Photo-Chemically Etched Construction Technology for Digital Xenon Feed Systems*†‡

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Abstract

A team led by VACCO Aerospace Products has designed xenon pressure and flow control modules utilizing a new proprietary technology called Chemically Etched Miniature Systems™ or ChEMS™. These modules have the ability to control pressure and xenon flow rate set points as well as compensate for changing inlet pressure and temperature conditions.

This paper documents the capabilities and attributes of these modules in sufficient detail to allow system designers to apply them in order to realize the full potential of electric propulsion.

† ChEMS™ is a trademark of VACCO Industries.
‡ Patent pending.

Xenon Feed System Overview

The subject Xenon Feed System (XFS) is an innovative design based on a new proprietary VACCO technology called Chemically Etched Miniature Systems or ChEMS™. As Shown in Figure 1, each XFS consists of (1) ChEMS™ Pressure Control Module (PCM), (1) ChEMS™ Flow Control Module (FCM) (per thruster) and (1) Electronic Controller.

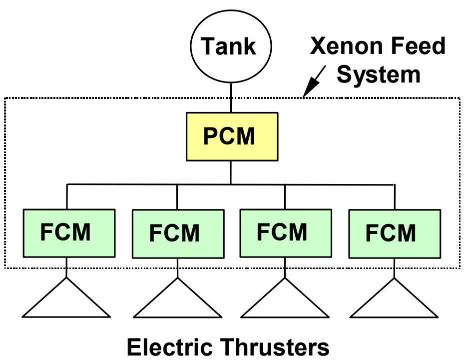


Figure 1: Xenon Feed System (XFS)

Several functional features make this system ideally suited to the control of xenon to thrusters in electric propulsion systems:

Xenon Flow Control
The XFS is specifically designed for the precision control of Xenon at extremely low flow rates. Mass flow rate set point is maintained under worst-case environmental conditions via open or closed loop control.

Variable Set Point
The XFS mass flow rate set point is variable. Pressure set point is also variable.

Pressure and Temperature Compensation
The range of flow control is such that mass flow can be accurately maintained over a wide band of propellant temperature and pressure.

Thruster Isolation
The XFS provides five interrupts against Xenon leakage. All valve are soft-seat designs that provide excellent leakage performance.

Xenon Filtration
The XFS features 5-micron absolute filters that protect the XFS and thruster against particulate contamination.

Design Robustness
The XFS is a small, compact arrangement of highly integrated components packaged in a stiff, robust structure.

Reliability
The only moving parts in the XFS are the suspended armatures for the twelve valves. The armatures are welded to "S" springs that guide them so they move without sliding against adjacent parts. To preclude failure, the "S" springs are designed for low stress and high fatigue life.

Failure Tolerance
The XFS is capable of functioning fter sustaining two isolation valve failures. In addition, failure of one or more of the valves in the digital flow control array will only degrade flow control accuracy and engine performance but not cause loss of the engine.

Value
The cost of components in ChEMS™ assemblies is dramatically reduced due to the inherently lower cost of micro machining as compared with traditional chip cutting machining.

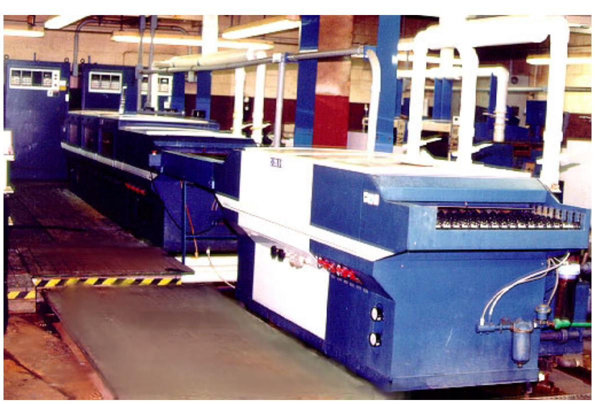
VACCO ChEMS™ Technology

As its name implies, ChEMS™ is based on VACCO's extensive in-house capability in the precision chemical micro machining of metals. ChEMS™ modules consist of multiple layers of micro machined metal layers that, when stacked and bonded together, form an assembly of all of the components and their interconnecting flow paths. Size and mass of the resulting module is drastically reduced by enabling fabrication of components and interconnecting features that are an order of magnitude smaller than practical using traditional machining techniques.

