

The Xenon Regulator and Feed System For Electric Propulsion Systems

IEPC-2005-066

*Presented at the 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005*

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At the start of the Eurostar 3000 development, EADS Astrium Ltd opted to implement electric propulsion on their largest telecommunication platform, using xenon as the propellant. The precise pressure required by the electric thrusters raised the question of developing a reliable xenon pressure regulator for the mission life. An internal investigation and trade off, including make or buy and mechanical regulator options, concluded that the best route was to select an electrical pressure regulator (Xenon Regulator and Feed System, XRFS); based on experience and expertise gained on the Artemis program, the decision was taken to design and qualify the equipment “in house”. This paper describes the XRFS and complete regulation system, summarizing its development, qualification, operation, and in-orbit results.

I. Introduction

Spacecraft Electric Propulsion (EP) systems, whether Hall Effect Thruster or Ion Thruster technologies, will require a regulated supply of inert gas propellant, typically xenon gas. The standard feed system for EP applications employ a pressure regulator to regulate the propellant tank pressure to a constant pressure over mission life as shown in fig.1. This regulated pressure of propellant is then fed to the thruster Xenon Flow Controllers and is controlled by the Power Processing Unit (PPU) in a feed back loop in response to the thruster performance.

The EADS Astrium electric propulsion system utilizes an electronic regulation scheme using a “bang-bang” method of control of the pressure by actuation of a regulating valve, with a plenum volume located downstream of the valve to provide damping of the resulting pressure ripple to within acceptable limits for the thrusters, whilst ensuring that the number of valve actuations are kept to an acceptable level for the valve design. Restrictors are included downstream of the regulating valves, in order to control the flow rate into the plenum and limit the rate of pressure change at XRFS outlet during plenum fill. This effect is most pronounced at beginning of life (BOL), when the XRFS inlet pressure is highest. The above requirement also has to be balanced against the need to be able to provide the required flow rate at end of life (EOL), when the XRFS inlet pressure is a minimum.

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The XRFS has been designed so that as a generic equipment it can meet the requirements of a wide range of potential applications, with a specific first application of the EADS Astrium Eurostar E3000 telecommunications platform^{4,5}. The XRFS is based on the Electric Pressure Regulator Mechanism (EPRM) qualified and delivered by EADS Astrium for ESA's Artemis satellite^{1,2}. This later regulator operated flawlessly throughout the EP part of the mission recovery orbit raising, following a launcher partial failure³.

The main design drivers that lead to this evolution from the EPRM design are:

1. Higher maximum operating pressures
2. Higher flow rates
3. Higher total mass of propellant

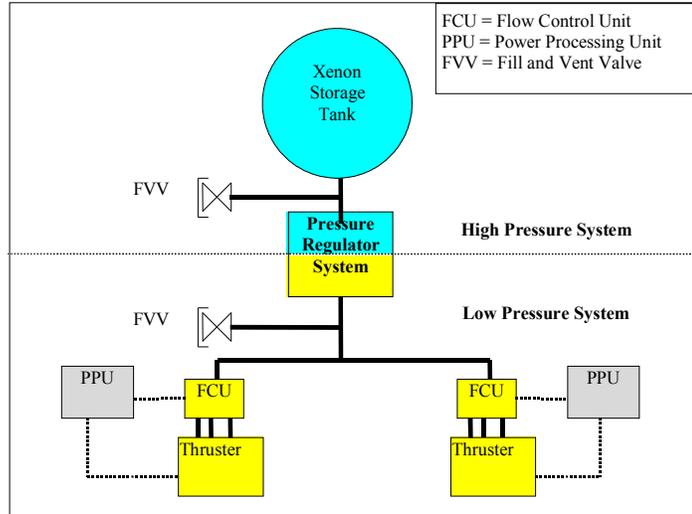


Figure 1. Typical Electric Propulsion System Block Diagram

As a result this design of the XRFS has improved performance and greater structural integrity over the EPRM and is also cheaper to build and is a more robust and versatile design.

