Development Status and 1U CubeSat Application of Busek's 0.5N Green Monopropellant Thruster

Michael Tsay, John Frongillo, Derek Lafko, Jurg Zwahlen
Busek Co. Inc.
11 Tech Circle, Natick, MA 01760-1023; 508-655-5565
mtsay@busek.com, jfrongillo@busek.com, dlafko@busek.com, jurg@busek.com
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ABSTRACT

The monopropellant community has been pursuing low-toxicity alternatives to hydrazine for the past two decades. One of such "green" monopropellants, known as AF-M315E, has caught attention of many by offering both improved performance and handling safety. A 0.5N-class, AF-M315E micro thruster was recently developed by Busek that can deliver >220sec vacuum Isp. Both steady-state and pulsed firings were demonstrated. The thruster, when cold, requires a small amount of pre-heating power to start which is no more than 12W or an equivalent of 1.6W-Hr energy input. The thruster is complemented by a novel piezoelectric microvalve that needs less than 200mW to operate and weighs a mere 67g. The valve features an all-welded, all-titanium wetted design for long-term propellant compatibility. It is rated for 1200sccm GN_2 max flow and 1.5×10^{-4}sccm GN_2 leak rate. The valve passed environmental testing before being integrated into the thruster, and together they demonstrated a minimum impulse bit of 0.036N-sec. Busek is currently developing a 1U CubeSat propulsion system centered on the integrated 0.5N thruster and microvalve. The system is designed to be self-contained and fully loaded with propellant, which allows for simple spacecraft integration and reduced operating cost.

INTRODUCTION

Since the late 1990s, there have been several efforts to develop high-performance, non-toxic monopropellants for the replacement of hydrazine. These green monopropellants typically are single-phase, very concentrated solutions consisting of a soluble oxidizer, in most cases a molten salt, and a hydrocarbon fuel. Some of them have slight water content for desensitization against explosions. Of all green monopropellant blends developed, AF-M315E has received the most attention in the U.S. due to its stability and ease of handling. AF-M315E is a pink-colored liquid with almost no vapor pressure in room conditions. Handling is simple and can be done with basic Personal Protective Equipment (PPE) such as gloves, goggles and lab coats. In comparison, handling of hydrazine would require a team of experts donning full Self Contained Atmospheric Protective Ensemble (SCAPE) suits.

The origin of AF-M315E can be traced to the U.S. Army's development of liquid gun propellants, which did not prove suitable for the relatively low combustion pressure in rocket engines.[1] The Air Force Research Laboratory at Edwards Air Force Base (AFRL/Edwards) recognized the blend's potential, modified the Army's formula and subsequently came up with this ultra stable and shock resistant green monopropellant for space propulsion applications.[2] Performance-wise, fully decomposed AF-M315E can produce an adiabatic flame temperature close to 1800^oC.[2] Compared to hydrazine, whose flame temperature does not reach much above 1000^oC, AF-M315E offers approximately 13% increase in specific impulse (Isp) and 63% increase in density-Isp. Furthermore, AF-M315E based systems can easily be stored on the shelf in a fully-loaded state, which could drastically simplify the spacecraft integration process and launch preparation.

Despite its potential benefits, industry-wide progress on AF-M315E thrusters has been slow due to the lack of suitable catalysts. Previous research showed that catalysts designed for hydrazine would quickly deteriorate when subjected to the high flame temperature of AF-M315E. The failure mechanism is apparently due to material sintering and substrate disintegration, which can lead to very limited thruster lifetime as well as continuous performance reduction. These problems are similar to the ones often observed in larger hydrazine thrusters.[3] Ever since its conception, catalyst attrition has always been a key obstacle to the general application of AF-M315E.[2] Realizing such a challenge, Busek has spent a great amount of effort developing and perfecting an alternative catalyst that is efficient yet robust.[4] It features a monolithic design that does not require a ceramic substrate or bed plates for containment. This pioneering work has led to a full U.S. patent application. Though the novel catalyst design was originally intended for the 0.5N thruster, it has since been adopted by Busek's other AF-M315E thrusters of larger scales.

The development of Busek's 0.5N AF-M315E thruster was motivated by the need of a small, non-toxic chemical thruster which can be used by developers of NanoSats or SmallSats. As these miniature satellites grow in functionality, their applicable missions seem to be limited only by the lack of propulsive capability. A small AF-M315E thruster offers the best solution from the perspectives of system simplicity, low power consumption and safety. The 0.5N size is also ideal for a wide range of applications. As primary propulsion on a CubeSat-class spacecraft, the thrust is low enough that it will not overwhelm the host and cause unrecoverable tumbling. On the other hand, the 0.5N thrust level is significant enough that it can be used for reaction control on larger spacecrafts.

It is worth noting that the AF-M315E propellant is currently being flight qualified for NASA's Green Propellant Infusion Mission (GPIM), scheduled for launch at the end of 2015 under the Space Technology Mission Directorate (STMD).[5] Though the thrusters flying are of different design and heritage, the propellant remains the same blend. A successful technology demonstration on GPIM therefore will have significant impact as AF-M315E will be recognized for being a legitimate alternative to hydrazine. Busek's 0.5N thruster and related technologies will benefit as a result.

BUSEK'S 0.5N AF-M315E THRUSTER

The solid model of Busek's flight-weight (FW) 0.5N micro thruster is shown in Figure 1 without the integrated piezo microvalve. Early development of the thruster, including the invention and characterization of its alternative catalyst, is discussed in detail in Ref. 4. The FW thruster's nozzle is made of a niobium alloy with a protective coating. This material combination is relatively inexpensive compared to the iridium-rhenium type seen on other green monopropellant thrusters[6], yet it offers decent thermal strength and allows the thruster to burn longer without excessive oxidation damage. Steady-state burns for up to 30sec have been demonstrated. Extended-duration firings are possible as the thruster did not show signs of failure during the 30sec operations. Figure 2 is a picture of the fully assembled thruster, taken post-test. The near-pristine condition of the niobium nozzle is a testament of successful material design and oxidation protection.