Figure 2: Development XFS Hardware

In traditional systems, components are made of piece parts that are individually produced by machining, casting, etc. The cost of the components in ChEMS™ assemblies is dramatically reduced by simultaneously machining the equivalent of individual piece parts for many components into a single sheet of material. The development hardware shown in Figure 2 illustrate a module with (36) valves, (34) flow resistors and (1) filter. Valves, filters and flow resistors are traditionally fabricated, assembled and tested as discrete components then integrated and tested as an assembly. With ChEMS™, the assembly of the components and the integration of those components into a module takes place simultaneously as the sheets are bonded together. This drastically reduces component assembly and system integration costs. It also eliminates the cost of redundant testing at both the component and module level.

ChEMS™ is conceptually similar to MEMS technology, with an important difference. MEMS is based on micro machining silicon as the primary manufacturing process. ChEMS™ is based on micro machining metals. Similar expansion rates allow all-metal assemblies to be used over a much broader temperature range than the silicon/metal composite structures found in MEMS devices. ChEMS™ assemblies also tend to be more rugged, more robust and less sensitive to environments than MEMS designs. Although silicon is stronger, metal is a tougher, less brittle material. This makes ChEMS™ assemblies less sensitive to shock, vibration and handling damage. ChEMS™ devices made from materials such as CRES or titanium are also compatible with most propellants and environments.



VACCO has developed a unique capability to produce ChEMS™ assemblies. Approximatelly one third of VACCO's business consists of an ISO 9002/QS-9000 registered precision micro maching operation where critical parts for space, aerospace, military, medical, computer and automotive applications have been produced for over 35 years. The multi-station micro machining production line shown in Figure 3 is one of eleven facilities at VACCO.

Figure 3: VACCO Micro Machining Operation

XFS Requirements Summary

To focus the design and development process, the team has produced a set of functional requirements for the XFS.

Fluid Compatibility:	Xenon, GHe, GN2, IPA
Operating Pressure:	1500 psia
Proof Pressure:	2250 psig
Burst Pressure:	3750 psia
Outlet Pressure:	vacuum
Fluid Temperature:	0 to 50°C
Internal Leakage:	0 mg/sec Xenon
External Leakage:	0 mg/sec Xenon
Power Consumption:	5 watts/ valve @ 28 Vdc
Filtration:	5 micron absolute
FCM (-1):	
Range:	0-25.5 mg/s Xe
Accuracy:	+/-0.1 mg/s
FCM (-2):	
Range:	0-2.55 mg/s Xe
Accuracy:	+/-0.01 mg/s