The design is such that the XRFS components, which change the performance, are isolated so that they can be easily altered to optimize the system for different performance requirements. The performance is changed by only a one for one replacement of 2 piece parts. The manufacturing processes remain unaffected

The requirements and therefore critical design drivers vary between applications; these are:

1. Inlet pressure
2. Regulated (output) pressure – typically $\pm 5\%$
3. Internal leakage
4. External leakage
5. Power
6. Mass
7. Minimum and maximum mass flow rate
8. Thermal and vibration survival
9. Proof and burst pressure limits

II. Design Description

The XRFS is an electronic pressure regulator which uses a system of valves, plenum volumes, pressure transducers and flow restrictors to regulate the high pressure xenon propellant stored in the Xenon Storage Tank (XST) to a nominal constant pressure over mission life, at the required mass flow rate. The Pressure Regulator Electronics (PRE) and Spacecraft Computer Unit (SCU) control the XRFS.

The XRFS comprises the following:

1. Normally closed Solenoid valves. The valves are arranged in 2 parallel redundant regulating branches, each branch capable of fulfilling all mission requirements. Each branch consists of 3 solenoid valves in series. This arrangement provides 3 independent inhibits for ground safety, as well as a high degree of reliability and failure tolerance in orbit. The valves are an EADS Astrium own design and are manufactured in-house. These valves are fitted with into a valve block. This arrangement minimizes the dead volumes, which leads to better control of the pressure ripples.
2. The XRFS also contains 2 high pressure and 4 low-pressure transducers that are used to monitor the inlet and outlet pressure conditions and provide inputs for the regulation control loop.
3. Flow restrictors to limit the plenum-filling rate.
4. A plenum volume which is sized in order to ensure the beginning of life valve 'open' times are in specification, and to limit the number of regulator valve cycles required by the system over mission life.

5. The inlet and outlet filters ensure the XRFS, and the thruster modules downstream, are protected from any anomalous particulate contamination, which could degrade the performance of the XRFS and the thruster modules.
6. Thermal hardware. Thermistors are required to monitor the XRFS temperature. Heaters and thermostats are provided to ensure that the temperature of the XRFS high-pressure system is kept above +27°C (to avoid, with margin, the possibility of xenon condensation).

The functional schematic of the XRFS is shown in fig. 2 below:

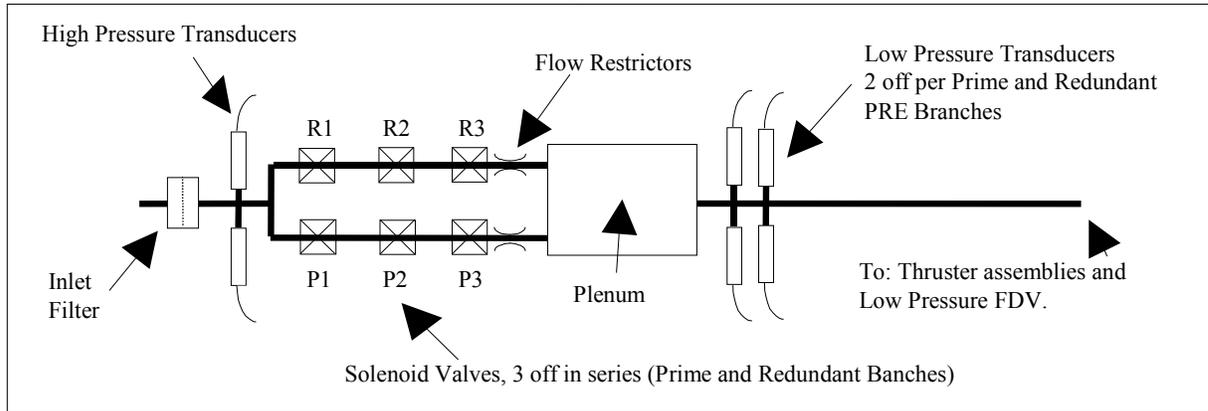


Figure 2. XRFS Functional Schematic

III. Baseline Performance Requirements

The main requirements, which the unit was developed to, are summarized in the table 1:

Table 1. XRFS Requirements

No.	Parameter	XRFS Requirements
1.	Max Inlet Pressure (Non operating) (MEP)	150 bar
2.	Max in flight operating pressure (MEOP)	120 bar
3.	Proof Pressure	270 bar
4.	Burst Pressure	450 bar
5.	Outlet (regulated) Pressure	2.65 bar \pm 0.2 bar
6.	In series Mechanical Inhibits	3
7.	Mass Flow Rate	>6mg/s gaseous xenon
8.	Total Propellant throughput	300 kg max.
9.	Total valve cycles	666000 (1 million qualification)

IV. Development and Qualification

The XRFS has evolved from the work carried out on the Artemis Electric Pressure Regulator Mechanical assembly (EPRM), shown in fig. 3, with design modifications to make it a more compact unit. The valve design was also enhanced to allow for higher pressures.

The strategy for the development of the XRFS was to use as much heritage from the Artemis programme as possible. Essentially the functional design of the valve remains unchanged. The XRFS development programme focused on the key areas of the XRFS that need to be redesigned, including the structural integrity of the pressurized system, the vibration qualification of the new layout and the new thermal performance of the equipment.

To meet the latest requirements the original EPRM required the following modifications:

- Three in series valves per regulator branch (previously two valve for Artemis IPP) to allow for a sufficient number of barriers.
- Valve structural integrity to be analyzed and increased for the higher-pressure requirements.

- Larger plenum to maintain the total number of valve cycles within acceptable limits, due to significantly higher propellant mass throughput over life.

The breadboard model was assembled early on so that pressure overshoots and plenum sizing could be optimized together with the overall number of actuations. This enabled the command algorithm to be frozen.

These modifications were tested through valve life cycle tests. In parallel the valve command interface was validated on an engineering model coupled with driving electronics. Once this validation was achieved, the design was frozen and ground support Equipment could be procured which mimicked the spacecraft driving electronics at XRFS interfaces.

This overall regulation system was qualified and validated as follows:

- All XRFS (development, qualification and flight units) have been subjected to pressure regulation acceptance tests performed at equipment level, coupled with the regulation EGSE. The XRFS engineering model regulation test provided the numerical inputs required for the flight regulation software
- Qualification of the complete XRFS regulation loop was achieved using the EM XRFS, and the EM PRE and SCU, with the flight regulation software resident in the SCU. This included testing under hot and cold conditions for both prime and redundant branches
- The final tests of the XRFS regulation loop was performed using the flight PRE, SCU and XRFS integrated onto the spacecraft. For the first E3000 application, these regulation tests were performed during the spacecraft thermal vacuum cycles, but for the following E3000 applications, these tests were performed only at ambient temperature

All the above tests were completed successfully, with all performances as expected. Of particular note was the excellent performance repeatability between units and between tests using the EGSE and the PRE/SCU combination.

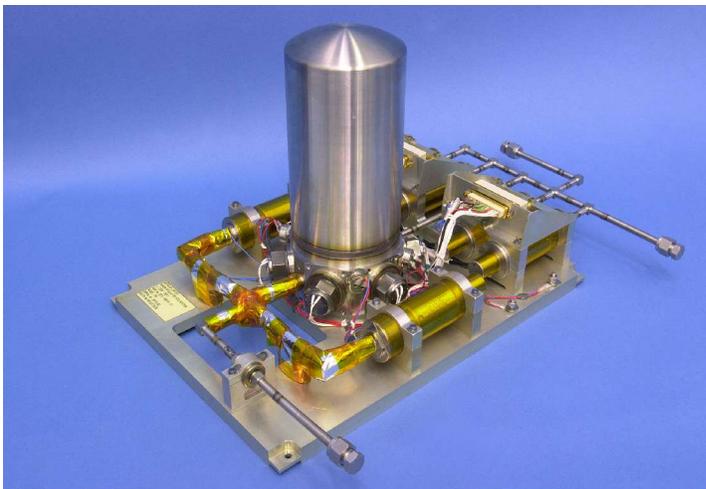


Figure 4. XRFS Hardware

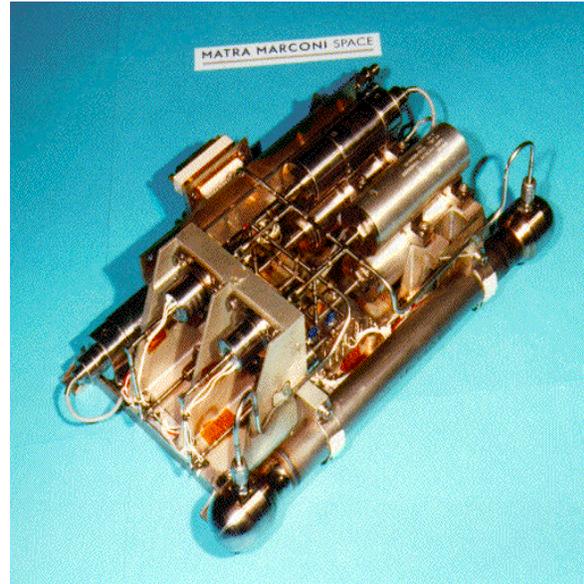


Figure 3. EPRM Hardware

This confirmed the acceptability of using EGSE for all flight unit acceptance tests.

In parallel to the above, coupled analyses were run to show that induced pressure ripples did not impact the thruster performances beyond acceptable specified limits. This successful system type verification was confirmed when an XRFS, fig. 4, was loaned for thruster ground firings over a significant number of hours (including EMI testing). The behavior was within 1% of the predicted accuracy.

Increased margin requirements were encountered with the production of flight units, which caused some fine-tuning to the design. The first PFM model was successfully tested and delivered for the first Inmarsat 4 spacecraft. To date the in flight behavior has confirmed all the predictions (see below).

V. Operation

During a maneuver with the plasma Propulsion System (PPS) the nominal operation of the XRFS is as follows:

- The two furthest most upstream valves in the active branch nominally operate as Isolation Valves (IV) and are maintained open.
- The third and furthest down stream valve operates as the nominal Regulating Valve (RV) and is pulsed to control the outlet pressure of the XRFS.

Any one valve in either regulation branch is capable of achieving the regulating valve life cycle requirements.

The pressure transducers are used to monitor the inlet and outlet pressure conditions to the XRFS. The PT's are capable of being powered continuously over mission life.

The XRFS can only be activated when the unit temperature is within the defined 'switch on' temperature range.

The thermistor telemetry is required to ensure that the XRFS temperature is within the defined equipment 'switch on' temperature range before switch on.

During all modes of operation the heater power circuit is powered, and the thermostats switch the heater on and off as required.

The XRFS modes of operation are as follows:

- a. Off Mode
During this non-operational mode neither the valves nor the PT's are activated.
- b. Stand-by Mode
During stand-by mode all 6 pressure transducers (2 high pressure and 4 low pressure units) are powered.
- c. On Mode
All pressure transducers are powered. One regulation branch is activated, any one or all valves can be operated in the SCU closed loop or open loop modes.

VI. XRFS Performance

Fig. 5 shows a typical regulation profile from the XRFS. It can be seen that there is a comparatively rapid pressure rise whilst the regulation valve is open, followed by a slow decay as plenum is emptied during the period that the regulation valve is closed, but with the thruster still consuming Xe.

