Development of a Propellant Supply Assembly for Small GEO

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Abstract

This paper presents the Propellant Supply Assembly (PSA) that IberEspacio is developing for the Small Geostationary Earth Orbit (GEO) satellite.

The Small GEO project looked for an existing European pressure regulator for the Electric Propulsion Platform System (EPPS), which were able to cope with very different mass flow requirements and also embedding a control logic allowing health monitoring of the unit without additional hardware. Because of the mission stringent requirements, none could be identified. SSC decided to support IberEspacio in the development of a regulator inherited from the Smart -1 Bang Pressure Regulator Unit.

The SGEO Propellant Supply Assembly (PSA) is a Xenon pressure regulator based on a Bang-Bang logic, whose function is to decrease the pressure from a Xenon tank to the required operational pressure of the downstream user, which can be Electric Propulsion (EP) unit or a Cold Gas Thruster unit (CGT). These two users require approximately the same pressure but rather different mass flows; CGT flows are at least order of magnitude higher than EP flows, making the PSA offer a unique feature in the propellant supply market.

The bang-bang regulator has to be able to provide accurate pressure regulation under a very wide range of operational conditions and it has to compensate the cooling effect of the Xenon expansion.

Performances of the new pressure regulator have been analysed and predicted using the Ecosimpro ESPSS (European Space Propulsion System Simulation tool) library. An Engineering Model shall be built and tested in order to confirm the predicted performances. A protoflight model will be use to complete the qualification test campaign.

Introduction

The Small Geostationary Platform (SGEO) is being developed in the frame of ARTES-11 by a consortium headed by the OHB-System AG with a core team line-up including LuxSpace Sàrl, the Swedish Space Corporation AB and Oerlikon Space AG [1].

SGEO is a European cost-effective platform to address the segment of small telecommunications satellites in geostationary orbit up to 300 kg of payload mass, 3 kW of payload power and a lifetime of up to 15 years.

The SGEO spacecraft uses an Electrical propulsion subsystem (EPPS) to perform all orbital manoeuvres with the exception of the transfer from Geostationary Transfer Orbit (GTO) to GEO, which is performed by a separate chemical propulsion system.

More specifically, the functions to be performed by the SGEO EP system are the following:

- Initial Detumble after separation from Launch Vehicle (Cold Gas Thruster Assembly)
- Station acquisition & Repositioning
- Station-keeping N/S and E/W during 15 years
- Momentum management during all phases except during GTO-GEO transfer
- Transfer to graveyard orbit at End of Mission

The SGEO EPPS is based on two EP thruster branches, denoted EPTA 1 and EPTA2, which operate in cold redundancy. In addition there are two cold redundant Xenon cold gas thruster branches (CGTA).

The selected approach for SGEO has been to break down the Electrical Propulsion (EP) subsystem into four EP subassemblies. The Xenon is provided in a blow-down mode.

The main function of the PSA is to supply a constant feed pressure to the thruster assemblies. There are two types of thruster assemblies: EP thrusters (EPTA 1 and EPTA 2), with typical Xenon flow rate requirements of 0.1-10mg/s, and 50 mN Cold Gas thrusters, with a flow rate requirement of 200 mg/s each.

To not exceed the upper flow rate limits of the PSA, the Cold Gas thrusters will operate in pulsed mode such that the total Xenon consumption of the Cold Gas thrusters during a single second will not exceed 200 mg at Beginning Of Life (BOL) up to 55 bar in the High Pressure Node (HPN). The instantaneous consumption of the Cold gas thrusters will however be up to 600 mg/s throughout the mission.

The SGEO PSA is composed by two parts: a Pressure Regulator Panel (PRP), where the fluid control hardware is mounted, and Supports and Control Electronics (SCE), with the purpose of driving and monitoring the PRP. These units are two physically independent units.

The main functions of the PSA are:

- To decrease the Xenon pressure from inlet tank pressure down to a regulated pressure of 2.2 bar minimum at the outlet (the set point can be changed by telecommand). The inlet pressure is at 186 bar maximum (BOL at 50°C) and decrease down to 3.3 bar (EOL at 20°C and density 18.33 kg/m3 corresponding to 1% unused propellant mass).
- To guarantee a total Xenon mass throughput of 250 kg without exceeding the solenoid valves 1 million cycles qualification limit.
- To ensure that the Xenon remains in a gaseous state throughout the passage from the HPN to the LPN. In other words, the Xenon temperature has to be maintained between 20 ºC and 50 ºC.
- To provide the necessary input-output ports to fill and drain the Xenon Tanks.
- To provide Telecommands/Telemetry interface functions to the S/C by a dedicated MIL-STD-1553B interface.
- To provide self health checks of the equipment and to enable diagnosis by manual operation

IberEspacio, PSA Prime Contactor, is in charge of the PRP design of the hardware, assembly integration and testing and definition of the control logic. EADS Astrium Crisa, as IberEspacio's subcontractor, is in charge of the SCE design, manufacturing and testing.

