A DIGITAL XENON FLOW CONTROLLER
BASED ON ChEMS™ TECHNOLOGY*†

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Abstract

Electric propulsion systems are quickly emerging as the preferred mode of propulsion for LEO, GEO and even interplanetary spacecraft. Systems using ion or Hall thrusters are currently planned or are in production for a wide variety of spacecraft and missions.

The driving force behind this shift from chemical to electric propulsion is the substantial reduction in the propulsion mass that can be realized. Unfortunately, system designers are often forced to utilize components designed for chemical propellants in their electric systems. Although functionally acceptable, these relatively large, heavy components are designed for the higher pressures and mass flow rates required by chemical systems. To fully realize the benefits of electric propulsion, components must be developed that are optimized for the low flow rates, critical leakage needs, low pressures and limited budgets of these emerging systems.

This paper describes a Xenon Flow Control (XFC) module utilizing a new proprietary VACCO technology called Chemically Etched Miniature Systems or ChEMS™. It will be shown that the size, mass and cost of the subject module is drastically reduced by etching components and interconnecting features that are an order of magnitude smaller and lighter and less costly than can be achieved using traditional machining techniques. XFC design requirements and how the resulting design solution meets these requirements will be discussed. Evolution of the design from the development of the functional components to the current XFC module to the preliminary design of future flight units will also be delineated.

Introduction

The Xenon Flow Controller (XFC) is an innovative design based on a new proprietary VACCO technology called Chemically Etched Miniature Systems or ChEMS™. The XFC has several functional features that ideally suit it to the control of Xenon to thrusters in electric propulsion systems:

- **Xenon Flow Control.** The XFC is specifically designed for the precision control of Xenon at extremely low flow rates under worst-case environmental conditions.

- **Variable Set Point.** The XFC is designed for closed loop control. Mass flow rate set point can also be changed from the ground as required.

- **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.

- **Thrustler Isolation.** The XFC provides three interrupts against Xenon leakage when all valves are closed.

- **Xenon Filtration.** The XFC features a 5 micron absolute filter that protects the XFC and thruster against particulate contamination.

The specific XFC design solution described in this paper has the following characteristics:

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

- **Low Mass.** The production XFC configuration shown in Figure 7 has a mass of only 0.82 kg.

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† ChEMS™ is a trademark of VACCO Industries.
‡ Patent pending.
➢ **Redundancy.** The XFC features quad redundant isolation valves.

➢ **Reliability.** The only moving parts in the XFC 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 infinite fatigue life.

➢ **Failure Tolerance.** The XFC is capable of functioning after 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 precision etching as compared with traditional machining.

**VACCO ChEMS™ Technology**

As its name implies, ChEMS™ is based on VACCO's extensive in-house capability in the precision chemical etching of metals and plastics. ChEMS™ modules consist of multiple layers of etched metal or plastic sheets that, when stacked and bonded together, form an assembly of all of the components and their interconnecting flow paths. Size and mass of the 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.

ChEMS™ modules are lower in cost and higher in precision than systems fabricated using other methods. 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 etching the equivalent of individual piece parts for many components into a single sheet of material. 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.

Although conceptually similar to MEMS technology, ChEMS™ is fundamentally different. MEMS is based on etching silicon as the primary manufacturing process. ChEMS™ is based on etching metals. Similar expansion rates allow these materials to be used over a much broader temperature range than the silicon/metal substrates found in MEMS devices. This allows ChEMS™ assemblies 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.

![Figure 1: Development XFC Hardware](image1.jpg)

![Figure 2: Chemical Etching Operations](image2.jpg)
VACCO is uniquely qualified to produce ChEMS™ assemblies. Approximately one third of VACCO’s business consists of an ISO 9002/QS-9000 registered precision etching operation where critical parts for space, aerospace, military, medical, computer and automotive applications have been produced for over 35 years. VACCO Space Products is located in the same California facility and there is a long and successful record of collaboration between the product groups.

**XFC Requirements Summary**

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

- **Fluid Compatibility:**
  - Xenon, GHe, GN2, IPA
- **Inlet Pressure:**
  - 0 to 60 psia
- **Proof/Burst Pressure:**
  - 100/200 psia
- **Internal and External Leakage:**
  - $10^5$ sccs Xenon @ 50 psia
- **Valve Cycle Life:**
  - 30,000 open/close cycles @ 50 psia
- **Gas Inlet Temperature:**
  - -4°F to 212°F
- **Non-Functional Temp:**
  - -67°F to 257°F
- **Power Consumption:**
  - 5 watts per valve @ 12 Vdc
- **Vibration/Shock:**
  - 19.1 Grms/16 G
- **Flow Control Range:**
  - 0 to 12 mg/sec Xenon
- **Flow Control Accuracy:**
  - +/-3% of full scale
- **Filtration:**
  - 5 micron absolute

**Development XFC Design**

**Functional Description**

The XFC design, as illustrated in the Block Diagram in Figure 3, is a simple arrangement of an Inlet Filter, dual redundant Isolation and an 8 bit array of Digital Control Valves.

Xenon is routed through a qualified five micron etched disc filter as it enters the XFC. This protects both the XFC 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 both a failure to close and a failure to open simultaneously.

