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Helium Electronic Pressure Regulator breadboard testing and development

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ABSTRACT

Nearly all current telecommunications platforms use mechanical pressure regulators (MPR) for Helium gas control in their chemical propulsion system. An alternative method is electronic regulation. These regulators consist of a pressure feedback system from the propellant tanks toggling flow control valves based on a desired pressure minimum. Such control schemes have been frequently used in Electric Propulsion (EP) systems for regulating low-flow, low-pressure Xenon applications where precision and variable control are the driving requirements. The objective of this work is to demonstrate that using electronic regulators can also be applied to high-flow and high-pressure stored gas applications, such as for large (420N) chemical propulsions systems typical of telecommunications platforms. OHB Sweden sees the electronic regulator as a key technology alternative to MPR for pressurizing chemical propulsion systems due to its pressure control performance and flexibility, simplicity, robustness and flight heritage from EP systems.

The Helium Electronic Pressure Regulator (HEPR) breadboarding project is funded by the European Space Agency (ESA) and the work is being performed by a team consisting of OHB Sweden, Airbus Defence and Space and Nanospace. Preliminary system level assessments have been conducted on the implementation of a HEPR in a chemical propulsion system and the performance impacts have been quantified. This initial study indicates significant improvements in the overall performance of the chemical propulsion system. A breadboard aimed at demonstrating the HEPR concept has been designed by OHB Sweden together with Nanospace and then assembled and tested. The initial estimates and design trade-offs have been validated through this breadboard campaign, showing promising results. The HEPR is presented herein with a focus on the breadboard test results and on the development of a flight product.

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ACRONYMS

AIT = Assembly, Integration and Test
CPS = Chemical Propulsion System
CV = Control Volume
ESA = European Space Agency
GEO = Geosynchronous Earth Orbit
GHe = Gaseous Helium
GTO = Geostationary Transfer Orbit
HEPR = Helium Electronic Pressure Regulator
HP = High Pressure
HPT = High Pressure Transducer
I_{sp} = Specific Impulse
LAE = Liquid Apogee Engine
LP = Low Pressure
LPT = Low Pressure Transducer
MEOP = Maximum Expected Operating Pressure
MMH = Monomethylhydrazine
MPR = Mechanical Pressure Regulator
NTO = Nitrogen Tetroxide
PT = Pressure Transducer
RCS = Reaction Control System
RCT = Reaction Control Thruster
SV = Solenoid Valve

INTRODUCTION

Though the idea of an electronic pressure regulator for a chemical propulsion system has been considered for other applications, it has been disregarded by the telecommunications sector due to the limited software capabilities on board the spacecraft, the absence of light high pressure solenoid valves and acceptable features of cheaper mechanical regulators. Increasing sizes of the telecom platforms, increasing performance requirements, changing regulatory environment and shrinking supplier base have prompted ESA to revisit the opinion and contracted OHB Sweden and their partners to explore the possibility of building an electronic pressure regulator based on the latest component developments. The first task of the study has been to gather the requirements from the Prime Airbus Defence and Space. Then a performance model was built to down-select candidate components. The last step in the study was to develop and test a breadboard, thus enabling paving the road to a flight product by identifying the next necessary steps.

In a Chemical Propulsion System (CPS), the objective of a typical mechanical regulator is to ensure delivery of Helium at the specified tank pressure for various operating modes. For example, for a GEO satellite placed by the launcher in GTO, these are:

- CPS activation and priming. During this phase, some isolation valves from the CPS are opened allowing high pressure Helium to flow to the regulator and be fed to the propellant tanks.

- LAE firing. The volume of propellant consumed during engine firing needs to be replaced in the tanks with Helium at the specified pressure.

- RCT firing. Similar than for the LAE firing, except that the flow rate of propellant consumed is much smaller in the RCT case. The flow rate of Helium through the regulator is therefore also reduced.

