Electrical Pressurization Concept for the Orion MPCV European Service Module Propulsion System

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The paper presents the design of the pressurization system of the European Service Module (ESM) of the Orion Multi-Purpose Crew Vehicle (MPCV). Being part of the propulsion subsystem, an electrical pressurization concept is implemented to condition propellants according to the engine needs via a bang-bang regulation system. Separate pressurization for the oxidizer and the fuel tank permits mixture ratio adjustments and prevents vapor mixing of the two hypergolic propellants during nominal operation. In case of loss of pressurization capability of a single side, the system can be converted into a common pressurization system. The regulation concept is based on evaluation of a set of tank pressure sensors and according activation of regulation valves, based on a single-failure tolerant weighting of three pressure signals. While regulation is performed on ESM level, commanding of regulation parameters as well as failure detection, isolation and recovery is performed from within the Crew Module, developed by Lockheed Martin Space System Company. The overall design and development maturity presented is post Preliminary Design Review (PDR) and reflects the current status of the MPCV ESM pressurization system.

Nomenclature

AUX	Auxiliary thrusters
CM	Crew Module
CMA	Crem Module Adapter
EPR	Electrical pressure regulation
ESA	European Space Agency
ESM	European Service Modue
FDIR	Failure detection, isolation and recovery
iCPS	interim Cryogenic Propulsion Stage
LAS	Launch Abort System
LOI	Lunar orbit insertion
LV	Latch Valve
MMH	Mono-methyl hydrazine
MON	Mixed oxides of nitrogen (tetroxides)

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$MPCV$	Multi-Purpose Crew Vehicle
ODN	Orion Data Network
$OMS-E$	Orbital maneuvering system engine
PCA	Pressure control assembly
PDE	Propulsion drive electronics
PDR	Preliminary Design Review
PDU	Power Distribution Unit
PRU	Pressure regulation unit
PT	Pressure transducer
RCS	Reaction control system
SA	Spacecraft Adapter
SAJ	Spacecraft Adaptern Jettisoned Fairings
SLS	Space Launch System
SM	Service Module
SV	Solenoid Valve
TEI	Trans-earth injection

I. Introduction

The Orion Multi-Purpose Crew Vehicle (MPCV) is the next generation spacecraft that NASA currently developing to send humans and cargo into low earth orbit and beyond and return them back to earth safely. The vehicle, which will be launched by the new Space Launch System (SLS), is designed to support long-duration deep space missions. The first exploration mission is planned to take place at the end of 2017 as an uncrewed lunar flyby mission followed by a second exploration mission at the end of 2021 taking astronauts to the moon. The second stage of the SLS, the interim Cryogenic Propulsion Stage (iCPS), will insert Orion into a lunar trajectory. Orion will use its main engine to place itself into lunar orbit. Orion must maintain attitude control during lunar operations, perform the trans-Earth injection maneuver to return from the Moon, and perform entry, descent and landing.

The MPCV itself resembles its Apollo predecessors and will consists of the Launch Abort System (LAS), the habitable Crew Module (CM) and the disposable Service Module (SM). The bulk of what makes up the SM is referred to as the European Service Module (ESM), which provides power, life support, and in-space propulsion. The SM also includes the Crew Module Adapter (CMA), the Spacecraft Adapter Jettisoned Fairings (SAJ), and the Spacecraft Adapter (SA) as shown in Figure 1.

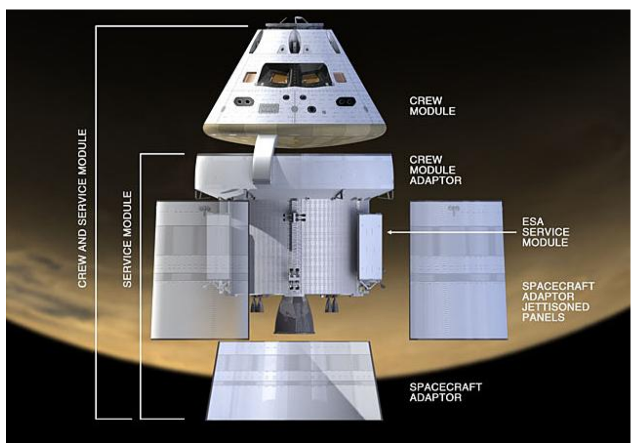

Figure 1. MPCV Vehicle Elements (Courtesy NASA)

The MPCVs technology is more advanced and with its capability to support up to four crew members for spaceflight missions, it is larger than Apollos Modules. While Lockheed Martin Space Systems represents NASAs MPCV Orion US industrial prime contractor, the European Service Module is developed in partnership with ESA and its industrial partner Airbus DS GmbH, who is responsible for the design and development. An overview description of the European contribution has been provided by Berthe et al.[1] In this paper the electrical pressurization system of the ESM propulsion subsystem, which is developed by Airbus DS GmbH in Bremen, Germany, is presented. After a short description of the overall propulsion subsystem the layout and the functional design of the pressurization system is presented in more detail. Furthermore, a description of the operational logic and implementation of a cross feed function is provided. The paper closes with a short summary and conclusions about the current design.

II. ESM Propulsion System

The ESM propulsion system is designed to provide thrust after separation from the upper stage of the SLS to adjust and change the flight trajectory during nominal mission operations. In addition, the ESM shall be capable to transfer the crew module into a safe earth orbit after certain launcher failures. The propulsion system as part of the ESM given in Figure 2 comprises three different types of engines / thrusters to fulfill its tasks.

