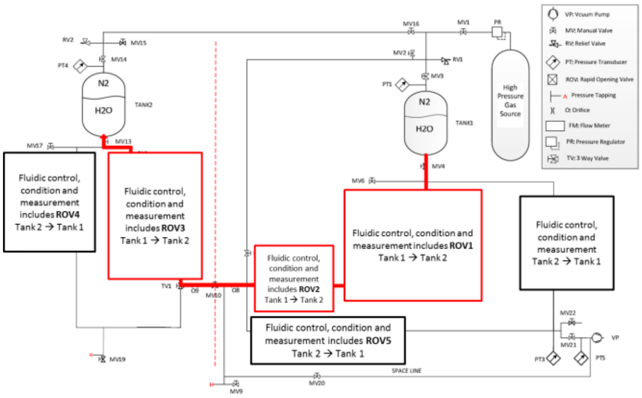

*Figure 3. BBM Refuelling Path*

Refilling: This activity represents the transfer of Hydrazine from a tanker to the ESPRIT tank. The tests were carried out to:

- Observe pressure peaks during priming from tanker to ESPRIT tank (Tank 2 to Tank 1 – see Figure 4);
- Simulate transfer of fuel which is fully pressure regulated at various set pressure difference;
- Observe mass flow and pressure drop when simulating blowdown transfer.

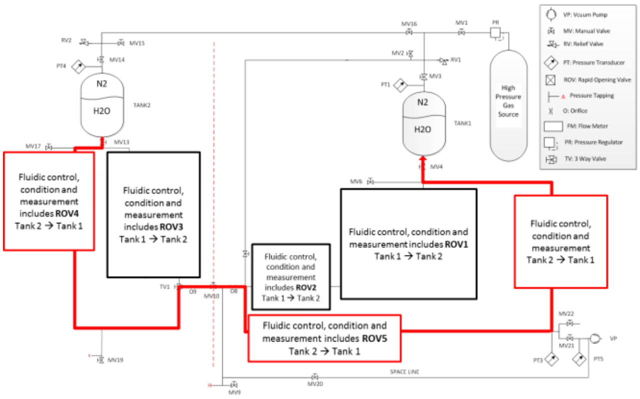

*Figure 4. BBM Refilling Path*

## 4. ANALYSIS SETUP

In order to perform the transient analysis, the commercial software EcosimPro (ESP) version 5.4.19 was used along with ESPSS toolbox and additional proprietary software and components developed in house.
The schematic was created using BBM measurements and known orifice data from acceptance testing of the orifices.

The main purpose of the analysis is to calibrate the model and consequently validate the flight setup using these calibrated models.

### 4.1. BBM components characterization

All the components used for the BBM were implemented in the analysis using the components specifications, i.e.: orifice size, length, pressure drop etc.
In addition to the above, all pipe length and angles were measured on site and input in the ESP BBM Model for analysis.

- The pipework included ¼" OD x 0.035"W/T Stainless Steel pipes with consistent bend radii. None of the pipework was fixed to the platform in the actual BBM test (un-anchored).
- Swagelok filters were used and pressure drop for ESP model was setup according to its specification.
- For ¼" Hand Stop Valves, Swagelok SS-43G-S4 orifice size were modelled in ESP.
- For Swagelok Pneumatically Operated Valves (ROV1,2,3,4 and 5), the same as for Hand Stop Valve was used and information on the opening speed was not available.
- Modelling of the flowmeter pressure drops was accomplished by extrapolation of the pressure drop vs flowrate curve available. A Digital Coriolis instrument was used.

### 4.2. Analysis assumptions

In order to complete the analysis and calibrate the model, some reasonable assumptions have been taken into account and are reported below:

1. Fluids are based on real Nitrogen and Water properties from EcosimPro database.
2. Depending on the experiment run on the BBM, vacuum level of 60-120mbar in the pipes (when vacuum was required) were achieved however the accuracy of the pressure transducer (0.5%FS of 150 bar => 0.75 bara) was not sufficient to record near-vacuum pressure levels. As there were no exact measurement for the vacuum level at initiation, the vacuum level when the pump was shut down was 60mbar, then it took several minutes (5-10min) to initiate the test – and it is expected that the pressure can rise during this timeframe. Due to this unknown, the analysis baseline assumption is that we start with 60 mbar (i.e. pressure in the lines when the pump was switched off prior to starting the test).
3. Near vacuum pressure (60 mbar) is performed using Nitrogen fluid.
4. Initial temperature across the system and outside temperature are equal to the temperature measured in the initial conditions of the flow meter.
5. Pipes are up-stream anchored – opposed to not anchored on the BBM. There is no option for non-anchored condition in

EcosimPro.