As with all designs, there are limitations to the operation of these mechanical regulators: they have single fixed set points so they cannot vary the gas pressure delivered to the propellant tanks. This requires separate fixed trim points for various spacecraft designs, limiting the usability of given units. A satellite product line that offers both chemical and electrical propulsion systems will have different spacecraft trim points depending on the final propulsion system configuration. They also have high internal leak rates compared to the electronic pressure regulators. Over time the pressure will equalise across the low and high pressure sections of the propulsion system, which is putting the propellant tanks and low pressure components at risk.

Many factors contribute to the Helium budget: tank volume, pad pressure, thermal environment, propellant expansion, leakage budget, pressurant absorption and minimum regulator inlet pressure. The last factor is a significant driver behind this study. Typically, a mechanical pressure regulator will deliver Helium at an outlet pressure of 15 to 18 bar. There is a design constraint to have a minimum inlet pressure to ensure operation of the regulator. This is due to the mechanical feedback nature of the design, and it is normally around 10 bar greater than the outlet pressure. In theory, for an electronic regulator, the minimum required inlet pressure could be very close to the outlet pressure. Consequently, the subsystem designer would need to use less Helium and could rely on a smaller and lighter tank.

Current CPS designs use a single regulator feeding both propellant tanks. This compromises the reliability of the spacecraft and the mixture ratio control. There are significant differences in the propellant vapour pressures and in their Helium absorption rates. Managing the propellant feeds separately is not an option unique to electronic regulators. However, the potential ability for an electronic regulator to modify the set points independently would make the option more attractive to a sub-system designer.

Besides, the smaller leak rates of electronic pressure regulators would make it possible to repressurize the propellant tanks towards the end of life. Typically, normally open pyrovalves are fired downstream the regulator in order to isolate the high pressure side of the CPS during the operational phase of a mission. The fact that the reaction control thrusters then operate in a blow-down mode has an impact their performances, especially towards the end of life when the tank pressures are at their lowest. Repressurization would allow the thrusters to work at nominal performance longer during the mission. If these goals can be demonstrated then the current high pressure isolation approaches could be reassessed. This would allow even more mission flexibility.

This paper first gives an overview of the analysis and proposed design covering the above improvements and then focuses on the breadboard results and on the development of a flight product.

1. CONCEPT

The Helium Electronic Pressure Regulator (HEPR) aims at fulfilling the role of a pressure regulator in a CPS without suffering from the drawbacks of the mechanical pressure regulators. The concept is a bang-bang regulator that consists of three solenoid valves in series and a cavity between the last two valves as shown in *Figure 1*.

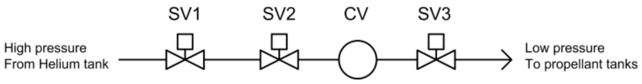

Figure 1 - Bang-bang pressure regulation concept

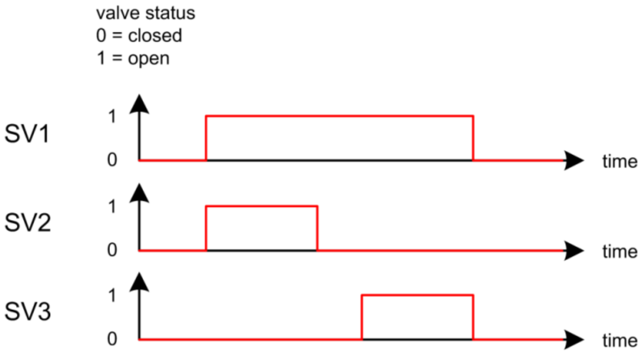

Figure 2 - Valve actuation sequence for one bang-bang cycle

Three valves are needed in order to comply with the launch site requirement of the three barriers between the Helium tanks and the propellant tanks. A typical valve actuation sequence is presented in *Figure 2*. At each given time, at least one control valve is in a closed position with a positive pressure upstream and thus preventing the fumes to travel upstream.

