SSC03-XI-8

A Cold Gas Micro-Propulsion System for CubeSats

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Abstract

Potential civilian and government users have expressed a strong interest in CubeSat class satellites for military, scientific and commercial purposes. The U.S. Air Force Research Laboratories (AFRL), using DARPA funding, have contracted with The Aerospace Corporation in El Segundo, California to develop a CubeSat class spacecraft called the MEMS PicoSat Inspector (MEPSI). In turn, AFRL and Aerospace Corporation selected VACCO to provide a Micro-Propulsion System (MiPS) for MEPSI. This paper describes the resulting system design and its capabilities. Related micro-propulsion activities will also be reviewed including work with AeroAstro Inc. to develop an advanced MiPS using decomposing nitrous oxide as the propellant.

The VACCO Micro-Propulsion System is an advanced subsystem based on our proprietary **Ch**emically **E**tched **M**icro **S**ystems™ (ChEMS™) integrated fluidic circuit technology (patent #6,334,301). Extremely flexible and easily expanded, MiPS can be adapted to a wide range of small spacecraft. The current isobutane unit can deliver 34 Newton-seconds of total impulse with over 61,000 minimum impulse bit firings. MiPS brings true propulsion capabilities to micro-spacecraft for formation flying, attitude control and velocity change (delta-V). Reliability features such as all-welded titanium construction and redundant soft-seat microvalves compliment the simple selfpressurizing design. Instead of simply creating a miniature version of a conventional system, VACCO has taken a highly integrated system level approach that eliminates all tubing connections in favor of a single ChEMS™ manifold. When combined with our system-in-a-tank packaging design, the resulting propulsion system is a significant advancement over published alternatives.

VACCO's ChEMS™ Micro-Propulsion System is a titanium weldment about half the size of a VHS videocassette. Four ChEMS™ 55 mN Micro-Thrusters are located around the periphery of the module tilting 15^o toward the mounting plane. A single axial 55 mN Micro-Thruster is located in the center of the XY plane. The axial Micro-Thruster nozzle doubles as a fill/vent port for the system. Two sets of connector pins protrude from the Tank through glass headers to retain pressure while making electrical connections to the host MEPSI spacecraft.

One flight MiPS unit has been designed, built and tested at both VACCO and Aerospace Corporation. This paper will describe the MiPS in sufficient detail for potential users to perform a preliminary assessment against their requirements. Performance test data will be presented and conclusions drawn. Lessons learned and future development plans will also be delineated.

VACCO will also outline a plan for making MiPS available for University CubeSat projects. The idea is to build a number of sets of MiPS parts less the core assembly. The core assembly controls all component interconnections and tangential thruster geometry. These critical features could be designed by the student team in order to customize MiPS for their purposes. By stocking the machined parts, lead times can be reduced to less than four months. In this way, students can gain valuable skills and experience while keeping the entire project to less than one-year in duration. In addition to providing a learning experience, students would benefit from the enhanced capability and flexibility propulsion would bring to their CubeSat design.

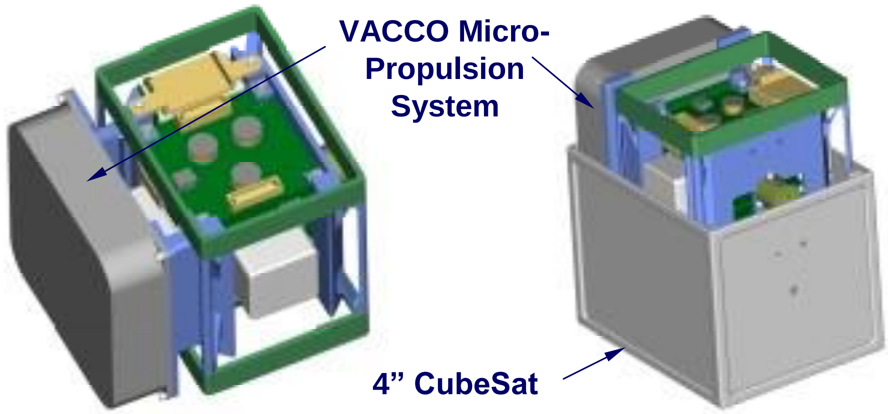

Figure 1: Aerospace Corporation MEMS PicoSat Inspector (MEPSI)

Background

Potential civilian and government users have expressed a strong interest in CubeSat class satellites for military, scientific and commercial purposes. The U.S. Air Force Research Laboratories (AFRL), using DARPA funding, have contracted with The Aerospace Corporation in El Segundo, California to develop a CubeSat class spacecraft called the MEMS PicoSat Inspector (MEPSI). In turn, AFRL and Aerospace Corporation selected VACCO to provide a Micro-Propulsion System (MiPS) for MEPSI. MiPS is designed to provide critical maneuvering capabilities that are essential to MEPSI's mission as an on-orbit inspector.

MiPS Requirements

The Micro-Propulsion System requirements were simple and left ample room for innovation. Requirements that drove the design were envelope, mass and the need for five Thrusters. The following table is a summary of specified requirements.