6. Pipe roughness is based on heritage values.
7. Orifice diameter is modelled as a perfect diameter, without deviations. The length of the orifice component is added to the immediate downstream pipe, as the orifice component in ESP doesn't have a length parameter.
8. As mentioned above, the flow meter is modelled as a filter in order to apply a specific pressure drop. The length of the flow meter is represented by adding length to the immediate downstream pipe.
9. Pneumatic valve pressure changes are modelled as a quick opening valve with a response time ("Tao") of 0.015s since no information regarding the opening speed was available. This value has been advised by the supplier as heritage from other programs.
10. Relative and absolute errors for the mathematical solution are set to 1e-5, it introduces small errors and mathematical convergence seen as "noise", but the analysis runs significantly faster.

## 5. TESTS RESULTS AND ANALYSIS COMPARISON

### 5.1. Initialisation

The first step of initialisation was tested, opening ROV1 while vacuum was introduced between ROV1 up to ROV2, this have given us enough data to calibrate the initiation model (see Figure 5).

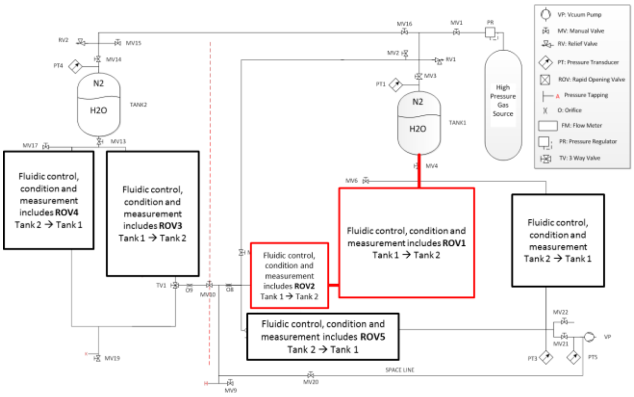

*Figure 5. BBM INI-1, INI-2 and INI-3 Path*

3 priming cases were replicated in ESP and compared to the experimental results – INI-1, INI-2 and INI-3. The different conditions and peak pressure at pressure port are reported in Figure 6. Related plots are provided in Figure 7, Figure 8, and Figure 9. The time lag reported in Figure 6 is the time between pressure peak observed in test and the simulation.

#### 5.1.1. Pressure Peaks

A lower pressure peak was expected as diameter of the orifice was decreased.

Simulation:

- A summary of what was observed can be found in Figure 6.
- Simulation pressure peaks are higher than those of the test. This is consistent with TAS (Thales Alenia Space) heritage knowledge of EcosimPro. Indeed the software has a tendency to overestimates peak pressures. This feature makes it worst case w.r.t flight conditions.

Test:

- A higher pressure peak during priming is observed for a 0.9mm diameter when compared to 1.1 mm diameter (INI-2 vs INI-3). However, test pressure peak for 1 mm diameter (INI-1) is similar than for the 0.9 mm diameter. We would have expected to obtain a peak with a magnitude between those of INI-2 and INI-3.
- A possible explanation is that the concerned orifice damping the pressure peak does not have perfect geometry (oval cross section area).
- Another possibility which accounts for this discrepancy is that the near-vacuum downstream conditions were not well monitored during the test.

#### 5.1.2. Time lag

In this paper, time lag defined as: the time interval between simulation and test pressure peaks. The time lags reported could have occurred due to cumulative uncertainties of the pipe length measured on the test bench.

| **Case ID** | **Orifice properties** | **Initial vacuum level** | **Initial pressure [bara]** | **ESP Peak [bara]** | **Test Peak [bara]** | **Error ESP vs Test** | **Time lag [s]** |
|---|---|---|---|---|---|---|---|
| **INI-1 (run1)** | Orifice D1: 1 mm | 60 mbar | 24.47 | 33.49 | 28.77 | 16.4% | 0.28 |
| **INI-2 (run1)** | Orifice D2: 0.9 mm | 60 mbar | 24.53 | 30.43 | 29.48 | 3.2% | 0.28 |
| **INI-3 (run1)** | Orifice D3: 1.1 mm | 60 mbar | 24.54 | 37.95 | 36.66 | 3.5% | 0.17 |