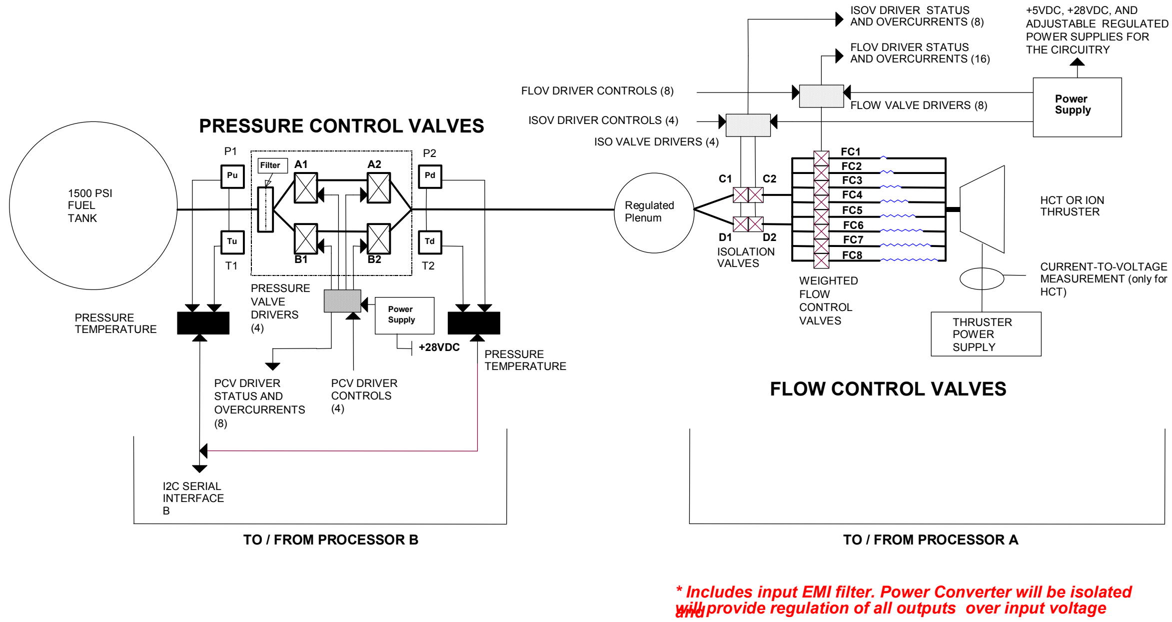


Figure 4: Xenon Feed System Bock Diagram

Development XFS Design

Functional Description

The XFS design is illustrated in the Block Diagram in Figure 4. Xenon enters the PCM from a storage tank through an Inlet Filter and into dual redundant digital Pressure Control Valves. These valves allow small amounts of xenon into the Plenum to pressure it to the selected set point. Xenon pressure and temperature are sensed at both the inlet and outlet of the PCM.

Xenon from the Plenum tank is routed to the FCM(s) and enters through an etched disc filter. This protects both the FCM and the downstream thruster from particulate contamination. Xenon flow beyond the Filter is controlled by four electromechanically actuated, normally closed Isolation Valves arranged in two parallel branches. Each branch contains two valves in series. This dual redundant configuration allows the module to tolerate a failure to close and a failure to open simultaneously.

When the Isolation Valves are open, Xenon is free to flow to the eight Flow Control Valves. These valves are identical to the Isolation Valves. They are digital in the sense that they have only two states, fully open or fully closed. The Flow Control Valves are grouped into an array to control mass flow to the thruster. The number of valves required for an array depends on the flow rate and control accuracy desired.

Each Flow Control Valve has a precision Flow Resistor micro machined immediately downstream of the seat. These are passive flow restrictors that reduce the mass flow rate through the valve to the desired level by acting as a frictional resistance to flow. The degree of flow resistance through each device is dependent on the geometry of its flow path. The geometry of these flow paths is controlled using the same miromachining techniques routinely used to make etched disc filters. Discharge from the array exits the FCM through the outlet port.

Physical Description

The Xenon Feed System (XFS) consists of three major components; the Electronic Controller (EC), the Pressure Control Module (PCM) and the Flow Control Module (FCM). The EC is being packaged for ground testing so will not be described physically. The development PCM and FCM look almost identical externally as shown in Figure 5.

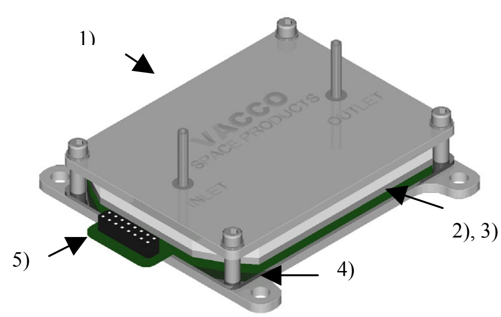


Figure 5: Development PCM/FCM

Pressure Control Module
The development PCM consists of the following elements:

1) (1) ChEMS^{tm} high-pressure manifold containing the inlet tube, five micron filter, four Pressure Control Valves, an outlet tube and all the interconnecting flow paths.
2) (4) Solenoid Stators.
3) (4) Solenoid Coils.
4) (1) Base Plate.
5) (1) Electrical Connector.

Flow Control Module
The development FCM consists of the following primary elements:

1) (1) ChEMS^{tm} low-pressure manifold containing the inlet tube, five micron filter, four Isolation Valves, eight Flow Control Valves, eight Flow Resisters, an outlet tube and all the interconnecting flow paths.
2) (12) Solenoid Stators.
3) (12) Solenoid Coils.
4) (1) Base Plate.
5) (1) Electrical Connectors.