The advantages of the HEPR compared to MPR are:

- Adjustable pressure set points along the whole mission leads to an overall mass saving due to better control over thruster feed pressure.
- Flexibility in exchanging thruster type or any component on the fluid path during spacecraft AIT with a minimum impact.
- Minimum required inlet pressure close to the outlet pressure makes it possible for a repressurization towards the end of life.
- Removal of pyrovalves (hence increasing on ground testability) thanks to the low internal leak rate.
- Three barriers scheme kept between the pressurant and the propellant tanks in order to comply with the launch facilities regulations and constant segregation between HP and LP sides.
- ITAR free product is a possible goal.
- Possibility to passivate the Helium tank at the end of the mission without additional hardware.

2. REQUIREMENTS

The target missions are the current GEO telecom platforms, which are bi-propellant driven and require a LAE and RCS over the duration of the nominal lifetime of 15 years. The requirements in *Table 1* are being considered for the HEPR [2]. Many of these have originated from more traditional mechanical regulators but have been adapted to specific needs of electronic ones.

MEOP	Inlet: 310 bar Outlet: 24 bar
Regulated pressure	10 → 24 ±0.05 bar
Helium flow rate	0.39 g/s GHe from 310 to 70 bar inlet pressure 0.03 g/s GHe for inlet pressure ≤ 70 bar
Temperature	Nominal operating: -30°C to +50°C Acceptance operating: -35°C to +55°C Qualification operating: -40°C to +60°C Qualification non-operating: -45°C to +65°C

Media compatibility	GHe, inert gases, MMH, NTO, Hydrazine, Isopropyl Alcohol, deionized water, HFE7100
Internal leakage	≤ 1 scc/h GHe at inlet MEOP
External leakage	≤ 10^{-6} scc/s GHe at inlet MEOP
Design life	15 years in orbit
Input voltage	In the range 26-29 VDC
Power	Average in operational mode: ≤ 15 W In standby mode: ≤ 5 W
RAMS	Functional in one valve and one pressure transducer fail
Mass	≤ 4 kg (including drive electronics and harness)

Table 1 – List of major requirements

The Helium flow rate requirements are intrinsically linked to the thruster specification. The regulator needs indeed to deliver enough Helium in order to compensate the propellant depletion in the propellant tanks due to the firing of the thrusters.

- Initial LAE burn during the transfer mode requires a mass flow rate of 0.39 g/s GHe for a standard LAE of 420 N (Isp of 320 s), assuming that the regulated pressure is 17 bar. This requirement would go up to 0.66 g/s GHe in case of a future LAE development of 500 N (Isp of 320 s) with a regulated pressure of 24 bar. The apogee burn brings down the pressure in the Helium tanks down to approximately 70 bar.
- RCS operation in orbit post LAE burn requires smaller mass flow rate: 0.03 g/s GHe for three RCT of 10 N (Isp of 320 s) being fired at the same time, assuming that the regulated pressure is 17 bar.

Passivation of the Helium tanks will most likely be required for future spacecraft. This can be done by fully opening the valves of the electronic pressure regulator so that the remaining Helium would vent into space.

3. ARCHITECTURE

The HEPR architecture baseline is presented in *Figure 3*. It has four parallel branches, of which two are redundant. Two branches are therefore being activated at the same time to deliver the correct Helium flow rate. The redundant branches (SV4-SV5-SV6 and SV10-SV11-SV12) would be activated in case of failure in the nominal ones. The cavities are however shared between the nominal and the redundant branches. The electronics part would consist of four identical blocks commanding respectively SV1+SV2+SV3, SV4+SV5+SV6, SV7+SV8+SV9 and SV10+SV11+SV12. Each electronic block needs to be able to command three different valves. Other types of lighter architectures with fewer valves are also being considered by OHB Sweden for the HEPR, but their selection would depend on the reliability assessment and the FMECA done with the customers.

