OVERVIEW AND ASSESSMENT OF THE ESM PRESSURE CONTROL PERFORMANCE ON ARTEMIS I

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Stephen Barsi(1), Tobias Langener(2), Victor Fernandez Villace(2), Jan-Hendrik Meiss(3)

(1)NASA Glenn Research Center, Cleveland, Ohio, USA
(2)European Space Agency, Noordwijk, Netherlands
(3)Airbus Defence and Space GmbH, Bremen, Germany

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ABSTRACT

The European Service Module propulsion system is a bipropellant hypergolic serial system used to provide translational thrust and attitude control for Orion. To control propellant tank pressure, a bang-bang pressure control system is employed. Each propellant commodity is regulated by a pressure control assembly consisting of two pressurization branches (a primary and redundant pressurization path) where each branch includes 3 valves in series. Regulation is accomplished via flight software control of two downstream solenoid valves triggered off propellant tank ullage pressure. This paper presents an overview of system level challenges which have been overcome to enable a successful Artemis I flight. Principle among the challenges was valve-to-valve pneumatic interactions which drove changes to the control scheme. During the Artemis I mission, the pressure control assembly was able to control tank pressure within allowable tolerances. Comparison between flight data and mathematical models are presented showing excellent agreement. Finally, during flight, a pressure surge was observed during the first regulation cycle when there was propellant in the upstream propellant tank. This was attributed to a gas hammer effect within the pressurization system and was not observable in a 1g environment. This paper also discusses the conclusion that this gas hammer effect is a nominal feature of the system during operations. Assessment of the in-flight performance of the electronic pressure regulation scheme on the European Service Module propulsion system shows the system behaved nominally during the Artemis I mission.

1. Overview of the Orion European Service Module Propulsion Subsystem

The European Service Module (ESM) propulsion system is a pressure fed bipropellant system used to provide translational thrust and attitude control for the Orion spacecraft. A general overview of the system is shown in Fig. 1.

The system consists of two serially connected propellant tanks per commodity (MMH and MON-3) feeding three classes of engines. First the 26.7 kN thrust class Orbital Manuevering System engine (OMS-E) is the main engine and provides thrust for large delta-V maneuvers. Around the main engine there are 8 auxiliary engines each providing 490 N of thrust and primarily used duing the separation maneuver when Orion separates from the upper stage and for low delta-V trajectory correction burns. For attitude control, the ESM employs two strings of reaction control system (RCS) jets with each jet providing 220 N of steady state thrust at standard inlet conditions. In addition to attitude control, the RCS may be used for low delta-V translational maneuvers. The main engine and auxiliary engines typically operate around discrete setpoints which are different for the two different engine thrust classes. The RCS jets, in contrast, typically operate in propellant tank blowdown mode.

To control propellant tank pressure during a main engine or auxiliary engine burn, each commodity's propellant tank is pressurized from a high pressure composite overwrapped pressure vessel (COPV). Electronic pressure regulation is used to control pressure at the different setpoints. Electronic pressure regulation is implemented via a pressure

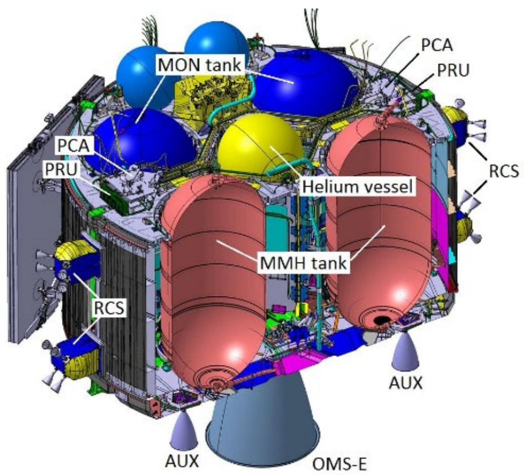


Figure 1: Overview of the ESM propulsion system [1]