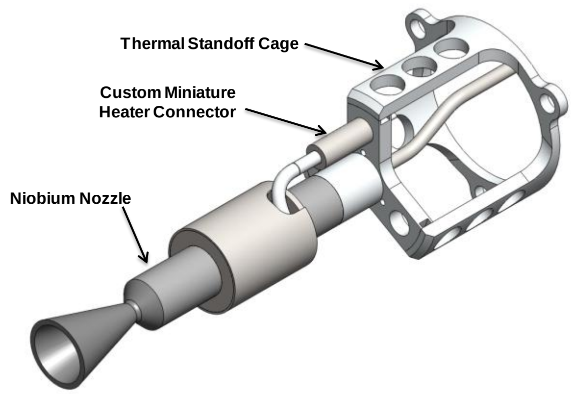

Figure 1: Solid Model of Busek's 0.5N AF-M315E Thruster

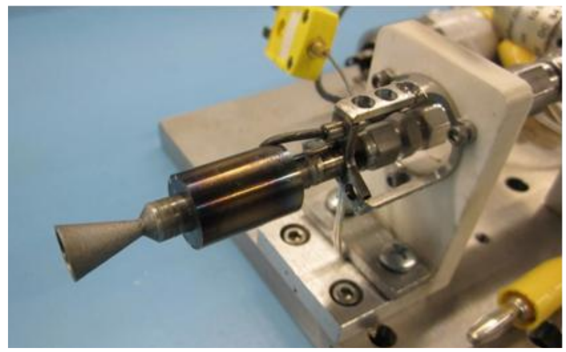

Figure 2: Post-Test View of a Fully Assembled 0.5N AF-M315E Thruster

Fabrication of the FW thruster's nozzle presented a unique challenge. Machining the niobium alloy to specification was difficult especially at such small scale. The nozzle's throat after the protective coating also looked very rough and irregularly shaped (Figure 3, middle), which is known to have adverse effect on the nozzle efficiency. An attempt was made to put these coated nozzles through Busek's proprietary polisher, and the result was surprisingly good (Figure 3, right). A post-processed niobium nozzle can consistently achieve 95% vacuum nozzle efficiency as illustrated in Figure 4.

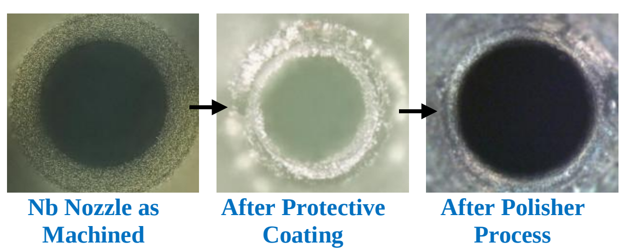

Figure 3: Downstream View of the Throat on the Micro Nozzle

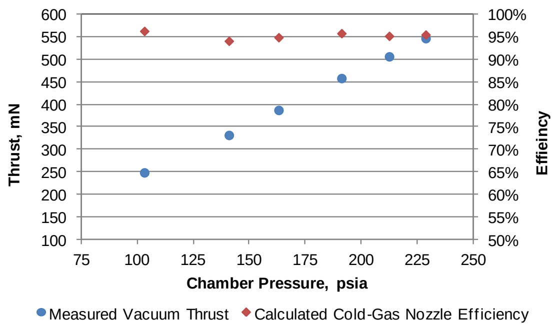

Figure 4: Cold-Gas Nozzle Efficiency, in Vacuum, of the Flight-Weight 0.5N Thruster

Preparation for Hot-Firing Tests

The flight-weight 0.5N thruster was installed on an inverted-pendulum style thrust stand in Busek's vacuum/high-altitude chamber for a series of validation tests. The test profiles consisted of steady-state, semi steady-state (consecutive long pulses), and short pulsed cycles. All tests were performed with background pressure in the 10mTorr range. A high-pressure syringe pump was used to feed the propellant at a pre-determined flow rate. For pulsed firings the pump was synchronized to the solenoid valve's opening so the feed system would never lose head pressure. The feed pressure was measured by a transducer just upstream of the solenoid valve.

A COTS solenoid valve, in lieu of the piezo microvalve, was used as the thruster control valve during the initial tests. With the solenoid valve there was an approximately 2"-long train of adapters and fittings between the valve and the thruster. As such the thruster had a slightly prolonged response each time after valve cycling. The relatively-long thrust "tail off" phenomenon was expected for each firing.

Results from Steady-State Firing

Figure 5 and Figure 6 show the measured thrust and the corresponding Isp from two steady-state firings. The displayed time stamp of "0sec" in these figures is arbitrary but representative of thruster ignition. Such uncertainty is related to the usage of a positive-displacement feed system, which is energized after opening the valve. This makes it very difficult to tell the exact moment when the propellant is injected.

The initial, 9mL/min flowrate run (Figure 5) was conducted when the thruster was cold, so the catalyst pre-heater was energized prior to propellant injection. The applied pre-heater power was approximately 12W at $19V_{DC}$ for 8 minutes, which was equivalent of 1.6W-Hr in energy input. The catalyst was preheated to $400^{o}C$ for a little safety margin against its $365^{o}C$ onset reaction threshold.[4] After propellant injection the thrust was seen climbing slowly and did not reach steady state until the 10sec-mark. The slow rise was believed to be caused by thermal soaking around the nozzle throat. For the second steady-steady firing (Figure 6), with a higher flow rate at 9.5mL/min, the thruster was already warm and no pre-heating was needed. The thrust rise was much more rapid and >500mN vacuum thrust was achieved during the 25sec-duration run. Although it still took about 10sec to reach steady state, at the 5sec-mark 90% of its full thrust was already obtained (compared to 33% in the initial "cold" run). Figure 7 shows the thruster in steady-state firing at full throttle, producing 506mN thrust and 223sec vacuum Isp.

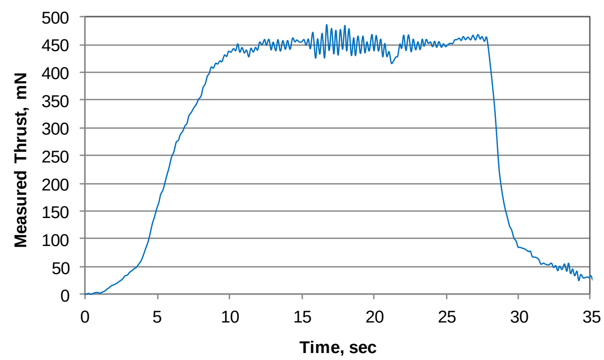

Figure 5: Steady-State Firing #1 with 9mL/min Flow that Resulted in 210sec Measured Vacuum Isp

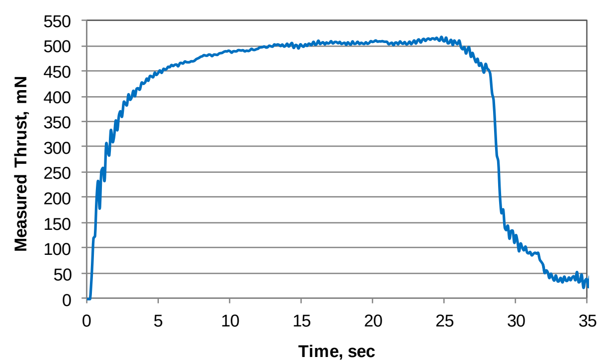

Figure 6: Steady-State Firing #2 with 9.5mL/min Flow that Resulted in 223sec Measured Vacuum Isp

Figure 7: Busek's 0.5N AF-M315E Thruster in Steady-State Firing at Full Throttle

Results from Semi Steady-State Firing

Figure 8 shows the result from a semi steady-state test in which two 25sec-long pulses were fired with ~90sec down time in between. The nominal "full throttle" flowrate of 9.5mL/min was used for both pulses. The catalyst preheater was used to ignite the first pulse, but it was turned off at the 10sec-mark for the remainder of the test. The second pulse was ignited with the residual heat on the catalyst. Both pulses achieved the 500mN target thrust, although the first pulse took about 15sec to reach steady state. This delay was related to thermal soaking by a "cold" nozzle throat but was much improved for the second pulse.