*Figure 6. INI-1,2&3 Results comparison*

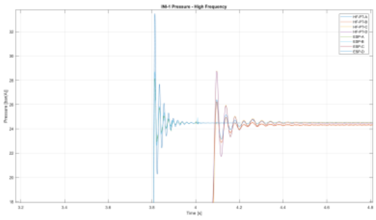

*Figure 7. INI-1 Results Comparison*

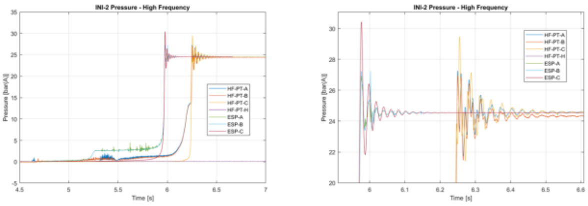

*Figure 8. INI-2 Results Comparison*

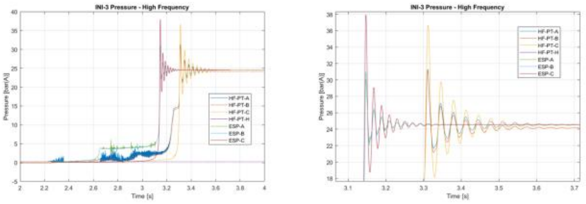

*Figure 9. INI-3 Results Comparison*

## 5.2. Refuelling

This section compares test data with simulation data from ESP for refuelling test activities (see Figure 3). In ESPRIT ConOPS this corresponds to the ESPRIT module refuelling the PPE module.

<u>Pressure Evolution (see Figure 10):</u>
Figure 10 depicts the pressure evolution across the subsystem:

- PT1 refers to the pressure in the tank #1 (ESPRIT);
- PT4 refers to the pressure in the refuelled tank #2 (PPE);
- PT2 refers to the intermediate pressure in the tubework;

A very good correlation between the test data and the simulation results can be seen in Figure 10. The main difference occurs for PT2 (intermediate pressure within the pipework) for which we observe in the transient phase a pressure difference up to 0.5 bara (see Figure 11) but this is attenuated once pressure stabilized. In both cases the transient phase lasts around 3000s before the pressure readings stabilize.

<u>Mass Flow Rate (see Figure 12):</u>
Figure 12 depicts the mass flow rate measured during the test and results of the simulation.

When the pressure stabilizes (see Figure 10):, we notice a persistent mass flow during the test whereas in the simulation the flow reduces to zero. This persistent mass flow is consistent with test pressure curves which depicts a residual pressure differential between tank 1 and tank 2 (~0.5 bara). This observation and the magnitude of remaining mass flow transfer was not expected.

Caveat: the accuracy of the pressure transducer being 0.75 bara, the real pressure in the test may be different than those reported by as much as 0.75 bara. However, this is unlikely since an actual mass flow was measured which would not have been the case if pressure were equalised. The root cause of this remaining mass flow is not understood, although it is suspected that some gravity, and temperature effects could play a role in the tank imbalance once pressures have “equalised”. This raises some questions on how well the fill fraction of the tank was controlled during the test. Nevertheless, this does not impact the validation and correlation of ESP with the pressure trend and the test results which aimed at verifying propellant transfer capabilities over the tested pressure ranges. This renders the test set up configuration and monitoring questionable.

Additionally, a significant difference in flow rate is observed: ~21 g/s in the analysis compared to 25 g/s at the start of the test. The simulation underestimates the mass flow measured during the test. This is in contradiction with the pressure evolution within the simulation which perfectly fits the test (see Figure 10).

Assuming that the PT reading is reliable, the accuracy of the test orifice cross section area could lead to errors as opposed to the simulation which assumes a perfectly shaped restriction. A deviation of 10% in cross section area would lead to a 10% deviation in mass flow. However, considering the mass flow rate discrepancy between the test and simulation (~20% at beginning of refuelling), all test orifices should have had on average a cross section area deviation of 20% which is very unlikely.