XFS Electronic Controller
The Electronic Controller, (EC) is ground-test version of a future flight unit. Emphasis has been placed on developing hardware and software architecture, not flight packaging.

The EC opens and closes valves in the system based on a combination of external commands from a personal computer acting as a satellite's On-Board Computer (OBC) and feedback signals from the system instrumentation. A separate power converter supplies power to the controller and valve drivers. The block diagram for the EC is shown in Figure 6.

External operator commands are supplied to the system via a PC-based Graphical User Interface (GUI). In addition to external commands, the system implements closed loop control of the plenum pressure and open or closed loop control of the system flow, depending on the thruster application. The system control is based on information supplied by two sensors providing both pressure and temperature measurements in digital format to the secondary microprocessor.

External commands are transmitted via an RS-232 serial connection to the master microprocessor. Sensor signals are transmitted through an I^2C interface to the secondary microprocessor. Analog signals representing the main power supply and the thruster current are filtered to remove noise and scaled to provide a five-volt range for each. A multiplexer within the master microprocessor directs these signals to an on-chip Analog to Digital converter (ADC). The master microprocessor measures these signals and uses the resulting information to determine how to control the system.

The EC monitors the pressure, and controls and actuates the valves based on measurements from the upstream and downstream pressure/temperature sensors. This controller operates in a closed-loop mode, adjusting the plenum pressure as necessary. The secondary microprocessor determines whether the plenum pressure has dropped below regulation pressure, and, if so, utilizes a pressure-control algorithm to determine the appropriate pulse width to achieve the appropriate increase in pressure. The pulse width modulator output of the secondary

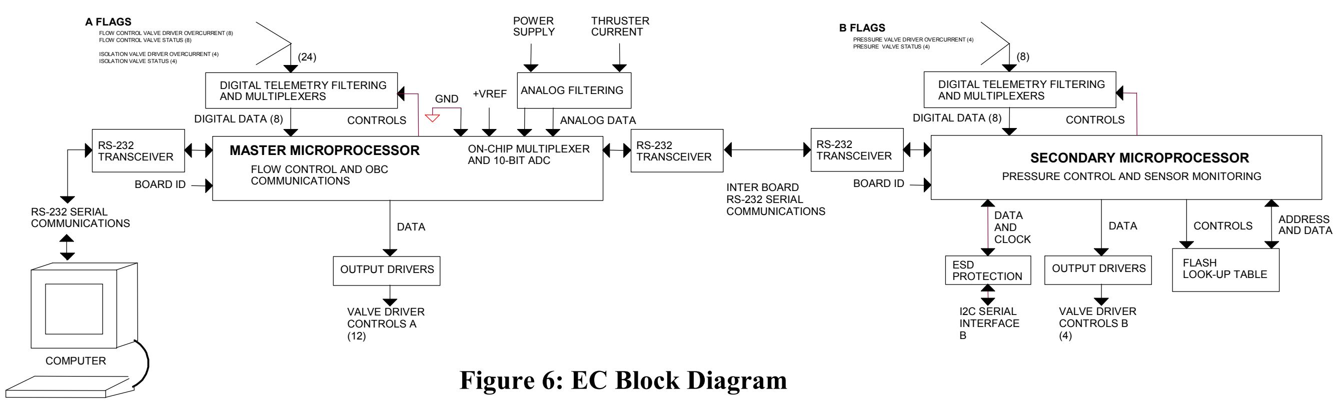


Figure 6: EC Block Diagram

microprocessor then activates the valve drivers to achieve this operation.

The EC manipulates the flow control valves based on external commands in open loop operation or external commands and current feed back during closed loop operation. Open loop operation is appropriate for Ion thruster feed systems, closed loop operation is appropriate for Hall thruster system.

A combination of equation and look-up table within the main microprocessor provides the appropriate valve combination for the commanded flow. This is the 'open loop' operational mode. In 'closed loop' control, a voltage representative of the thruster current is fed as an input to the master microprocessor's ADC for measurement. The results enable control of the system to a set point of operation. For both modes of control, the valve drivers are controlled such that, when the flow requirements change, only the valve or valves that must go open or closed are cycled. Those valves that will be in the same position for the new flow requirement will not be cycled.