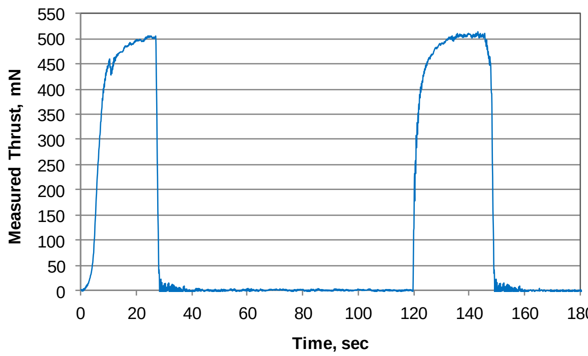

Figure 8: Semi Steady-State Firing with Two Long Pulses; Propellant Flow Rate Fixed at 9.5mL/min.

Results from Pulsed Firing

After the baseline performance had been validated, the thruster was put through a series of pulsed firings. The pulses were performed by cycling the solenoid valve and the syringe pump. The pump was rigged to energize simultaneously with the valve at a flow rate of 9.5mL/min. Constrained by the pump's reaction time, the pulse width was limited to a minimum of 0.5sec. Low duty-cycle profiles were focused since they are considered more relevant for ACS application. Table 1 shows the summary of the test profiles and their results.

Table 1 Summary of Pulsed Firing Profiles

Run	Freq, Hz	Duty Cycle, %	No. of Pulse	Pulse Width, sec	Peak Thrust, mN	Avg I-bit, N-sec
1	0.05	20	2	4	345	0.690
2	0.05	10	4	2	320	0.320
3	0.05	5	4	1	130	0.165
4	0.05	2.5	6	0.5	14.5	0.040
5	0.2	50	5	2.5	360	0.540

Profile #1 (Figure 9) contained two 4sec pulses at a period of 20sec. The pulse responses had a triangular shape reflecting both slow rise and long tail-off. The slow rise was contributed by the cold nozzle throat, and the long tail-off was caused by the line volume downstream of the solenoid valve. Nevertheless, the performance was repeatable, with peak thrust around 350mN and impulse bit averaging at 0.690N-sec. The measured feed pressure was between 300-325psia.

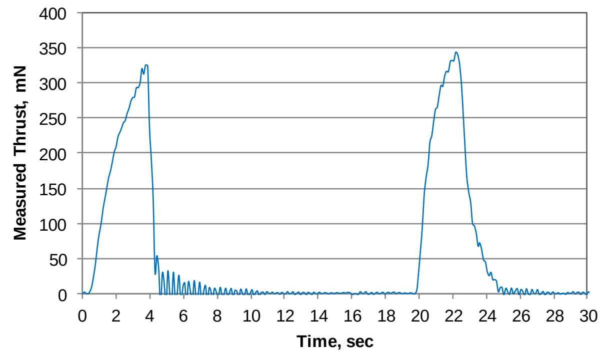

Figure 9: Profile #1 of Pulsed Firing: 0.05Hz Frequency at 20% Duty Cycle

Profile #2 (Figure 10) contained four 2sec pulses at a period of 20sec. The pulse responses were much sharper, though the tail-off was still long due to the line volume. The initial pulse produced significantly lower thrust than the other three. This was again caused by a cold nozzle, since the thruster was allowed to cool down completely after the profile #1 test. The three subsequent pulses, however, were steady and repeatable. Their peak thrust was around 300-320mN and the impulse bit was averaged at 0.320N-sec. Feed pressure was nominally at 325psia.

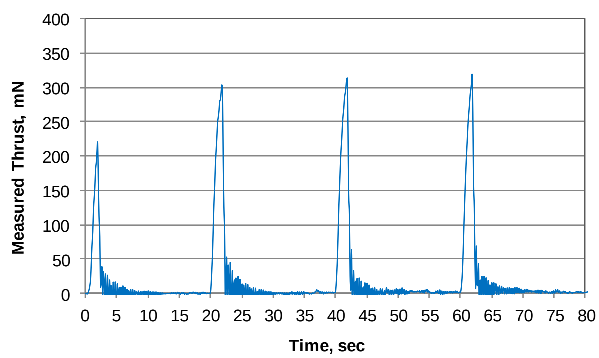

Figure 10: Profile #2 of Pulsed Firing: 0.05Hz Frequency at 10% Duty Cycle

Profile #3 (Figure 11) was commenced immediately after profile #2, and it contained four 1sec pulses at a period of 20sec. Since the thruster did not have time to cool down, the initial pulse response was strong and on par with the ones from subsequent firings. The peak thrust of each pulse varied slightly, ranging from 100 to 130mN. This fluctuation may be related to the syringe pump not being able to resolve the cycling command very well at this time scale. As the result, the amount of propellant injected every time may be a slightly different. Because the pump cannot react fast enough, the peak thrust was lowered and the feed pressure only reached 200psia. The 0.165N-sec averaged impulse bit, however, continued to be on a linear scale with respect to the pulse width.

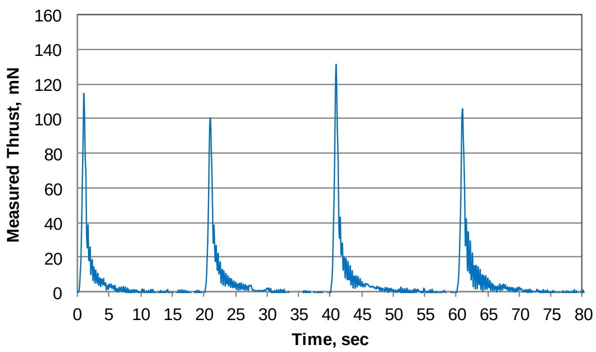

Figure 11: Profile #3 of Pulsed Firing: 0.05Hz Frequency at 5% Duty Cycle

Profile #4 (Figure 12) had the shortest duty cycle and pulse width during this round of testing. It contained six 0.5sec pulses at a period of 20sec, equivalent of 2.5% duty cycle. It was immediately evident that the pump cannot catch up at such cycling rate. The pulse responses were distinct, but the values were very low. The variation of 6-14mN peak thrust also fell under the category of measurement noise, as our typical thrust accuracy was approximately ±4mN. Despite having miniscule thrust output, profile #4 did demonstrate the thruster's minimum impulse bit at around 0.040N-sec. This result was significant because it proved that Busek's alternative catalyst is capable of providing fast responses.