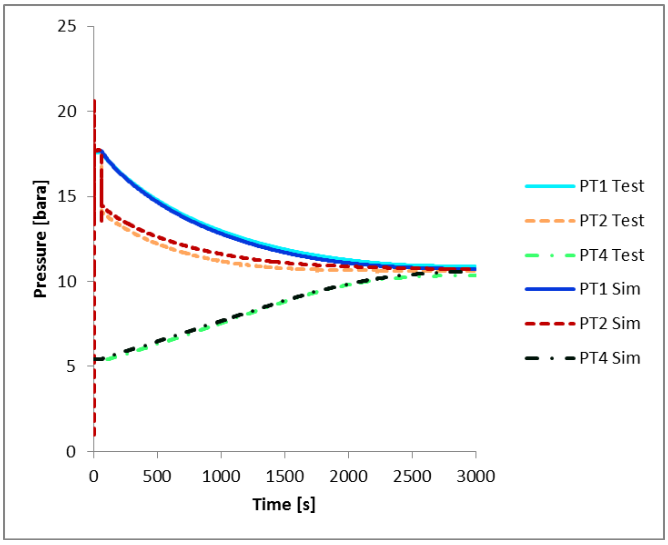

*Figure 10. Refuelling Pressure - test vs analysis*

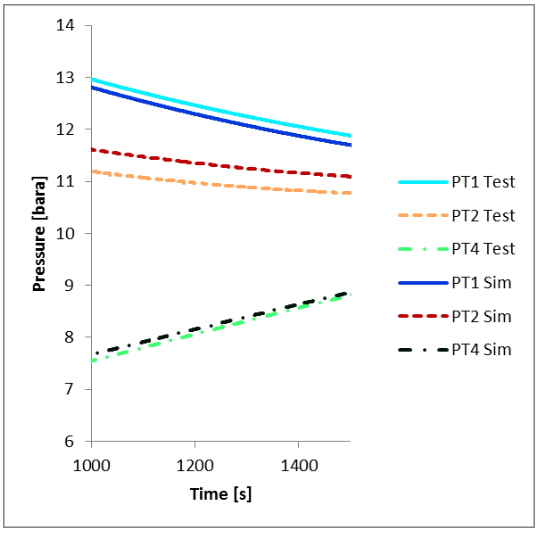

*Figure 11. Refuelling Pressure - test vs analysis detail*

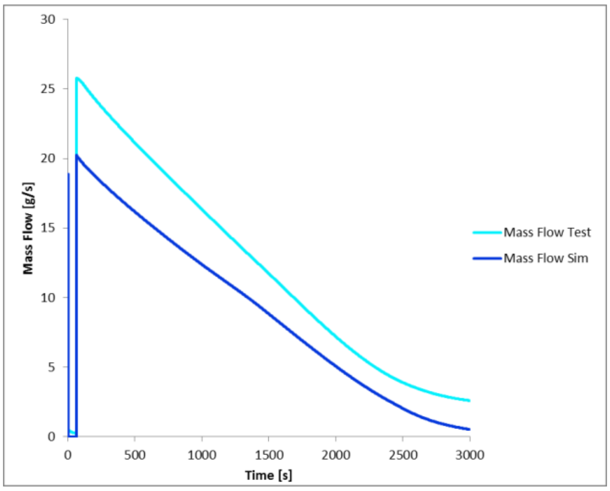

*Figure 12. Mass Flow rate comparison*

### 5.3. Refilling

Since the refilling activities used a different path but same setup, it was decided that analysing those cases for calibration purposes was not a priority, as other calibration cases were successful.

## 6. BBM ANALYSIS CONCLUSION

Comparison of the BBM test data and ESP analysis results allows the following qualitative and quantitative statements about the fidelity and credibility of the models to be made:

- Peak pressures simulated for priming show relative good correlation with the test data. Especially the trend of the peak pressure magnitude decreasing as the orifice size decreases. The maximum error is a 16% deviation with respect to test data (causes of deviation are discussed below). The simulations always over-predict the pressure peak meaning the analysis represents a worst case.
- Pressure evolution during refuelling: Test results show a very good quantitative agreement with the simulation (see Figure 10).
- Mass flow rate during refuelling: Although the trend of the mass flow rate evolution is similar to the test, the magnitude of the flow rate was off by 20%. (Causes of deviation are discussed below).

Differences in peak pressure levels and time to peak in priming are attributed to:

- EcosimPro software physical modelling deviations.
- Un-anchored BBM pipes may affect the pressure peaks magnitude and frequency.
- Pipe length measurement cumulative error will have an effect on the time-to-peak and peak pressure value.
- Orifice from was assumed as a perfect diameter, but r manufacturing will result in deviations from said diameter and from true circularity, resulting in differences in time-to-peak and peak pressure value.
- Exact downstream vacuum level is unknown as only the initial level was measured prior to shutting down the vacuum pump. Vacuum level deviation has an important effect on time-to-peak and peak pressure value.

Differences in mass flow rate between test and simulation are attributed to:

- Test setup characterisation and monitoring such as initial tank filling ratio, pressure sensor accuracy, etc.
- Gravity and temperature effects once pressures have equalized leading to an imbalance and residual mass flow.
- Test orifice cross section area imperfections: However, as discussed above, due to the number of orifices in the system, it is unlikely that all of them have been affected.

## 7. ACKNOWLEDGEMENTS

The BBM activity has been conducted as part of the ESPRIT mission, which is under contract to ESA as part of the international partnership for the Lunar Gateway. The testing activities were conducted by European Astrotech Limited.

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