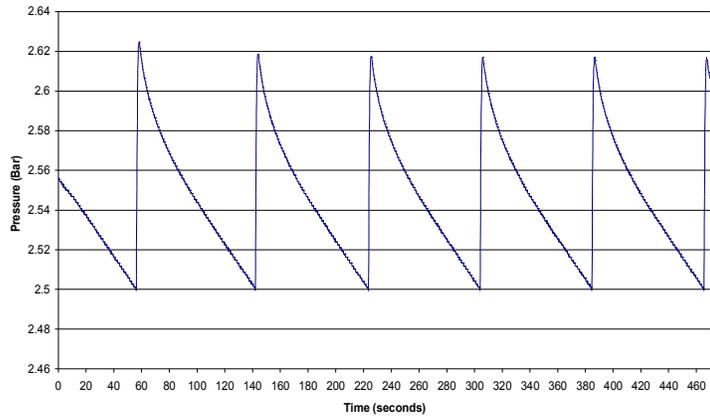


Figure 5. Typical XRFS Regulation Profile

The XRFS outlet pressure ripple (minimum to maximum pressure variation) varies only very slightly with XRFS inlet pressure, as shown in Fig. 6 below (the minimum pressure at which the regulation valve opens does not vary with the inlet pressure). Hence it can be seen that the XRFS provides excellent performance stability independent of its inlet conditions.

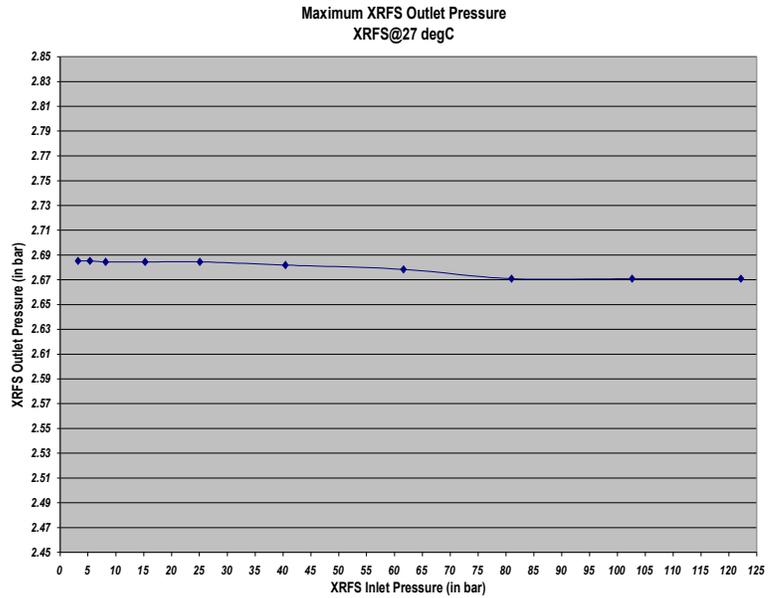


Figure 6. XRFS Maximum outlet pressure vs inlet pressure

The Valve Opening Duration (VOD) increases as the inlet pressure reduces over time. As can be seen from Fig. 7 the VOD can vary from a few milliseconds at BOL to many hundreds of milliseconds at EOL.

Fig. 8 shows the evolution of the Pressure Ripple Duration (PRD) during regulations. The PRD is defined as the time it takes for the pressure at the XRFS outlet to rise from the minimum to the maximum pressure.