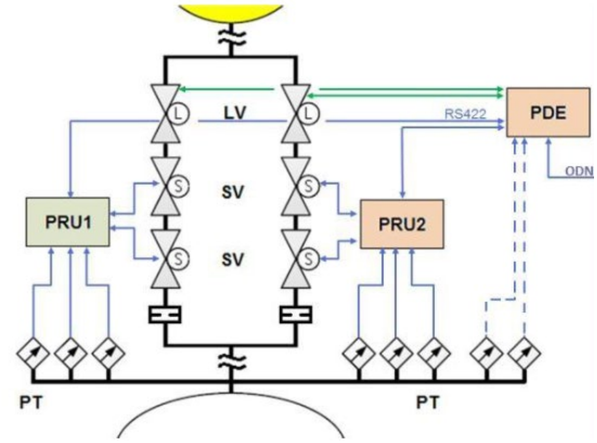


Figure 2: Layout of the Pressure Control Assembly [1]

control assembly (PCA) located between the COPV and upstream propellant tank. The PCA is schematically shown in Fig. 2. Each PCA consists of two branches which provide a redundant pressurization path if a failure occurs in one branch. Each branch is composed of three valves in series. Downstream of the COPV, there is a latching isolation valve (LV) which provides a means to isolate the high pressure COPVs from the propellant tanks. The latch valves are commanded open and closed by flight software through the propulsion drive electronics (PDE) box.

Downstream of each latch valve are two fast acting solenoid valves which open/close in response to tank pressure. The solenoid valves are controlled by the Pressure Regulation Unit (PRU) which was intended to read in ullage pressure, calculate a weighted average, and send an electrical stimulus to the open the solenoid valves if ullage pressure reached a lower regulation threshold while propellant is flowing out of the propellant tanks. With all three valves opened, flow would be initiated from the COPV to the propellant tanks causing the tank pressure to increase. When the PCA branch is flowing, the flow rate is controlled by an orifice downstream of the most downstream solenoid valve in each branch. Tank pressure increases as flow is occuring and when the upper regulation threshold is reached, the PRU would remove the electrical stimulus from the solenoid valves causing them to close. This process, known as bang-bang regulation, repeats itself during a burn if the pressurization function is enabled. This process is shown notionally in Fig 3.

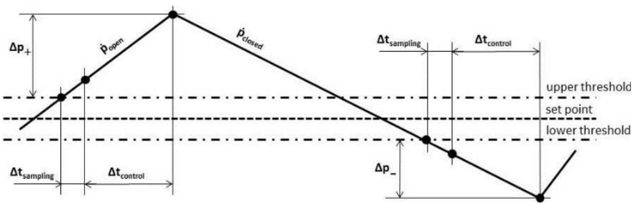


Figure 3: Bang-bang pressure control characteristic [1]

2. Design Evolution

The design pedigree of the ESM high pressure gas valves traces back to the Space Shuttle program where a similar valve design was used to provide isolation upstream of a mechanical regulator in the Shuttle OMS pod pressurization system. The key differences between the high pressure gas valves used on Orion and the valves used in the Shuttle OMS pod include:

1. The maximum design pressure on the ESM is 33% greater than the valves used on Shuttle OMS pod

2. On the ESM, the environments (for example, vibe, shock, and thermal) are different than the environments on the Space Shuttle

3. On the ESM, there are three valves (latch valve, solenoid valve, solenoid valve) in series vs the one latch valve in each branch of the Shuttle OMS pod

4. On the ESM, the valves operate in a bang-bang pressure regulation mode vs on the Shuttle OMS pod where they just provided isolation

These key differences led to valve design modifications that had to be qualified for use on the ESM. The last two items in particular led to challenges with respect to valve-to-valve pneumatic interactions that had to be overcome. An example of the pneumatic interactions are the highly transient pressure surges that occur when one valve opens relative to another which could result in a valve surging closed. The gas valves are pilot-operated valves that rely on internal pressure balancing to assist valve actuation. Transient pressure disturbances within a PCA branch may impact valve opening and closing. To address this pneumatic issue, a new mode of PCA regulation was employed where flight software calculated an average ullage pressure using all available measurements and sent commands to simultaneously open/close the two solenoid valves in the flowing branch depending on whether the averaged pressure was at the lower/upper regulation threshold. Additionally in the flowing branch, whenever the solenoid valves were open, flight software sent commands for the PDE to energize the latch valve. This is shown notionally in Fig. 4.