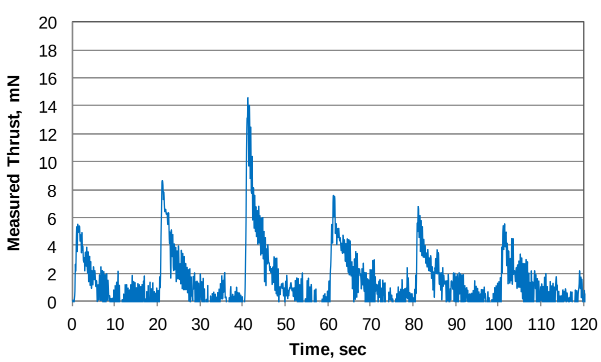

Figure 12: Profile #4 of Pulsed Firing: 0.05Hz Frequency at 2.5% Duty Cycle

Profile #5 (Figure 13) was an attempt to fire at a higher frequency, while maintaining a pulse width of >2sec in order to obtain substantial peak thrust. It was the last validation test for the flight-weight 0.5N thruster. The selected cycling profile contained five 2.5sec pulses at a period of 5sec, which was equivalent of 50% duty cycle at 0.2Hz. The pulse responses were very impressive, highlighted by good repeatability and ~360mN peak thrust values. These responses also began to resemble a square wave. The impulse bits were averaged at 0.540N-sec. The maximum feed pressure was again below 350psia.

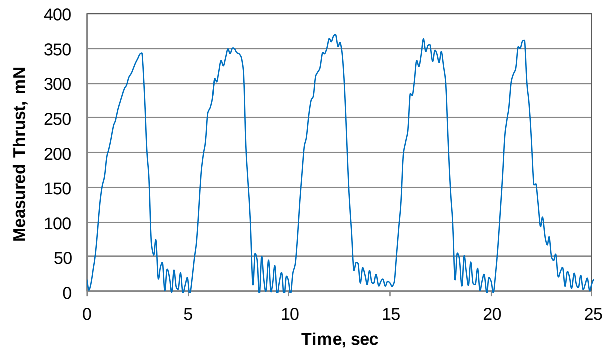

Figure 13: Profile #5 of Pulsed Firing: 0.2Hz Frequency at 50% Duty Cycle

COMPLETION OF PIEZO MICROVALVE DEVELOPMENT

The flight-weight 0.5N thruster, after being successfully validated, was integrated with a Busek piezoelectric microvalve. The engineering model (EM) microvalve, shown in Figure 14, was specially designed for green propellant use and was meant to be a complementary technology to the 0.5N thruster. Background and early development of the valve are detailed in Ref. 4.

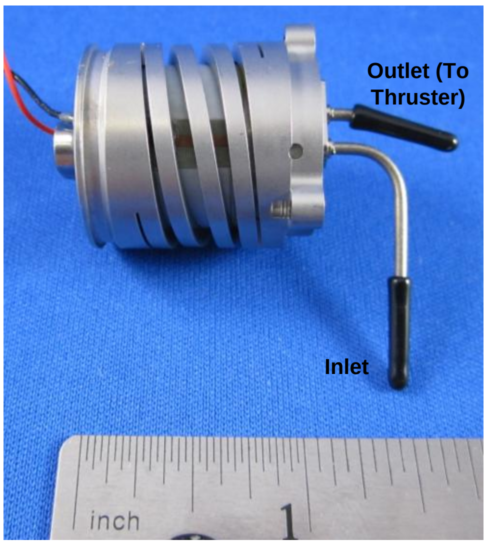

Figure 14: Busek's Piezo Microvalve for Green Propellants

Busek's green-propellant microvalve is a truly "micro" device in the sense that it weighs a mere 67g and consumes less than 200mW of power. In comparison, state-of-the-art solenoid valves of similar flow level would weigh more than 100g while requiring 10-15W to operate. Busek's piezo microvalve is unique in its size, power, as well as its compatibility with green propellants. Highlights of its design include 1) an all-welded construction without any elastomer seal, 2) all wetted parts are made of titanium, the only material proven long-term compatible with AF-M315E, and 3) capability for dynamic pulsing operations. The valve has passed shock and random vibration qualification, and was pressure-tested up to 400psig without bursting. Its current maturity status is TRL 5.

It should be noted that because of its unique construction method and material, Busek's microvalve is actually compatible with a wide range of reactive fluids. Although the green monopropellant AF-M315E was selected for its initial application, the valve is equally capable for metering other liquid and gaseous propellants.

Design Methodology

Busek followed the same methodology developed in the previous flight program effort to build a high-performance, lightweight piezo microvalve for green propellants. To be able to claim it flight-worthy, extra attention was paid to lessons learned from the NASA/JPL ST7-DRS program[7], where the piezo valve's viability does not so much depend on the ability to regulate flow in a controlled lab environment, but rather to be able to reproduce such performance in a flight-reliable design. It was deemed that a good valve design consequently must address all of the following issues in order to be suitable for space flight:

1. <u>Thermal expansion balancing of valve components:</u> With piezo actuation displacements of ~10μm or less, temperature fluctuations of as little as 20°C can cause inadvertent valve opening, decrease operating range, or prevent valve opening. From this aspect, it is actually desirable to make the valves as small as possible to reduce absolute thermal dimensional changes while preserving the actuator stroke.
2. <u>Actuator positioning:</u> With only ~10μm available stroke, the actuator must be positioned within a matter of 1-2μm in order to preserve its operational range. This is beyond normal machining tolerances and requires either a creative design that eliminates machining tolerances, or a reliable, precise, locking adjustment mechanism. In either instance, the design must incorporate a mechanism to compensate for all tolerance stack-ups in the final assembly step and the mechanism shall not lose its adjustment through thermal or mechanical cycling or vibration/shock loading.
3. <u>Valve seat/orifice selection and mounting</u>: All serially loaded components cannot strain under sealing loads such that relaxation of strain overwhelms the piezo actuation stroke. Serially loaded components must behave elastically since any plastic deformation would consume available actuation stroke, and viscoelastic deformation (such as certain polymeric seals) may lead to performance variation as a function of valve opening time. The orifice/seal interface must align and not leak appreciably.
4. <u>Reliability in manufacturing and assembly</u>: Considering the reduced price tags for small satellites and their subsystems, a repeatable and reliable manufacturing process for the microvalve needs to be established to prevent excessive cost in production and acceptance testing. The same methodology applies to the assembly process, which can affect performance consistency and ultimately the delivery cost.