PARAMETER	*REQUIREMENT*
Design Flexibility	**Expandability: # of Thrusters, Ullage Volume, etc...**
Propellant	**Gaseous, stored as gas or liquid.**
Ullage Volume	**19 cc, expandable.**
Mass	**<=500 grams, dry.**
Envelope	**25 mm x 91 mm x 91 mm**
Nozzle Geometry Accuracy	**+/- 2 degrees.**
Thrust Axis	**(5) Thrusters (locations per drawing)**
Minimum Impulse Bit and Continuous Thrust	**Approx 1.0 mN-sec @ >= 20 Hz, 0.1 N Continuous.**
Supply Voltage	**4.0 to 6.0 Vdc.**
Internal Leakage	**Leakage across any valve seat <=1 x 10^{-3} sccs.**
External Leakage	**External propellant leakage , <=1 x 10^{-6} sccs.**
Burst Pressure	**600 psia**
Redundant Seals	**Minimum of two seals during launch.**

Table 1: MiPS Requirements Summary

MiPS Design Overview

The Micro-Propulsion System is an advanced subsystem based on VACCO's patented

ChEMS™ integrated fluidic circuit technology. Extremely flexible and easily expanded, it can be adapted to a wide range of small spacecraft. The subject isobutane MiPS can deliver at least 34 Newtonseconds of total impulse spread over a maximum of 62,000 minimum impulse bit firings through any one of five thrusters. This brings true propulsion capabilities to micro-spacecraft for formation flying, attitude control and velocity changes (deltaV). Reliability features such as all-welded titanium construction and redundant softseat micro-valves compliment the simple self-pressurizing design. Instead of simply creating a miniature version of a conventional system, VACCO has taken a highly integrated system-level approach that eliminates all tubing connections in favor of a single ChEMS™ manifold. When combined with our system-in-a-tank packaging design, the resulting propulsion system is a significant advance in capability, packaging density and reliability over published alternatives.

The MiPS design is ideally suited for the MEPSI application for the following reasons:

Low Mass. MiPS has a dry mass of only 456 grams.

Reliability. "Solid State" design has no tubing interconnections. Suspended armature ChEMS™ titanium solenoid valves have no sliding fits and only one low stress flexing part.

High Total Impulse. MiPS has a total impulse capacity of 34 N-sec that can be output through five thrusters over 62,000 minimum impulse bit firings.

Redundant Valves. At least two softseat ChEMS™ valves prevent leakage from the propellant storage tank.

Self-Pressurization. Isobutane is loaded as a liquid and self-pressurizes to 44 psia at 20°C. Pressure will be maintained as long as liquid is present.

Design Robustness. The MiPS design is a highly integrated ChEMS™ assembly packaged in a stiff, robust titanium structure that doubles as the propellant storage tank.

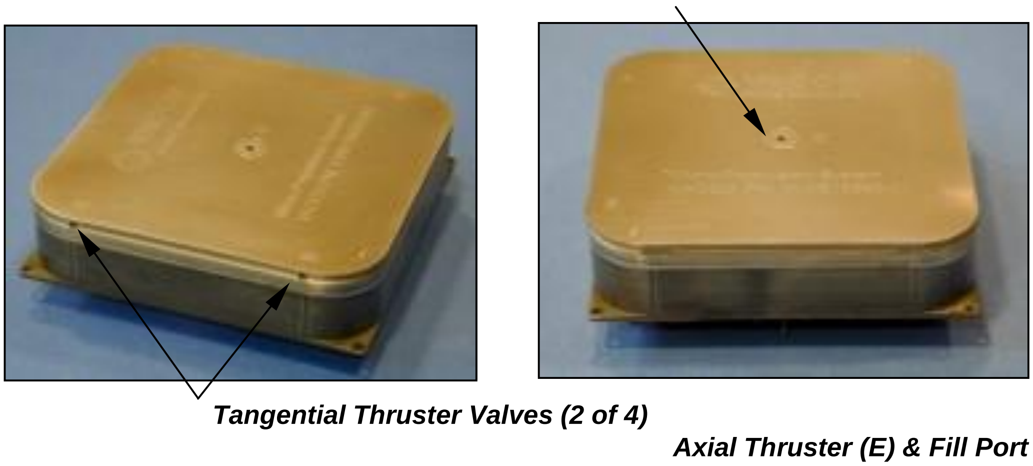

Figure 2: Flight Isobutane MiPS Hardware

Symbiotic Thermal Relationship. Electrical/electronic components are immersed in the propellant. This helps cool the electronics while the dissipated heat helps make up for cooling that occurs as the propellant evaporates to maintain pressure during consumption.

VACCO ChEMS Technology

The MiPS design utilizes VACCO's proprietary **Ch**emically **E**tched **M**icro **S**ystems (ChEMS) technology (patent #6,334,301 official). As its name implies, ChEMS is based on VACCO's extensive in-house capability for precision chemical micromachining of metals. A subset of MEMS technology, ChEMS modules consist of multiple layers of etched metal sheets that, when stacked and bonded together, form an assembly of all of the components and their interconnecting flow paths. The size and mass of resulting modules are drastically reduced by the ability to fabricate components and interconnecting features that are smaller and lighter than possible using conventional machining techniques.

