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Study of Electronic Pressure Regulator for Telecommunications Satellite Applications

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ABSTRACT

This paper presents a study, funded by the European Space Agency, to seek alternative for traditional mechanical pressure regulators (MPR) used for Helium pressure control for chemical propulsion systems of telecommunications satellites. All current telecommunications platforms utilize mechanical regulation for helium gas control in the chemical propulsion system. An alternative method is electronic regulation. These regulators consist of a pressure feedback system from the downstream tanks toggling flow control valves based on a desired pressure minimum. Such control schemes have been frequently used in Electric Propulsion 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 gas applications, such as for large (500N) chemical propulsions systems typical of telecommunications platforms. OHB Sweden sees the electronic regulator as a key technology alternative to MPR for pressurizing future chemical propulsion systems due to its simplicity, robustness and flight heritage.

The study has been supported by Astrium SAS, a prime contractor in the European satellite sector. Preliminary system level assessments have been conducted on the implementation of a Helium regulator in a chemical propulsion system. The performance impacts have been quantified. These initial studies indicate significant improvements in the overall performance of the chemical propulsion system. In addition, operational flexibility and inherent compliance with emerging regulations have been identified as key aspects of this design approach. System level requirements have been determined to optimize the functionality of such a regulator at an early stage. Nanospace is validating these initial estimates and design trade offs through breadboard design and testing of an electronic helium regulator. These assessment, the development of the requirements, the system level impacts along with the baseline design and functionality of the electronic regulator are all presented and discussed herein.

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NOMENCLATURE

Acronyms

AOCS = Attitude and Orbit Control System
CPS = Chemical Propulsion System
CV = Control Volume
EQM = Engineering Qualification Model
ESA = European Space Agency
FDV = Fill and Drain Valve
GEO = Geosynchronous Earth Orbit
GTO = GEO Transfer Orbit
LAE = Large Apogee Engine
MEOP = Maximum Expected Operating Pressure
MMH = Monomethyl Hydrazine
MPR = Mechanical Pressure Regulator
NTO = Nitrogen Tetroxide
PT = Pressure Transducer
RCS = Reaction Control System
RCT = Reaction Control Thruster
SV = Solenoid Valve
TP = Test Port

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 solenoid valves and acceptable features of 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. Then a performance model was built to down-select candidate components. The last step in the study will be to develop and test a breadboard before paving the road to a flight product by identifying the next necessary steps.

The objective of the typical mechanical regulator is to ensure delivery of helium at the specified tank pressure for various operating modes. For example on GTO missions these are:

- CPS activation and priming. During this phase the isolation valves for the various legs of 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 with helium at the specified pressure.

As with all designs, there are limitations to the operation of these 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. So a regulator configured for an all chemical system will not be usable on a space craft that also uses electrical propulsion. They also have comparatively high internal leak rates. Over time the pressure will equalise across the low and high pressure sections of the propulsion system. When the regulator requirements and helium budget contingencies are considered this pressure exceeds the operating capability of the propellant tank and downstream propulsion system components. Many factors contribute to the helium budget; tank volume and loading, pad pressure, thermal environment, tank expansion, leakage budget, propellant 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 15-18 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. Typically this is 10 – 15 bar greater than the outlet pressure. Pressure drops across the high pressure components needs to be accounted for and additionally conservative engineering practice will require a budget engineer to add some margin on that stipulated minimum inlet 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 employ a smaller and lighter tank.

Current designs utilise a single regulator feeding both propellant tanks. This compromises the safety of the space craft and the mixture ratio control. There are significant differences in the propellant vapour pressure and their helium absorption rates. Managing the propellant feeds separately is not an option unique to electronic regulators. However the potential ability of an electronic regulator to modify the set points independently would make the option more attractive to a sub-system designer.

With reduced inlet pressures, resulting in lower leak rates possibly sustained for a 15 year mission life then the option to repressurize the propellant tanks towards the end of life could be realised. Typically reaction control thrusters operate in a blowdown mode during the operational phase of a mission. Their performance will suffer towards the end of life when the tank pressures are at their lowest. Repressurization would allow the thrusters work at nominal performance for longer in 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 gives an overview of the analysis and proposed design covering the above improvements, and a summarized development plan for future activities.