- A single main engine (OMS-E), which is a re-use of one of the Space Shuttle's orbital maneuvering system (OMS) engines, with a thrust level of 26.7 kN. The engine is used for ascent abort maneuvers and orbit change maneuvers, e.g. for lunar orbit insertion (LOI) or trans-earth injection (TEI).
- Eight (8) auxiliary (AUX) thrusters, similar to those used on the European ATV, with a thrust level of each 490 N. The thrusters are used for ascent abort maneuvers, launcher separation, trajectory correction maneuvers, and in addition serve as back-up for the main engine.
- Twenty-four (24) reaction control system (RCS) thrusters, which correspond to the ones used on ATV, with a thrust level of each 220 N. The thrusters, which are accommodated in six pods with each four thrusters, are used for translation and attitude control maneuvers

Each of these thrusters utilises MON-3 as oxidizer and MMH as fuel at the same nominal mixture ratio of 1.65. The propellants are stored in two serial connected tanks per type. The downstream tubing towards the engine / thrusters comprises several electro-mechanical valves to ensures isolation of the engine / thrusters from the propellant tanks during launch, docked phase to the ISS and other mission events where isolation becomes necessary. For each propellant type, the separated pressurization system upstream of the propellant tanks mainly consist of a high pressure Helium vessels, a pressure control assembly (PCA) housing electro-mechanical isolation and regulation valves and pressure transducers, and two shared pressure regulation units (PRU), which perform the electrical bang-bang regulation, which is described in more detail in the following course of this paper. The pressure-fed propulsion system is controlled by the Propulsion Drive Electronics (PDE) which handles all nominal propulsion related commands issued by the CM's Vehicle Management Computer and provides feedback via the CMA Power Distribution Units (PDUs).

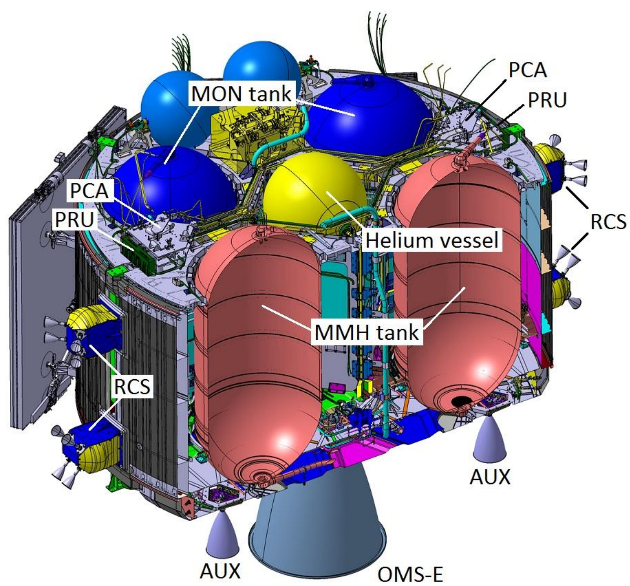

Figure 2. MPCV-ESM Propulsion subsystem

III. Pressurization System Design

To pressurize the propulsion subsystem, an electrical pressurization concept is used on the man-rated spacecraft. Separate pressurization for the oxidizer and the fuel tank permits mixture ratio adjustments and prevents vapor mixing of the two hypergolic propellants. The pressurization function dispenses helium from a 400 bar vessel to replace propellant in the propellant tanks. The pressure in the propellant tanks is adaptable and conditioned according to the engine needs via a bang-bang regulation concept, which opens and closes high pressure solenoid valves depending on the propellant tank pressure. A similar approach has also been suggested and investigated in the past by Lockheed Martin Space Systems.

In the following subsections a detailed description of the layout of the pressurization system, the underlaying regulation concept, and the tank pressure evaluation used to trigger valve activation is given.

III.A. Layout

To realize the regulation concept, the pressurization system mainly consists of a series of bi-stable high pressure gas latch valves (LV), mono-stable high pressure solenoid valves (SV) that are commanded by dedicated pressure regulation units (PRU), and pressure transducers that measure the propellant tank pressure, Figure 3. To limit the Helium mass flow at begin of a mission, when the pressure in the Helium vessels is still high, flow limiting orifices are implemented downstream of the regulation valves. For activation and deactivation of the mono-stable regulation valves, the pressure regulation unit acquires three tank pressure values, calculates a weighted average, compares it to a set point, and commands the solenoid valves accordingly.

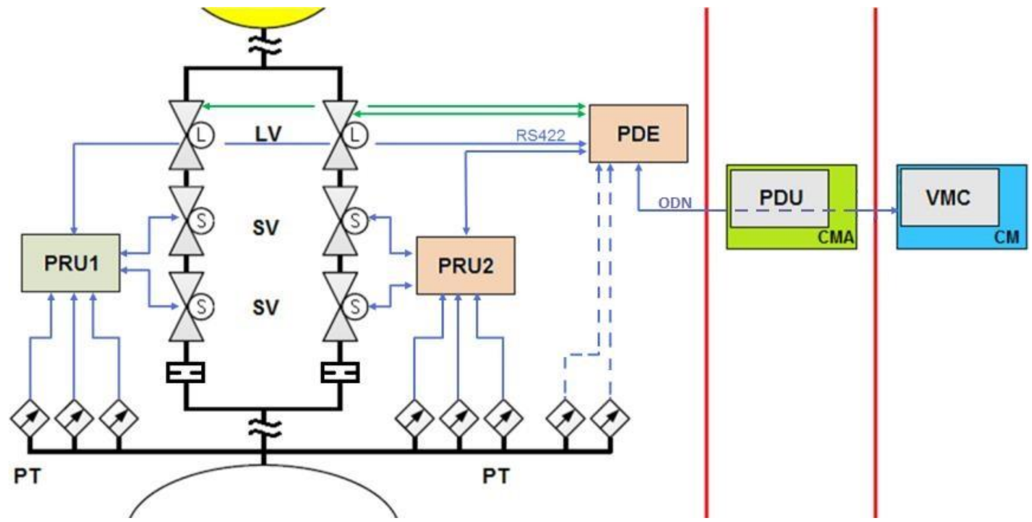

Figure 3. MPCV-ESM Propulsion subsystem

The bi-stable high pressure gas latch valves serve as a system required third barrier between the Helium vessel and the propellant tank to be two fault tolerant against propellant tank over-pressurization. During pressurization phases, these valves remain open and are not involved in the active regulation loop. Thus they are directly commanded by the vehicle management computer (VMC) located in the crew module via the power distribution units (PDU) on CMA level and propulsion drive electronics (PDE) on ESM level.

