A Xenon Propellant Management Sub-Unit For Ion Propulsion *

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Abstract

This paper describes the methodology employed to create an electric propulsion module through the combined expertise of VACCO Industries, NASA, and Mitsubishi Electric Corporation. The result, the Propellant Management Sub-unit (PMS), incorporates a pressure regulation module (PRM) with flow control modules (FCMs). The PRM regulates the high supply pressure to a constant low operating pressure; the flow control modules provide propellant isolation and precision flow to the ion thrusters.

The PMS is modular in design; composed of individual pieces connected by the customer to the spacecraft structure, avionics, piping, and pressure transducers. The basic functions of this PMS are:

- prevention of contaminants from flowing into the propulsion system by use of a 5 micron system filter;
- regulation of xenon gas pressure to an appropriate range;
- isolation control of xenon gas at each latching valve; and
- control of xenon mass flow to each ion thruster within a specified range.

Introduction

Electric propulsion systems are quickly becoming the preferred mode of propulsion in many low earth orbit (LEO), geostationary earth orbit (GEO), and even planetary spacecraft applications. Systems using ion or Hall thrusters are currently planned, or in production, for a wide variety of spacecraft and missions. The driving force behind this shift to electric propulsion is the substantial reduction in propulsion mass that can be realized. Unfortunately, system designers are often forced to use components designed for chemical propellants in their systems. Although functionally acceptable, these relatively large, massive components are designed for the higher pressures and mass flow rates often required by chemical systems. To fully realize the benefits of electric propulsion, modular systems must be developed that are optimized for the low flow rates, critical leakage requirements, low pressures, and limited budgets of these systems.

This paper describes the xenon Propellant Management Sub-unit being produced by VACCO, et al, for the NASA/MELCO flight ion propulsion subsystem. This subsystem is used on the ETS-VIII Satellite (Engineering Test Satellite VIII). The ETS-VIII Satellite will be used to acquire bus technology for 3-ton class geostationary satellites, and basic technology for on-board large scale deployable structures. The Propellant Management Sub-unit (PMS) consists of a pressure regulation module (PRM) and four flow control modules (FCM). Functionally, the PMS filters the xenon, regulates high pressure gas down to the appropriate range, provides the ability to select either the primary or redundant thrusters, facilitates isolation of individual

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thrusters and controls the mass flow to each ion thruster within a specified range as shown in Figure 1.

![Propellant Management Sub-Unit Diagram](image)

**Figure 1. The Propellant Management Sub-Unit**

The PMS, including the pressure regulation module, flow control module and their components are described in this paper. A summary of the requirements at the module level, along with an assessment of the resulting design against those requirements, is included. Each component is individually addressed regarding design features, specification compliance, performance, and heritage.

**Propellant Management Sub-unit (PMS) Description**

The PMS consists of a pressure regulation module (PRM) and four flow control modules (FCM). The PMS provides several key functions for the NASA/MELCO flight ion propulsion subsystem, such as xenon filtering, isolation, pressure control, and flow control. The components required to accomplish these functions have been fully developed and tested. Key components, such as the mechanical regulator, low-pressure torque motor latch valves, and filter, have all been space qualified.

The design represents an excellent combination of low-mass, high reliability, and cost effectiveness. By integrating components together, the number of discreet components required for integration becomes minimized. The remaining components are welded together with 1/4 inch tubing to form the various modules. To minimize cost and facilitate welding, weld fittings, designed for in-house ASTRO ARC Orbital TIG welding equipment are used.

**Pressure Regulation Module (PRM)**

The PRM design (Figure 2) is a precision series redundant pressure regulator, a system inlet filter, and isolation valves for use with xenon gas. This straightforward architecture is similar to pressurization assemblies traditionally used in chemical propulsion systems. The regulator is a conventional mechanical series redundant type requiring no external control. Each regulator of the redundant set is capable of accepting net inlet pressure from the xenon storage tanks (TK Xe) and providing a regulated downstream pressure at a flow rate sufficient to meet specified requirements. The flow of regulated xenon to primary and redundant flow control modules can be isolated by two low-pressure latch valves at the outlet of the PRM.