When the Isolation Valves are open, Xenon is free to flow to the twelve Digital 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 Digital Control Valves are grouped into an array for control mass flow to the thruster. The number of valves required for an array depends on the flow rate and control accuracy required.

Each Digital Control Valve has a precision Flow Resistor chemically etched 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 are controlled using the same chemical etching techniques routinely used to make VACCO filters.

Discharge from the array exits the XFC through the outlet port.
Physical Description

The XFC design, as shown in Figure 4 is a compact, low mass, rugged module containing all the required functional components and their interconnections. The XFC is comprised of the following major parts:

(1) Distribution Manifold       (12) Stators
(1) Coil Assembly               (1) Base Plate

Figure 4: Development XFC

The XFC module contains the equivalent of 21 functional components and their interconnections. If an equivalent system were built with discrete components, they would require approximately 66 fasteners, 49 orbital welds and 12 cables to integrate it with the spacecraft. The XFC as shown requires only four fasteners, 2 orbital welds and 1 cable.

Similar economies are realized in the footprint and mass of the XFC relative to traditional approaches. An equivalent module using state-of-the-art miniature discrete components would cover a 180 square inch footprint with an approximate mass of 8.0 lbm. The ChEMS™ XFC by contrast will only cover about 11 square inches with a mass of 1.8 lbm.

Materials in contact with the propellant are limited to passivated CRES and Teflon. No plating is used.

The major components of the XFC are held together by 4 tie wired capscrews that thread into the cast aluminum Base Plate. These fasteners are lightly loaded since all pressure-induced loads are borne by either EB welds or diffusion-bonded interfaces.

The Distribution Manifold contains the Inlet and Outlet Interface Tubes, Inlet Filter, distribution channels and Valve Bodies in a single welded assembly. The body of the Distribution Manifold consists of 10 layers of CRES sheet material. The layers are bonded using a combination of diffusion bonding and EB welding. The result is an all welded assembly that contains all of the pressurized parts and is positively sealed against external leakage.

Xenon enters the Distribution Manifold through a 1/8" diameter 304L CRES inlet tube EB welded to it. Propellant entering the inlet tube is forced through a fully qualified, 304L CRES, 5 micron diffusion-bonded Filter Element. Filtered Xenon is then routed throughout the body of the Distribution Manifold through channels etched between layers.

Xenon discharging from each Digital Control Valve is routed to an individual Flow Resistor etched into layers of the Distribution Manifold body. Additional channels then route the xenon to the 1/8" outlet tube.

The twelve Stators are 430 CRES Turned parts that provide the magnetic circuit for each of the valve actuators. Slots in the Coil Assembly allow the Stator to make intimate contact with the Valve Assembly.

The Coil Assembly is a proprietary VACCO design that contains the twelve valve coils, power leads, and an electrical connector. Since all twelve coils are produced and installed as a single unit, production, handling and integration costs are lower.

Twelve identical normally-closed solenoid valves are used for both isolation and flow control. These double-pole, suspended armature designs only differ from their conventional counterparts in that they are manufactured using ChEMS™ technology instead of being machined from bar stock. To maximize producibility the valves have substantially more flow capacity than the flow resistors.

The aluminum Base Plate acts as the structural backbone of the unit. All other major components of the XFC mount to this part. Four mounting ears on the Base Plate facilitate attachment of the XFC to the spacecraft. The Base Plate is unpressurized and does not come in contact with propellant.

When the Distribution Manifold is attached to the Base Plate they form an enclosure for the electrical parts. An o-ring seal environmentally seals the enclosure. The Base Plate also acts as an excellent heat sink for the solenoid valves. This is important given the long thruster firings required by electric propulsion systems.
Flow Control and Accuracy

The distribution of flow resistances in the eight-bit flow control array is illustrated in Figure 5. The minimum flow bit (resistor #1) is 0.08 mg/sec xenon at 50 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 0.16 mg/sec. Flow through resistor #3 is twice the flow through #2 and so on. This results in a flow range of 0 to 20.4 mg/sec xenon with all eight valves open.

In order to maintain the mass flow rate set point under variable inlet pressures and temperatures, the XFC must have an adequate range of flow. As stated earlier, the maximum flow is 20.4 mg/sec xenon at 50 psia and 70°F. This same configuration results in a maximum flow of 16.3 mg/sec xenon at 212°F and 45 psia. This provides adequate margin over the requirement to maintain up to 12 mg/sec over this range of conditions.

Closed-Loop Flow Control

The XFC 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. For this reason, a dedicated electronic controller is not required. A simple control loop can be programmed into the existing spacecraft avionics. The mass flow rate is sensed, compared to the desired set point and the error calculated. The computer then iterates through the proper configuration of Control Valves 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.
The four valve low pressure test bed shown in Figure 7 was specifically designed to develop ChEMS™ valves for Xenon flow control applications. Extensive functional testing has been performed on this unit. Data is 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 & 70°F

**Planned Design Enhancements**

Enhancements planned for the XFC 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.

The enhanced XFC envisioned in Figure 8 is very similar to the development XFC. The most obvious difference is the separate outlets for anode and cathode flow.

As shown in Figure 9, the enhanced XFC 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 8: Enhanced XFC](image)

![Figure 9: Enhanced XFC Block Diagram](image)

The Coil Assembly 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™ XFC provides system designers with a technology that allows them to realize to the full potential of electric propulsion.

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