SGEO PSA Design Description

The primary function of the PSA is to decrease the Xenon storage pressure in the Xenon tanks to the operational pressure ranges required by the EP thrusters and Cold Gas thrusters.

The way the pressure regulation is performed by controlling two solenoid valves using a Bang-Bang Logic (BB). The BB logic can be summarized as the following: when the pressure in the low pressure node of the PSA (LPN) decreases below the programmable pressure set-point (typically 2.2 bar), the Bang-Bang valve system is actuated. The upstream valve is opened to fill the internal cavity between the two valves which are operating the pressure control, for a duration time T1. The upstream valve is then closed, and the two valves stay closed for a period T2. The downstream valve is finally opened for a T3 opening time, in order to fill the plenum tank. Simultaneous opening is not permitted by design of the driving electronics, feature that adds safety to the system. The valve timing is part of the control logic, and is changed during the PSA life (i.e. Xenon density) and according to the downstream user, in order to obtain the required pressure regulation minimizing the valves actuation.

Figure 1 reports a schematic of the PSA. The PRP is detailed in all its components, while the SCE is reported only in terms of interface to the PRP.
The PSA is cold redundant, both in the PRP and SCE. The Satellite's On Board Computer (OBC) is in charge of choosing which branch to operate. The nominal and redundant SCE can be activated simultaneously for reading the pressure transducers or thermistors values (i.e. identification of a faulty sensor, etc).

The nominal branch in Figure 1 is in green, while the redundant branch is in red; the redundant components have also a "-r" suffix. The PRP is redundant in all its electro-mechanic components (solenoid valves, pressure transducers, thermistors, heaters): the nominal and redundant branches share the same inlets-outlets tubing, plenum and filtering elements. The SCE is basically made of two identical electronic cards, since they are connected to the same hardware configuration.

The BB logic requires only two valves to be operated, but one isolation valve for each branch is required for reliability and leakage issues.

In a standard design, the isolation valve is normally a latch valve. The PSA is instead equipped with six solenoid valves of the same type (labelled SV1 to SV3r in Figure 1). One branch has 3 solenoid valves in line: this feature permitted to include the possibility of choosing which valves operate as BB valves and consequently which one acts as isolation valve. It shall be possible to switch the role of the valves during the operation of the system by means of a telecommand.

The BB logic fills and discharges a fixed volume for each cycle: for a given input density, it is possible to increase the mass delivered only by making more frequent actuations. On the other hand, in order to no exceed the valves maximum qualified number of cycles, it's desirable to have a bigger inter-cavity volume when the pressure is low or when the mass flow required is high (CGT mode).

The PSA can operate the BB with SV1 and SV2 (or SV2 and SV3), with only one cavity, or operating SV1 and SV3 (SV2 as isolation), using then two cavities for the BB, as indicated in Figure 2.

The implementation of this strategy permits to minimize the number of actuations of the valves, since it is possible now to select two filling levels, and it is also possible to work with the upstream or downstream cavity, when only one cavity is needed, splitting the number of total actuations on SV1 and SV3. The sizing of the system, and the all life simulations performed using Ecosimpro EPSS library, guarantee that SV2 stays far from its 1 million cycle qualification. Two cavities are used for the CGT mode and in the EP mode when the Xenon pressure is below 60 bar.