1. APPLICATION / REQUIREMENTS

The target missions are the current GEO telecom platforms, which are bi-prop driven requiring a LAE and Reaction Control Systems over the duration of a nominal lifetime of 15 years in orbit operation. The design is also intended to capture the requirements of near future apogee engines delivering a thrust of 500 N (resulting in an increased requirement on the maximum helium flow rate). Ideally having set of multiple end users would ensure a design that would ensure a common design, but during this work OHB Sweden has worked together with Astrium SAS to capture the first sets of requirements. The following operational criteria have been identified as main driver for the current design layout:

- Initial priming of each tank prior to the 1st firing of the chemical system. This will require that both the fuel and oxidizer tanks to be pressurized to 24 bars (worst case filling scenario) within two minutes after launcher separation. The estimated flow rate of the gaseous Helium is around 3 g/s for each branch.
- Initial burn during the transfer mode, it is estimated a mass flow of 0.36 g/s GHe is required for a standard LAE of 400 N (Isp of 315 s). However the requirements for this design of the regulator shall support engine larger than 500 N and will therefore require a mass flow rate of around 0.50 g/s GHe. The flow rate during the initial burn shall be maintained from 300 bars down to around 70 bar of the Helium inlet pressure.
- The Reaction Control System (RCS) operation post LAE burn will require much less mass flow and is it currently estimated that baseline flow rates of 0.02 g/s GHe will be required from 70 bars down to 24 bars. Once this point is reached, the mass flow cannot be maintained during the firing of the RCS thrusters. The system will then enter a phase of re-pressurization where the tanks will be pressurized to the same pressure as in the Helium tanks between burns. This will allow the thruster to begin firing at their optimum operating point with decreasing performance as the pressure in the tank drops.
- Passivation of the Helium tanks will most likely be required by future space crafts. This can be done upon completion of chemical tank passivation, then the valves can be opened fully and the remaining Helium vented into space.

Astrium SAS provided a detailed description of the hardware requirements both on component level and subsystem level in order to ensure a proper interface with their current and future platforms. Many of these have originated from more traditional mechanical regulators but have been adapted to specific needs of electronic ones.
Though the two (mechanical and electronic regulators) will offer similar overall performances, the electronic regulator shall be able to have a tighter control over a larger pressure range where it is foreseen to have full pressure control down to 27 bar inlet pressure while operating the RCS thrusters. The list of major applicable requirements is shown in *Table 1* and has been used to identify the baseline components used in the testing of the regulator. The system level environmental and interface requirements have been considered on a component level but not addressed on a system level as this is considered beyond the scope of this work.

Requirements	Description
Test Media Compatibility	MMH (Monomethyl Hydrazine) Hdrazine MON1/MON3 (Multiple Oxides of Nitrogen) Inert gases IPA (Isopropyl Alcohol) Deionised / Demineralised water HFE7100
Temperature	Normal Operating -30 -> 50 degC Acceptance (Operating) -35 -> 55 DegC Qualification (Operating) -40 -> 60 DegC Qualification (non-operating) -45 -> 65 DegC Storage -40 -> 65 DegC
MEOP	Inlet=310 bar and Outlet=24 bar
Regulated Pressure Range	10->24±0.1 bar
External Leakage	$<10^{-6}$ sccs at Inlet MEOP
Internal Leakage	<1 scch at Inlet MEOP
Electrical Interface	Input Voltage=100V Maximum Power=200W Interface=MIL-1553
Design life	8 years ground storage and 15 years in orbit
RAMS	Functional if one valve and one pressure transducer fails
Vibration loads	31.8grms(random) Parallel to mounting plane 20g (sine) and 20.1grms(random
Mass	<4Kg (including drive electronics and harness)

Table 1: List of major applicable requirements

Using a classic design principle from electrical propulsions system regulator design (three valve barriers in series), the main challenge has been to identify and select components that the requirements shown in *Table 1*. Once selected the system has scaled in order to meet the pressure control accuracy throughout a wide range of inlet pressures. *Figure 1* shows how a simple bi-prop system equipped with an electronic regulator and an alternative propellant gauging device from Nanospace [1].