Two mono-stable solenoid valves are implemented in series, which are commanded by the PRU in hot redundancy, such that a failed open valve will have no effect on the propellant tank pressure. To identify this failure mode, which cannot be monitored via the propellant tank pressure, each solenoid valve is equipped with a position indicator in the open position.

To be single fault tolerant against loss of pressurization, two parallel branches are implemented. During active regulation phases, only one branch per propellant side is used for pressurization. In case of loss of pressurization, which is detected by a decreasing tank pressure, automatic switching-over to the redundant branch is performed within less than one second.

For pressure monitoring and evaluation, eight propellant tank passive pressure transducers are attached to each propellant side. Three pressure transducers are attached to each of the two PRUs, which perform regulation of the nominal, and the redundant branch, respectively, based on a weighted average of three pressure data inputs. Two additional pressure sensors are connected with the PDE directly to allow pressure monitoring during long cruise phases, when the pressure regulation is shut down and as such the pressure sensors attached to the PRUs are not active.

The overall design concept of one pressure regulation unit is presented in Figure 4. Each PRU consists of four identical FPGA-based regulators, two for the serial solenoid valves of one MON branch and two regulators for the serial solenoid valves of one MMH branch. Each regulator is connected to a dedicated high pressure solenoid valve and receives commands from the VMC via the PDE and provides data to the VMC for monitoring using the same data link. Moreover, both PRUs house separate power supply for three pressure transducers per propellant side and for the two regulators of one branch, which allows individual powering and commanding of each pressurization branch. Once a PRU is powered on, each regulator can be put into an active mode, which gives the full functionality of pressure data acquisition and evaluation, valve

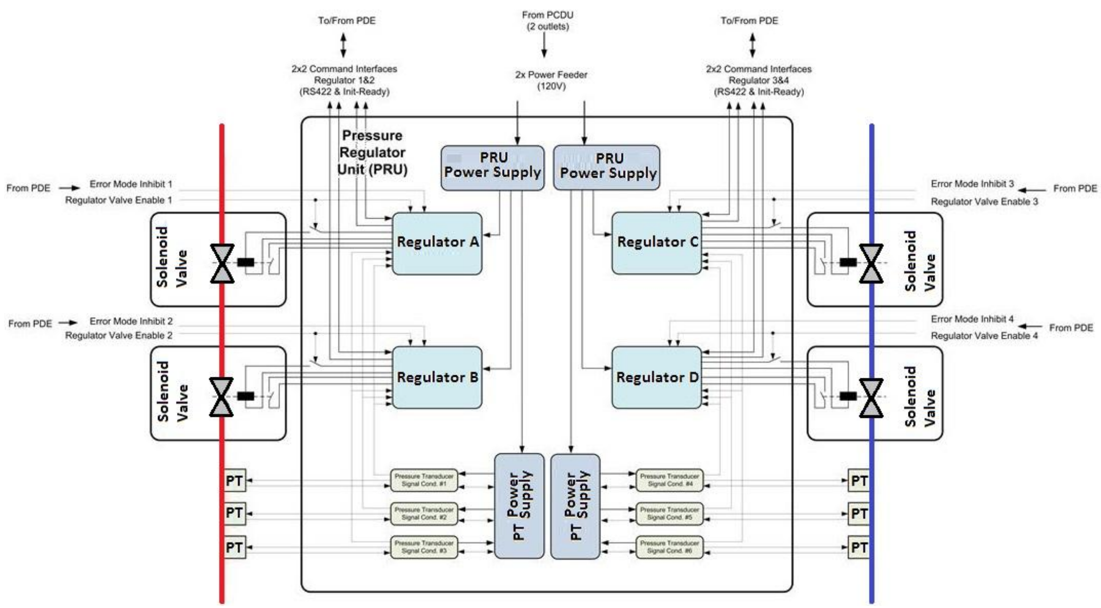

Figure 4. PRU overall design and interface concept

switching and data exchange with the VMC. A second mode, stand-by, gives all the functionality of an active mode, but automatic valve switching is inhibited. During nominal pressurization phases of a mission, the PRU channels controlling the active branch are in active mode, while the regulator channels of the redundant branch are put into stand-by mode.

With its given design, the EPR allows to pressurize the MON and MMH propellant tanks independently to different pressure levels. The different pressure levels allow compensation of different initial pressure drops in the propellant network, compensation of different pressure drop evolutions due to draining of the upper propellant tanks and the serial lines (connection between upper and lower propellant tanks) and an adaptation of the mixture ratio for performance improvement.

III.B. Bang-Bang Characteristics

Using a bang-bang regulation concept, valves do not control pressure continuously like common mechanical pressure regulators. Instead, regulating valves behave approximately digital by either being fully open or fully closed (neglecting the opening and closing time). To control pressure in a pressure-fed system, mainly three values are needed.

1. The current pressure in the propellant tank to be controlled,
2. a target pressure, i.e., a set point, and
3. a regulation bandwidth, which defines an upper and a lower threshold, at which the command to open/close the valve is triggered.

When a control valve is open during a propulsive phase, pressure in the propellant tanks increases approximately linearly by $\dot{p}_{open}$, Figure 5. When the pressure is detected to be beyond the upper threshold, a control command is processed and the valves are commanded closed such that the pressure in the tank decreases approximately linearly by $\dot{p}_{closed}$ due to continuous propellant consumption. When the pressure is detected to be below the lower threshold, a second control command is processed and the valves are commanded open and the cycle starts again.

Due to this behavior, the maximum pressure bandwidth within the propellant tank during controlling is composed of the delta pressure between the upper and lower threshold plus the pressure deviations due to positive overshoot ($\Delta p+$) and negative overshoot ($\Delta p-$).