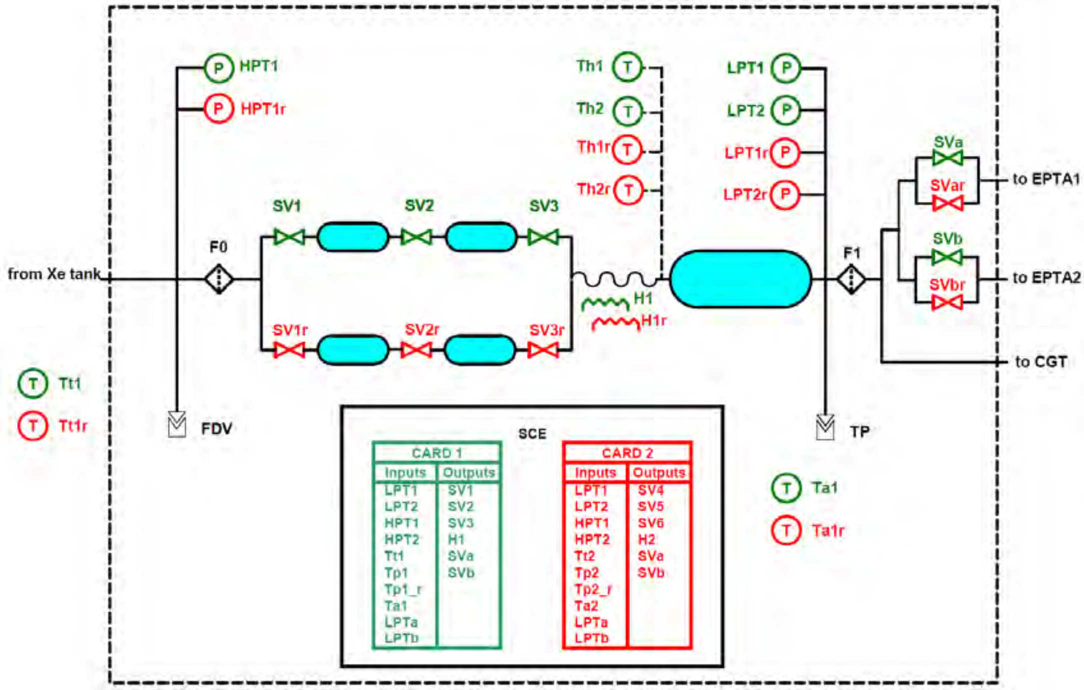

Figure 1 SGEO PSA FM flow diagram

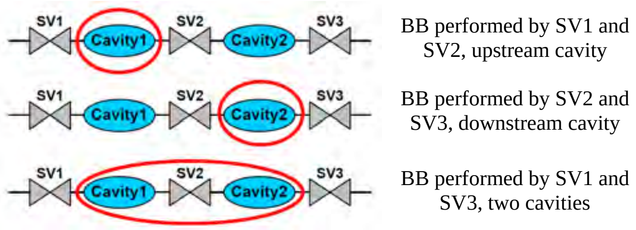

Figure 2: PSA's BB valves: Upstream Cavity BB, Downstream Cavity BB, Double Cavity BB

The dedicated electronics SCE has the purpose of controlling all relevant PSA-internal components and gathering PSA health information. Including the SCE unit into the PSA allows to design and test the PSA separately from other platform systems.

In general the SCE takes charge of pressure and temperature acquisitions and heaters and valves power driving in order to control the Xenon flow to user; in addition it interfaces with the on-board computer to provide and to receive commands via MIL-BUS-1553.

The SCE is composed by two Modules or Cards, one Nominal and one Redundant which are identical. The control logic applied to the redundant branch of the PSA is equal to the control logic of the nominal branch. Figure 3 depicts a simplified block diagram of the SCE.

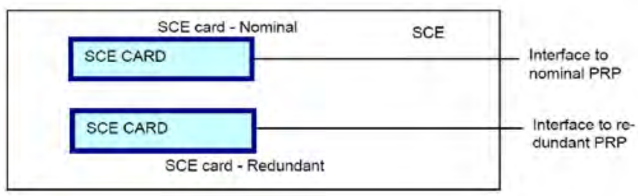

Figure 3: PSA SCE schematic block diagram

During the nominal operation of the PSA, the two SCE modules/cards are in "cold redundancy", i.e. one of the SCE card switched on and the other one switched off. However it is possible to switch on both SCE cards in order to acquire the telemetry of the sensors of the redundant card. In this situation the SCE cards would operate in "hot redundancy".

The SCE implements the control logic of the PSA (pressure and temperature regulation). Based on the pressure indication from the low-pressure transducer (LPT), the SCE CARD will actuate the Bang-Bang valves. When the pressure measured by the low pressure transducers (LPT) is less than the required preset pressure level (PPL), the BB sequence is triggered.

In order to avoid a Xenon temperature decrease in the plenum, the SCE CARD may turn on one of the two parallel heaters placed in the back side of the heating plate (heating zone of the PRP), according to temperature measured by the thermistors in the heating plate. This involves a two position (on/off) control logic with a temperature threshold, which is set by telecommand.

The PSA implements the operational modes depicted in Figure 4.