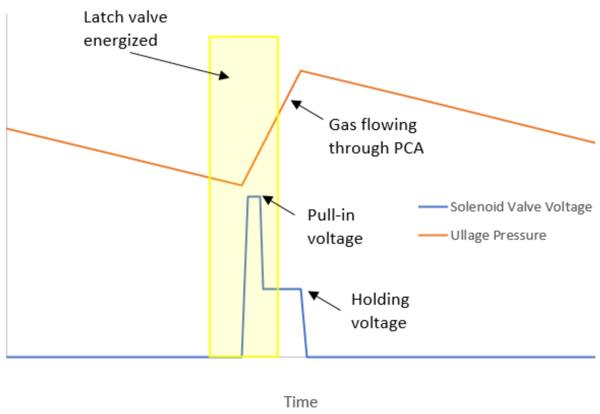


Figure 4: Notional view of PCA mode of operations where latch valve is energized during flow through the branch

3. Flight Observations

During the Artemis I mission, there were nineteen discrete translational maneuvers over the twenty-five day mission as shown in Table 1. These burns included the Upper Stage Separation burn (USS-1), six Outbound Trajectory Corrections (OTC), two Orbit Maintenance burns (OM), six Return Trajectory Correction burns (RTC), the Outbound Powered Flyby (OPF), the Distant Retrograde Orbit Insertion burn (DRI), the Distant Retrograde Orbit Departure (DRD) burn, and the Return Powered flyby (RPF) burn.

Table 1: Overview of the Artemis I Mission

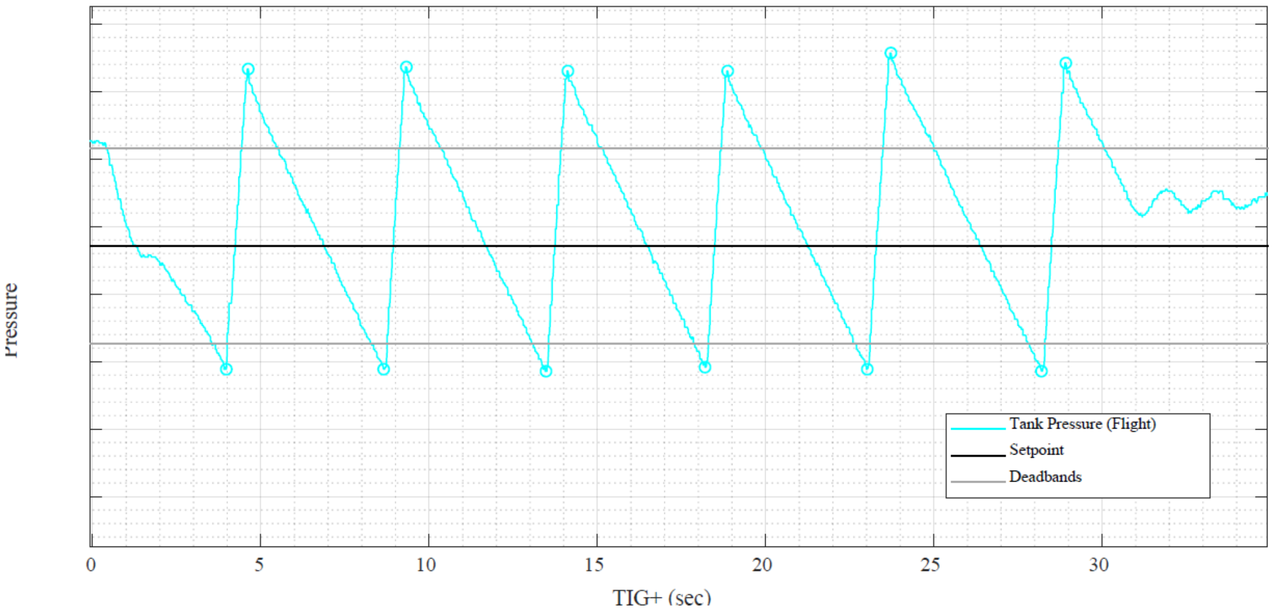
Event	Engine	GMT Day	GMT Time	Duration (sec)
USS-1*	Aux	320	08:46:44	10.5
OTC-1*	OMS	320	14:32:39	30.5
OTC-2	RCS	321	11:32:39	8.6
OTC-3	Aux	324	12:12:44	5.5
OTC-4	RCS	325	06:44:14	7.5
OPF*	OMS	325	12:44:14	149.6
OTC-5*	Aux	326	06:02:44	5.6
OTC-6*	Aux	328	21:52:28	15.2
DRI*	OMS	329	21:52:28	87.9
OM-1	RCS	330	21:52:28	1.23
OM-3	Aux	334	21:53:57	94.9
DRD*	OMS	335	21:53:57	105.1
RTC-1	RCS	336	03:53:56	4.8
RTC-2*	RCS	338	16:43:20	17
RTC-3	RCS	339	10:43:20	21.92
RPF*	OMS	339	16:43:20	207.1
RTC-4	RCS	340	10:43:20	5
RTC-5	Aux	344	20:20:14	7.2
RTC-6	RCS	345	12:20:14	8.4

Due to high propellant flow demand required for an OMS burn, regulation always occurred. For auxiliary engine and RCS burns, regulation is enabled but depending on the length of the burn may not occur if the burn is completed before ullage pressure reaches the lower regulation threshold. Burns in which regulation occurred are denoted with an asterisk (*) in the table.