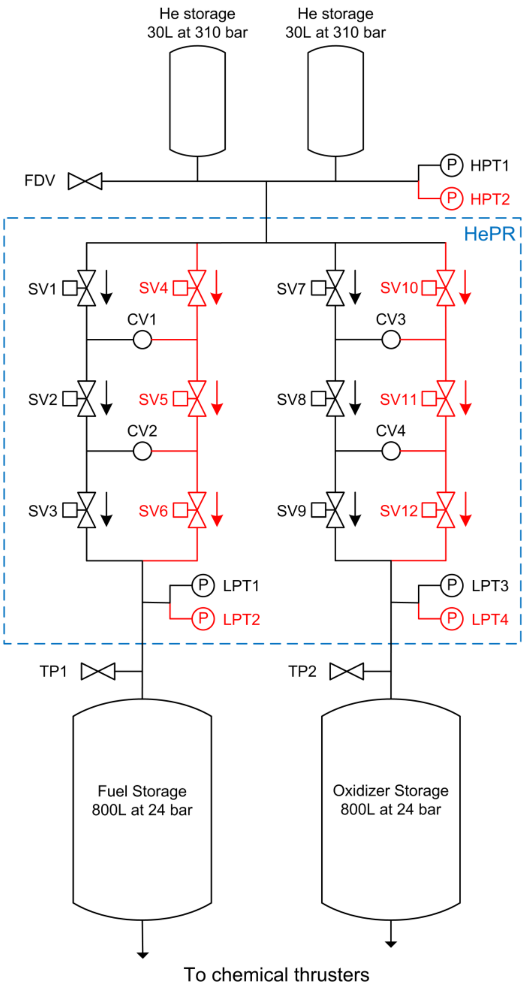

Figure 3 - HEPR architecture baseline. Redundant components in red.

This architecture also makes it possible to integrate the accurate propellant gauging device from Nanospace [1] in parallel of SV3 and SV9 for an even more optimal use of the propellants.

4. BREADBOARD DESIGN

The next step was to design and test an electronic pressure regulator breadboard in order to validate the concept and the chosen components. The breadboard aims at simulating one branch of the HEPR. As shown in *Figure 4* and *Figure 5*, it consists of three solenoid valves in series with one cavity between each of them. High pressure Helium is fed at the inlet from a pressurized bottle. The first valve *SV1* is not used for the purpose of the regulation and is kept open. *SV2* and *SV3* are the two active valves for the regulation, using *CV2* in between them as control volume. The outlet of the regulator is leading to a 16.4 L plenum. The propellant depletion due to thruster firing is simulated by the loss of Helium through a needle valve whose orifice can be adjusted to simulate different thrust levels. The regulated pressure was chosen to be 20 ±0.05 bar.

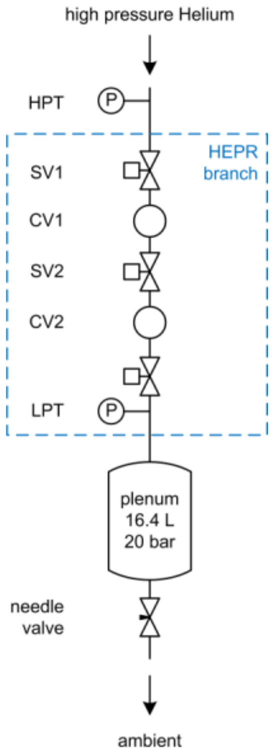

Figure 4 – Schematic view of the breadboard design

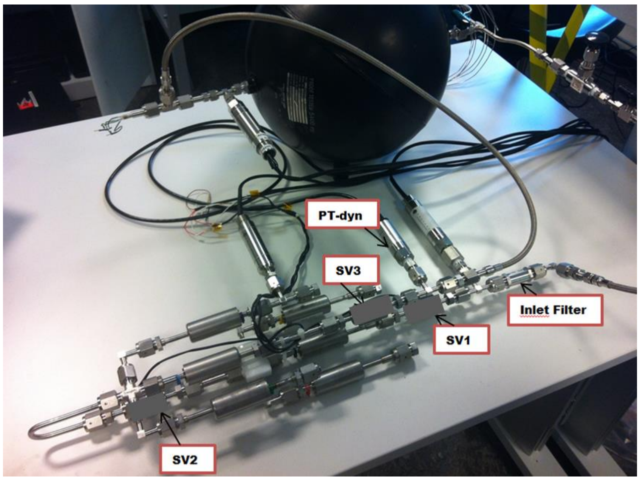

Figure 5 - Helium electronic pressure regulator breadboard during the tests

The low pressure transducer is used to feedback the plenum pressure to Labview. The bang-bang sequence is designed to be activated when the plenum pressure reaches 19.95 bar and to stop when it goes over 20.05 bar.

5. BREADBOARD TEST RESULTS

a. *Internal leak rate*

A long duration internal leak test was performed on the complete electronic pressure regulator breadboard. After more than 16 hours with a pressure of 304 bar applied to the inlet, the internal leak rate stabilized at the excellent value $3.5*10^{-8}$ scc/s GHe. Projected on the 15 years of the mission, this leak rate would lead to a loss of Helium of only 2.96 mg through one branch. This would be an insignificant pressure variation in the downstream tanks.

b. *Flow tests*

Pressure regulation of the plenum at 20 ±0.05 bar was achieved during breadboard flow tests with the needle valve fully opened in order to simulate a LAE flow rate demand. As shown in *Figure 6*, the pressure in the plenum is kept within its pre-defined boundaries and the overshoot is negligible.

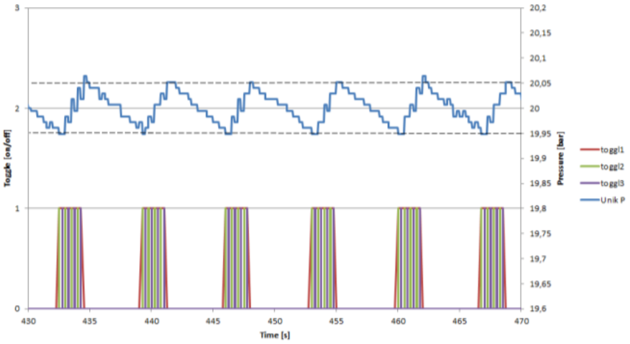

Figure 6 – Breadboard flow test: pressure regulation at 20 ±0.05 bar (inlet pressure: 164 bar)

A parallel can be drawn with a real bipropellant CPS. Due to fuel and oxidizer consumption, the volume of propellant in the tanks is decreasing when the thrusters are being fired, which results in a volume increase for the ullage. The Helium in the ullage expends and the pressure in the tanks is therefore decreasing. The greater the thrust, the greater the propellant mass flow rate is, and consequently the steeper the pressure loss rate is. In the case of the breadboard, the plenum tank has a constant volume and, due to the open needle valve, the pressure is decreasing when the bang-bang regulation is not activated. It is therefore possible to correlate the pressure loss rate in the breadboard plenum to the thrust of a RCT/LAE in a bipropellant CPS.

By assuming an MHH/NTO blend with a mixture ratio of 1.65 and an I_{sp} of 320 s, it was found that the pressure loss rate in the plenum was equivalent to the one that a 119 N thruster would generate. This relatively low thrust is due to the fact that the toggling sequence for the valves actuations was chosen so that there would be sufficient time for pressure variations in the system to dampen. It was not chosen to optimize the Helium mass flow rate. If the later would have been considered, a simple scaling calculation with a new toggling sequence using shorter waiting time between valves actuations shows that the breadboard could have managed to regulate the plenum pressure at 20 ±0.05 bar if the pressure loss rate due to a 995 N thruster was being simulated. This conclusion is however possible to draw only for the 164 bar inlet pressure for which the breadboard was tested, see *Figure 6*.

c. Comparison with EcosimPro

In order to extend the applicability of the HEPR breadboard flow tests that were carried out for only a few sets of inlet pressures and Helium flow rates, a validation of the tests was performed with EcosimPro. The model used is presented in *Figure 7* and is reproducing the breadboard architecture. As in the real system, high pressure Helium is feed to the breadboard via a tube. The HEPR part consists of three solenoid valves in series with one cavity between each of them. The downstream side of the breadboard leads to the plenum, called *ullage* in the schematics. The plenum loses constantly Helium via the valve *Valve_prop* which is modelling the needle valve.

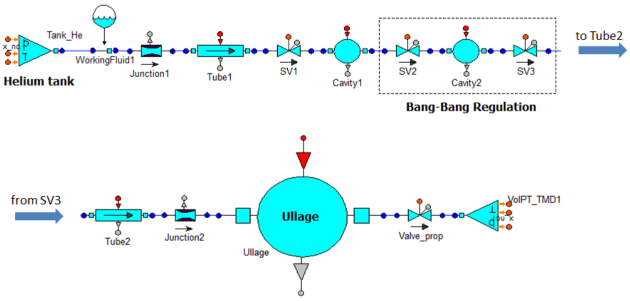

Figure 7 - Schematics for the EcosimPro simulations of the breadboard tests

An EcosimPro simulation was run by using the same parameters (toggling sequence, inlet pressure, temperature, regulated pressure range, etc.) used in the breadboard flow test of *Figure 6*. The simulated regulated pressure in the plenum is presented in *Figure 8*. It shows that the Helium flow rate through the electronic regulator is at least as high as the flow rate obtained with the simulation. As a result, the EcosimPro model can be used to simulate the breadboard for cases that were not tested in reality, in particular for different inlet pressures. It shows for example with the simulation of *Figure 9* that the HEPR breadboard would have been able to sustain a pressure regulation at 20 ±0.05 bar with an inlet pressure as low as 70 bar.

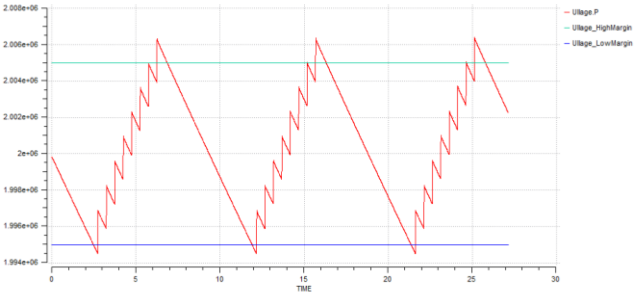

Figure 8 – EcosimPro simulation: pressure regulation at 20 ±0.05 bar (inlet pressure: 164 bar)

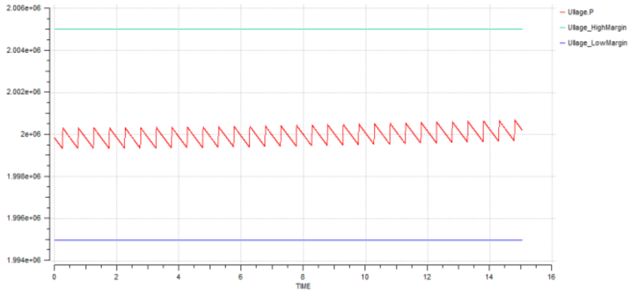

Figure 9 – EcosimPro simulation: pressure regulation at 20 ±0.05 bar (inlet pressure: 70 bar)

As a result, the conclusion of Section 5.c. can now be extended to lower inlet pressures. The breadboard tests and the EcosimPro simulations have shown that with a particular valve toggling sequence, the Helium flow rate delivered by the HEPR is big enough to compensate the pressure loss in the MMH and NTO propellant tanks due to the firing of a 995 N thruster, and this down to 70 bar inlet pressure. Consequently, the flow rate requirements of Section 2 are met.

d. Overshoot

Overshoots with an electronic pressure regulator can happen due to the fact that the quantity of Helium introduced in the ullage in one cycle is too big, consumes the entire pressure range and leads to an overshoot. Another reason for overshoots is that the system suffers delays and cannot process the pressure input fast enough to send the correct signals to the valves on the output. This would lead to an overshoot if the regulator starts another bang-bang cycle while the pressure in the propellant tank has actually reached the high threshold.