![Pressure Regulation Module Diagram](image)

**Flow Control Module (FCM)**

The flow control module (FCM) design, as illustrated in Figure 3, provides propellant isolation or precision flow to the ion thrusters (TRS). Flow to each thruster is controlled by individual FCMs. The FCM is a weldment consisting of two low-pressure latch valves and four flow control devices. A low-pressure latch valve (LVL-1) provides the isolation function by controlling the flow of propellant to the whole FCM and its TRS. LVL-1 includes a 25μm inlet filter that helps protect the FCM and TRS from contamination. Downstream of LVL-1, the flow divides into three branches that provide separate flow input to the TRS. One branch contains flow control device #1 and nominally provides 0.65 mg/sec xenon to the main propellant feeder.
A second branch provides xenon flow to the neutralizer hollow cathode. This branch is divided into two parallel paths. One leg contains flow control device #2; the other contains device #3 and low-pressure latch valve #2. These two parallel legs converge into a single output to the neutralizer hollow cathode. When latch valve #2 is closed, flow control device #2 nominally provides 0.06 mg/sec xenon to the neutralizer hollow cathode. When latch valve #2 is open, flow through flow control devices #2 and #3 nominally provide 0.20 mg/sec xenon to the neutralizer hollow cathode.

The third branch contains flow control device #4 and nominally provides 0.20 mg/sec xenon to the main hollow cathode.

Figure 3. Flow Control Module

PMS Performance Analysis

The Propellant Management Sub-unit analysis is comprised of the pressure regulation module analysis and the flow control module analysis. The PRM analysis results show maximum and minimum regulated output pressures the PRM supplies to the FCM across the full performance range of operating conditions and flows. The FCM analysis uses the PRM analysis results to determine the FCM output flow ranges across the full performance range of operating conditions.

PRM Performance Analysis

A PRM mechanical subsystem was simulated to determine system performance during steady state flow demands between 0.0013 and 0.0000 g/s, with temperatures between 45 and 55°C. (The regulator is essentially unaffected by the ±5°C temperature band.) Results of the analysis, as shown in Figure 4, demonstrate a regulated tolerance band of ±0.12 psi (±0.0085 bar):

Figure 4. PRM Inlet Pressure vs. Regulated

Outlet Pressure Across the Full Performance Certified Temperature Range (50 ±5°C)

The PRM is required to control the inlet pressure to the FCM at the nominal set point of 2.76 bar (40 psi) within a tolerance range of ±0.0248 bar (±0.36 psig, or ±0.90% of nominal set point). Regulator testing demonstrates and actual regulation range of ±0.138 bar (±0.20 psi) around the 40 psi nominal set point.

FCM Performance Analysis

The primary purpose of this module is to control outlet flow through each outlet port to within the close tolerance requirements of the performance specification and as noted in the FCM description. This tolerance is maintained across the anticipated temperature and pressure conditions. The system environmental temperature is controlled to 50°F ± 5.

The flow control device (FCD) is a simple static laminar flow restrictor based on VACCO's proven etched disc technology. The FCD is a single piece monolithic device with no moving parts and with multiple flow passages to provide accurate flow resistance and contamination tolerance. The diffusion bonded stacked etched discs form a set of long paths of closely controlled geometry through which the xenon must flow before reaching the FCM outlet. Each FCD can be closely controlled to the approximate flow required, and then finely adjusted to the precise requirement. For higher

1 Patent 5,935,424.
flows to the main propulsion feeder and main hollow cathode, the flow is adjusted to within ±0.90% of the set point flow at nominal temperature and pressure. For lower flow to the neutralizer hollow cathode, the flow is adjusted to within ±5.90% of the set point flow at nominal temperature and pressure.

The flow through the flow control passages can be treated as laminar flow between two parallel plates since the aspect ratio (width/depth) is large. Because the FCD is a static restrictor operating in the laminar flow region, the flow through it can be initially characterized as proportional to:

- Pressure drop across the FCD (dP1)
- Density of the fluid flowing through the FCD (ρ)
- Width of the flow channel (w)
- Cube of the depth of the flow channel (pd).