In addition to the PCA operating during burns, other pressurization events occurred throughout the mission. The PCA was first used during launch ascent to prime the system by raising the propellant tank pressure from the initial ground fill level to flight pressure. To manage the setpoints leading up to a burn, occasionally a burn preparation activity was performed to raise the ullage pressure. Other PCA activities nominally included performing a helium flush of the system. In all cases, system pressures responded as expected. In total over the twenty-five day mission, there were 78 regulation cycles performed on MON branch 1, 9 regulation cycles performed on MON branch 2, and 99 regulation cycles performed on MMH branch 2.

Example results summarized below are from OTC-1. During the burn, 6 regulation events occurred on the MON-side PCA and 8 regulation occurred on the MMH-side PCA as shown in Figs. 5a and 6a. Clearly, ullage pressure overshoots beyond the upper regulation threshold are observed. This is not a concern and is expected. These overshoots are primarily attributed to software latency as a result of the PCA operating mode where flight software is controlling the regulation function. Once software detects that ullage pressure has reached the upper regulation threshold, there is a latency associated with processing that data, sending a command to stop regulation, and then the solenoid valves physically closing to stop the flow. During that latency period, before the solenoid valves physically close, ullage pressure continues to rise while flowing through the branch. Helium consumption during OTC-1 is shown in Figs 5b and 6b yielding consistent results with pre-flight consumption expectations.

(a)



(b)

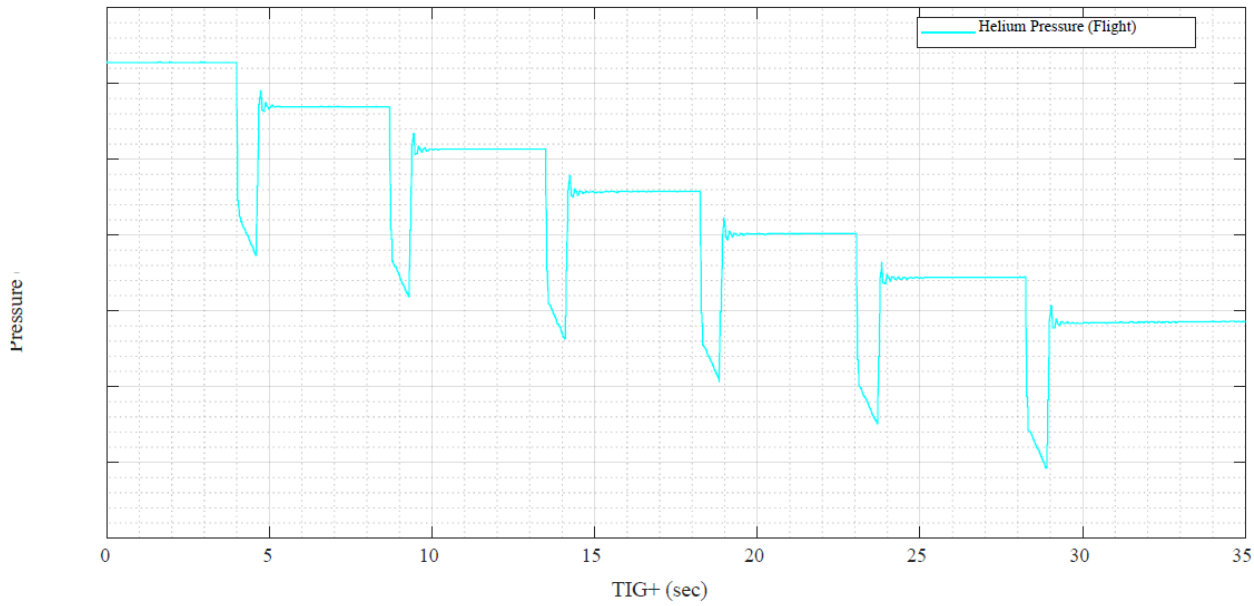
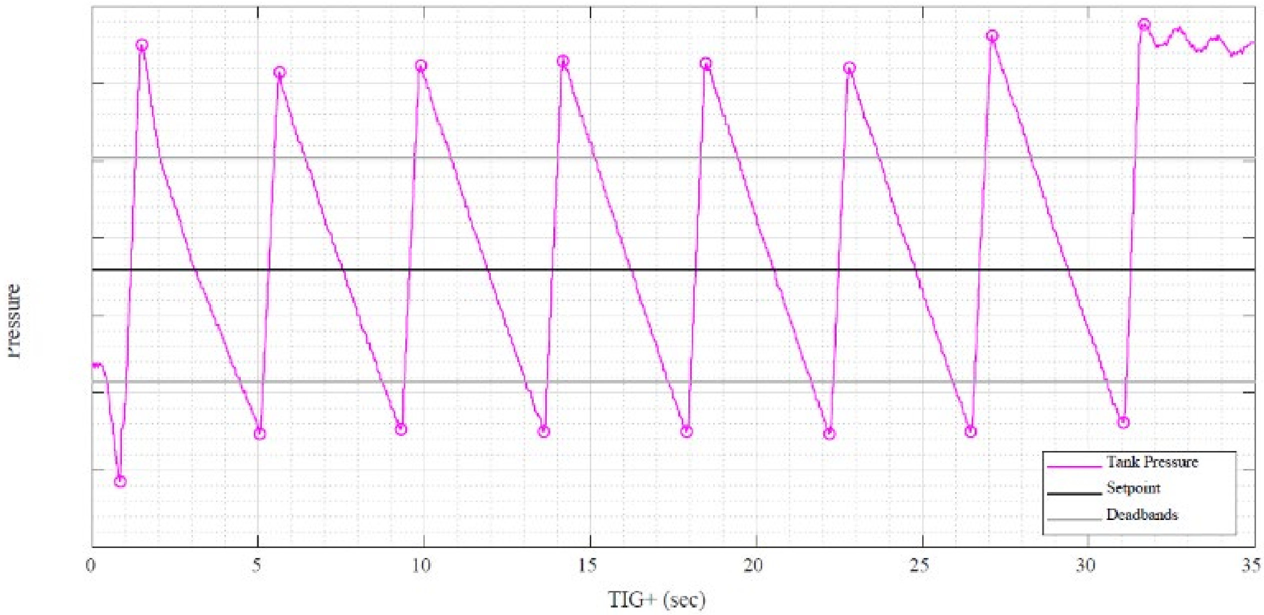