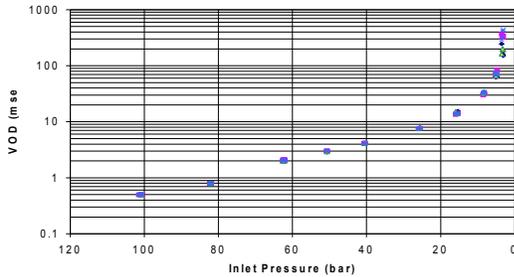


Figure 7. VOD vs. Inlet Pressure

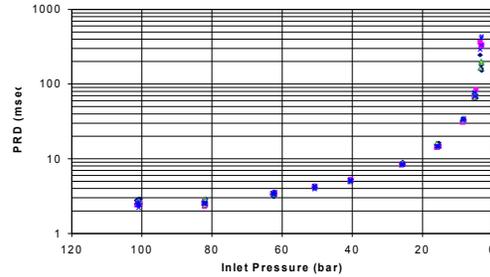


Figure 8. PRD vs. Inlet Pressure

Comparing Fig. 7 and Fig. 8 it can be seen that at inlet pressures below 40-50 bar the VOD is almost equal to the PRD whereas for pressure above 40-50 bar there can be a significant difference between the VOD and the PRD. This is simply due to the fact that the effect of a pressure overshoot resulting from the small trapped volumes in the XRFS, which is less significant under low XRFS inlet pressure conditions.

VII. In Orbit Experience

The XRFS has been embarked and is now operating in orbit on the Inmarsat 4F1 spacecraft⁶. Fig. 9 below shows a typical pressure trace of the XRFS outlet pressure during a thruster firing, taken from the flight TM; it can be seen that this shows excellent stability and cycle to cycle repeatability. The XRFS inlet pressure was gradually increasing during this period of operation, as can be seen from Fig. 9; this is simply due to a slight increase in the tank temperature, and is normal.

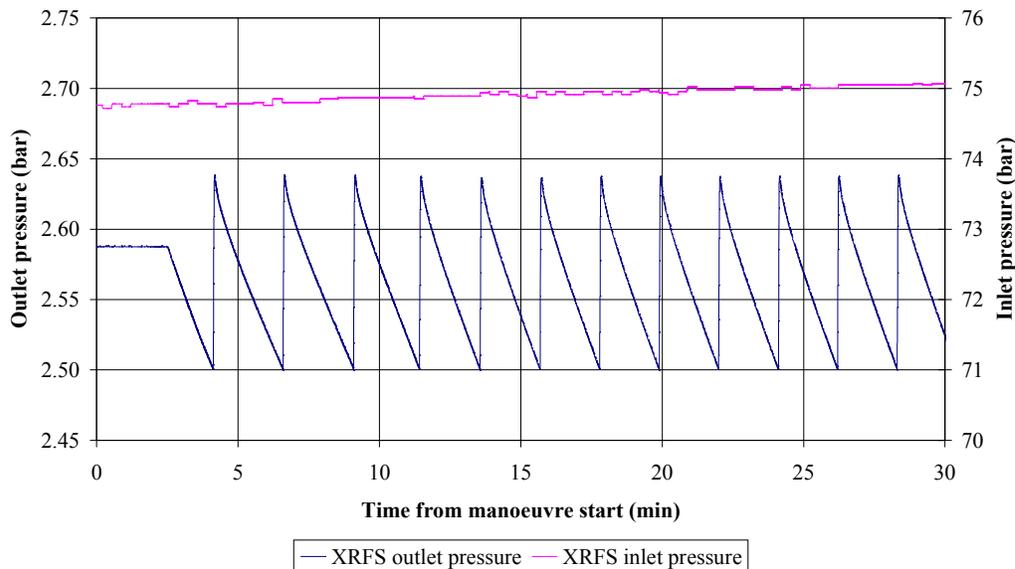


Figure 9. XRFS in orbit performance

VIII. Conclusions

The XRFS takes its heritage from many years of valve design. It has improved performance over the EPRM and is cheaper to build and is more compact. It is versatile in that it can easily be adapted to different mission requirements. The pressure ripple demonstrated from ground tests and in orbit operations is as predicted, and is of sufficiently small duration and magnitude as to have negligible impact on the overall thruster performance. Life testing has shown the XRFS to be robust and maintain excellent leak tightness even at the end of 1000000 cycles.

IX. References

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