Valve Builds and Initial Gas Flow Tests

Two EM piezo microvalves were successfully built for the completion of the development effort. Their components and assembly procedures were identical to ensure manufacturability and repeatability. The assembled EM valves were first leak-checked with nitrogen gas (GN_2), followed by an examination of its flow characteristics when opening. The build #1 valve met or exceeded performance standards in both sealing and opening abilities. Sealing-wise approximately 1.5×10^{-4} sccm GN_2 leak rate was recorded. This leak rate was calculated from the result of a long-duration (12hr), pressure-based leak test. It was suspected that the leak rate can be further reduced by improving the surface polishing on the titanium orifice. Nevertheless, the number is believed to be more than adequate for liquid flow applications.

In addition to having a satisfactory leak rate, the build #1 valve also exhibited high flow capability. Figure 15 shows the GN_2 flow curve that was used as bench mark. The valve allowed ~820sccm of N_2 to flow through at the full opening voltage and 50psi differential pressure. This is quite high, compared to our earlier "good" valve that maxed out at 550sccm.[4] To make sure the build is solid and all internal parts have settled from any movement, a series of "tap tests" were performed. The tap test entails a controlled hammer drop from 6" height to a rigid plate mounted to the valve's base. It can be considered as a manual shock test at 5-10G level. Each of the tap tests is followed by a flow curve check, and the pass criteria for it are 1) less than 5% shift of full flow rate and 2) no noticeable change in the opening voltage. The build #1 valve passed the tap tests as evidenced in Figure 15. The max flow rate shifted only 2.5% (down to 800sccm) and the opening voltage was unchanged at 40.6V.

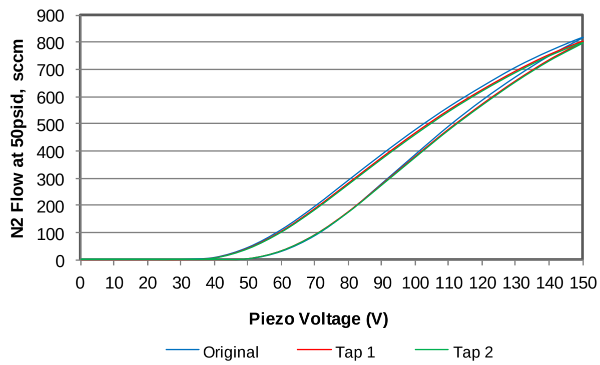

Figure 15: GN_2 Flow Curve of EM Valve Build #1

Since a higher-flow capacity valve could drastically reduce the ΔP requirement for metering AF-M315E, the previous build was repeated with a slightly different setting. For valve build #2 the pre-load force was decreased during assembly, in hope that the piezo would engage earlier and valve would open at a lower voltage. The result, shown in Figure 16, was better than anticipated as 1280sccm GN_2 was achieved at max open, doubling what we had with the build #1 valve. The much reduced opening voltage (to ~20V) reflects earlier piezo engagement and less wasted stroke. The two tap tests also confirmed build quality as shifts in max flow were within 3.5% of the initial value.

The one minor issue with this valve was that due to the lower pre-load setting (in order to achieve lower-voltage opening), the leak rate was slightly higher than before and hovered around 7×10^{-4}sccm GN_2. Such a leak rate should not pose a huge issue for the liquid application, judging from the propellant's viscosity and its resistance to flowing through small orifices. Because of its slightly better flow performance, the build #2 valve was selected to be integrated with the 0.5N thruster for combined firing.

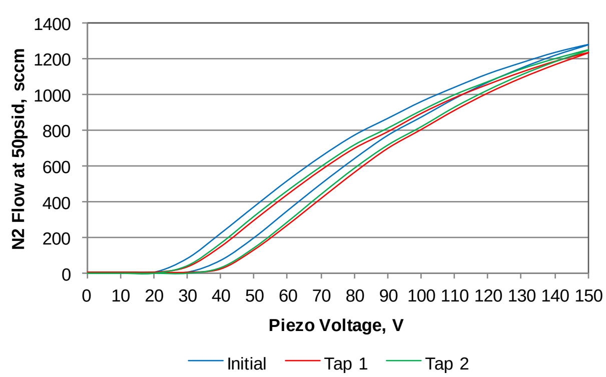

Figure 16: GN_2 Flow Curve of EM Valve Build #2

Results from Liquid Flow Tests

The build #1 valve was subjected to a liquid validation test. The plan was to measure the pressure drop at various water flow rates, then rely on an orifice flow calibration to predict the pressure drop for the real AF-M315E flow. Because of potential contamination issues, AF-M315E was not directly put through the valve. This was because any trapped propellant within the valve would pose a hazard when the valve is being integrated with the 0.5N thruster. Specifically, the high temperature environment used to braze the tubing together could potentially trigger an exothermic reaction from the stagnant propellant inside the valve.

The orifice flow calibration was conducted first. A syringe pump was used to meter water, and then AF-M315E, through a 0.010"-diameter orifice. A pressure transducer was set up upstream of the orifice to measure the pressure drop, with the downstream open to atmosphere. The result is plotted in Figure 17. In general, AF-M315E requires 2.2x differential pressure for the same flow rate as water. For reference, 9.5mL/min is the target flow rate as it was used to validate the 0.5N thruster's performance of 220sec vacuum Isp at full thrust.

It was noticed that flowing AF-M315E became more difficult as the orifice size was reduced. It was later discovered that any leading air pocket or trapped air bubble can create an adverse effect akin to vaporlock. This problem seems to be most prominent when testing in atmosphere. The propellant is essentially too viscous and has too much surface tension to collapse the bubble. As a result it can have trouble "squeezing" the bubble through a small orifice. It was somewhat concerning as the piezo valve's stem lifts <12µm (<0.00047") from the sealing surface. However, having vacuum downstream of the valve's orifice, in addition to a bubble-free propellant reservoir, should be able to mitigate such an issue.

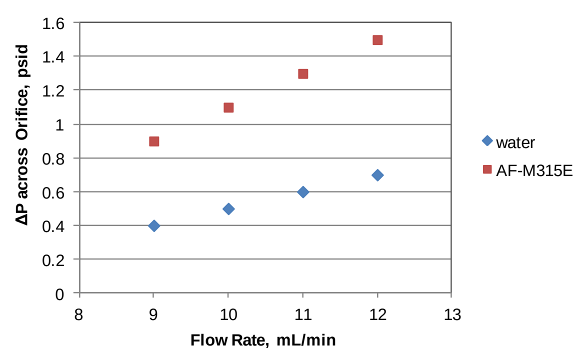

Figure 17: Orifice Calibration Test for Pressure Drop versus Liquid Flow Rates

After obtaining the orifice calibration data, the build #1 valve was subjected to a water flow test for "ΔP vs. flow rate". At the flow rate of interest (9.5mL/min) the ΔP required for water flow was approximately 19.2psi. Using the 2.2x conversion factor, the ΔP requirement equates to 42.2psi if the liquid medium is AF-M315E. Since this 42.2psi ΔP is associated with an 800sccm GN_2 rated valve, it would be interesting to see what the pressure drop would be for a valve that can open to higher flows. Figure 18 shows an estimate of such a relationship, assuming a fixed AF-M315E flow rate at 9.5mL/min.