Figure 5: MON-side pressurization system performance during OTC-1 from Time of Ignition (TIG). (a) Ullage pressure. (b) Supply pressure.

(a)



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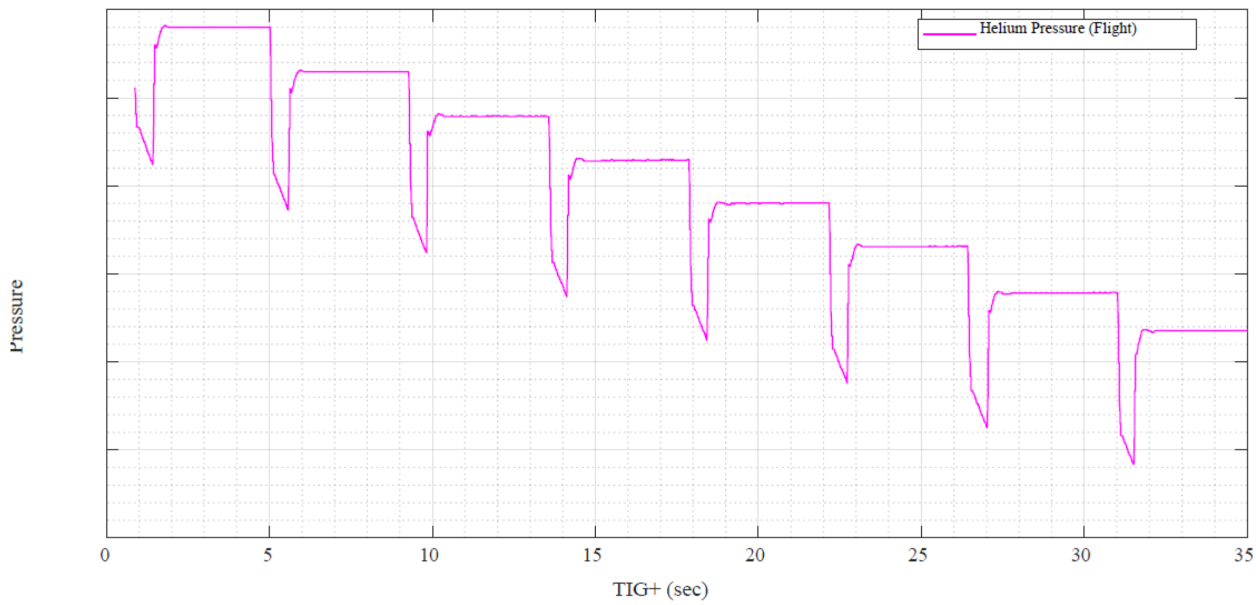