Likewise, the FCD can be initially characterized as inversely proportional to:

- Length of the flow channel (L) and
- Viscosity of the fluid flowing through the FCD (μ).

\[ q = \frac{dP1 \cdot w \cdot pd^3 \delta}{\mu w L} \]

At a nominal pressure and temperature, the density and viscosity of the xenon gas is a fixed value, and the FCD path geometry (width, depth, and length) can be etched in such a way as to closely approach the required flow. The final flow can then be precisely adjusted by opening additional sealed paths in controlled steps to reach the exact flow requirement within the referenced flow tolerance of ±0.90% in the case of MPF and HFC flows, and ±5.90% in the case of the lower NHCF flows. That set point flow is then affected only by variations in:

- FCM inlet pressure that directly affects the density of the xenon gas at the FCD, and
- the xenon gas temperature that affects both the viscosity and density of the xenon gas.

As the xenon gas pressure increases at the inlet to the FCM, the gas density also increases in reasonably close adherence to the ideal gas law. This is true at 2.76 bar, but would not hold true at higher pressures where xenon does not closely follow the ideal gas law.

As the xenon gas temperature increases, the gas density decreases in reasonably close adherence to the ideal gas law. This is true at 2.76 bar, but would not hold true at higher pressures where xenon does not closely follow the ideal gas law.

As the xenon gas temperature increases, the gas viscosity also increases in a reasonably linear way within the temperature range of 17 to 65°C. The viscosity of xenon gas at 40 psi, in micro-poise, can be closely approximated by the equation:

\[ \text{Viscosity} = 0.75 \times (T) + 211 \]

Where T is the gas temperature °C, and Viscosity is in micro-poise.

Based on these analytically derived relationships, the specified allowable temperature range of 50°C ±5 can be shown to have a temperature related viscosity effect of ±1.56% on the final flow; likewise, a temperature related density effect of ±1.60% can be shown. In addition, the effect of pressure variations at the inlet to the FCM due to the PRM regulated pressure tolerance of ±0.90% has a direct effect on the final flow of ±0.90%.

These analytical values are solidly backed by development test data that show a direct effect to flow by the FCD inlet pressure. Likewise, across a temperature range of 70 to 120°F (a difference of 25.56°C), test data show a combined temperature related viscosity and density affect of ±3.16 to ±3.24% across an equivalent variation of ±5°C. This closely matches the sum of the ±1.56 and ±1.60% temperature related viscosity and density effects as shown above (±1.56% + ±1.60% = ±3.16%). These test data include a small measurement related error over and above the temperature related affects.

**PMS Performance Analysis Conclusions**

At a nominal temperature of 50°C, and a nominal regulator set point of 2.76 bar, the system tolerance for the flow from FCD #1 to feed the main propellant feeder, and from FCD #4 to the main hollow cathode can each be
controlled to within ±5% of the nominal set flow as tabulated in Table 1.

<table>
<thead>
<tr>
<th>ITEM #</th>
<th>ITEM DESCRIPTION</th>
<th>± FLOW TOLERANCE EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Assembly &amp; Mfg. Tolerance of FCD</td>
<td>0.90%</td>
</tr>
<tr>
<td>2</td>
<td>Viscosity Effect due to Temperature</td>
<td>1.56%</td>
</tr>
<tr>
<td>3</td>
<td>Density Effect due to Temperature</td>
<td>1.60%</td>
</tr>
<tr>
<td>4</td>
<td>Assembly &amp; Mfg. Tolerance of Regulator</td>
<td>0.28%</td>
</tr>
<tr>
<td>5</td>
<td>Inlet Pressure Related Tolerance of Regulator</td>
<td>0.62%</td>
</tr>
<tr>
<td>6</td>
<td>Temperature Related Tolerance of Regulator</td>
<td>0.00%</td>
</tr>
<tr>
<td></td>
<td>Total Cumulative Flow Tolerance</td>
<td>4.98%</td>
</tr>
</tbody>
</table>

Table 1. Performance Analysis Conclusions for FCD #1 and #4

At a nominal temperature of 50°C, and a nominal regulator set point of 2.76 bar, the system tolerance for the flow from FCD #2 to feed the neutralizer hollow cathode, and from FCD #3 also to the neutralizer hollow cathode will each be controlled to within ±10% of nominal set flow as tabulated in Table 2.