From the estimated "ΔP vs. Max Opening" relationship shown in Figure 18, the build #2 valve was expected to require very little pressure drop when metering AF-M315E. Since its max opening was rated at 1200sccm GN_2, its ΔP for the nominal 9.5mL/min propellant flow rate should be close to just 18.8psi.

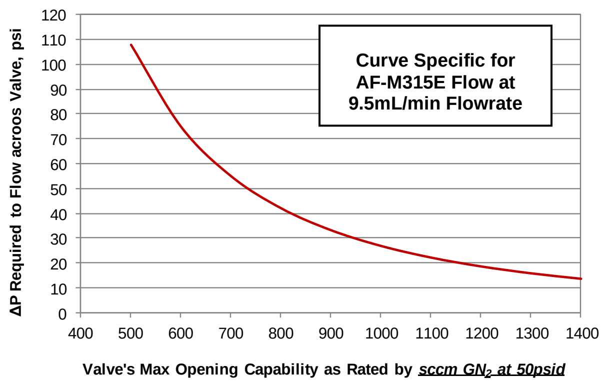

Figure 18: ΔP Requirement as Function of Valve's Max Opening Capability

Environmental Qualification

The build #1 valve was sent to environmental testing that included shock and random vibration. In preparation for the vibe test, the valve first received some structural Epoxy adhesives to lock down the tightening mechanism. This locking procedure ensures that all the internal parts are permanently secured in axial (z-axis) compression. The use of Epoxy for such "lock tight" purpose is customary in Busek's flight hardware.

The vibe test was performed by National Technical Systems (NTS) with supervision from one of Busek's engineers. A total of four tests were conducted for each axis, including random vibration, 26G quasi-static load, 20G sine wave and Shock Response Spectrum (SRS) shock. Figure 19 shows the test setup on the NTS vibe table and Table 2 lists the qualification tests that were performed. Specifications of the vibe test were borrowed from Busek's previous flight valve development, under the NASA/JPL ST7 colloid thruster program.

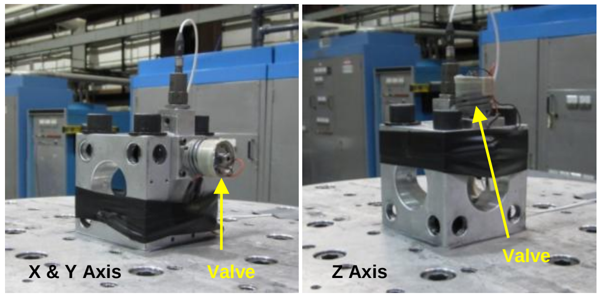

Figure 19: The EM Valve Seen on the Vibe Table

Table 2 Summary of Environmental Tests

Test 1	Random Vibration			
Axis	X & Y		Z	
Qual	Hz	PSD	Hz	PSD
	20 20-80 80-400 400-2000 2000	0.096 +3dB/octave 0.384 -5dB/octave 0.040	20 20-80 80-400 400-2000 2000	0.192 +3dB/octave 0.76 -10dB/octave 0.0036
Test 2	**Quasi-Static Load**			
Axis	X & Y		Z	
Qual	100Hz @ 20G		100Hz @ 26G	
Test 3	**Sine Vibration**			
Axis	X, Y & Z			
Qual	5-21Hz @ 22mm p-p 21-100Hz @ 20G			
Test 4	**SRS Shock**			
Axis	X, Y & Z			
Qual	100Hz @ 20G 1,500Hz @ 1000G 10,000Hz @ 1000G			

Real-time pass/fail assessment cannot be made during the vibe test, because there was no room to attach an accelerometer on the valve. Instead, a blind test was performed in which the valve went through all the qualifications before its state of health was verified by another GN_2 flow curve. The criterion for passing the vibe test was then defined as a "predictable but minimum" change in flow characteristics. Any post-vibe flow change needs to be a single occurrence, meaning that it has to be a controlled phenomenon caused by component settling. Subsequent tap tests were performed to verify that the max flow does not decrease continuously. Failing these tap tests would be the tell-tale sign of a non-compliant valve, as it suggests unpredictable valve opening due to loose parts. A valve with very limited opening capability will require too much pressure drop when metering the liquid propellant. For practical purposes, any valve which requires >>50psid at the designed propellant flow rate would be scrapped.

The build #1 valve received a passing grade for the vibe test as it had an acceptable shift in the max opening flow. Subsequent tap tests (4 conducted) confirmed that the shift was a one-time occurrence as follow-up changes were all within 5% of the newly established flow curve. It was projected that the post-vibe, build #1 valve would not require pressure drops much higher than 50psid at the target 9.5mL/min AF-M315E flow rate.

Development of Miniature Valve Driver Electronics

A valve driver is required to operate the piezo-actuated microvalve. Its main function is to convert a 0-5V command input voltage and generate a proportional 0-150V output to drive the piezo valve. The board needs to be as small as possible, judging that Busek's previous flight driver board was way too large for nano-satellite applications. In addition, the board needs to consume as little power as possible and still respond fast enough to pulse the valve quickly for ACS functions. A maximum pulsing frequency of 5Hz (0.1sec on, 0.1sec off) was used as the upper bound for design guideline purpose.

Several topologies were investigated for the valve driver. A fly back converter, a feed-forward converter, and a Royer oscillator were all considered and tested, but proved to be too large (in terms of parts count and mass) and inefficient. The simplest approach was to use a modified tank circuit with a feedback winding to generate the AC source signal from a DC level. The high-voltage output was full bridge rectified, combined with a PNP transistor and diode configuration to provide a fast shut off of the piezo-actuated valve. An inverse F-class oscillator was used to step up the 5V input to 150V output. Following a careful selection of the toroidal core, an EM driver board was developed that satisfied both size and power goals. It is shown in Figure 20.

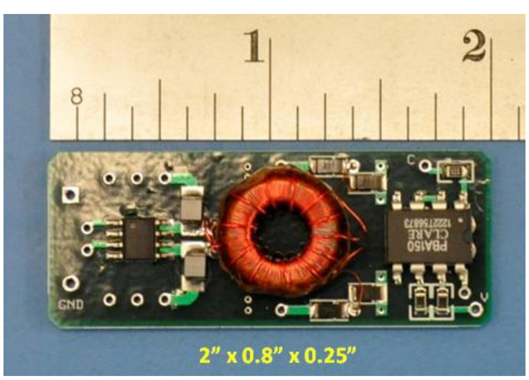

Figure 20: Miniature Piezo Valve Driver Board

One key feature of this valve driver design is the ability to operate in a continuous pulsed mode. Pulsing the piezo valve from 0-150V at high frequencies requires a large amount of energy storage. This was achieved by using as much capacitance as possible on the small PCB footprint. A large amount of input capacitance helps to buffer the burden on the power supply, and a large amount of capacitance on the high voltage output helps to ease the burden on the valve driver circuit. This output buffer helps to maintain the 150V high voltage rail by reducing the power required to maintain the rail. The valve is commanded on and off at the specified pulse widths by a separate 5V TTL level signal command the valve on or off at the specified pulse widths. Figure 21 shows the test data of the valve driver, pulsing at 1Hz frequency and 50% duty cycle (0.5sec on, 0.5sec off).