Figure 6: MMH-side pressurization system performance during OTC-1 from Time of Ignition (TIG). (a) Ullage pressure. (b) Supply pressure

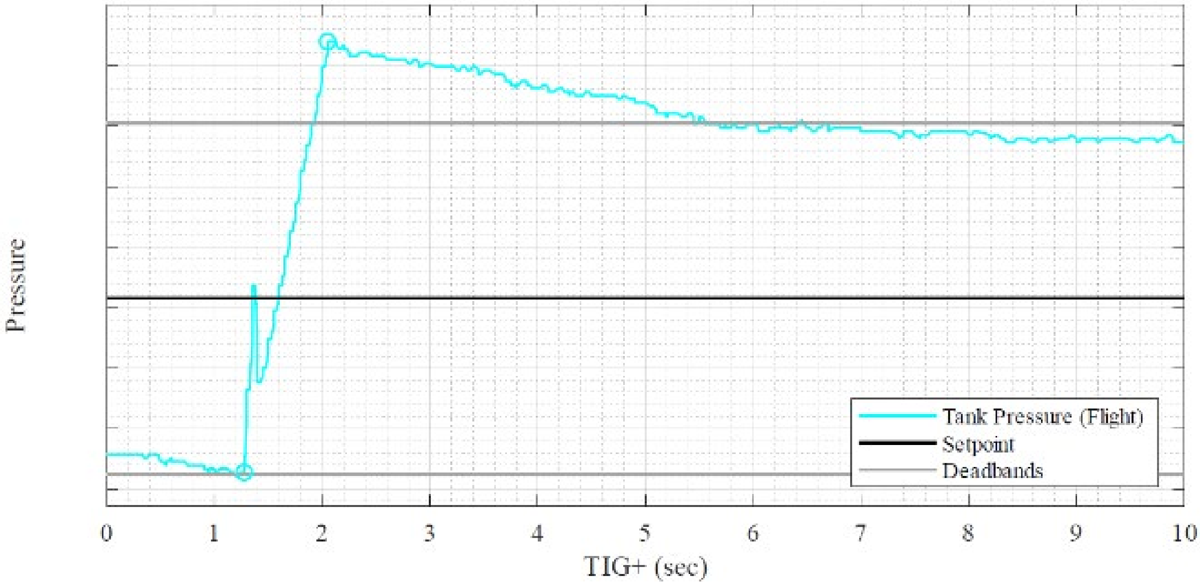


Figure 7: Pressure surge observed during MON-side initiation of regulation during OTC-5

Despite regulation performing nominally and pressure being controlled within the allowable regulation band, there were several observations during regulation initiation when a transient pressure surge was observed. This was generally observed when there was propellant present in the upstream propellant tank and most noticeable during OTC-5. As shown in Fig. 7, when regulation was first initiated, a pressure surge on the order of approximately 2% of initial pressure was observed at the start of the first regulation cycle.

The observation that this generally occurred with propellant in the upstream propellant tank provides a clue to the source of the surge. The upstream propellant tank has a liquid retention device (LRD) where the pressurization line enters the tank. As shown in Fig. 8, the vaned retention device relies on surface tension forces to prevent bulk liquid migration from the propellant tanks into the pressurization system. In a low-gravity environment prior to engine ignition, the vanes are wetted with propellant. Upon initiation of gas flow through the PCA, a gas hammer effect occurs – a pressure wave is reflected off of the liquid trapped in the LRD back to the upstream sense line containing the pressure transducers. Once the engines ignite and generate thrust, the induced acceleration settles the propellant in the tank. Because the vanes are no longer fully wetted under this settled environment, the pressure surge does not occur on subsequent regulation cycles.