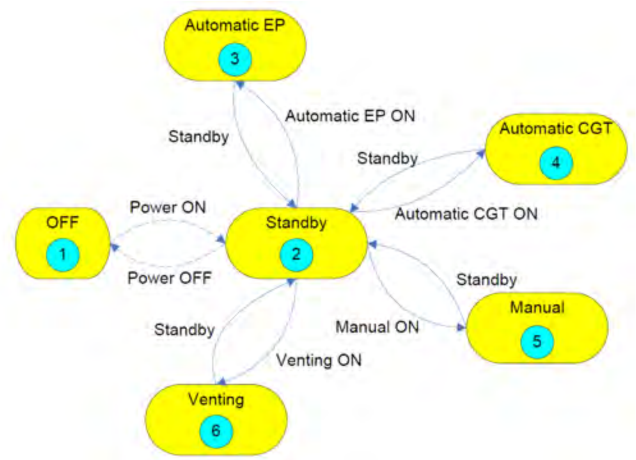

Figure 4: PSA SCE schematic block diagram

The modes are described hereafter:

- Stand-by (2): This mode allows setting the operation parameters of the PSA Control Logic. All control loops are inactive. When the power is applied to the SCE module/card, the SCE module goes into the Stand-by mode. No other transitional mode is allowed during the power ON transient.
- Automatic EP mode (3): it allows supplying Xenon automatically to the EPT.
- Automatic CGT mode (4): allows supplying Xenon automatically to the CGT.
- Manual mode (5): it allows carrying out manually BB activation sequences and heater activations. The manual mode is assumed for flexibility during ground testing, trouble-shooting etc.
- Venting mode (6): it allows generating a number of Bang-Bang activations for the first increases of pressure into the plenum tank. This mode only occurs few times throughout the PSA life, mainly during the initialisation of the system.

SGEO PSA – PRP Description

The SGEO PSA Pressure Regulator Panel is the mechanical part of the PSA. A picture of the 3D model is reported in Figure 5. Components labels are in line with the diagram shown in Figure 1.

The PRP components are mounted on an Aluminium base plate, solution that makes the PRP a standalone unit which can easily be integrated in the system. The inlet, connected to the Xenon tanks, and the 3 outlets, two for the EP and one for the CGT, are located in the left part of the PRP, as shown in Figure 5. Fill and Drain Valve and Test Port valve outlets are located on the right side of the PRP, according to Figure 5. All the inlet-outlet tubing is Titanium (O.D. 6.35 mm).

The system is equipped with a high pressure filter (F0), and two high pressure transducers (HPT1 and HPT1r). A transition joint allows the change to stainless steel in the line, together with a change in diameter (O.D. 3.17 mm). The six solenoid valves (SV1 to SV3r) are the BB valves, core of the regulator.

At the BB valves outlet a Heating Plate compensates the strong Joule-Thomson cooling effect, mainly in the CGT modes at the Beginning of Life (BOL). In this situation, the average heating power required to keep the Xenon at 20 °C

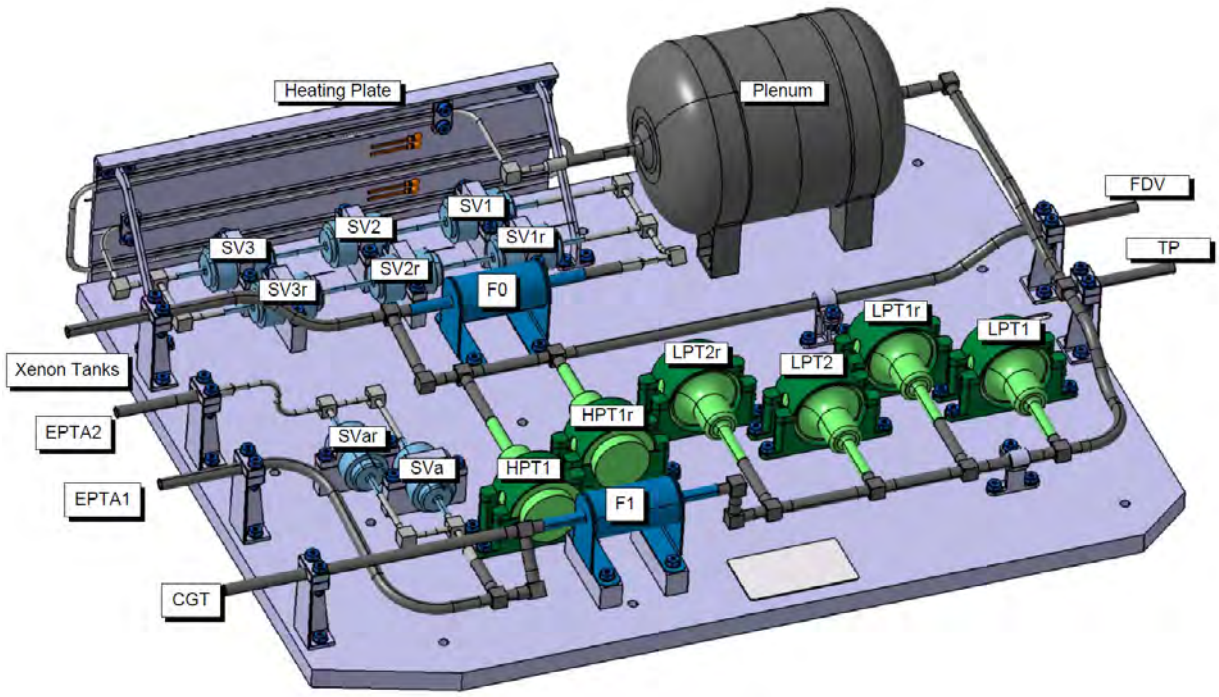

Figure 5: SGEO PSA PRP 3D view - PFM

is approximately 13 W (assuming a maximum mass flow of 200 mg/s). In order to provide such power, two Kapton strip heaters H1 and H1r are installed on the back side of the Heating Plate, (not visible in Figure 5); on the front side four thermistors (Th1 to Th2r) are measuring the temperature of the plate on points close to the tube outlet (visible in Figure 4 but not labelled), feeding the thermal control loop.

The line is changed back to Titanium, and a Plenum is included to damp pressure spikes during valve operation, and especially during Cold Gas Thruster operation. The volume of this plenum tank is directly related to the range of the pressure oscillations during the Bang-Bang regulation. The greater the volume of the plenum, the lower the range of the pressure oscillations, but the greater the system mass.

The four low pressure transducers (LPT1 to LPT2r) are located right downstream the Plenum. A second filter (F1) is located before the splitting of the tubing, filtering all the outlet tubing.

In the current PFM configuration, only EPTA2 line is equipped with isolation valves (SVa and SVar). These valves are normally closed and only one of them is opened if the EP thruster branch associated is going to be operated. Only one outlet will be operated each time: no simultaneous feeding of different branches is allowed.

The PRP size is 480 mm x 372 mm x 122 mm (LxWxH). The estimated mass is 4.8 kg.

The power consumption in the worst case of the PRP is:

- Stand-by mode: 1.3 W
- EP mode: 8.8 W
- CGT mode: 23.30 W

SGEO PSA-SCE Description

The SCE unit is composed of two identical and redundant modules (SCE module1 and SCE module2), interfacing respectively with the nominal and redundant actuators and sensors of the PSA PRP.

Each SCE module is connected to the spacecraft primary power bus through a dedicated Latching Current Limiter (LCL). Each SCE module is set ON and OFF through dedicated telecommands sent by the spacecraft and provides a direct ON/OFF status, a direct telemetry of the current on the primary power bus (excluding the consumption of the heater) and a direct telemetry of the SCE PCB temperature.

Each SCE module interfaces with the spacecraft nominal and redundant (A and B) MIL-STD-1553B buses and responds to a specific RT address, whose value is fixed by a set of strapping on an external connector.

Each SCE module is functionally and electrically independent, no electrical cross-strapping is done between both modules.

The main functions of the SCE module are:

- An Input Power Switch to set ON and OFF all the SCE electronics by connecting the power bus to the SCE converter and to the Heater driver.
- A Heater line driver supplying the heaters on the PRP.
- A DC-DC converter, providing secondary voltages to supply the module electronics, a secondary supply to the external Pressure Transducers and a secondary supply to command the PSA solenoid valves.
- A valve driver function, including an over-current protection and 5 valves drivers (SV1, SV2, SV3, SVA and SVB) to command the PSA solenoid valves situated on the.
- An Acquisition function providing a polarisation voltage for the PSA pressure transducers through an over current protection and acquiring the thermistors (Th1, Th2, Ta1 and Tt1) and pressure signal (HPT, LPT1and LPT2) of the PSA, as well as internal voltages and temperature of the SCE module.
- A 1553 and Control function, making receiving Telecommands and sending Telemetries through the MIL-STD-1553B bus (MIL-1553-IF) and controlling the pressure and thermal regulation of the PSA, managing the

Heater and Valves drivers and the PT and Thermal acquisition chain.

All these functions are managed by a FPGA.

The SCE operate in cold redundancy. Nevertheless, it is possible to power ON the redundant module while the nominal is ON for monitoring. In this case the second module shall be in Standby Mode.

The two cards are installed in a classic box, depicted in Figure 6.

Figure 6: PSA SCE Box Outline

The SCE is 250 mm x 210 mm x 75 mm (LxWxH). The estimated mass is around 2 kg. The nominal power consumption of the SCE itself is around 5 W.

SGEO PSA Performances

The SGEO PSA performances have been predicted using a dynamic simulation model of the PSA. This model has been built using the dynamic simulation tool called EcosimPro [2] and the propulsion libraries developed under the ESA project named ESPSS (European Space Propulsion System Simulation) [3].

EcosimPro is a powerful mathematical tool capable of modelling any kind of dynamic system represented by differential-algebraic equations (DAE) or ordinary-differential equations (ODE) and discrete events. Easy to learn and use, EcosimPro is an integrated visual environment similar to Microsoft Visio and Visual Studio. It can be used to study both steady states and transients.

The purpose of the ESPSS libraries is to provide standard set of libraries with components and functions for the simulation of launch vehicle propulsion systems and spacecraft propulsion systems. The ESPSS also provides a standard database for propellants, pressurants and other fluids for simulation.

The EcosimPro model can compute the Xenon state in its passage through the PSA solving the thermal-fluid model of the system and simulating the control logic which commands the valves and the heaters. It is important to highlight that the simulation model takes into account real properties of the Xenon fluid.

The schematic of the EcosimPro simulation model of the SGEO PSA is shown in Figure 7.

The simulation model enables the following analyses:

- To support the sizing of the Xenon heating plate and the electrical heaters
- To verify that the PSA design copes with the operational requirements of the system
- To calculate the maximum mass flow that the PSA can deliver depending on HPN pressure and temperature
- To estimate the opening time of the bang-bang valves in order to keep the pressure overshoot within the accuracy requirement of the regulator (+5%/-5% for the Electric Propulsion Mode and 5%/-20% for the Cold Gas Thruster Mode through-out the PSA life).

One of the most important analyses carried out was to verify the fulfilment of the PSA mass flow requirements under the most critical inlet conditions for each operation mode, that is:

- The calculation of the total number of activations of the Bang-Bang sequence throughout all the mission life
- EP: EOL conditions, tank pressure is lower than 15 bar
- CGT: EOL conditions, tank pressure is lower than 15 bar
- CGT: pressure in the HPN is around 55 bar.

For EP mode there are two EP thruster branches (EPTA1 and EPTA2) that will demand a different Xenon mass flow.