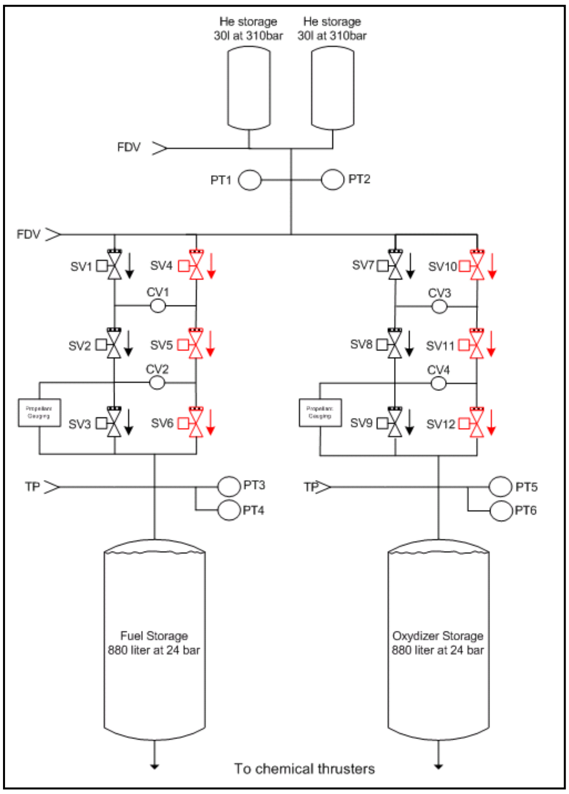

Figure 1: Baseline design of the electronic regulator

In such design all flow requirements specified by Astrium SAS can be met as the there are two individual regulator used for the a) propellant and b) the oxidizer. This will also allow for controlling different mixture ratios should the end user require it.

2. PRELIMINARY DESIGN

The EcosimPro code presented in *Figure 2* has been used in order to simulate the electronic pressure regulator during the different phases of the mission. The primary objective is to demonstrate the feasibility of putting three solenoid valves in series and their ability to deliver the desired mass flow of Helium.

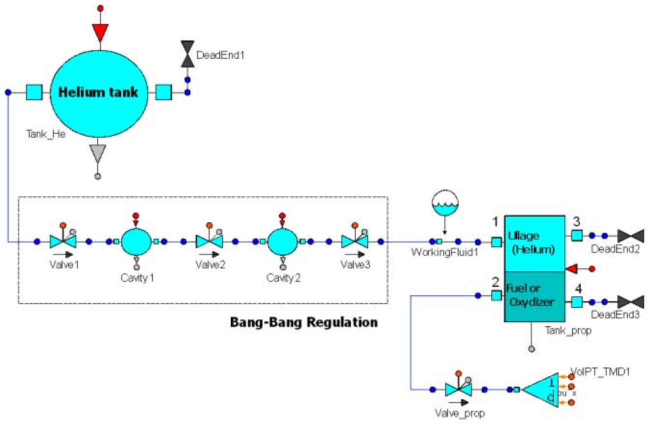

Figure 2: EcosimPro model of the electronic pressure regulator

The first component is the Helium tank. Then, the electronic pressure regulator is modeled by three valves in series with one cavity in between each of them. The last valve is connected to a two-phase propellant tank, filled by either fuel or oxidizer and pressurized with Helium. Downstream the propellant tank, a valve simulates the flow of propellant that is delivered to the chemical system. The valve seat area for the propellant is sized in order to obtain the correct flow rate of fuel or oxidizer, depending on the thrust and specific impulse considered. Eventually, a boundary condition simulates space conditions. The function of the electronic pressure regulator is to regulate the propellant tank pressure to 24 ±0.1 bar.