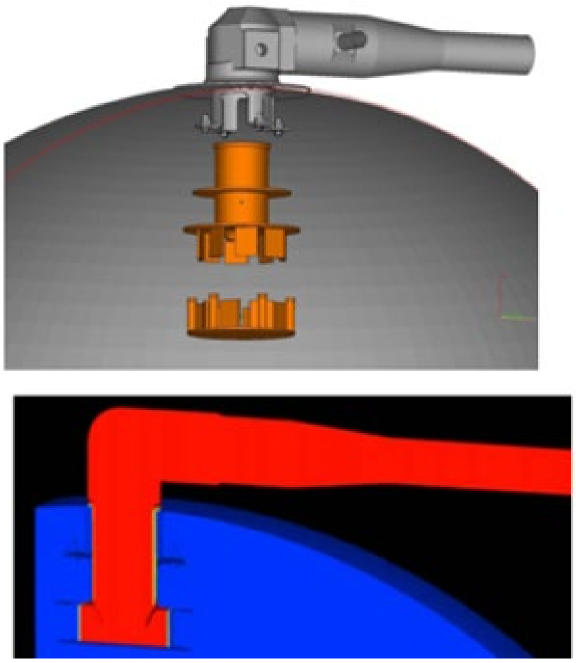


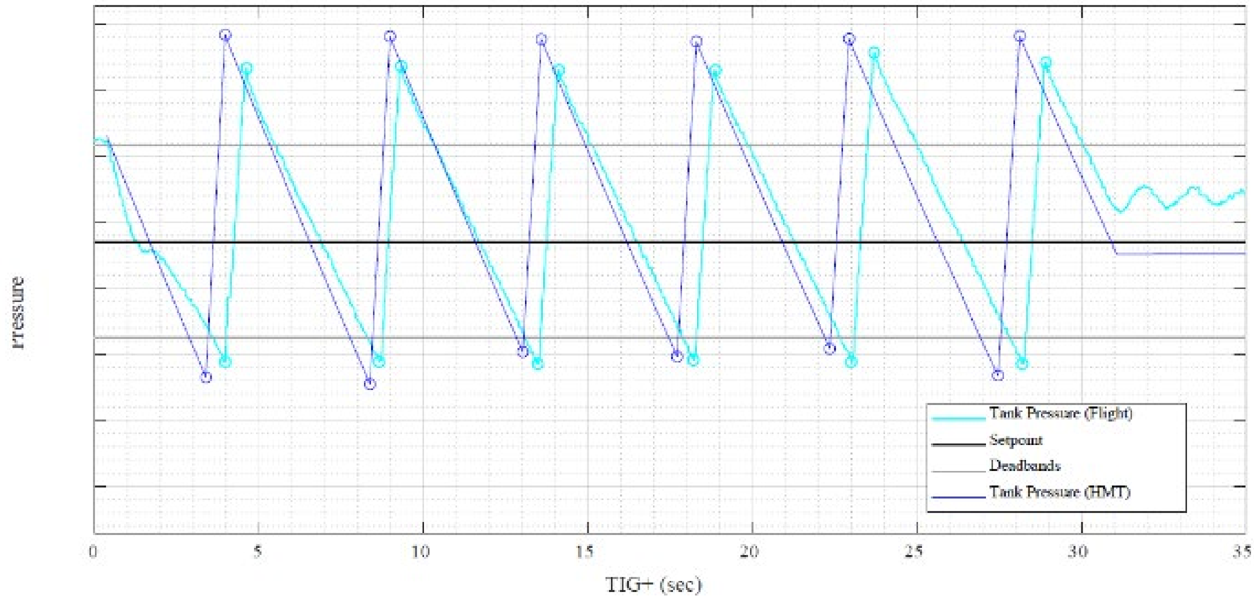
Figure 8: Graphic of LRD in upstream propellant tank (top). Analysis showing wetted (in blue) volume in upstream tank during low-g environments (bottom)

The LRD was designed to operate in a low gravity environment where surface tension forces are not overwhelmed by 1g buoyancy forces. Consequently, ground testing is not an effective environment to test LRD functionality and subsystem ground testing did not include such a device. Instead, analysis was performed which mimicked the response observed in flight which was subsequently evaluated to be a nominal response of the system.

4. Model Comparisons

A Heat and Mass Transfer model (HMT) of the propulsion system was used to analytically assess performance and compare to in-flight data. In general, the model compared well with the flight data generally predicting number of pressurization cycles within 1 cycle over the course of the entire mission. The pressure traces also match generally well with differences attributed to small differences in undershoot, overshoot, repress rate, and depress rate. The comparison is shown in Fig. 9 for OTC-1.