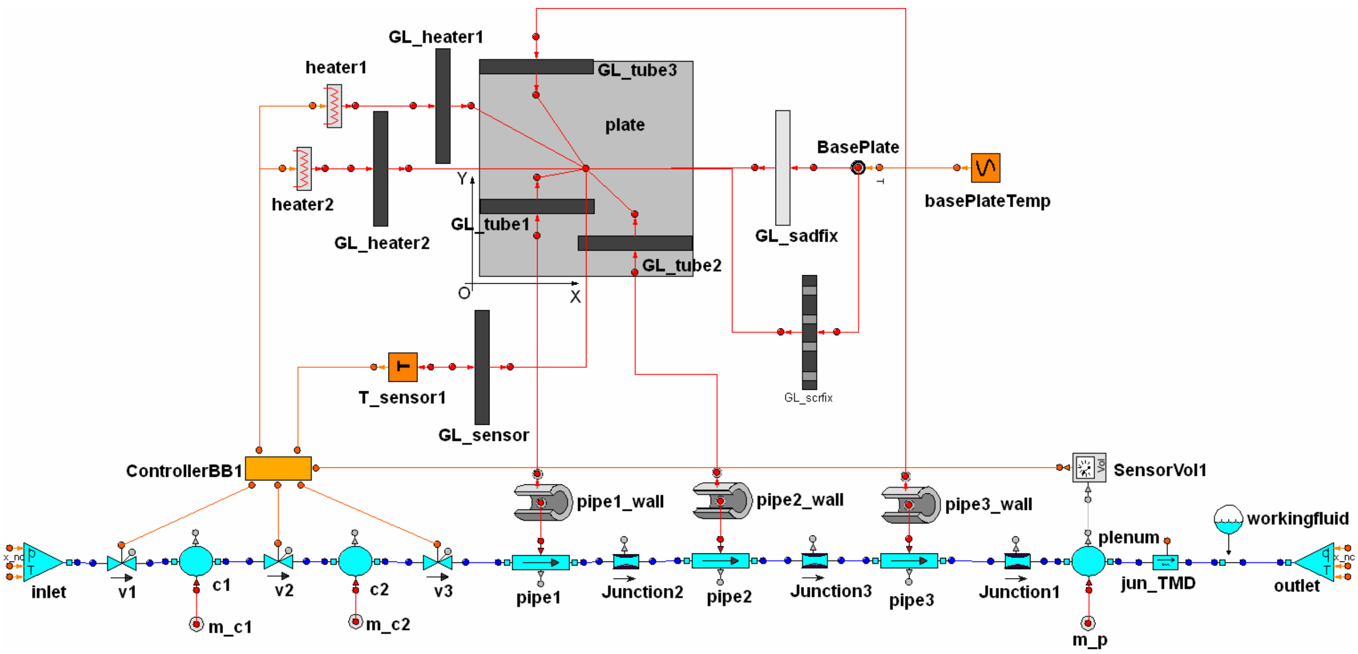

Figure 7: Schematics of the EcosimPro simulation model of the SGEO PSA

The maximum mass flow that PSA can provide at different HPN conditions at EOL is shown in Figure 8.

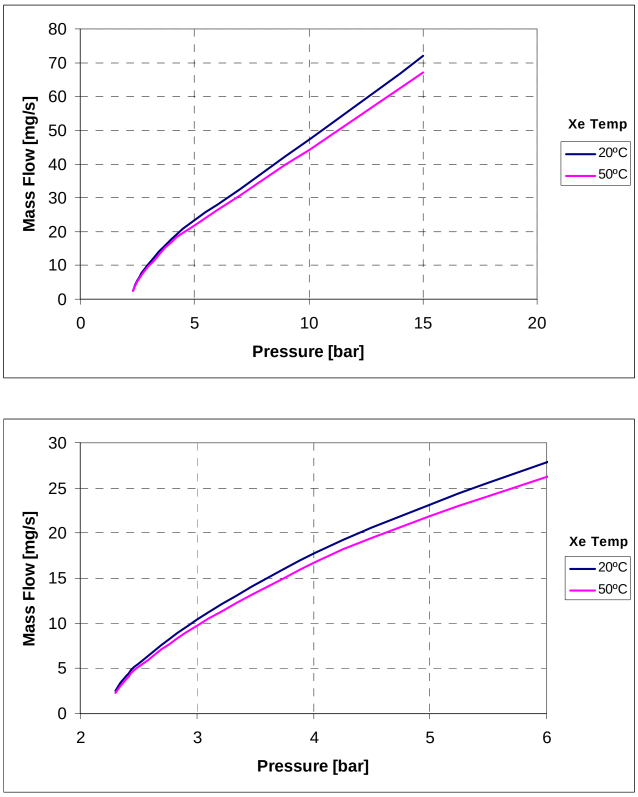

Figure 8: Maximum mass flow at different HPN conditions at EOL

From Figure 8 we can draw the minimum HPN pressure at which PSA can maintain different Xenon mass flows. These values are depicted in the table below:

Table 1: Minimum operation pressure for different Xenon mass flows

Xenon mass flow [mg/s]	HPN Pressure [bar] @ 20 ºC	HPN Pressure [bar] @ 50 ºC
2	<2.3	<2.3
4	2.39	2.41
5	2.46	2.48
10	2.95	3.03
25	5.4	5.7

The PSA must maintain a Xenon mass flow rate of 200 mg/s in CGT mode for HPN pressure greater than 55 bar. Figure 9 shows the mass flow that the PSA can maintain when the pressure condition at the HPN is 55 bar versus the opening time of the Bang-Bang valves (considering, in the presented analysis, the same opening time for both the valves operating the BB).

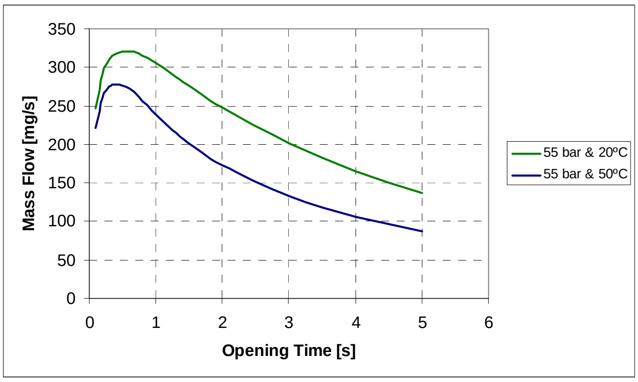

Figure 9: Average mass flow supplied by PSA at 55 bar in HPN

According to the previous results, the minimum pressure at HPN for operating in CGT mode at EOL would be around 6 bar, while the minimum pressure for operating in EP would be around 3 bar but it depends on the mass flow demanded by the EPTA. In addition, the PSA can maintain a Xenon mass flow of 200 mg/s in CGT mode for HPN pressure greater than 55 bar according to Figure 9.