The first operating phase is the priming of the ullage tanks. For this, the propellant valve is closed and the three valves in the electronic pressure regulator are opened. If the initial pressure in the Helium tank is 310 bar, the EcosimPro model demonstrates that is it possible to pressurize a 200 l ullage from P_{ini} = 5 bars to P_{final} = 24 bars in less than 5 min.

The LAE considered is a bipropellant thruster MMH/NTO with a thrust of 400 N. For this type of engine, the mixture ratio by volume is exactly equal to 50% MMH and 50% NTO. Consequently, choosing MMH or NTO in the simulation does not matter as their volumetric flow rate is identical. The LAE has a specific impulse of 320 s, which gives a mass flow rate of MMH of 48.1 g/s. When the LAE is started, the quantity of propellant in the tank decreases, the ullage expands and therefore the pressure decreases. The bang-bang cycle of the electronic pressure regulator is activated when this pressure reaches a lower limit and is stopped when it reaches an upper limit. Thus, the propellant tank pressure can always be 24 ±0.1 bar.

The electronic pressure regulator has three solenoid valves, but only two are needed in order to perform the bang-bang regulation. In case of failure of one of the SV in the open position, the two other valves have to be used for the pressure regulation. Consequently, the bang-bang regulation needs to be able to work throughout the mission with Valve2/Valve3 (one cavity in between) and with Valve1/Valve3 (two cavities in between). The simulations below are made with Valve2/Valve3.

At the beginning of the apogee raising, the pressure in the Helium tank is 280 bars. The bang-bang regulation at this moment of the mission is presented in *Figure 3*. They show that the bang-bang regulation in the propellant tank is compliant with the requirement of a 24 ±0.1 bar regulated pressure for P_{init} = 280 bars.

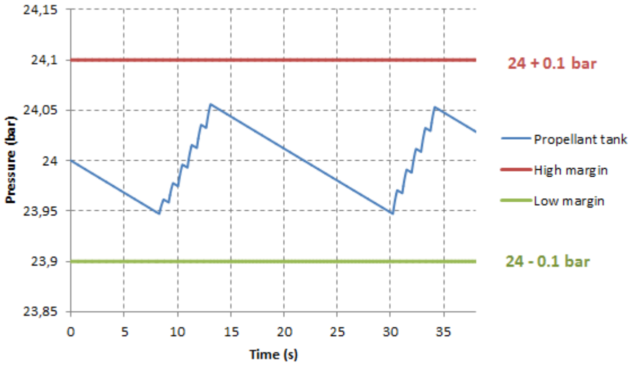

Figure 3: Simulation at P_{init} = 280 bars and T_{LAE} = 400 N

At the end of the apogee raising, the pressure in the Helium tank drops down to 70 bars. For this value of Helium inlet pressure, the bang-bang regulation is presented in *Figure 4*.

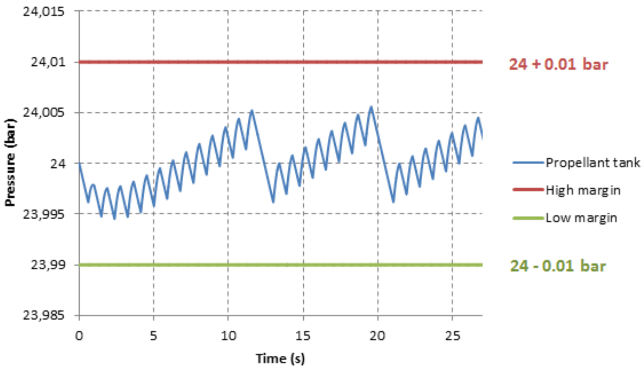

Figure 4: Simulation at P_{init} = 70 bars and T_{LAE} = 400 N

When the satellite reaches its orbit, the pressure in the Helium tank is 70 bars. On orbit, the satellite is using a maximum of 3 RCT thrusters of 10 N at the same time. The RCT considered have a specific impulse of 290 s, which gives a flow rate of MMH of 4.0 g/s. The pressure regulation at this moment of the mission is presented in *Figure 5*.