Flow Control and Accuracy
The distribution of flow resistances in the -1 eight-bit flow control array is illustrated in Figure 7. The minimum flow bit (resistor #1) is 0.10 mg/sec xenon at 40 psia and 70°F. Flows less than a tenth of this amount have been demonstrated during Flow Resistor development testing at VACCO. Flow through resistor #2 is twice the flow through #1 or 0.20 mg/sec. Flow through resistor # 3 is twice the flow through #2 and so on. This results in a flow range of 0 to 25.5 mg/sec xenon with all eight valves open.

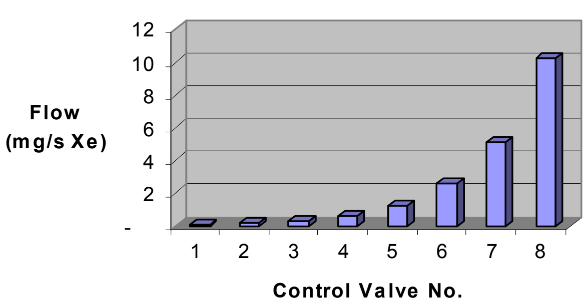


Figure 7: Valve Flow Rates

Since each valve has two states (open or closed) there

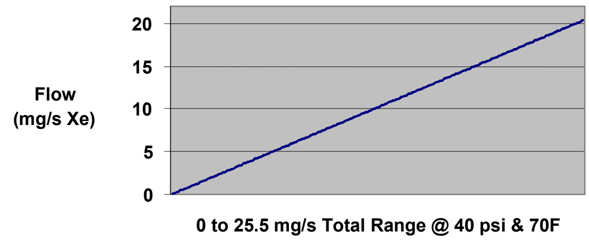


Figure 8: Linear Flow vs. FCN

are 256 unique combinations. Each combination of valves states results in a unique flow that is different from the next closest flow by the minimum bit size (0.10 mg/sec). As shown in Figure 8, this results in flow control from 0 to 25.5 mg/sec in 256 discrete increments of 0.10 mg/sec. Since each step is 0.10 mg/sec, the maximum error will be half of this or 0.05 mg/sec. The resulting flow control accuracy is +/- 0.2% of full scale. This provides a healthy margin over the typical accuracy requirement of +/-3.0%.

Open-Loop Flow Control
Open-loop control can be used with either Hall-effect or Ion thrusters. Open-loop control consists of simply selecting a Flow Control Number (FCN) corresponding to desired flow from a look-up table. The FCN is then adjusted for pressure and temperature of the xenon at the inlet of the FCM using additional tables. This is repeated up to ten times per second depending on the refresh rate selected.

Closed-Loop Flow Control
Closed-loop control can only be used with Hall-effect thrusters. The XFS is designed to function as the key element in a closed-loop system. Thruster burns in electric propulsion systems tend to be of an extremely long duration. This results in a quasi-static control environment where response is not a design driver. The feedback current is sensed, compared to the desired set point and the error sign calculated. The computer then iterates one FCN to incrementally increase or decrease flow as required. This process continues until the error is below a pre-set threshold.

ChEMS™ Valve Development

For some time VACCO has undertaken a major R&D program to apply ChEMS™ technology to electric propulsion system applications. A key objective of this program is the development of a low pressure ChEMS™ solenoid valve. This effort has been extremely successful.

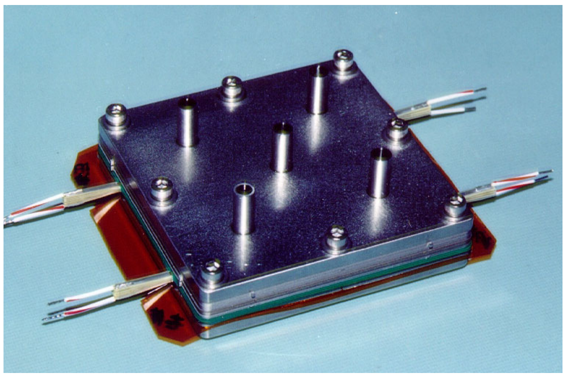


Figure 9: ChEMS™ Development Valve

The four-valve low-pressure test bed shown in Figure 9 was specifically designed to develop ChEMS™ valves for Xenon flow control applications. Extensive functional testing has been performed on this unit.