While the thresholds are adjustable boundary conditions, the positive and negative overshot are a result of the regulation concept used, namely the sampling rate, which defines the maximum time after which

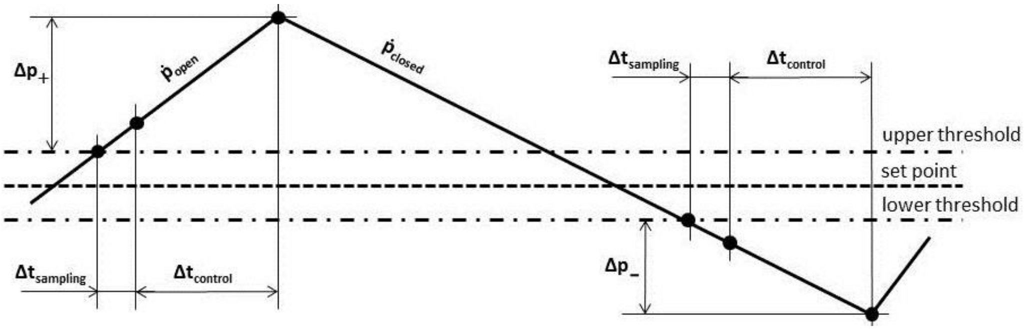

Figure 5. Schematic of bang-bang regulator characteristic in terms of propellant tank pressure

crossing thresholds is detected ($\Delta t_{sampling}$) plus the control loop time ($\Delta t_{control}$), which defines the time between detection of threshold crossing and fully opening/closing of the valves.

III.C. Tank Pressure Evaluation

The electrical pressure regulation controls the pressure of the propellant tank in dependence of measured pressure values at the tank inlet. Three independent pressure signals are used to determine a single weighted average pressure value, which is used for regulation. The pressure of three pressure transducers are evaluated with weights on each single measurement proportional to quadratic distance between remaining measurements according Equation 1.

$$p_{avg} = \frac{p_1(p_2 - p_3)^2 + p_2(p_1 - p_3)^2 + p_3(p_1 - p_2)^2}{(p_2 - p_3)^2 + (p_1 - p_3)^2 + (p_1 - p_2)^2} \quad (1)$$

The function displays a weighted average that reduces the influence of outlier readings due to drifting, failed, or otherwise malfunctioning transducers. The weighting formula possesses a pole at $p_1 = p_2 = p_3$. In this case, the PRU channel sets the average pressure value to the value of p_1.

The effect of the weighting function on a single pressure transducer (PT) failure in terms of drifting is depicted in Figure 6.

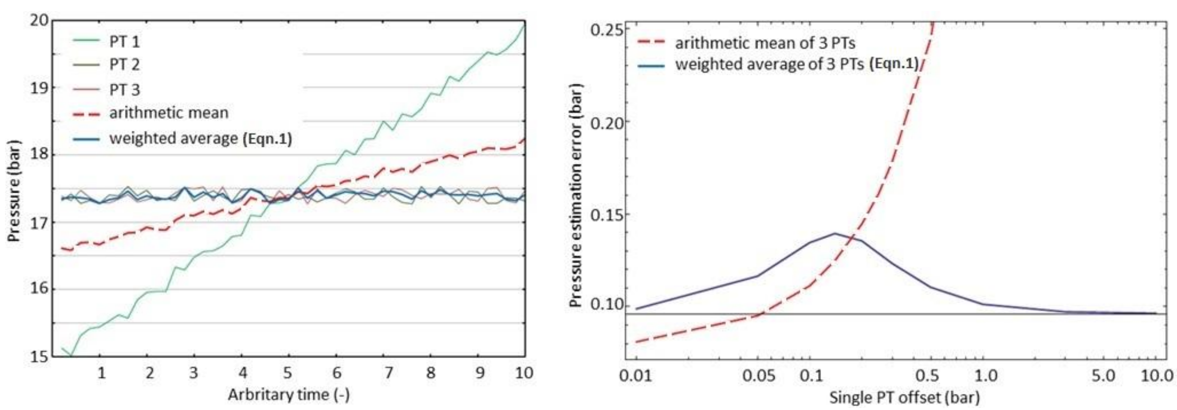

Figure 6. Behavior of weighted pressure value with one of three pressure values drifting

While an arithmetic mean of all three pressure signals follows a PT drift with a factor of one third, the presented weighted pressure filters the offset of a single PT over the whole range. An increased pressure measurement uncertainty is limited to a small bandwidth of a systematic single PT offset. With the given overall characteristic, the weighting function can be regarded a two out of three voting function, which neglects the influence of a single pressure transducer that differs significantly from the remaining two pressure transducer values.

III.D. Tank Pressure Regulation

The parameters for regulation are - beside the pressure signal - the set point and the regulation bandwidth, which are commanded by the VMC. The set point defines the demanded tank pressure value and the regulation bandwidth defines the upper and lower threshold. At a pressure value of the set point plus half the regulation bandwidth, i.e., at the upper threshold, the valve is commanded close. At a pressure value of the set point minus half the bandwidth, i.e., at the lower threshold, the valve is commanded open. The nominal set point in the propellant tank is set to obtain the nominal pressure of the OMS-E engine at its inlet taking into account all pressure losses between propellant tank and engine inlet.

The regulation bandwidth depends on (1) the maximum allowable MON to MMH pressure deviation, (2) the pressure measurement inaccuracy and (3) the overshoots due to latency, Figure 7. The regulation bandwidth is determined as the allowable MON to MMH pressure deviation minus two times the measurement accuracy minus the positive and the negative overshoot.