Another interesting study was the calculation of the total number of activations of the Bang-Bang sequence throughout all the mission life. Figure 10 shows the accumulated number of Bang-Bang actuations as a function of the HPN pressure and temperature. The HPN pressure limit used for operating with 1-cavity mode and 2-cavity mode is represented with the orange dashed line. When the HPN pressure is lower than 60 bar, the PSA will operate using the 2-cavity mode, i.e. the Bang-Bang valves used are SV1 and SV3.

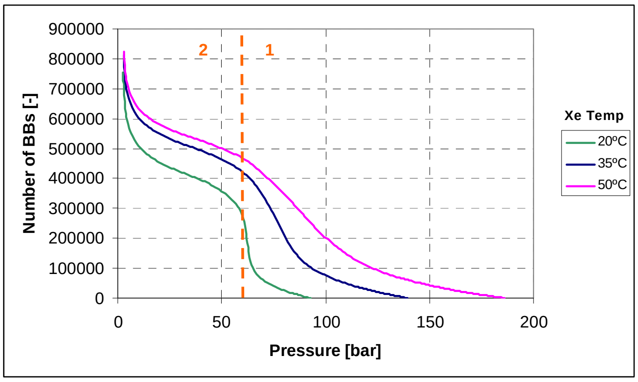

Figure 10: Accumulated number of BB actuations vs. pressure at HPN

Finally, Figure 11 shows the number of Bang-Bangs activations performed as a function of the mass throughput.

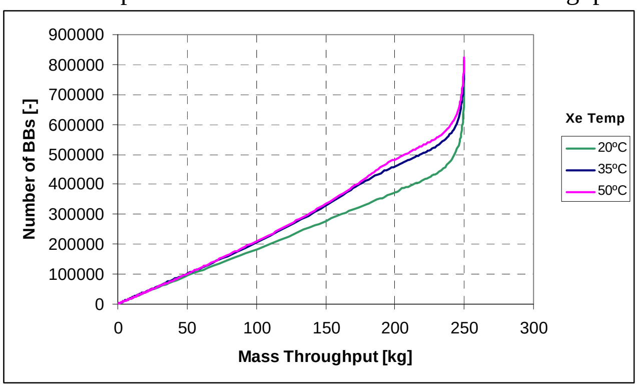

Figure 11: Number of Bang-Bang Activations vs. Mass Throughput

Development and Qualification philosophy

The PSA proposed by IberEspacio is a new development of a Bang-Bang Pressure Regulation Unit based on the BPRU of the SMART-1 Probe, which was flight qualified and operated successfully between 2001 and 2003.

The SMART-1 EPS was designed as single-string system, but with some internal redundancy. The SMART-1 mission not only showed that the propulsion system performed as expected, but also that the system reliability (designed mostly as “single-string”) was very good, despite the challenging environmental conditions throughout the mission (repeated crossings of radiation belts, solar flares, lunar albedo). This was achieved whilst complying with the SMART-1 programme low cost approach [4].

Similarity to SMART-1 has been kept whenever it was possible, and modifications to the SMART-1 BPRU conceptual design have only been made to accommodate the new requirements for a telecommunication satellite.

The qualification approach, for the PSA PRP, is based on the manufacturing of two models:

1. Engineering Model (EM): identical to the Protoflight Model in components and design, but without hardware redundancies. The EM will be used to perform a complete life test, validating the control setting deduced by analysis and the different operational mode (EP and CGT). Compatibility tests to the EP and CGT will also be performed.
2. Protoflight Model (PFM): used to perform all the qualification testing levels at acceptance duration.

For the PSA SCE, three models will be used for the qualification:

1. EM: functional model, no redundant, with commercial components.
2. EQM: same PFM design but without redundant part. Qualification levels and durations will be used. The redundant card will be replaced by a mass and geometrical representative dummy.
3. PFM: used to perform acceptance testing at acceptance levels.

Conclusions

The development of SGEO Propellant Supply Assembly (PSA) that IberEspacio is performing supported by the Swedish Space Corporation has been introduced and presented.

The PSA design and architecture has been described, indicating how the stringent requirements imposed at system level have been implemented and solved, with a limited total mass and size of the system.

An Ecosimpro simulation analysis has been included, in order to demonstrate that the system can supply the desired outlet pressure despite the downstream user mass flow (EP or CGT), keeping the number of actuation far from the qualification limit up to a total throughput of 250 kg of Xenon.

The development status of the project has been reported, indicating that in a short term the PRP qualification will go through en Engineering Model for the functional part, and a Protoflight Model for a full test campaign. The SCE qualification will be based also on a third EQM unit.

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