Data are summarized below:

Response:
2.5 milliseconds @ 50 psi & 12 Vdc
Power Consumption:
5.2 watts @ 12 Vdc
Internal Leakage:
Zero bubbles GHe @ 50 psia
External Leakage:
Zero bubbles GHe @ 50 psia
Pull-In Voltage:
12 Vdc @ 50 psi & 70F

Planned Design Enhancements

Enhancements planned for the PCM include:

1) Integral high and low pressure transducers.
2) Integral temperature sensors.
3) Integral Plenum.

Like the development PCM the flight versions-like the unit shown in Figure 10, will consist of a ChEMS™

Figure 10: Flight PCM

manifold containing all of the xenon-wetted components. This includes the pressure and temperature transducers as well as the Plenum. These components will be arranged as shown in the block diagram in Figure 11.

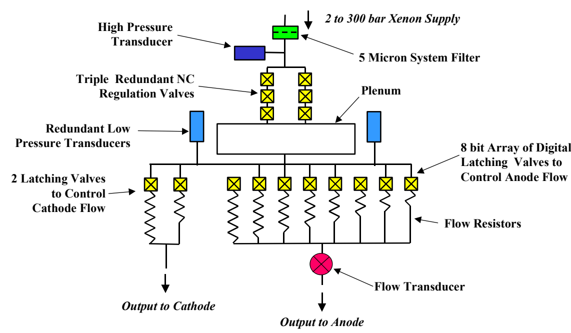


Figure 11: Flight PCM Block Diagram

The flight PCM will include a printed circuit board containing the signal conditioning electronics.

Enhancements planned for the FCM include:

1) Combination of Anode and Cathode flow control into a single module.
2) Addition of pressure and temperature sensors.
3) Conversion to latching valves for ultra low power consumption.

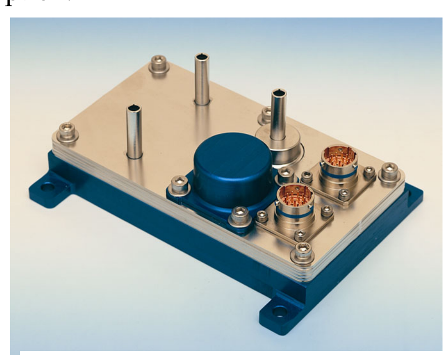


Figure 12: Flight FCM

The flight FCM envisioned in Figure 12 is very similar to the development FCM. The most obvious difference is the separate outlets for anode and cathode flow.

As shown in Figure 13, the enhanced FCM also features two flush mounted Pressure Transducers located immediately downstream of the Isolation Valves. These transducers are provided with a built-in temperature sensor. Temperature compensation is not required for the Pressure Transducers to meet their accuracy requirement of +/- 0.5%.

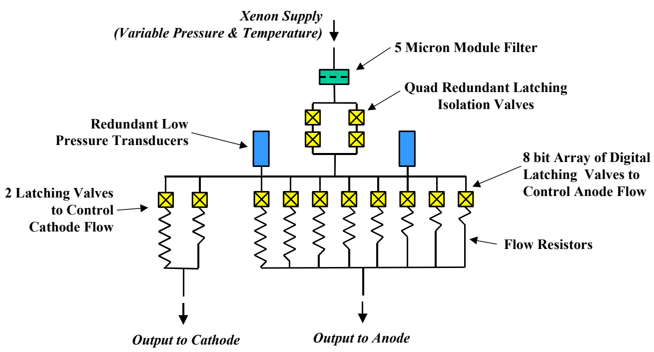


Figure 13: Flight XFS Block Diagram

The Flight FCM includes a printed circuit used to mount the pressure transducer conditioning electronics. This avoids the need for a separate housing for the pressure transducer electronics.

Conclusion

In conclusion, the VACCO ChEMS™ technology represents an important breakthrough in the size, mass and cost of miniature fluid systems. The application of ChEMS® technology to Xenon Flow Control has resulted in a module ideally suited for electric propulsion applications. The VACCO ChEMS™ XFS provides system designers with a technology that allows them to realize to the full potential of electric propulsion.

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