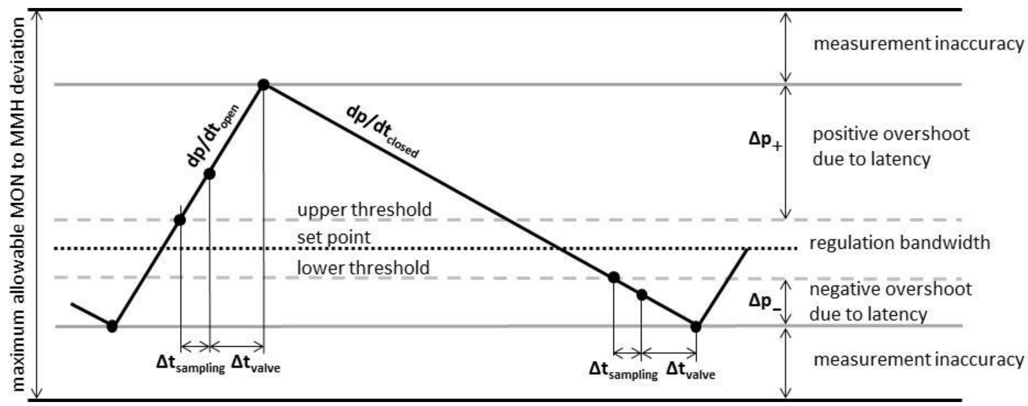

Figure 7. Contributions to the bang-bang regulator characteristic

The positive overshoot, i.e., the pressure increase after the pressure reaches the upper threshold, depends on the latency time of the pressure acquisition/evaluation, the valve closing time and on the positive pressure gradient.

The negative overshoot, i.e., the pressure decrease after the pressure reaches the lower threshold, depends on the latency time of the pressure acquisition/evaluation, the valve opening time and on the negative pressure gradient.

The pressure gradient varies over the mission as it depends on the Helium mass flow (for positive gradient only), the propellant expulsion rate and the ullage volume. While the propellant expulsion rate and the consequent increase of ullage volume is defined by the thruster and OMS-E needs, the Helium mass flow rate is defined by the size of the flow limiting orifice. It controls the helium mass flow when the solenoid valves are in the open position. A single orifice is used to limit the initial mass flow, while concurrently allowing sufficient mass flow at the end of mission, when pressure and temperature in the helium tank is minimal. Assuming choked flow conditions with the orifice representing the critical cross sectional area of the PCA, the mass flow rate is given as function of the orifice's cross sectional area A according to Equation 2.

$$\frac{\partial m}{\partial t} = CA\sqrt{\gamma \rho_0 p_0 \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{2}$$

Within the given design and boundary conditions, i.e., a pressure in the Helium vessel of approximately 400 bar at ambient temperature conditions the maximum Helium mass flow rate at begin of a mission is in the order of 120 g/s, and at end of the mission the mass flow decreases to approximately 20 g/s.

Due to the separate pressurization system for oxidizer and fuel, the pressure deviation between both propellant component tanks has to be limited in order to ensure a certain mixture ratio. With a bang-bang regulation concept, the maximum pressure deviation presents the maximum instantaneous pressure deviation rather than the effective/integral pressure deviation, Figure 8. The regulated pressure is controlled by the PRU based on the set point provided by VMC to each propellant side. This pressure corresponds to the effective tank pressure. The maximum possible effective pressure deviation of the two tanks corresponds to two times the pressure measurement accuracy.

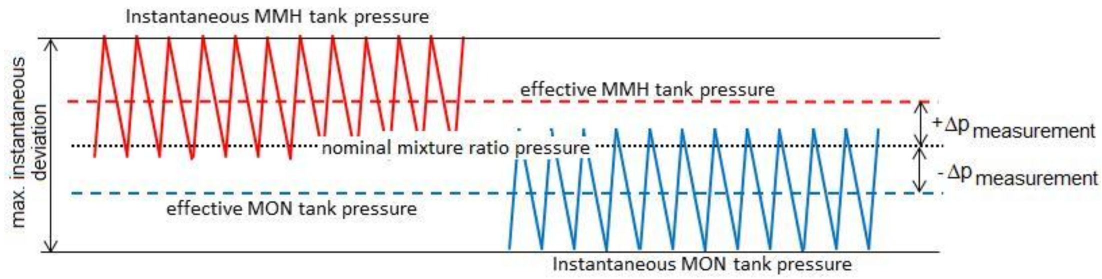

Figure 8. Schematic of tank pressure deviation due to bang-bang regulation

IV. Operational Design

In this chapter, the operational design of the EPR is presented, i.e., the operational logic for pressure conditioning prior and during a regulated boost phase is described. To receive an optimal fuel to oxidizer mixture ratio of 1.65, both propellant sides require approximately the same pressure values inside the propellant tanks.

IV.A. Mode of Operation

With electrical pressure regulation only needed during boost phases, where significant amounts of propellants are expulsed from the tanks, three basic modes of operation are defined.

- A cruise mode, where no thruster / engine firing is performed and during which pressure regulation is powered-off
- A re-pressurization mode, during which the propellant tanks are conditioned after a long duration cruise phase prior an active boost phase
- An active pressurization mode, during which pressure regulation is fully active with thruster / engine firing.

Cruise Mode

During cruise mode the PRUs and thus regulation and data exchange between PRU and VMC is deactivated. Pressure monitoring is performed via the remaining two propellant tank pressure sensors per propellant side that are directly connected to the PDE. In case of deviation of the two sensors, a PRU will be switched on to receive additional pressure sensor readings, which allow to identify the failing sensor. Necessary attitude control maneuvers performed by any combination of RCS thrusters can be performed in blow down mode due to limited propellant expulsion rates and thus limited tank pressure drops.

Different thermal behavior of MON and MMH lead to different pressure evolution in the propellant tanks during passive cruise phases with a higher increase of the MON pressure than the MMH pressure. This might lead to a violation of the operational domain of the main engine, such that prior each boost phase, a reconditioning of the propellant tank pressure will be performed.

Re-pressurization Mode

Pressure variations of the propellant tank due to thermal excursions during mission cruise phases require an adaptation of the regulation set point prior to a boost to bring the pressure ratio of MON and MMH back into the operational domain of the OMS-E engine, i.e., the pressure in the MON tank and the MMH tank need to be equalized. Since the EPR is only able to increase pressure by valve activation, but does not allow an active pressure release of one propellant side, both propellant tanks will be pressurized to the higher of both propellant pressures prior to a pressure regulated boost phase. After re-pressurization, the set point is set back to the nominal value. Thresholds are not being changed. The according logic is given in Figure 9.