Figure 3: VACCO ChEMS Development Module Hardware

Under internal funding, VACCO evaluated the applicability of chemical micromachining to the production of micro scale propulsion systems. Existing propulsion systems were analized to determine the physical features requiring the highest precision. It was determined that the etched disc filters, with thousands of 5micron passages, each micromachined to tolerances of millionths of an inch, were the most precision propulsion system components. Since VACCO routinely uses precision etching to produce spacecraft filters, ChEMS assemblies were clearly feasible. The samples shown above were produced by VACCO to demonstrate this capability. The resulting module had (71) components packaged in an envelope equivalent to a thick credit card.

Traditional MEMS are fabricated by etching silicon as the primary manufacturing process. ChEMS is a branch of MEMS based on etching metals, i.e. "metal MEMS". These materials can 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. Metal is also a tougher, less brittle material than silicon making ChEMS assemblies less sensitive to shock, vibration and handling damage. ChEMS devices can be made from any etchable material such as CRES, titanium, aluminum, copper, brass, nitinol (super-elastic nickel titanium alloy), molybdenum and even kapton.
Given the wide choice of materials that can be used, ChEMS devices can be designed for virtually any propellant and environment.

ChEMS assemblies are produced by an ISO 9001:2000 and AS9100A:2001 certified precision micromachining operation. Our facility in Los Angeles includes the largest precision chemical micromaching operation in the western United States where we have produced critical parts for space, aerospace, military, medical, computer and automotive applications for over 40 years. VACCO Space Product and Photofabrication Product groups are co-located in this facility where there is a long and successful record of collaboration between them.

Figure 4: VACCO Precision Chemical Etching Facility (one of eleven lines)

VACCO has produced thousands of precision etched disc fluid filters, propellant acquisition devices and flow resistors for spacecraft propulsion systems. We regularly manufacture components that require features as small as 2 microns in size. Capability exists to manufacture ChEMS™ modules significantly smaller that the subject MiPS.

Physical Description

The Micro-Propulsion System is a titanium weldment is about half the size of a VHS videocassette. Four 55 mN Micro-Thrusters are located around the periphery of the module tilting 15° toward the mounting plane. A single axial 55 mN Micro-Thruster is located in the center of the X-Y plane facing in the +Z direction (out of the paper). The axial Micro-Thruster nozzle doubles as a fill/vent port for the system. Two sets of connector pins traverse the pressurized Storage Tank through glass headers to facilitate connections to the CubeSat.

MiPS is a complete system containing:

One Storage Tank
Two Pressure Transducers
Two Temperature Sensors
Four 5 Micron Filters
One Isolation Valve
One Heat Exchanger
One Gasification Plenum
Five Micro-Thrusters

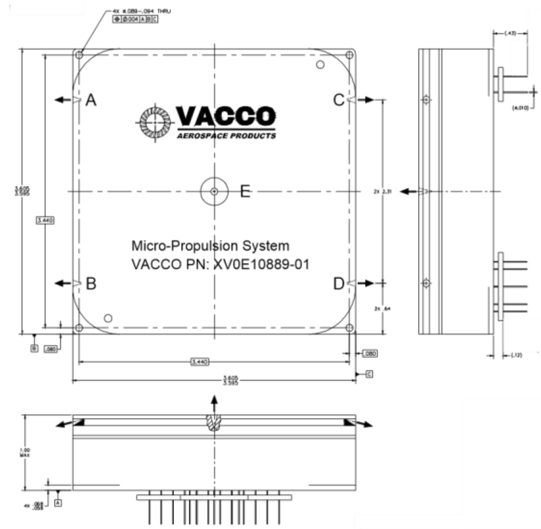

Figure 5: MiPS Envelope Drawing

In addition, the VACCO MiPS has the following design features:

Designed for operation at vapor pressure of isobutane propellant:
Eliminates Pressurization System
Stored as Liquid, expelled as cold gas
Highly integrated ChEMS™ manifold:
Propellant storage volume maximized
Plumbing connections are eliminated
Storage tank doubles as main structure
Electrical components cooled by immersion in propellant
Robust titanium construction:
All-welded against external leakage
Unique titanium micro-valves High reliability valve design: Proven soft seat, suspended armature solenoid valves No sliding fits, only one low stress flexing part per valve Redundant valves against external leakage
Four-point liquid propellant acquisition/filtration **Functional Description**

The MEPSI Micro-Propulsion System (MiPS) is an innovative design utilizing VACCO's unique ChEMS™ technology and system-in-a-tank design approach. The schematic for the isobutane MiPS is as follows:

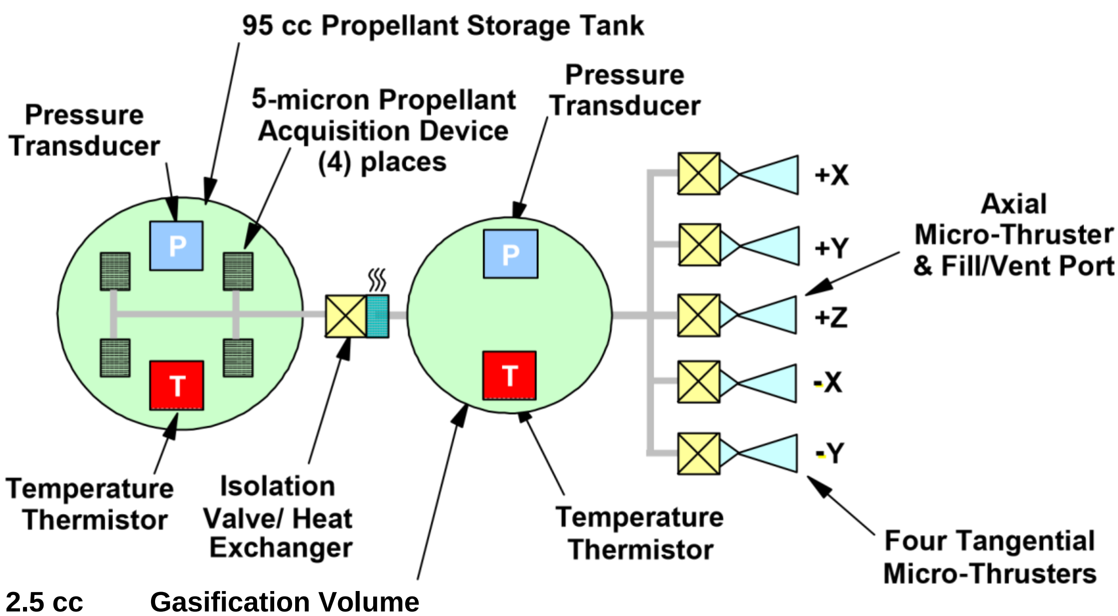

Figure 6: VACCO MEPSI Micro-Propulsion System Schematic

Liquid isobutane (C_4H_{10}) is stored in the 95 cc Propellant Storage Tank at vapor pressure. At room temperature (20°C) Tank pressure is approximately 44 psia. A Micro Sensor Assembly consisting of an absolute pressure transducer and Resistance Temperature Device (RTD) sense both pressure and temperature of the stored isobutane. A Micro Isolation Valve controls flow from the Tank into the 2.5 cc Gasification Volume. A passive Heat Exchanger accelerates replacement of heat lost during vaporization. A second Micro Sensor Assembly senses pressure and temperature in the Gasification Volume. Using the Isolation Valve and Gasification Volume sensors as a simple closed-loop electronic regulator, isobutane pressure is controlled. In order to insure 100% gaseous isobutane in the Gasification Volume, pressure is limited to 90% of vapor pressure at the prevailing temperature. Isobutane vapor is then expelled through any of five Cold Gas Thrusters to achieve roll, pitch, yaw and delta V. Adjusting pressure in the Gasification Volume controls thrust magnitude.

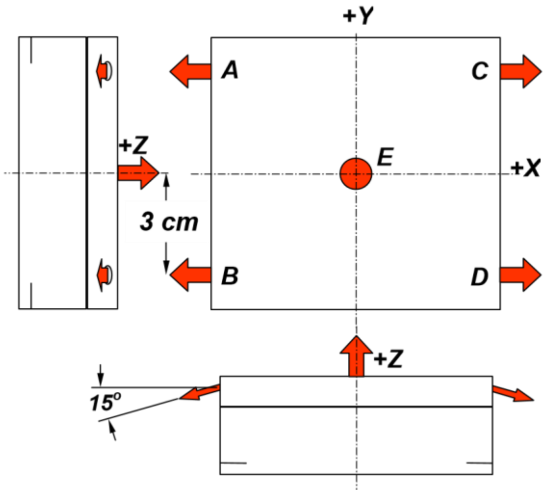

Figure 7: MiPS Thrust Vector Diagram

Manuver	Thruster(s)
+Yaw (+X)	AB
-Yaw (-X)	CD
+Pitch (+Y)	Roll 90° CW then CD
-Pitch (-Y)	Roll 90° CW then AB
CW Roll	AD
CCW Roll	CB
Delta V (+Z)	ABCD
Delta V (-Z)	E

Table 1: Thrust Control Table

MiPS thrusters are arranged with one oriented in the axial (+Z) direction and four tangential thrusters directed at 15° from the XY plane. The axial thrust vector passes through the MEPSI center of mass. Firing the axial thruster causes spacecraft motion in the (-Z) direction and is used for virtually all delta-V maneuvers. A unique feature of the MiPS is its ability to impart +Z motion by firing all four tangential thrusters simultaneously. Their 15° off set from the XY plane creates component force vectors in both the X and Z directions when fired. Due to symmetry, force components in the X direction cancel leaving only force components in the Z direction. This allows the MEPSI to "back up" in the +Z direction presenting the axial thruster. Since the system is filled through its axial thruster nozzle, this maneuver facilitates future onorbit refueling.

The four tangential thrusters are arranged in pairs with thrusters A & B firing in the –X direction and C & D firing in the +X direction. Force vectors from the tangential thrusters are offset from the MEPSI center of mass. Firing the tangential thrusters imparts both force and torque to the spacecraft. To "yaw" MEPSI in a positive direction about Y-axis, Thrusters A & B are fired simultaneously. To "yaw" in a negative direction about the Y-axis, Thrusters C & D are used. Firing thrusters A & D simultaneously "rolls" the spacecraft in a negative direction about the Z-axis, thrusters C & B "roll" MEPSI in a positive direction about the Z axis. To "Pitch" MEPSI, the spacecraft is "rolled" 90° then thrusters A & B or C & D are fired in pairs.

Micro-Propulsion System Capability

Given that the specifications called for a cold gas propellant, the specific impulse was limited by definition. Compressed nitrogen (GN_2) was the baseline against which other propellants were compared. Isobutane $(CH_3)_2CHCH_3$ was ultimately selected as the MiPS propellant for several reasons:

1. **Green Propellant -** Isobutane is a colorless, stable gas that is noncorrosive to most materials, nonreactive with water and is considered a "green" substance that is commonly handled with minimal safety restrictions.
2. **Flight Proven -** Butane was flight proven propellant through its use in the SURREY Satellite Technology SNAP-1 (ref 1) spacecraft.

3. **Good Storage Density** - Isobutane can be stored as a liquid at the ambient temperature of the spacecraft. Liquid isobutane with a density of 0.56 g/cc has 2.5 times the mass storage density of GN2 at 3,000 psia.
4. **Self-Pressurizing** - The vapor pressure of isobutane at 20°C is approximately 44 psia. The Propellant Storage Tank will remain at the vapor pressure as long as it contains liquid isobutane. "Selfpressurization" of the propellant eliminates the mass, volume and cost of a separate pressurization system required by other liquid propellants.
5. **Low Storage Pressure** - Even accounting for worst-case thermal environments, maximum expected operating pressure (MEOP) was only 150 psia. This fact was critical to our ability to maximize storage volume by conforming to the rectangular prism shape of the specified envelope. Even at this low operating pressure, special internal structure was required to prevent excessive deflection of the flat Storage Tank faces.

Given the extremely small (210 cc) envelope allocated to the entire system, propellant volume and density were critical to maximizing total impulse capacity. The specified envelope for the Propellant Storage Tank was a rectangular prism shape 25 mm x 91 mm x 91 mm. Storage volume was maximized through our unique systemin-a-tank design approach. Essentially the entire volume was allocated to propellant storage. All the functional components were mounted inside the Storage Tank, which also acted as the systems main structural element. Space was utilized between and around electrical components that is wasted in a conventional system. This resulted in a propellant storage volume of 95 cc.
Although the actual volume is slightly larger than this, a small vapor bubble is created during the fill sequence to prevent hydraulic lock-up.

A unique characteristic of the MiPS design is that all the electrical components; electronics, wiring and valve actuators are immersed in the propellant. This fact has several beneficial implications beyond maximizing propellant volume. Immersion of the electrical components allows dissipation of waste heat through conduction and convection to the propellant. A symbiotic relationship is created where heat flux into the propellant replaces heat absorbed by vaporization of the propellant as it is consumed. Since vapor pressure is a function of temperature, electrical components can be activated between firings to act as heaters that raise system pressure to desired levels.

The impulse imparted to a spacecraft by any given "burn" is dependent on thrust magnitude and duration. Given flow rate data and an assumed Specific Impulse (I_{sp}) of 65 seconds, nominal thrust for MiPS was 55 mN at 40 psia. Actual thrust and Specific Impulse will be determined by upcoming system testing at Aerospace Corporation. Thrust magnitude is proportional to Gasification Volume pressure. The ability of the MiPS to set Gasification Volume pressure allows thrust to be throttled to lower levels when desired. We expect reduced I_{sp} at lower thrust levels will limit throttling to about 25% of maximum available at any given temperature (~10 mN at 20°C). Burn duration is controlled by operation of the thruster valve. High performance titanium micro-valves used for this purpose allow precise control over burn duration. Minimum thrust duration is a function of valve opening and closing response characteristics. MiPS was extensively tested by VACCO in the pulse mode using GN_2. Under all specified conditions, thruster response was substantially faster than the 10-millisecond requirement. Based on this data, minimum impulse duration was set at 10-milliseconds. This results in a calculated minimum impulse bit of 0.55 mN-Sec at 40 psia. At lower Gasification Volume pressures, the minimum impulse bit is proportionately less. These extremely small impulse bits are essential to supplement reaction wheels for fine camera pointing and positioning required to meet mission objectives.

Value	Units	Description
95	cc	Propellant Volume
0.556	g/cc	Propellant Density (liquid)
2028	sccm	Isobutane Thruster Flow Rate (40 psia)
0.01	sec	Minimum Pulse Duration
65	sec	Specific Impulse Isp
55	mN	Thrust @ 40 psia
1000	g	MEPSI Spacecraft Mass
53	g	Propellant Mass
616	sec	Total Thrust Duration
34	N-s	Total Impulse
34	M/s	Total Delta V
0.55	mN-s	Minimum Impulse Bit
61564		Max No. of Minimum Impulse Bit Firings

Table 2: MiPS Capability Summary

MiPS Testing

Testing of the MiPS was divided into two parts, functional acceptance testing at VACCO using referee fluids and system level at Aerospace Corporation using isobutane. Testing at VACCO is complete and the flight system has been delivered to AFRL. The system has, in turn, been forwarded to Aerospace Corporation for integration and additional testing.

In order to build confidence in material selection, Aerospace Corporation conducted isobutane compatibility testing early on in the program. VACCO provided Aerospace Corporation material samples that were carefully inspected, immersed in isobutane for several weeks then re-inspected. No evidence of material degradation was observed. Before acceptance testing at VACCO, the finished MiPS was provided to Aerospace Corporation where it was pressurized with isobutane and functionally checked after several days. Inconsistent sensor readings were noted. An investigation revealed residue from leakcheck solution on the exterior of the unit provided an electrical path to ground. Subsequent exterior cleaning solved the problem.

Acceptance testing at VACCO consisted of the following:

1. Examination of Product
2. Proof Pressure
3. Leakage at 20°C 4. Flow Rate/Opening Response at 20°C
5. Electrical Tests at 20°C
6. Thermal Cycle Test
7. Cycle Life Test
8. Leakage at 20°C 9. Flow Rate/Opening Response at 20°C
10. Electrical Tests at 20°C

Examination of product revealed no damage and a dry mass of 455.8 grams. Proof Pressure was conducted for five minutes at ambient temperature with no damage or deformation observed. Potentially destructive tests such as 100 on/off cycles per valve and three thermal cycles were performed first. The following data was taken after potentially destructive testing.

Internal Leakage essentially measured leakage across the Isolation Micro-Valve. Leakage rates were extremely low for all combinations of pressure and temperature. This excellent leakage performance was attributed to the soft seat design of the VACCO Micro-Valve.

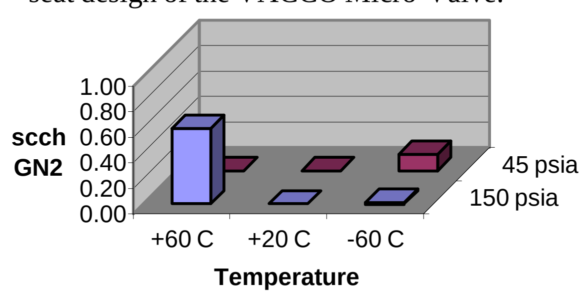

Figure 8: Internal Leakage Data

External Leakage measures leakage from the Storage Volume to the outside of the unit. External leakage was a recurring problem during assembly due to the design and location of the hermetic feed through headers. These are copper pins set in glass that that create a positive barrier against leakage while allowing electrical power and data signal transfer across the pressure boundary. The problem was minimized by development of the proper glass chemistry. The balance of the problem lay in the fact that the header pins were located in holes machined directly in the flat wall of the Storage Tank. Under pressure, deflection of the sidewall created micro-cracks in the glass allowing nitrogen gas leakage. Since leakage requirements were specified in isobutane and not nitrogen, it was decided to deliver the unit so Aerospace Corporation could definitively verify leakage using isobutane.

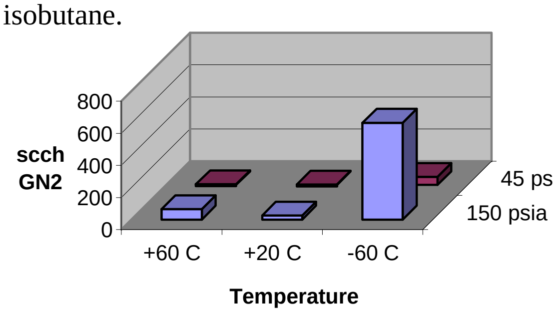

Figure 9 External Leakage Data

Flow testing was conducted to give some insight into thrust level and consistency. Thrust levels averaged the equivalent of 55 mN. Thruster to thruster consistency, was acceptable but not ideal with Thruster C significantly less that the other four. This was attributed to manufacturing tolerances in the ChEMS™ manifold. Improved bonding techniques developed in a parallel internal research and development program will be used to produce future manifolds.

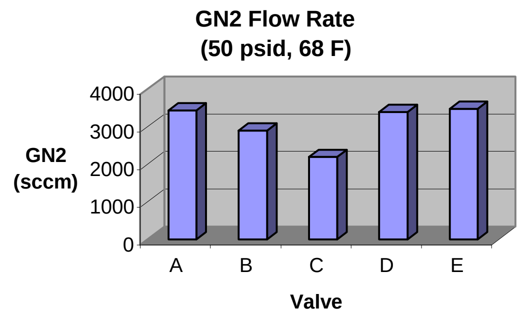

Figure 10: Thruster Flow Data

Electrical Tests including Insulation Resistance, Coil Resistance/Inductance, Pull-In Voltage and Drop-Out Voltage were performed to determine the electrical characteristics of the MiPS. Pull-In Voltage is used to determine the operating margin of the Micro-Valves. As can be seen in the chart below, Pull-In Voltage did not exceed 50% of the minimum voltage available.

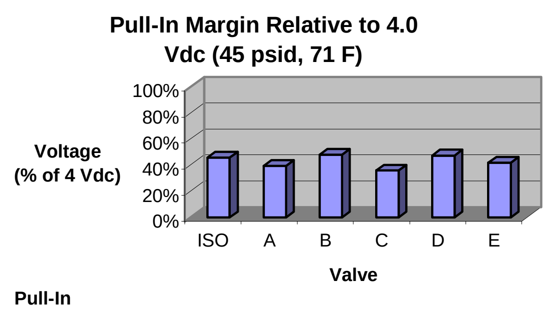

Figure 11: Pull-In Margin Data

Opening Response is critical to meet minimum impulse requirements. As shown in the data below, Opening Response times were well below the 10mSec requirement.

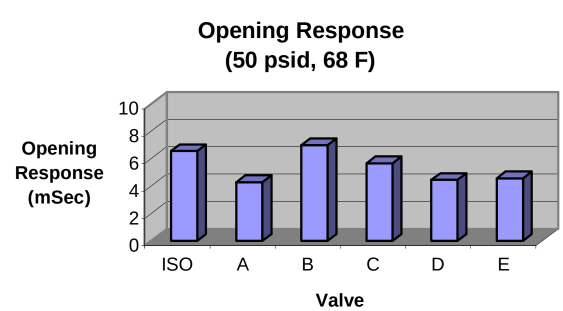

Figure 12: Opening Response Data

Future MiPS Enhancements

The design of the Micro-Propulsion System is extremely versatile limited only by the imagination of its designer. Various enhancements have been suggested for future systems. These fall into several categories:

- High Capacity Isobutane MiPS
- MiPS using Decomposing Nitrous Oxide as the Propellant
- Low Power/Mass Upgrades
- MiPS as an Educational Tool

High Capacity Isobutane MiPS

Given the extremely small (210 cc) envelope specified for the subject MiPS, only 95 cc of propellant volume was available. This is impressive given the total envelope but is still quite limited. One idea for significantly expanding propellant volume is to "stretch" the height to the MiPS to the full size of the CubeSat or 91 mm x 91 mm x 91 mm. To accomplish this, electronics associated with other systems would be located inside the Propellant Storage Tank and stacked with the PC board already there. All the functional components mounted to the manifold assembly would remain unchanged. Only the Tank would be affected.

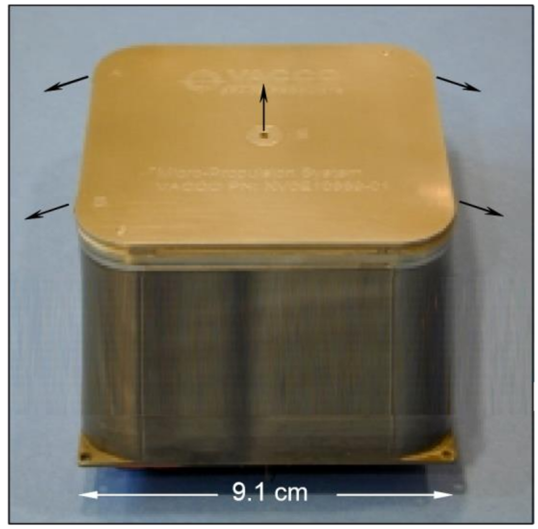

Figure 13: High Capacity MiPS

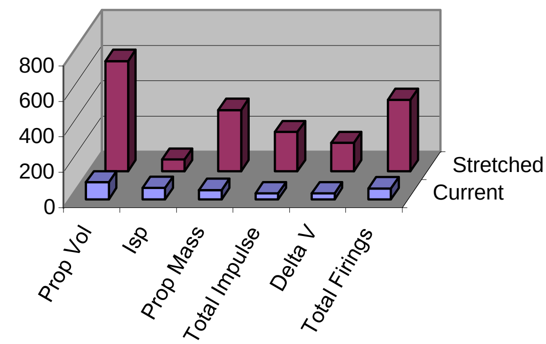

Figure 14: High Capacity MiPS Comparison

Another path to increasing total impulse is to utilize a propellant with higher I_{sp}. Ammonia (I_{sp} = 105 sec) was briefly considered to achieve an incremental increase in performance. Ultimately it was rejected due to its inherent toxicity and incompatibility with materials such as copper.

Decomposing N_2O MiPS

Substantial increases in performance can be achieved by utilizing "green" monopropellants. AeroAstro Inc. and VACCO Industries Inc. have teamed to develop a high performance Nitrous Oxide Micro-Propulsion System (N_2O

MiPS) for NASA Johnson Space Center under a Phase I SBIR. The resulting design is a straightforward adaptation of the subject isobutane MiPS for N_2O service. The N_2O MiPS incorporates all of the features of the isobutane system including a ChEMS™ manifold and system-in-a-tank construction. The major design change consists of altering the structure for 1300 psia maximum operating pressure. As can been seen in the drawing below, the rectangular prism shape of the isobutane MiPS was abandoned in favor of a cylindrical design to accommodate increased pressure.

Figure 15: Nitrous Oxide MiPS Concept

Nitrous oxide technology offers several features that made it the selected solution to enhance the MiPS capability. In addition to the inherent safety of nitrous oxide, it can be stored as a relatively dense liquid. As a cold gas, nitrous oxide provides an I_{sp} similar to isobutane, but when decomposed into a hot gas it may be possible to achieve an I_{sp} approaching 200 sec. As part of the Phase I SBIR, AeroAstro built and fired a simple decomposing N_2O thruster controlled by a VACCO valve. Full development and definitive testing of a decomposing N_2O thruster is planned if Phase II is funded. For the purpose of the following comparison propellant storage volume was held constant and a conservative I_{sp} of 155 sec was assumed.

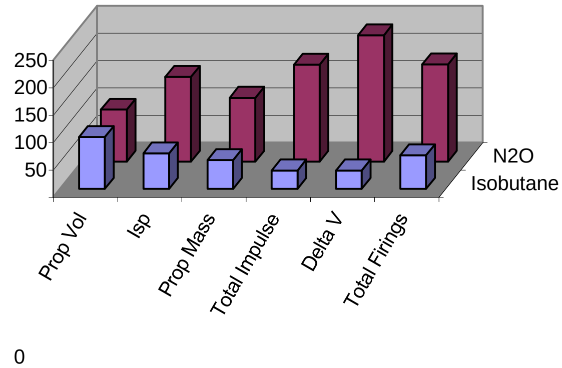

Figure 16: N_2O, Isobutane MiPS Comparison

Even with the additional structure required to adapt the isobutane MiPS to support the higher pressure of nitrous oxide, overall performance can be dramatically increased. If N_2O is simply used as a cold gas, total impulse doubles. If used with decomposing N_2O thrusters as shown above, total impulse increases by a factor of 5.2! The combination of decomposing nitrous oxide thrusters and MiPS packaging will produce a 650 gram MiPS with over 117 grams of propellant and 177 N-s of total impulse. By "stretching" the N_2O MiPS to a high capacity configuration these numbers can be increased by a similar proportion to those shown in Figure 14 for isobutane.

Low Power/Mass Upgrades

VACCO has already demonstrated manufacturing parts for ChEMS™ microvalves that fit in a 1cc envelope. Development of these valves would proportionately lower both mass and power consumption.

In addition to making functional components smaller, VACCO is developing

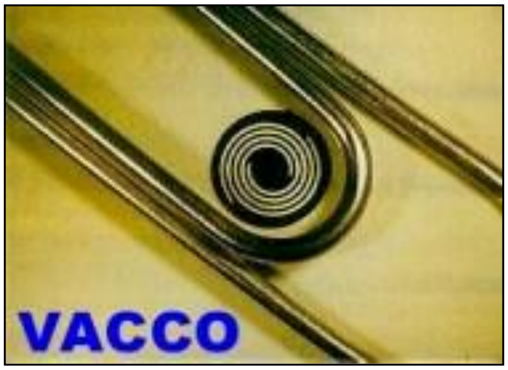

Figure 17: VACCO Micro-Spring

a latching version of our normally closed Micro-Valve. This proprietary design (patent #6,450,197 official) is a minor modification to the existing valve. Adding a magnet to the existing flux path and adjusting the assembly procedure accomplish conversion from normally closed to latching. Latching valves have an advantage in that they only require power to change state. As a result, power consumption can be reduced by 90%. This has obvious advantages in CubeSats where power is always at a premium.

MiPS as an Educational Tool

Making low cost MiPS available for University CubeSat projects would add a valuable new resource to the growing CubeSat toolbox. MiPS would be allocated to worthy CubeSat projects by the funding agency. VACCO would build and stock a number of MiPS parts less the bonded core assembly. The core assembly controls all component interconnections and tangential thruster geometry. The selected student team would learn by designing these critical features in order to customize a MiPS for their purposes. By stocking the pre-made machined parts, lead times can be reduced to less than four months. In this way, students gain valuable skills and experience while keeping the entire project to less than one year in duration. In addition, students would benefit from the enhanced capability and flexibility propulsion would bring to their CubeSat projects.

Conclusions

VACCO has designed, built, tested and delivered a flight Micro-Propulsion System for the Aerospace Corporation's MEPSI spacecraft. The resulting MiPS is the most capable and versatile propulsion system available for CubeSat class spacecraft. With five thrusters, 34N-sec of total impulse and up to 62,000 minimum impulse bit firings, MiPS brings substantial propulsion capability to CubeSats. Its robust, compact, lightweight design is ideally suited for the unique requirements of a CubeSat application. Inherently simple, the selfpressurizing isobutane propellant eliminates the need for special handling and a separate pressurization system. Reliability is enhanced by virtue of its highly integrated design with no tubing connections and redundant suspended armature valves with only one flexing part.

Testing of the MiPS flight unit at VACCO is complete with system level testing scheduled at Aerospace Corporation. Observations from testing include moderate external leakage and thruster-to-thruster flow consistency. External leakage has been traced to electrical feed-through headers and stem from an attempt to integrate them directly in the flat walls of the pressurized Propellant Storage Tank. In the future, these feed-through headers will be separate purchased parts that are EB welded to the Tank. Thruster-to-thruster consistency will be greatly improved in future MiPS by applying improved techniques for bonding the ChEMS⍰ manifold layers.

In summary, a great deal was learned about applying the ChEMS⍰ technology to micropropulsion that has led to a variety of similar activities for other customers. High capacity versions, MiPS using decomposing N_2O thrusters and smaller/low power components are all under development.

Taken together, these developments comprise an emerging propulsion capability that will allow CubeSat class spacecraft to take full advantage of their potential.

References

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Acknowledgements

The authors wish to thank the following people without whose skill, imagination, and hard work this work would not have been possible; Ben Otsap, Greg Terrones, Rick Hoppe, Rich Maschner and Chris Copley of VACCO Industries as well as Dave Hinkley of The Aerospace Corporation.