(a)



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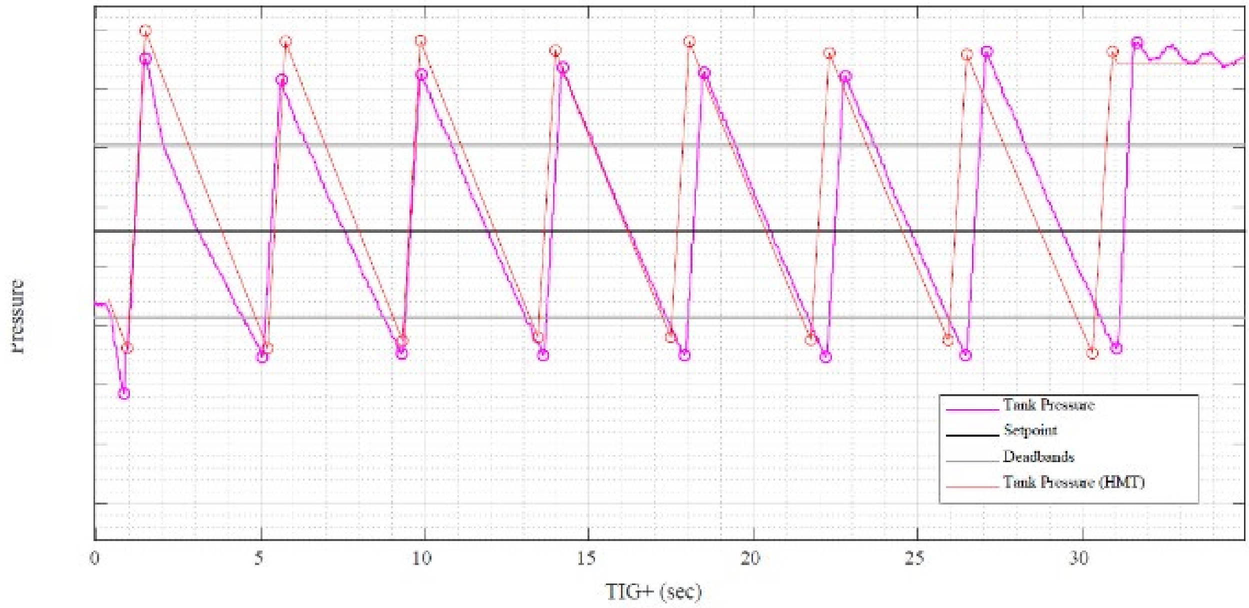

Figure 9: Model comparisons with in-flight pressurization data during OTC-1 burn. (a) MON-side. (b) MMH-side

5. Conclusion

The European Service Model propulsion system performed very well on Artemis I. The pressurization system, when regulation was enabled, was able to control ullage pressure within allowable tolerances. Analytical models predicted performance generally well including the initial surge during regulation initiation. Looking forward towards the first crewed Artemis II flight and beyond, modifications at the valve-level and PCA-level are being on-ramped to make the system more robust.

6. References

[1] J.H. Meiss, J. Weber, T. Kachler, F.D. Quinn, J. Paisley (2015), Electrical Pressurization Concept for the Orion MPCV European Service Module Propulsion System. *AIAA Space Conference & Exposition* (AIAA 2015-4636)

[2] D.B. Stephens, M.L. Belair, F.D. Quinn (2020) A Heat and Mass Transfer Model of the Orion European Service Module Propulsion Subsystem. *AIAA Propulsion and Energy 2020 Forum*.

7. List of Acronyms

AUX	Auxiliary Engine
COPV	Composite Overwrapped Pressure Vessel
DRI	Distant Retrograde Orbit Insertion
DRD	Distant Retrograde Orbit Departure
ESM	European Service Module
LV	Latch Valve
MMH	Monomethylhydrazine
MON-3	Mixed Oxides of Nitrogen
ODN	Orion Data Network
OM	Orbital Maintenance
OMS-E	Orbital Maneuvering System Engine
OPF	Outbound Powered Flyby
OTC	Outbound Trajectory Correction
PCA	Pressure Control Assembly
PDE	Propulsion Drive Electronics
PRU	Pressure Regulation Unit
PT	Pressure Transducer
RCS	Reaction Control System
RPF	Return Powered Flyby
RTC	Return Trajectory Correction
SV	Solenoid Valve
TIG	Time of Ignition
USS	Upper Stage Separation