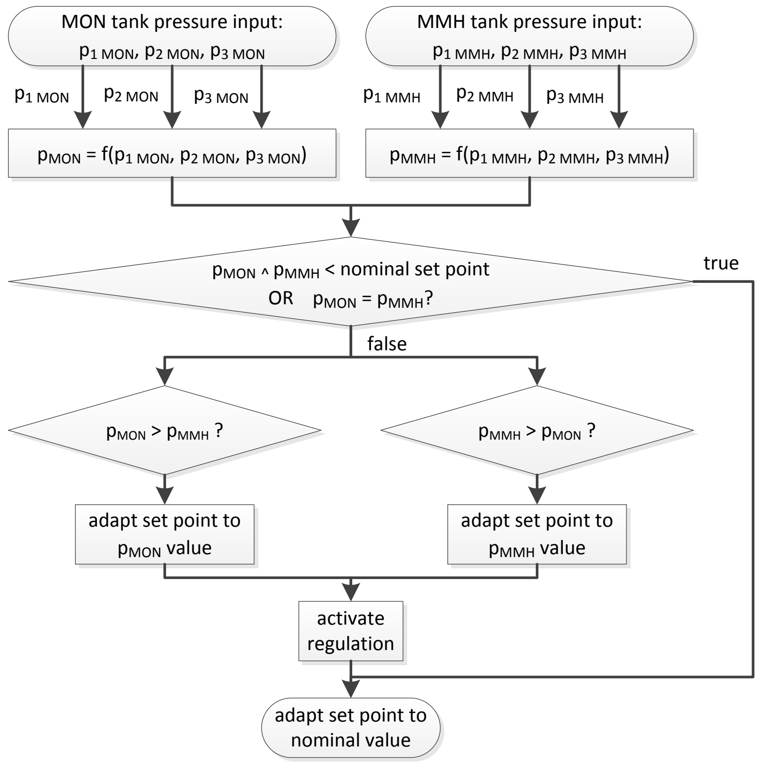

Figure 9. Re-pressurization logic performed prior a boost phase

After activation of the PRU, the pressure values for both propellants are evaluated and compared. If one value is larger than the other, the regulation set point for all regulator channels is set to the higher set point and regulation is activated. Consequently, only the solenoid valves of the tank with the lower tank pressure open, such that the established Helium mass flow increases the tank pressure. Upon reaching the upper threshold the solenoid valves close again with the pressures in both propellant tanks being on an equal level. Afterwards, the set point will be set to the nominal engine / thruster set point after which the boost phase can be initiated. If the nominal set point is below the current pressure level, thrusters / engine will operate in a blow down mode until the nominal pressure level is reached and active regulation sets in.

Active Pressurization Mode

For pressurization of a propellant tank during active boost phases, the solenoid valves of the PCA are commanded open/close by the PRU by evaluating tank pressure values and comparing them with an upper and lower threshold of a VMC commanded set point and regulation bandwidth. Besides providing set point and threshold prior to a regulation phase, VMC is not actively involved in the nominal pressurization process. Although possible, the baseline logic of set point and thresholds management is to not change their values during active pressure regulation. The corresponding nominal pressurization logic, which is carried out by each active PRU regulation channel, is given in Figure 10. If the pressure level in the tanks is above the lower threshold, i.e. set point minus half the regulation bandwidth, the valves remain closed until the pressure reaches this lower threshold. Consequently, each bost starts with a limited blow down phase, the duration of which mainly depends on the initial tank pressure level.

The overall concept including hot redundant serial valve activation based on the given pressure weighting function has already been successfully tested during development tests performed by Airbus DS at a Lampoldshausen test facility. Corresponding publication is planned in the near future.

IV.B. Fault Detection, Isolation, and Recovery (FDIR)

In order to maintain operation of active engine / thrusters, the propellant tank pressure is monitored and switching to the redundant pressurization branch will be performed before the pressure exceeds the oper-

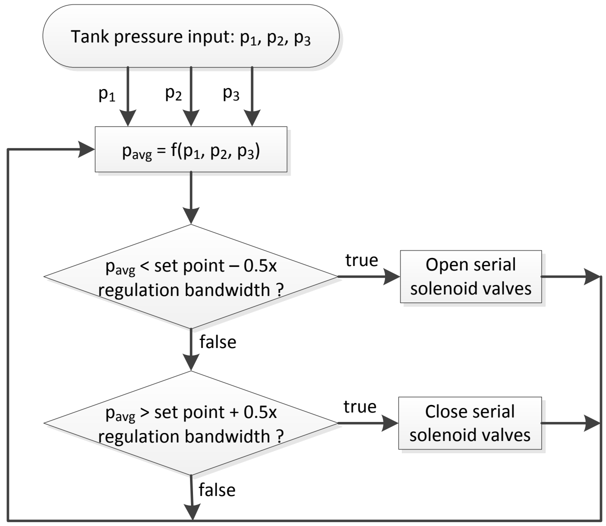

Figure 10. Pressurization logic during a boost phase

ational domain of the active engine during regulated boost phases. Due to the arrangement of two hot redundant solenoid valves in series, a single failure cannot lead to an over-pressurization of the propellant tank, but only to an underpressurization in case any active solenoid valve does not open. To be able to control the pressurization system and to be able to perform manual recovery in case of excess of the required failure tolerances, FDIR and safe limits are defined for PSS safing. All FDIR task will be performed and commanded centrally by the vehicle management computer (VMC) inside the crew module.

Prior each actively regulated boost phase, the pressure of the propellant tank will be repressurized to at least the nominal set point. After initiation of a maneuver the regulation bandwidth allows a nominal pressure variation within +/-0.3 bar around the set point.

Lower FDIR limit (under-pressurization)

The lower FDIR limit in terms of tank pressure is set closely below the lower limits of the regulation domain, i.e. slightly below the lower regulation threshold including a defined margin. Consequently, if the propellant pressure decreases below this lower FDIR limit during a boost phase, an FDIR process within VMC is triggered to switch to the redundant branch (e.g., in case of a failed close solenoid valve) by isolating the first branch and activating the redundant branch thereafter. In case of a further failure, which leads to a pressure decrease or remaining pressure below the lower FDIR limit when already using the redundant branch, loss of pressurization capability is assumed and the VMC puts the propulsion system into a safe state with all thrusters shut down, the latch valves and solenoid valves of the PCA closed and the PRUs in stand-by mode for continuous data monitoring. Manual recovery with malfunction procedure is then to be performed by Ground.

Upper FDIR limit (over-pressurization)

After initiation of a maneuver and after initial blow down phase the regulation bandwidth allows a nominal pressure variation within +/-0.3 bar around the set point. After each initial blow down phase at the beginning of a boost the upper FDIR limit is set closely above the upper limit of the regulation domain, i.e. above the upper regulation threshold including a defined margin. Consequently, if the propellant pressure increases above this upper FDIR limit during a boost phase, the FDIR process within VMC is triggered to switch to the redundant branch by isolating the first branch and activating the redundant branch thereafter. Note, however, with two hot redundantly operating serial solenoid valves, the system is two fault tolerant against over-pressurization, e.g. over-pressurization can occur only after both serial solenoid valves fail to close.

V. Common Pressurization Mode

In case of a failing pressurization function of one propellant side, e.g. caused by blockage of a PCA or external Helium leakage, a Helium cross feeding system is implemented in addition to the nominal pressurization system to bypass the nominal PCA of the failing propellant side in order to improve survivability of the crew. In the following sections, the common pressurization mode as part of the electrical pressure regulation system of the Orion MPCV European Service Module, is shortly described. A more extensive description of the system currently under development is planned for future publication.

V.A. Layout Design

The common pressurization system, also referred to as He X-feed, consists of three interlinking lines between the two propellant sides within the pressurization system, Figure 11.

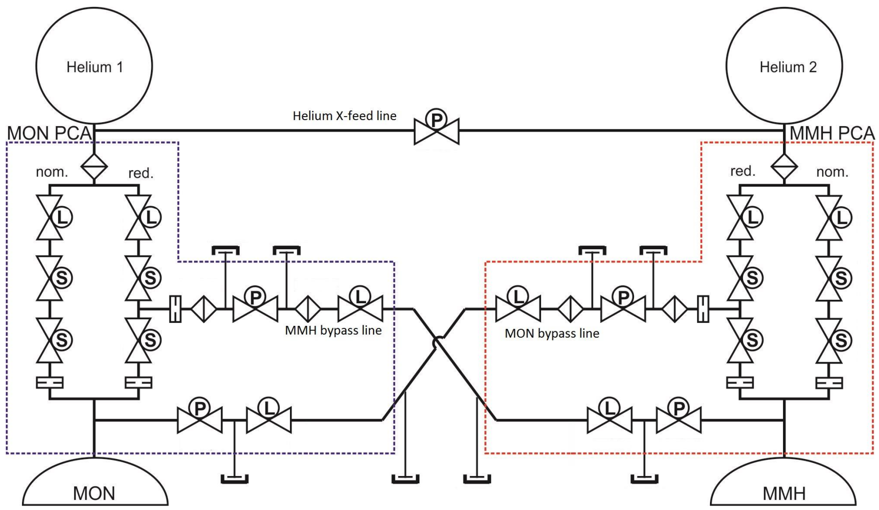

Figure 11. Schematic of He X-feed implementation

- A Helium cross feed line connecting the two Helium vessels upstream of the two PCAs
- An MMH bypass line running from between the two solenoid valves of the redundant MON PCA branch to the MMH PCA, where it connects to the nominal PCA downstream of the junction of the nominal and the redundant regulation branch
- A MON bypass line running from between the two solenoid valves of the redundant MMH PCA branch to the MON PCA, where it connects to the nominal PCA downstream of the junction of the nominal and the redundant regulation branch

All lines will be activated by normally closed pyro valves. The two bypass lines each include two normally closed pyro valves, two helium filters, two latch valves, an additional flow limiting orifice, and corresponding test ports. In active regulation mode, all valves of the bypass line remain fully open. The overall mass flow is controlled by the solenoid valves of the redundant branch of the nominally working PCA, while equal mass flow distribution betweeen both propellant sides is realized by adjustment of the nominal and the He X-feed orifice.

The tie in of the bypass lines between the two serial solenoid valves is realized based on results showing a propellant pumping effect if no regulating solenoid valve is located within the connection of the MON and the MMH tank as introduced by the bypass lines.

The He X-feed orifice is located at the most upstream position of the bypass line. The positioning is based on results showing that after each solenoid valve closure during pressurization, the high pressure Helium between the solenoid valves and the orifices expands to tank pressure level leading to an additional pressurization of the propellant tanks. To avoid excessive pressure deviations between the actively controlled nominal side and the passively controlled failed side, it is mandatory to have approximately the same volumes between the regulating solenoid valves and the orifices (nominal PCA and He X-feed).

V.B. Mode of Operation

The He X-feed system is designed to bypass a blockage of any of the two PCAs, or to re-establish pressurization after the loss of any of the two Helium vessels caused by external leakage In all of these cases, not all cross feed lines will be activated by firing according pyro valves, but only part of the Helium cross feed system. The not-activated cross feed lines remain isolated. In total, four different activation modes are possible, two to bypass the MON side and two to bypass the MMH side. The Helium flow path and initial conditions leading to the corresponding activation mode when bypassing the MMH side are indicated in Figure 12. Due to its symmetrical setup, bypassing the MON side is performed in the same manner.