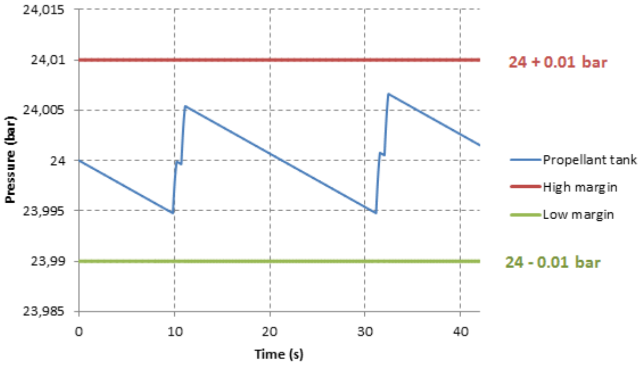

*Figure 5: Simulation at P_{init} = 70 bars and T_{RCT} = 3*10 N*

At the end of life, the pressure in the Helium tank drops down close to 24 bars. The simulation presented in *Figure 6* shows that the pressure regulation with 3 RCT firing at the same time is possible with a Helium tank pressure of 27 bar. Further simulations have shown that when the pressure in the Helium tank reaches 26 bar, the propellant tank pressure is still within 24 ±0.1 bar. Below this, the regulation can be possible only when the thrusters are not being fired.

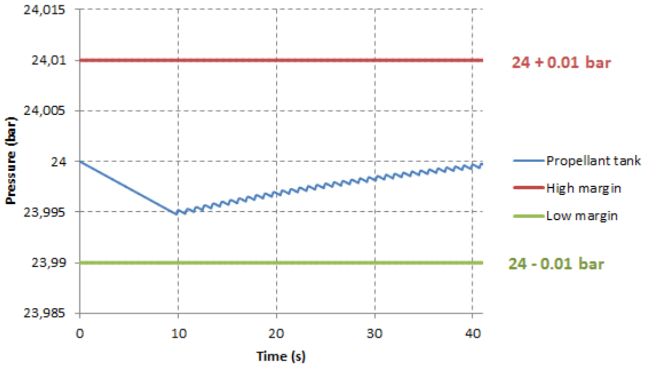

*Figure 6: Simulation at P_{init} = 27 bars and T_{RCT} = 3*10 N*

The simulations with Valve1/Valve3 work as the ones presented above for Valve2/Valve3.

If a LAE of 500 N and 320 s of I_{sp} is considered, the only issue is at the completion of the apogee raising. At this moment, the pressure in the Helium tank drops to 70 bars. For this value of Helium inlet pressure, the electronic pressure regulator is unable to regulate the pressure in the propellant tank at 24 ±0.1 bar. The pressure in the Helium tank is too low to flow through the valves of the electronic pressure regulator the amount of Helium required to compensate the flow of MMH out of the propellant tank. Though, it should be noted that the end-of-LAE-burn performance increases with respect to the current generation platforms, which operate down to 15-17 bar.

The graph presented in *Figure 7* shows that the pressure regulation is possible only down to 76 bar. With the current baseline valve, the maximum thrust possible for a LAE (I_{sp} = 320 s) such that the pressure regulation functions as specified between the full range of 280 to 70 bar inlet pressure is 460 N. This can be increased to 500 N with the development of a high pressure solenoid valve with a larger seat area. A scaleable approach of increasing the number of branches is also feasible, with or without new valve development. This flexibility could in theory even allow for systems in size up to the planned 1.1kN thrust range.

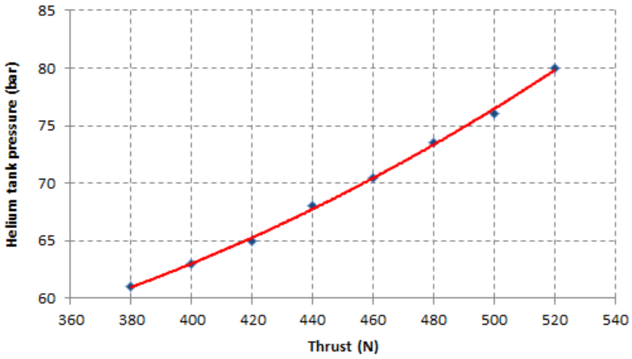

Figure 7: Minimum pressure in the Helium tank so that the pressure in the propellant tank is regulated at 24 ±0.1 bar in function of the LAE thrust (I_{sp} = 320 s)

3. DEVELOPMENT PLAN

The initial proposal of OHB Sweden to ESA is to manufacture and test a breadboard. The successful completion of the test campaign, with the demonstration of achieving the performances expected by the satellite prime manufacturers, shall then allow selecting the baseline for the development of a flight pressure regulator. The current activities around the breadboard are then critical and OHB Sweden aim to demonstrate that the baseline design as tested is as close as possible to offering a flight design. The breadboard phase shall then be followed by a qualification phase before the production of the first flight model.

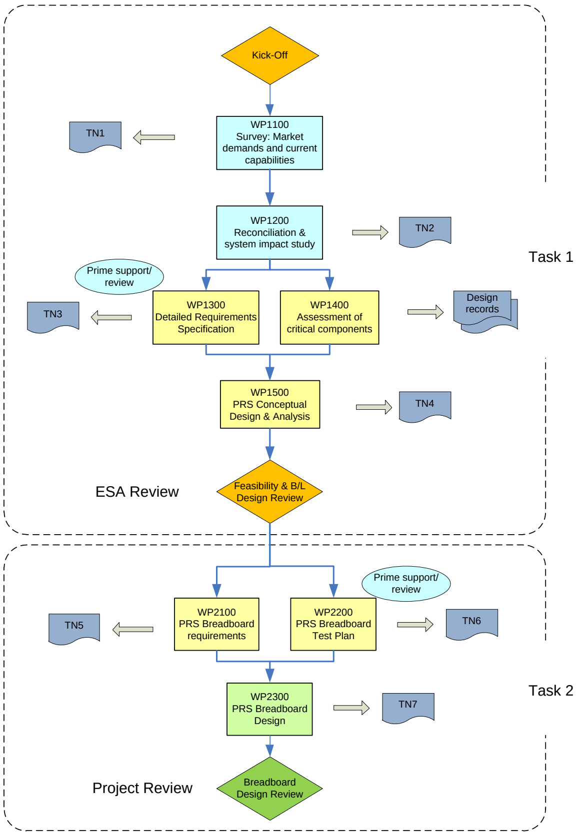

Figure 8: Study logic for Tasks 1 & 2

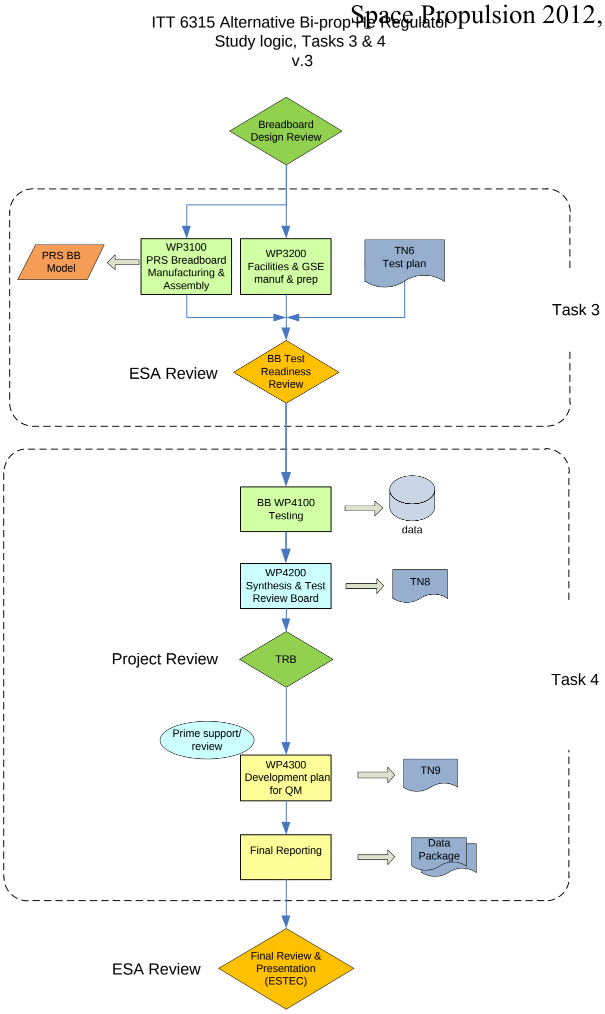

Figure 9: Study logic for Tasks 3 & 4

The breadboard phase is currently under implementation as proposed to ESA (*Figure 8* and *Figure 9*). The first step has been the consolidation of the pressure regulator requirements. These activities have been followed by the simulation of performances around possible valve candidates, the key component to the system. The breadboard design review completed this activity and granted the selection of the breadboard parts. This was dictated by the objective of minimizing the development efforts to a first flight model while meeting the requirements as established by ESA and consolidated by Astrium. In order to reach these requirements, the partners agree to select the offer of a valve supplier undertaking the improvement of the driver coils of a previously qualified and flight proven valve. This choice introduced significant delays in the preparation of the breadboard but provides benefit of the proven seat/poppet arrangement for the specified pressures, temperatures and mediums. This mass optimization is all the more important to the study since none of the candidate valves offered a sufficient flow rate to meet the requirements.

Upon completion of the breadboard the development steps to a first flight version of the electronic regulator shall be minimal. The hardware will be updated into an EQM by incorporation of the valves onto a representative baseplate populated with mass dummies to represent the redundant parts. Thermal and electrical parts will be flight representative. In this way, the upgraded breadboard shall undergo an extensive environmental test campaign aiming at demonstrating that the valves are kept within their qualified environment and hence guaranteeing their life capability in terms of cycles and throughput.

The development of the associated driving electronics will then be discussed with the potential customers. The satellite prime manufacturers, for the most part in favour for mass and cost, wish to centralize such types of drive electronics. As a result a driver card to be integrated with existing on-board systems will be designed. Should a market be identified for a self-standing regulator, OHB Sweden will lead the driver electronics design and team up with a partner for the manufacturing and qualification. The qualification of this first version of the regulator shall address the immediate market needs. This version will segregate the oxidiser and the fuel side. This allows also a safe implementation of the Nanospace gauging system [1], should it be requested by the prime, since half of the possible fuel mass savings are associated to this accurate gauging system. Candidate missions are already under discussion with ESA and Primes for a maiden flight in the turn of 2014.

Nurtured by the feedback of the first product, OHB Sweden could simply continue with further recurrent production. However the breadboard activities have already highlighted the need for a suitable valve in terms of flow, pressure and temperatures in a single string of valves, for both fuel and oxidiser branches. A subsequent natural activity shall be the development of such a valve with established valve manufacturer. Taking in to consideration the breadboard results, discussions will be started in due time and will hopefully allow the development of the second generation of the electronic pressure regulator. The valve development shall be the main activity of this future step, whose constraints will be:

- Respecting the interfaces of the first generation
- Minimizing the drive electronics change
- Embed robustness to future need evolutions
- Offer an attractive recurring price

Ideas for such a valve have already been considered internally in OHB Sweden and the candidate design shall soon be presented to potential valve suppliers. If the market survey is unfruitful in identifying a product close to the desired one, OHB Sweden will be prepared to take up discussions with valve development partners concerning the desired features.

This long term view does not preclude that the immediate focus remains the successful completion of the breadboard activities in the spring 2013. This could open the path for the first flight models in the turn of 2014.

4. 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 it's partner's efforts are currently focused on demonstrating 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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[1] Rangsten P., et al., "Satellite Propellant Volume Gauging using Gas Injection", SP2012-2366097, Space Propulsion Conference 2012, Bordeaux, France, May 2012