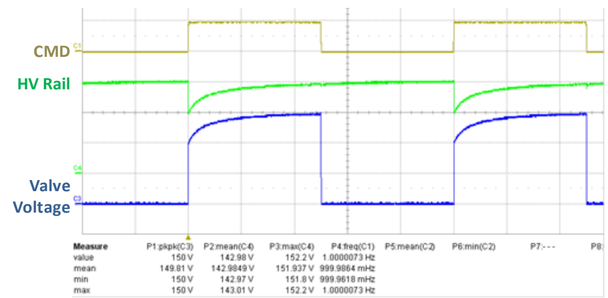

Figure 21: Test Data of the Valve Driver Pulsing at 1Hz Frequency and 50% Duty Cycle

As can be seen in Figure 21, the valve driver operates quite nicely even at the fastest switching speeds. It should be noted that the driver was operating continuously at 1Hz, so the overall power and the voltage sag on the supply rail was larger during these tests than would be during a short duration firing. There is about a 50V sag in the supply rail during each “on” pulse, which translates to a slight delay for delivering full 150V to the piezo valve. This could be mitigated in future designs by increasing the output capacitance of the valve driver, thus providing a more rigid high voltage output. The voltage sag should not be a real issue with the actual operation as the piezo valve's opening is predictable in the 100-150V range. Since the valve is meant to work with a thruster, letting through a controlled, repeatable amount of the propellant during the pulsed mode is paramount for achieving constant impulse bit performance.

During the continuous pulsing mode, the input power required to operate the valve was measured. The average power decreases as the frequency goes down, as the high voltage rail does not need to be charged back up as frequently at the lower frequencies. This again shows the importance of the bulk capacitance on the output and how the power draw can be improved with more capacitance during any future design iterations. A summary of the test data is shown in Table 3. Notice the mere 102mW power that is required to maintain the valve wide open (idle) at 150V.

The input power, shown in Table 3, represents nearly 100% of the power requirement of the piezo valve system. This is because the piezo actuator itself is a purely capacitive load with very minimum internal leakage. Since it is unlikely that the valve will be asked to pulse much faster than 1Hz in actual operations, it can be concluded that the valve requires less than 200mW nominally.

Table 3: Power Required by the Valve Driver at Various Pulsing Frequencies

Frequency	Input Voltage, V	Avg Input Current, A	Power Drawn, mW
Steady-State	5.001	0.0204	102
0.1 Hz	5.001	0.0210	105
1 Hz	4.999	0.0331	165.5
5 Hz	4.998	0.0756	377.8

VALVE-THRUSTER INTEGRATED TESTING

With the 0.5N thruster and the piezo microvalve both completing their respective developments, a final hardware integration took place. The resultant product is shown in Figure 22. The valve chosen for integration was build #2, which was rated for ~1200sccm GN_2 max opening flow. Its required pressure drop at the 9.5mL/min nominal propellant flow should be around 18.8psi, according to Figure 18. At such a low ΔP the resultant feed pressure (under hot-firing) was expected to be almost identical to the one with a solenoid thruster valve, which was slightly below 350psia.

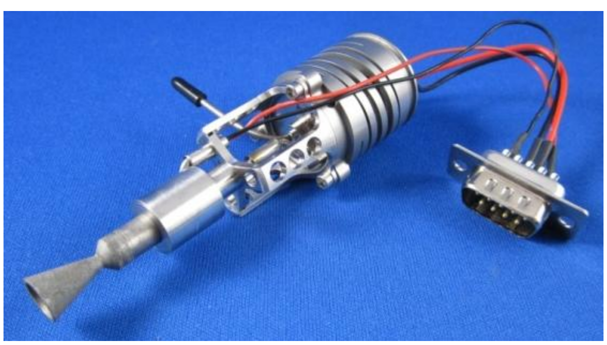

Figure 22: Busek's Flight-Weight 0.5N AF-M315E Thruster with Integrated Piezo Microvalve

Hot-Firing Tests

The integrated thruster-microvalve unit was subjected to a functionality test. The test was somewhat abbreviated due to time and budget constraints. Two vacuum hot-firings were conducted with different propellant feed mechanisms; the first was a short duration burn, for which a syringe pump was synchronized with the piezo valve opening. The second was a pressure-regulated feed using only 50psia head pressure, in an attempt to measure the minimum impulse bit.

Both of these feed systems had similar challenges in regards to maintaining an air-free feed line. The viscosity of the propellant poses difficulty when dealing with leading air pockets or air bubbles within the propellant. As such, by having small "orifices" inline there could be potential trouble spots for vaporlocks. One of such spots is the microvalve's sealing surface, since the stem only lifts ~10µm. The other location is the 0.5µm propellant filter upstream of valve, which was needed to prevent particulates entering the valve and wedging in between the sealing surfaces.

The integrated hot-firing demonstration was carried out with the potential vaporlock issues in mind. The piezo microvalve was connected to the miniature valve driver board, which had been made vacuum compatible. The first test involved a short, 4sec-duration burn with the pump supplying 9.5mL/min flow rate. The resultant data (Figure 23) showed large thrust oscillations, which from experience suggested trapped air bubbles. The propellant essentially was having problems flowing through the microvalve smoothly. Nevertheless, the data were encouraging as the peak thrust was in the 350- 400mN range, similar to the thruster-only test data shown in Figure 9 (also a 4sec firing). In addition, the maximum feed pressure recorded was under 350psia as expected, which validated the ΔP estimation for the microvalve. The most interesting result from this firing was perhaps the square response with a short tail-off. This was contributed by the valve's fast actuation, as well as the minimum line volume between the thruster and the integrated microvalve.