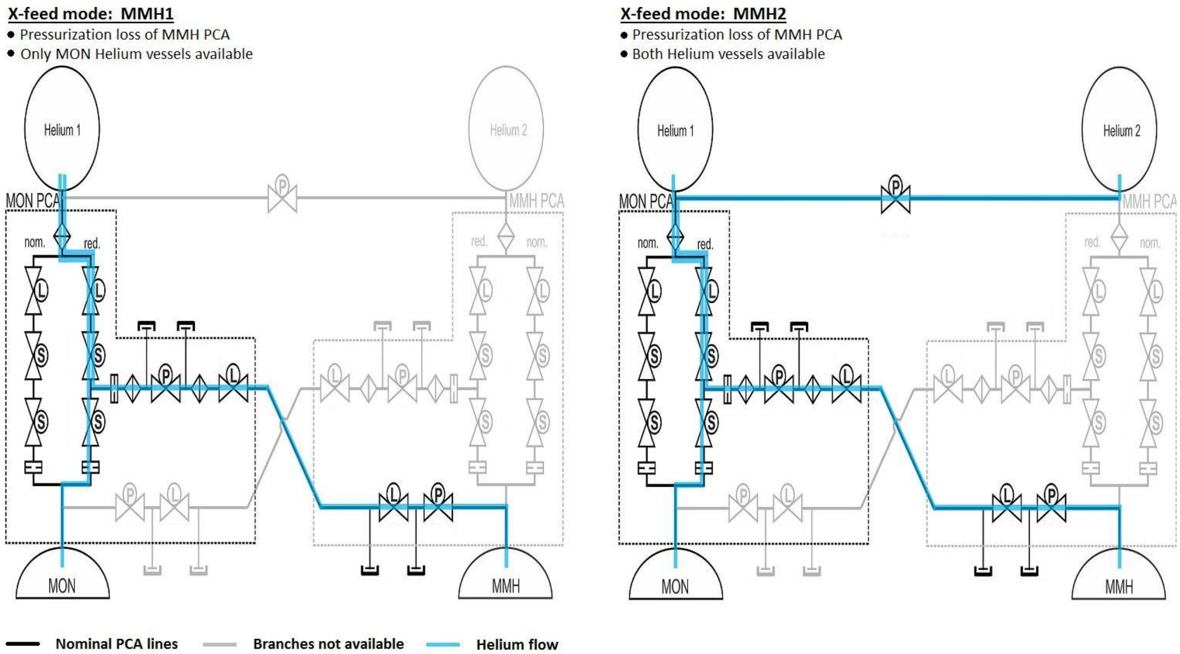

Figure 12. Activated states of the He X-feed system

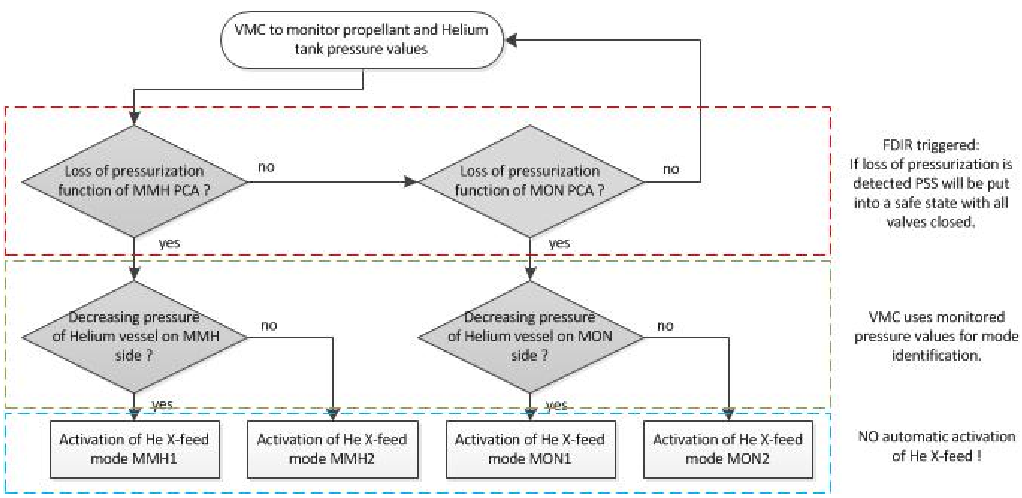

Figure 13. Logic for He X-feed mode identification

The general logic for determination of the Helium cross feed mode to be activated is displayed in Figure 13. The need for use of He X-feed is detected by a continuous pressure drop inside a propellant tank, which remains even after branch switching. FDIR will then automatically put the propulsion system into a safe state with all thrusters shut down, the latch valves and solenoid valves of the PCA closed and the PRUs in stand-by mode for continuous data monitoring. Follow-up monitoring of Helium vessel pressure data will allow to identify the He X-feed mode to be activated, i.e. if only a single Helium vessel can be used, or if both vessels are available. The given logic only displays the logic on how to derive the correct He X-feed mode to be activated. The activation process itself, which is irreversible due to firing of normally closed pyro valves,will not to be performed automatically, but manually out of a defined PSS safe mode prior a regulated contingency phase.

VI. Summary and Conclusion

In this paper the current design of the pressurization system of the European Service Module for Orion MPCV was described. The system realizes an electrical bang-bang regulation concept on a separate pressurization system for the two propellants MON-3 and MMH. The regulation algorithm, which uses a special weighting function mimicking a robust 2-out-of-3 voting, is implemented on service module level within a dedicated FPGA-based pressure regulation unit. Target values for regulation and FDIR task are commanded and controlled by MPCV's central vehicle management computer located inside the crew module.

The given design, which successfully passed the PDR milestone, allows flexible adaptations of the nominal regulation pressure to condition the propellants according to engine needs. The system is single fault tolerant against loss of pressurization capability and two fault tolerant against over-pressurization of the propulsion system.

A common pressurization mode, He X-feed, is implemented in order to maintain pressurization capabilities in case of extended failures on a single propellant side to improve survivability of the crew.

Feasibility of the pressurization concept has been demonstrated during development tests performed by Airbus DS at a Lampoldshausen test facility.

Additional tests are to be performed until end of 2015 to further support a successful CDR of the overall ESM propulsion system thereafter.

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