<table>
<thead>
<tr>
<th>ITEM #</th>
<th>ITEM DESCRIPTION</th>
<th>± FLOW TOLERANCE EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Assembly &amp; Mfg. Tolerance of FCD</td>
<td>5.00%</td>
</tr>
<tr>
<td>2</td>
<td>Viscosity Effect due to Temperature</td>
<td>1.56%</td>
</tr>
<tr>
<td>3</td>
<td>Density Effect due to Temperature</td>
<td>1.60%</td>
</tr>
<tr>
<td>4</td>
<td>Assembly &amp; Mfg. Tolerance of Regulator</td>
<td>0.28%</td>
</tr>
<tr>
<td>5</td>
<td>Inlet Pressure Related Tolerance of Regulator</td>
<td>0.62%</td>
</tr>
<tr>
<td>6</td>
<td>Temperature Related Tolerance of Regulator</td>
<td>0.00%</td>
</tr>
<tr>
<td></td>
<td>Total Cumulative Flow Tolerance</td>
<td>9.96%</td>
</tr>
</tbody>
</table>

Table 2. Performance Analysis Conclusions for FCD #2 and #3

This ±10% tolerance target allows for additional margin in achieving the lowest nominal flow of 0.06 mg/s to the neutralizer hollow cathode through FCD #2 when LVL #2 is closed.

The flow measurement instrumentation tolerance is separate from, and not included in this total cumulative flow tolerance. To minimize the effect of instrumentation error, high accuracy unit mass flow meters were selected. These mass flow meters provide for measurement accuracy of ±1% of reading.

Component Performance

**Flow Control Device**

VACCO's flow control device (see Figure 5) is a single piece, all metal, passive flow restrictor that accurately delivers a precise gas flow. VACCO's FCD provides a number of practical benefits over other products considered or used for the same application. The FCD makes use of a flight-proven stacked-etched disc technology VACCO used on thousands of units over the past 50 years for space flight applications.

Figure 5. VACCO Flow Control Device

The design and performance characteristics are:

- Operating pressure: 0 to 5 bar
- Proof factor of safety: > 20
- Burst factor of safety: > 36
- Operating temperature: 45 to 55°C
- Non-operating temperature: −40 to 70°C
- Flow tolerance: <± 3.24% of set point flow across 10°C temperature range
- External Leakage: <1 x 10⁻⁶ scce/sec GHe at 5 bar inlet pressure.

**5 Micron Inlet Filter**

Figure 6. VACCO's 5 Micron Inlet Filter

VACCO's 5 micron inlet filter (see Figure 6) assures that no particles larger than 5 microns will enter the pressure regulation module. The

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1 Patent 5,935,424.
PRM inlet filter is similar to others designed and built by VACCO since 1963.

The Design and Performance Characteristics of the 5µm inlet filter are:

- Operating pressure: 0 to 150 bar
- Proof pressure: > 413 bar
- Burst pressure: > 825 bar
- Operating temperature: 17 to 70°C
- External leakage: < 1 x 10^{-6} sccs GHe at 150 bar inlet pressure
- Dirt capacity: 0.11 grams AC fine dust

The design heritage includes: the Space System/Loral-LS1300 bus (manufactured in CRES), the Matra Marconi/British Aerospace cluster filter (manufactured in titanium), and the Hughes HS-601, HS-601HP, and HS-702 (all manufactured in titanium).