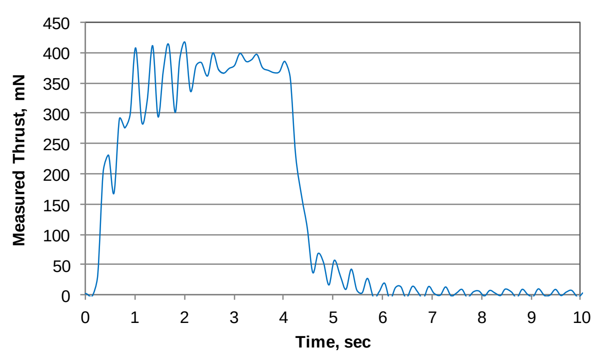

Figure 23: Integrated Thruster-Microvalve Test; Pump Fed with 4sec-Duration Burn

The second integrated test consisted of four 2sec pulses. Figure 24 shows the firing results. The test was performed without the syringe pump; instead, a 50psia regulated propellant pressure was used. The much lowered feed pressure explains the low peak thrust of ~18mN. The pulse responses were highly repeatable, and the thrust trace resembled a square-wave pattern. The tail-offs were also very short, similar to the result seen in Figure 23. The averaged impulse bit for each pulse was easier to calculate, thanks to the distinct square-wave response. The number was approximately 0.036N-sec. Since additional tests were not performed afterward, the 0.036N-sec value would represent the minimum impulse bit for the integrated thruster as demonstrated to date. A full duty-cycle workout is planned for future work.

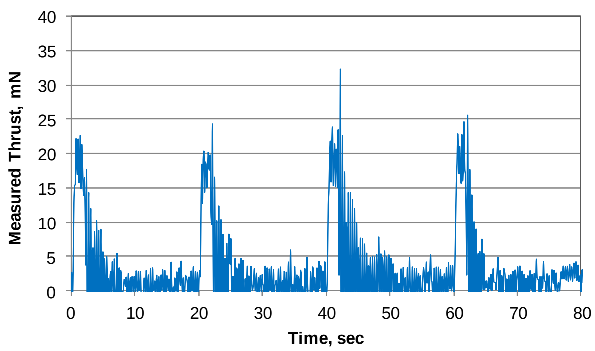

Figure 24: Integrated Thruster-Microvalve Test; 50psia Regulated Feed Pressure with Valve Pulsing at 0.05Hz and 10% Duty Cycle

1U CUBESAT GREEN PROPULSION SYSTEM

Busek is currently developing a 1U CubeSat propulsion system based on the 0.5N AF-M315E thruster and its integrated piezo microvalve. The system will also feature an innovative post-launch pressurization scheme, in which an inert pressurant gas is generated in space while requiring ~1W of power. With the ability to launch completely unpressurized, the system will pose minimum hazards to the spacecraft integrator, the primary payload and the launch vehicle. In essence, it will be a better candidate for rideshare opportunities than other state-of-the-art CubeSat propulsion devices because of its low toxicity, safety and minimum need for launch waivers.

The 1U propulsion system will be fully integrated and can be pre-loaded with propellant. Shelf-storage will not be a concern as the propellant is not pressurized on the ground. Figure 25 illustrates the concept. In the preliminary design the dual-bellows, toroidal propellant tank can carry up to 170cc propellant, which leads to an estimated system wet mass of 1.2kg. All propellant-wetted surfaces within the storage tank and valves will be made of titanium for long-term material compatibility. The thruster will be placed coaxially with the toroidal propellant tank for maximizing volume efficiency. Its slight protrusion will occupy the volume available inside the ejector spring of a CubeSat launcher (e.g. P-POD). The propellant tank will house two concentric, welded bellows that form the propellant reservoir while providing the pumping mechanism. These bellows will be driven by inert pressurant gas generated after launch.

With the 0.5N thruster delivering close to 220sec of vacuum Isp, the 1U system is capable of approximately 475N-sec total impulse. This number is equivalent to 122m/s of delta-V performance for a 3U, 4kg CubeSat. Overall power requirement is on the order of 15W, most of which is used to pre-heat the thruster's catalytic reactor when cold. Since the heater can be turned off after successful thruster ignition, the bulk power consumption is on the order of only 1W during steady-state or pulsed firings. The onboard PPU is designed to handle any DC voltage supplied by the spacecraft bus. It will have an integrated Digital Control Interface Unit (DCIU) that permits RS-232 communication for thruster command and data relay. Integration with the bus will be simple as no other connector ports will be required besides power and communication.

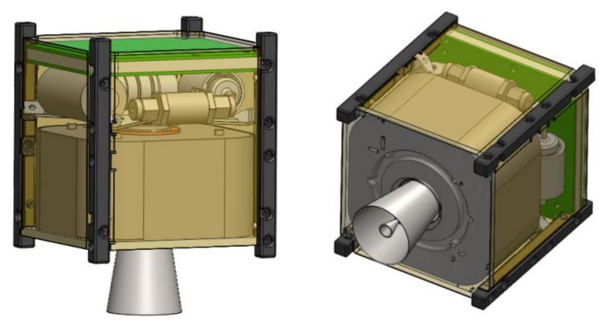

Figure 25: Conceptual Solid Model of Busek's 1U CubeSat Green Propulsion System

CONCLUSION

A flight-weight 0.5N AF-M315E micro thruster was successfully developed by Busek. It can deliver 220sec Isp nominally at full thrust in vacuum. Both steady-state and pulsed firings, including 2.5-50% duty cycles, have been demonstrated. The thruster requires 12W for 8min (1.6W-Hr input energy) for catalyst pre-heating when cold, but the heater can be turned off once the ignition temperature threshold is reached.

The thruster is complemented by a novel piezo-actuated microvalve that is currently at TRL 5. It weighs just 67g and requires less than 200mW to operate via a custom, miniature valve driver. The valve features an all-welded, all-titanium wetted design that is unique in the industry. It is rated for 1200sccm GN_2 max flow and 1.5×10^{-4}sccm GN_2 leak rate. The valve passed environmental testing before being integrated into the thruster.

The integrated thruster-valve unit was briefly tested. The results were very promising, as good controllability and 0.036N-sec minimum impulse bit were demonstrated. However, due to the very-limited displacement of the piezo actuator, the microvalve was found to be highly susceptible to vaporlock issues when metering AF-M315E. Proper venting of the feed line, in addition to a completely-degassed propellant reservoir, is paramount to the valve's successful operation. The required 0.5µm filter upstream of the valve is another trouble spot for vaporlocks. Any trapped air pockets there can also cause disruptions to the propellant feed. Maintaining an air-free propellant reservoir and thruster feed line remains a critical issue for future work, where more duty-cycle tests are to be performed.

One near-term application of the 0.5N AF-M315E thruster is presented in the form of a 1U CubeSat propulsion system. Busek is leveraging several existing technology foundations for such work. This includes the thruster, the piezo microvalve, the post-launch pressurization system and the CubeSat class propellant tank. CubeSat propulsion in general has multiple challenges associated with it. Simple cold-gas thrusters do not provide adequate performance for a multitude of mission profiles. Electric propulsion systems are compact and low mass, but require substantial amount of power, which raises difficulties for CubeSats due to low power availability, or high waste heat dissipation. Chemical propulsion systems largely resolve these problems, but they typically have the dual safety hazards of pressure and toxicity. Busek's 1U propulsion system resolves both of these hazards by providing an inert post-launch pressurization device, as well as a safe, green propellant.

ACKNOWLEDGMENTS

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