In the case of the HEPR, several factors tend to decrease the real consequences of the overshoot:

- The plenum used in the breadboard had a volume of 16.4 L. The ullage of a propellant tank is in the order of magnitude of 3% to 10% in volume in the beginning of a mission, so between 24 and 80 L for a propellant tank of 800 L. This ullage increases as soon as the apogee burn starts. The fact that the ullage increases its volume leads to smaller pressure increase steps for each HEPR cycle, hence reducing the risk of overshoot.
- The LAE burn is the first manoeuvre to be performed when the satellite reaches GTO. It is also the manoeuvre that requires the highest Helium flow rate. The high Helium flow required when the ullage is at its smallest volume is another factor limiting the risk of overshoot later on.
- A small overshoot of < 0.02 bar is present in the graph of *Figure 6*. This overshoot could however be removed with an optimized pressure range. For example, a modification of the high threshold from 20.05 to 20.03 bar would certainly cancel the overshoot.

6. DEVELOPMENT PLAN

The HEPR breadboard activities have allowed demonstrating the feasibility of such a bang-bang regulator for high pressure Helium expansion. The thorough hardware survey conducted in the first phase has allowed identifying flight qualified components enabling to achieve an attractive design.

The primary objective of the HEPR development is to make an electronic regulator whose features and prices are competitive with respect to MPRs when looking at the additional benefits of embarking the regulator.

A first step is to decide the baseline architecture configuration as highlighted earlier since several are possible. But the design drivers are numerous: cost, reliability, propellant segregation, driving electronics simplicity, reuse of fully qualified valves, refined propellant gauging. They consequently need to be ranked with the view of allowing a relatively short time to market. A driving electronics concept development is certainly part of this step.

Once the architecture is frozen, the heritage of the components will have to be revisited to judge the adequacy of their development status in their new use. It could be for instance beneficial to explore a valve modification to enhance the flow rates, judging the driving electronics design limits or retune the pressure transducers performances. The key steps in this assessment would be detailed discussion with the component suppliers, a thorough modelling of the performances using the tools developed during the study and early testing of available flight hardware.

This test step for validating the performances and precisely characterizing the hardware and electronics interactions has already been prepared by the development of a hardware in the loop test bench allowing real-time interaction between a simulated electronics and a real valve or vice versa and comparing the behavior with the expected outputs from the models. This has lead already to identify the prime importance of the cavity shape.

Thanks to the intermediate step and assuming that the components are individually qualified separately to the desired level, the engineering qualification model assembly in view of the qualification shall be a rather safe step which once successful will pave the way to the first flight model.

It is important to note that the development plan is also very open to continuous improvements and introductions of new components. OHB-SE and their partners or suppliers could discuss in parallel of the baseline qualification introduction of new components that to which the HEPR will be able of increased performance (higher flow rates, higher pressure, better gauging accuracy, etc.).

CONCLUSION

The massive introduction of software in the satellite design and the increase of performance of electronics and their enhanced features have led to the reconsideration of embarking electronic pressure regulators versus mechanical regulators.

OHB Sweden and its partner’s efforts have demonstrated with a breadboard, made of flight standard valves, that performances and features as required by the satellite primes and ESA can be met. The product definition can even offer the addition of the Nanospace propellant gauging system [1].

An electronic regulator built to meet commercial satellite chemical propulsion requirements as describe above would represent a significant technological improvement. The electronic regulator with appropriate feedback and control would be more flexible than current mechanical designs. It is also an ideal vehicle for developing a second source for a vital European component and an internationally competitive product. An electronic regulator would be free of the mechanical design constraints that limit the current market options. In turn, if demonstrated as feasible, these features would translate into an increase in satellite capabilities and mission flexibility.

Maiden flight opportunities are under preliminary discussion while the long term plan shall address the valve manufacturers for an enhanced valve design which will optimize mass and price of the second generation of pressure regulator.

ACKNOWLEDGEMENT

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