**Miniature Latching Valve**

VACCO's miniature latching valve is ideally suited to the flow control module because of its uniquely simple design, small size, and superior performance. It is a highly robust design with redundant position indication and an integral flow control device. The valve is fully developed, and provides a strong magnetic latching circuit using simple and reliable construction. The only materials within the seal welded flow path are stainless steel, and Viton. Figure 7 shows the miniature latching valve VACCO designed, developed, and delivered to Lawrence Livermore National Laboratory - Tango Program.

- Operating voltage: 21 to 32 VDC
- Response time: < 50 ms
- Power consumption: < 31 W @ 17°C and 32 VDC
- Operating pressure: 0 to 5 bar (capable of > 20 bar)
- Proof pressure: > 31 bar (Demonstrated proof pressure at 310 bar)
- Burst pressure: > 1344 bar
- Operating temperature: 17 to 70°C (Demonstrated operating temperatures from -18 to 71°C)
- External leakage: < 1 x 10^{-6} sccs GHe at 5 bar inlet pressure
- Internal leakage: < 1 scch at 0 to 5 bar inlet pressure (Demonstrated < 1 x 10^{-6} sccs GHe at up to 20 bar inlet pressure)
- Cycle life: > 10,000 cycles (Demonstrated 20,000 life cycles)

**Series Redundant Xenon Pressure Regulator**

The PRM uses a fully qualified xenon regulator previously qualified for a European satellite for use in their plasma propulsion system (Figure 8). This regulator is a proprietary design of the Stanford Mu Corporation Space Components Division. This direct acting, series redundant regulator was designed, developed, and qualified for high pressure xenon service.

![Figure 7. Miniature Latching Valve](image)

![Figure 8. Stanford Mu Corporation's Series Redundant Xenon Pressure Regulator](image)
• Regulation accuracy: within ± 0.36 PSI of nominal regulated outlet pressure
• Inlet pressure range: 2200 PSIG to 73 PSIG
• Nominal temperature range: 50 ±5°C
• Nominal flow demands: 0 to 4 mg/sec (40 sccm) GxHe
• Dynamic stability under all operating conditions including rapid application of inlet pressure by a pyrotechnic valve and system flow demands
• Operating pressure: 0 to 150 bar
• Proof pressure: > 225 bar
• Burst pressure: > 382 bar
• Operating temperature: 17 to 70°C
• External leakage: < 1 x 10⁻⁶ sccs GHe at 150 bar inlet pressure
• Internal leakage: < 1 scch at 5 to 150 bar inlet pressure
• Internal leakage: <1 x 10⁻⁶ sccs xenon over full inlet pressure range @ lockup
• Additional Features: Qualified active flow limiter to minimize slam start effects.

• Operating voltage: 21 to 32 VDC
• Response time: < 50 ms
  (Typical response in <15 ms at the noted conditions)
• Power consumption: < 30 W @ 17°C and 32 VDC
• Operating pressure: 0 to 5 bar (designed for up to 31 bar operating pressure)
• Proof pressure: > 62 bar
• Burst pressure: > 165 bar (actual burst > 620 bar)
• Operating temperature: 17 to 70°C,
  (qualified to -18 to 70°C.)
• External leakage: <1 x 10⁻⁶ sccs GHe at 5 bar inlet pressure.
• Internal leakage: <1 scch at 0 to 5 bar inlet pressure
• Cycle life: > 10,000 cycles
  (Demonstrated life > 20,000 cycles)

Summary

The xenon Propellant Management Sub-unit being designed and manufactured for the NASDA/MELCO flight ion propulsion subsystem represents an important advancement in feed system technology. The modular approach employed here results in an economical, high performance system while significantly lowering both procurement and integration costs. This work is expected to have an industry-wide impact by making qualified, low cost, standardized feed system modules available for the first time. This should assist designers of electric propulsion systems to realize the full potential of this technology in future applications.

Torque Motor Latching Valve

VACCO's torque motor latching valve (see Figure 9) has a long and successful heritage in similar applications. It has been used for chemical systems in both gas and liquid applications. Most recently, it has been qualified and flown for xenon propulsion systems. The valve provided for high reliability and long life operation.

Figure 9. VACCO's Torque Motor Latching Valve

The design and performance characteristics of our torque motor latching valve are: