Development of Long-Lifetime Pulsed Gas Valves for Pulsed Electric Thrusters

Wendel M. Burkhardt,* John M. Crapuchettes†
WASK Engineering, Inc., Cameron Park, CA 95682, USA

and

Brad M. Addona,‡ Kurt A. Polzin§
NASA-George C. Marshall Space Flight Center, Huntsville, AL 35812, USA

The design and test results for two types of pulsed gas valves are presented. The valves, a piezo valve and a solenoid actuated valve, must have exceedingly long lifetime to support gas-fed pulsed electric thruster operation for missions of interest. The performance of both valves was tested, with both demonstrating the capability to throttle the gas flow rate while maintaining low leakage levels below 10^{-3} sccs of He at the beginning of valve lifetime. The piezo valve varies the flow rate by changing the amount that the valve is open, which is a function of applied voltage. This valve demonstrated continuous throttlability from 0-10 mL/s, with opening and closing times of 100 μs or less. The solenoid actuated valve flow rate changes as a function of the inlet gas pressure, with demonstrated flow rates in these tests from 2.7-11 mL/s. The valve response time is slower than the piezo valve, opening in 1-2 ms and closing in several ms. The solenoid actuated valve was tested to one million cycles, with the valve performance remaining relatively unchanged throughout the test. Galling of the sliding plunger caused the valve to bind and fail just after one million cycles, but at this point in the test the valve sealing surface leak rate still appeared to be well below the maximum target leak rake of 1$\times$10^{-3} sccs of He.

I. Introduction

PULSED electric thrusters operate by storing energy, typically in a capacitor, and then rapidly discharging that energy either directly into a gas to form and accelerate a plasma or through an inductive coil that couples to a plasma through an electromagnetic field that acts to accelerate the gas. In both cases, acceleration arises from the Lorentz body force produced through the interaction of plasma currents and a magnetic field generated during thruster operation, expelling propellant at high exhaust velocities ($\sim$10-100 km/s). Pulsed thrusters can operate at very high instantaneous (during pulse) powers of hundreds of kW to multi-MW, but their pulse rates can be adjusted to permit maximum per pulse operation over a wide range of input power levels.

It is advantageous for gas-fed pulsed electric thrusters to employ pulsed valves so propellant is only flowing to the device during operation. The propellant utilization of the thruster will be maximized when all the gas injected into the thruster is acted upon by the fields produced by the electrical pulse. Gas that is injected too early will diffuse away from the thruster before the electrical pulse can act to accelerate the propellant. Gas that is injected too late will miss being accelerated by the already-completed electrical pulse. As a consequence, the valve must open quickly and close equally quickly, only remaining open for a short duration. In addition, the valve must have only a small amount of volume between the sealing body and the thruster so the front and back ends of the pulse are as coincident as possible with the valve cycling, leaving very little latent propellant remaining in the feed lines after the valve is closed. For a

*President.
†Valve Design Engineer.
‡Propulsion Component Engineer, Valves, Actuators, and Ducts Design and Development Branch, Propulsion Systems Department, brad.m.addona@nasa.gov.
§Propulsion Research Engineer, Propulsion Research and Technology Applications Branch, Propulsion Systems Department, kurt.a.polzin@nasa.gov. Associate Fellow AIAA.

real mission of interest, a pulsed thruster can be expected to pulse at least 10^{10}-10^{11} times,[1] setting the range for the number of times a valve must open and close.

The valves described in this paper have been fabricated and tested for operation in an inductive pulsed plasma thruster (IPPT) for in-space propulsion.[2] In general, an IPPT is an electrodeless space propulsion device where a capacitor is charged to an initial voltage and then discharged, producing a high-current pulse through a coil. [3] The field produced by this pulse ionizes propellant, inductively driving current in a plasma located near the face of the coil.

Two different valves designed for the IPPT application have been fabricated and are presented in this work. The first is a piezoelectric valve while the second is a conventional valve opened using a solenoid electromagnetic actuator. Both valves have undergone benchtop testing, with the conventional valve also undergoing a large number of cycles.

In this paper we describe in Sect. II the requirements that the valves were attempting to meet for this particular design iteration. After that, we describe the design of a long lifetime piezo electric valve and solenoid actuated valve in Sects.III and IV, respectively. In Sect. V, we present the results of benchtop valve performance evaluation, while Sect. VI contains a discussion of a one million cycle life test of the solenoid actuated valve.

II. Valve Design Requirements

The valve characteristics needed for the IPPT application require a fast-acting valve capable of a minimum of 10^{10} valve actuation cycles. Since even 10^9 cycles is well above anything demonstrated, this lower value was selected as the design point for the present work. The valve seal must remain leak-tight throughout operation, and the body must maintain a low internal leakage at relatively high operating temperature. The design requirements used for this work are given in Table 1.

Table 1. Long-lifetime pulsed valve design requirements.

Parameter	Requirement
flow rate	$\geq$ 164 sccm (10 scim) GAr @ 276 kpa (40 psia) inlet pressure, 0 kPa (0 psia) outlet pressure and 21°C (70°F)
opening & closing response	$\leq$ 1 ms (goal) at 103-690 kPa (15-100 psid) and 21-149°C (70-300°F)
internal leakage	$\leq 1\times10^{-3}$ sccs GHe at 103-690 kPa (15-100 psid) and 21-149°C (70-300°F)
cycle life	$> 10^9$ cycles
operating temperature	up to 149°C (300°F)

III. Piezoelectric Valve Design

The fast acting valve, shown in Fig. 1, is a small, piezo crystal actuated, normally closed valve. The basic layout of the valve and dimensions are shown in Fig. 2. The valve 1.44 inches long and is 0.72 inches wide at the largest point of the base. The valve seat is very close to the base of the valve, ensuring minimal dribble volume.

Piezo crystal actuators have a very limited stroke. This required the valve to be designed with features to ensure the valve operation would not be affected by the valve temperature. The pintle portion that is welded to the bellows is similar to the conceptual design. The valve also included features that allows for very precise adjustments, less than 0.0002 inches, to control preloads within the unit. The gas inlet line was selected to be a bolt on unit to simplify the design and place the valve inlet at a location that is easily accessible once the valve is mounted to an IPPT. Critical parameters of the piezo crystal actuator used in the valve are shown in Table 2.

To achieve optimum sealing of the valve for the lengthy cycle life requirement, a seat arrangement was selected that uses spherical surfaces on both the end of the pintle and the mating surface in the seat. This was selected in that it provides sufficient surface area to maintain the contact loads within the loading regime where the Inconel 625 seat material will not work harden. Also, the technology to manufacture the surfaces is based on the grinding of ball bearings where very precise tolerances can be achieved. The load on the seat has been estimated to be 18 lbs. With the contact area selected, the contract stress is anticipated to nominally be 7,200 psi with a potential worst case value of 14,000 psi, well below the 60 ksi work hardening value of Inconel 625. Future development efforts will examine alternate seat designs to achieve the strenuous life requirement.

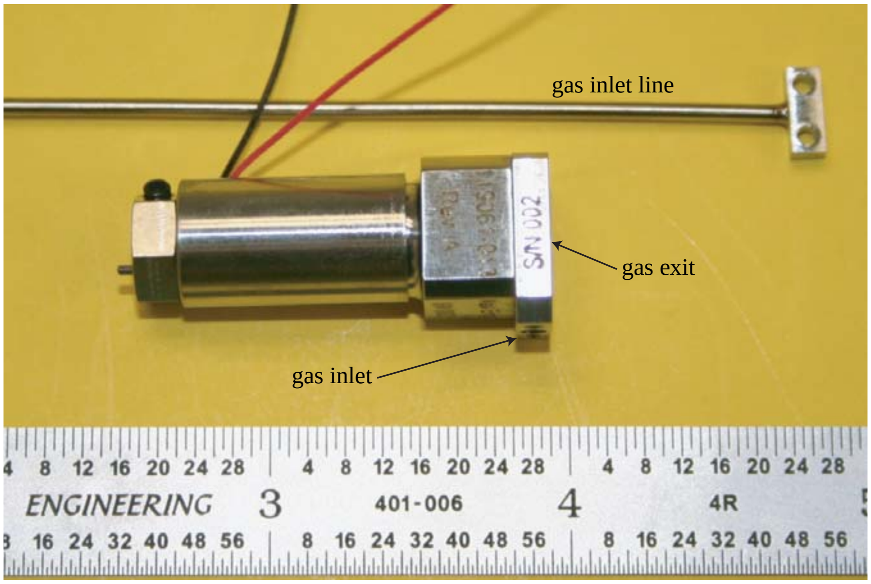


Figure 1. External view of the final fast acting valve design.

Table 2. Low voltage piezo crystal parameters.

Parameter	Value	Units
voltage range	0 to 100	V
temperature range	-40 to 150	°C
nominal travel	11±2	μm
blocking force	825	N
stiffness	75	N/μm
capacitance	1.7±0.34	μF
resonant frequency	85	kHz
average power (1 kHz, 3%)	5.1	mW
est. insulated heating rate	2.58	°R/s

To test the valve, a special test fixture, shown in Fig. 3, was designed and fabricated that held a tube to capture gas exiting the valve outlet. The tube was sealed to the exit face of the valve using an O-ring.

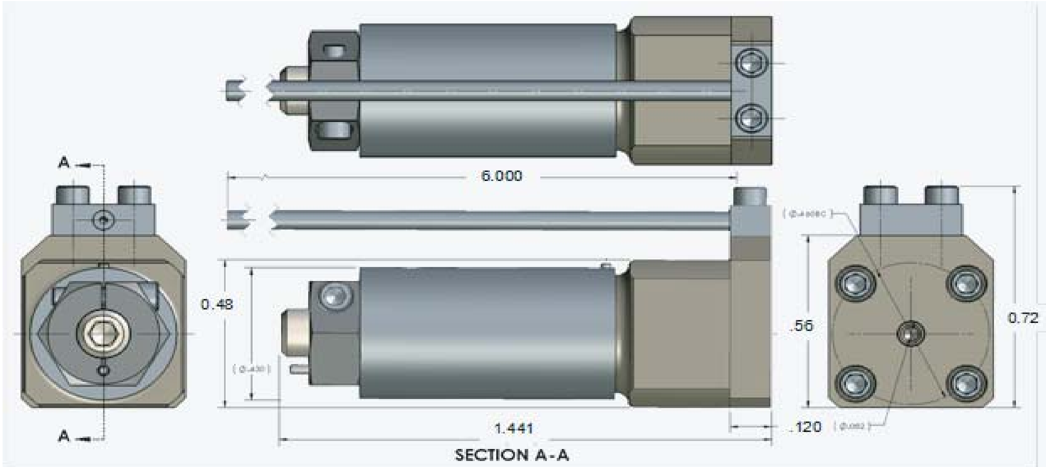


Figure 2. Layout of the fast acting valve.

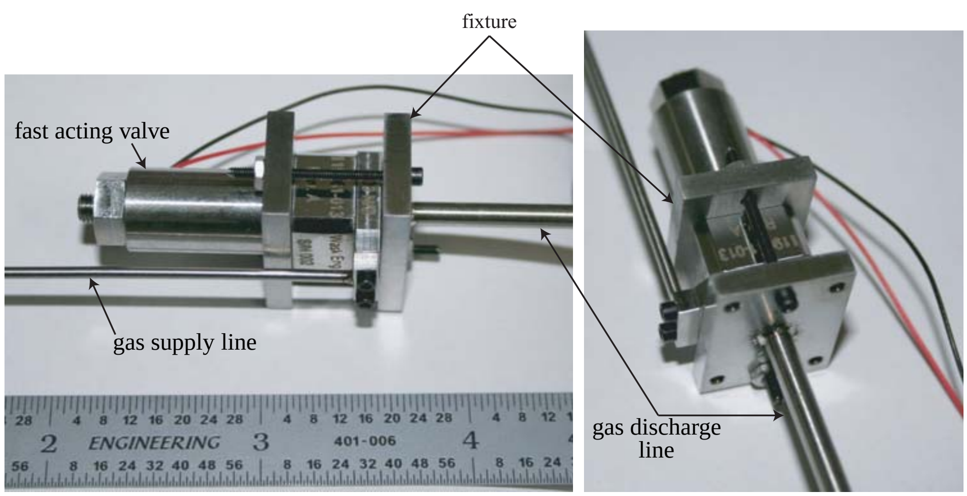


Figure 3. Fast acting valve with test fixture for measuring gas flow rate attached to the valve exit plane.

IV. Solenoid Actuator Valve Design

Opening of the valve, shown in Fig. 4, is accomplished by use of a solenoid electromagnetic actuator. The valve is normally closed and will fail closed upon loss of electrical power. When current is applied to the solenoid coil, magnetic forces pull the plunger away from the valve seat, allowing fluid to flow through the valve. Removal of the electrical current permits the spring and fluid pressure to seat the plunger, thus stopping the flow of fluid.

A flange-mounted interface is used between the valve and the IPPT chamber. In the apparatus used for testing the valve, this interface contains both the supply and outlet ports to the valve and is sealed using two concentric O-rings.

The valve is primarily fabricated from 304L corrosion resistant steel (CRES) and 430 CRES. The 430 CRES material is used in the parts of the valve that form the magnetic circuit, such as the plunger housing and spool end pieces, which must have a high magnetic permeability. This material does not have optimum magnetic properties, but its corrosion resistance permits incorporation in a design without requiring an additional plating process.

A viton O-ring compound (Parker V0884-75) was used for the valve seat seal due to its mechanical strength at elevated temperatures. This seal material was installed into the plunger using a process that eliminates the need for a separate seal retainer. The valve pressure boundary is sealed using electron beam welding at all valve joints as per AMS 2681. Inspection of pre- and postweld samples and proof pressure testing were employed to verify weld integrity.

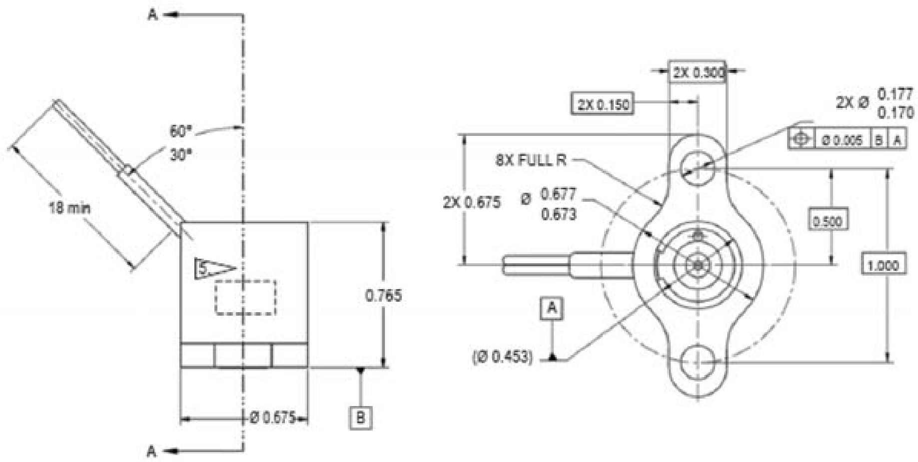


Figure 4. Drawings of the long-lifetime solenoid-actuated pulsed gas valve showing (left) a profile view of the overall valve and (right) a view from the bottom.

V. Valve Benchtop Test Results

Both valves were evaluated for performance to see how they compared to the performance goals given in Table 1. The results from these tests are reported in this section.

A. Piezoelectric Valve

The testing effort on the fast acting valve began by performing flow calibrations. The valve was designed to allow the pintle seat pressure to be adjustable. Therefore a number of calibrations were performed with differing preloads. At each preload the leakage rate of the valve was assessed to determine whether it met the leakage requirement. The flow calibrations were performed using gaseous nitrogen while each of the subsequent leak checks were performed using helium.

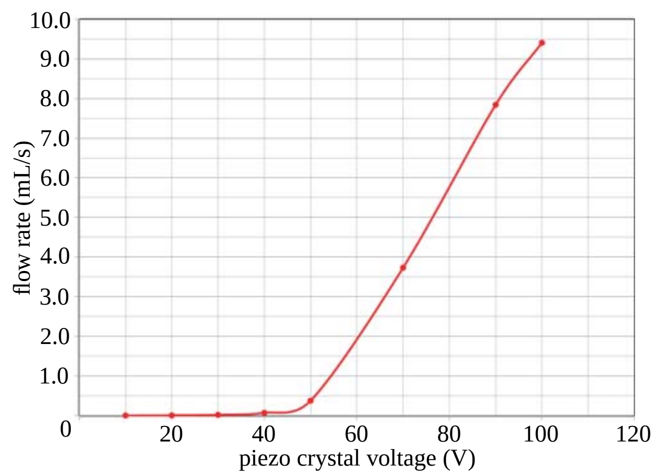


Figure 5. Fast acting valve flow rate calibration as a function of applied piezo crystal voltage (40 psi supply pressure).

The GN_2 flow rates measured through the fast acting valve during the final calibration test are shown in Fig. 5. During the various calibration tests performed the piezo voltage required to initially open the valve varied from 10V to nearly 40V, reflecting the change in the preload on the piezo crystal. The preload analysis performed during the design indicated that the valve should begin to open at a piezo voltage of 30V, which compares favorably to the 35V obtained for the valve calibration.

Table 3. Helium leak test results.

Initial Burette He Volume (mL)	Final Burette He Volume (mL)	He Leakage Volume (mL)	Test Duration (sec)	Leak Rate (cc/sec)
7.45	8.40	0.95	1,125	8.44×10^{-4}

The helium leakage rate of the valve was measured by capturing the helium in a 10 mL burrette for a chosen period of time. The leakage rates, as expected, depended on the applied valve preload. The helium leakage rate associated with the flow calibration in Fig. 5 was measured to be 8.44×10^{-3} cc/sec, with the actual measured values shown in Table 3. One of the significant benefits of piezo actuation of the valve can be observed in Fig. 5. Specifically, the valve can be readily throttled over a wide range of flow rates merely by varying the input voltage to the piezo actuator.

For the piezo crystal employed in the fast acting valve, the fastest response time possible is roughly 670 ns. As this is much faster than the 1 ms required for the valve, the critical parameter in determining the overall response is the rate at which the voltage signal to the piezo crystal can be changed. To determine this, the voltage signal to the piezo crystal was monitored with a high speed digitizing oscilloscope to measure the rise and fall of the voltage to the piezo crystal. The signal at 40 Hz with a 10 ms pulse width is shown in Fig. 6. The valve was opened to 67 V. Details of the rise and fall rates of the voltage are shown in Fig. 7. These show that the input voltage to the piezo crystal could change from 0 to 67 V in 80 μs. In addition, it could drop from 67 V to 0V in the same amount of time. As the response capability of the piezo crystal is two orders of magnitude faster, the valve opening and closing rates should follow the electrical inputs very well.

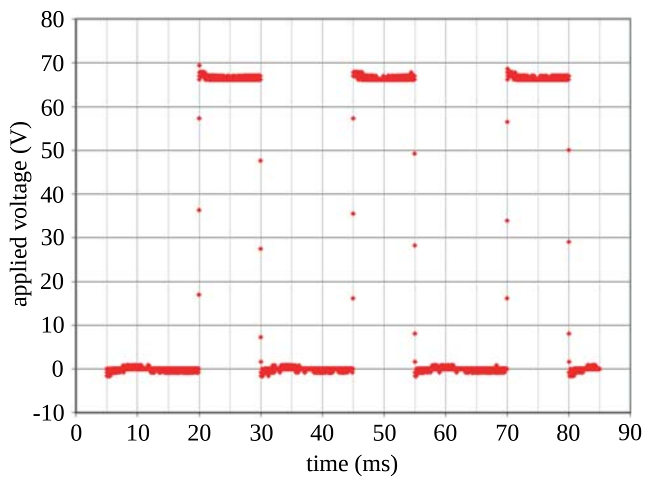


Figure 6. Piezo crystal input signal for square wave operation at 40 Hz with a valve open duration of 10 ms.

A summary of the valve design and operational parameters is shown in Table 4.

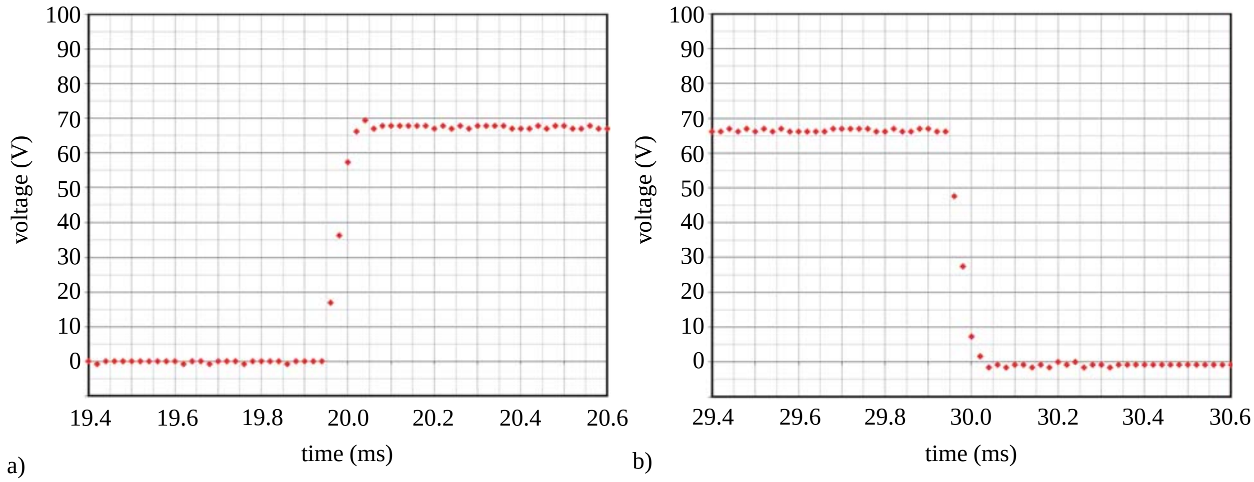


Figure 7. Signal a) rise (valve opening) and b) fall (valve closing) rates for a piezo crystal input signal for square wave operation at 40 Hz with a valve open duration of 10 ms..

Table 4. Summary of the fast acting control valve design and operating parameters.

Parameter	**Value**	**Units**
flow rates (at 40 psia and 70°F)	0-10	mL/s
pulse width	2 ms to inf	–
opening time	100	μs
closing time	100	μs
throttling	0-100% of flow	–
internal leakage	0	sccm of He
valve seat leakage	8.44×10^{-4}	sccs of He
operating temperature range	-40* to 300	$^\circ$F
current/voltage/power	5.1** / 100 / 0.51	mA / V / W
displacement	0.00032	inches
force margin	429%	–
proof factor	1.5*MEOP	–
factor of safety (ultimate / yield)	$>$2.5 / $>$1.4	–
mass	22.5	g

* Limited by piezo crystal, which has been operated to temperatures well below this value.
** Current requirement a function of operating frequency (1 kHz assumed here).

B. Solenoid Actuator Valve

Baseline testing of the valve was performed to determine the solenoid actuated valve compliance with the requirements listed in Table 1. Testing consisted of the following tests over a range of operating pressures and temperatures:

- Internal Leakage
- Pull-In Voltage
- Drop-Out Voltage
- Flow Rate / Pressure Drop
- Opening Response Time
- Closing Response Time

Testing was performed with the valve in a thermal chamber and with gaseous helium as the test media. A helium mass spectrometer was used to perform the internal leakage measurements, with the exception of the high pressure room temperature test, which required the use of an inverted graduated cylinder to record the leakage. The test setup is shown in Fig. 8. The results of the baseline testing are shown in Table 5.

Figure 8. Test setup to obtain solenoid actuated valve data presented in Table 5.

Table 5. Results from baseline testing of the solenoid actuated valve.

temperature (°F)	pressure (psig)	internal leakage (sccs)	pull-in voltage (VDC)	drop-out voltage (VDC)	flow rate (scim)	opening response time (ms)	opening response time (ms)
68	20	1×10^{-4}	15.1	1.6	15.9	1.7	8.7
	40	1×10^{-4}	15.0	1.5	22.8	1.8	8.8
	140	6×10^{0}	16.0	1.4	38.1	2.0	8.9
305	20	1×10^{-4}	11.2	1.8	12.5	1.0	6.4
	40	8×10^{-5}	11.7	1.6	20.6	1.0	6.4
	140	1×10^{-3}	12.4	1.8	36.9	1.0	6.5

The baseline testing showed that the valve exceeded the external leakage rate at the high pressure level for the room temperature test, however met this requirement at the low test pressure and over the entire pressure range at the 300°F normal operating temperature. It should be noted that the 140 psig test condition was really 155 psid for the internal leakage test due to a vacuum being pulled on the valve outlet during the measurement. This was a much higher pressure differential than the requirement for this application and therefore can be considered an overtest.

The change in pull-in voltage observed was due to the valve elastomeric seat swelling with increased temperature and thereby reducing the valve stroke. The lower flow rate seen at the higher temperature was also caused by the reduced stroke. This improved the solenoid efficiency, resulting in a lower pull-in voltage and opening response time. When the solenoid was hot, its electrical resistance increased, lowering the available current powering the valve, based on the $V = I\,R$ relationship. The faster closing response time at the higher temperature was the result of the solenoid producing a smaller magnetic field at the elevated temperature, which was dissipated more rapidly than the larger room temperature magnetic field.

The valve did not meet the response time goal of less than one millisecond. This was likely due to the solenoid being more powerful than the conservative design calculations assumed. A much larger magnetic field was produced, which took more time to dissipate.

VI. Solenoid Actuator Long Duration Test

The cycle life requirement for the long life pulsed gas valve is orders of magnitude beyond that of traditional solenoid valve applications which require no more than one million cycles. Cycle life testing was performed on the solenoid actuated valve to validate the design for the high cycle life requirement.

Testing was performed with the valve at an inlet pressure of 40 psig and a temperature of 300 °F to simulate the nominal operating conditions of the valve. The valve was cycled at a rate of 50 Hz (10 ms ON time, 10 ms OFF time) to allow rapid accumulation of cycles. Periodic performance testing was conducted to determine any degradation in performance parameters, such as internal leakage and response time.

The cycle life data are shown in Table 6. The data highlighted in yellow are questionable. These data points are not within the same range as the other data and represent extremely low leakage values for a soft seated valve. We speculate that the helium mass spectrometer may have not been functioning properly for these tests. The data highlighted in red was not read properly by the data acquisition system, consequently making it impossible to determine the value for these test parameters.

Table 6. Cycle life test results for the solenoid actuated valve.

	number of cycles							
test parameter	**0**	**1,000**	**5,000**	**10,000**	**50,000**	**150,000**	**250,000**	**1,000,000**
internal leakage (sccs)	$8{\times}10^{-5}$	$2{\times}10^{-5}$	$2.4{\times}10^{-4}$	$1.4{\times}10^{-6}$	$1.0{\times}10^{-6}$	$4{\times}10^{-5}$	$2{\times}10^{-5}$	$1.2{\times}10^{-6}$
pull in voltage (VDC)	11.7	11.4	11.1	11.1	11.2	11.9	12.6	11.4
drop-out voltage (VDC)	1.6	2.1	2.1	2.0	2.0	1.6	1.6	1.7
open response time (ms)	1.0	1.0	1.0		0.9	1.0		0.9
close response time (ms)	6.4	6.3	6.1		4.1	4.8		4.4

YELLOW cell color: data questionable. RED cell color: data not read properly/no data.

After the million cycle performance check, a short pause to testing occurred while the system was reconfigured to allow the valve to be cycled without operators present. When testing resumed, the valve periodically failed to cycle, then ceased to cycle after about 10 cycles. This is illustrated in Fig. 9, where the notch in the voltage and current traces represents the valve plunger motion.

Troubleshooting the failure revealed that striking the valve with a hammer while voltage was being applied would result in a cycle. This was indicative of binding of the valve plunger. A detailed inspection of the valve was performed under high-power magnification. Inspection showed excessive wear on the plunger sliding surface, as illustrated in Fig. 10a, and contaminant in the plunger bore in the valve body as shown in Fig. 10b.

An analysis of the contaminants was not performed, but it is likely they were self-generated by sliding contact

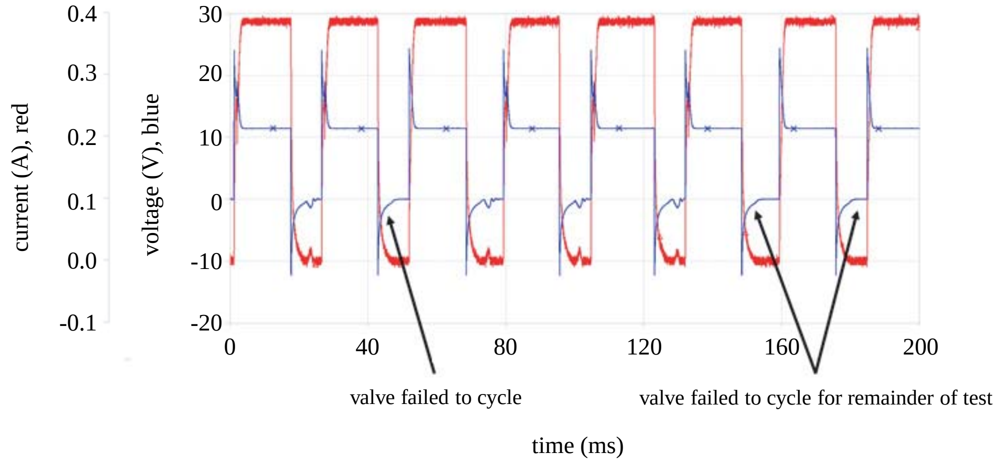
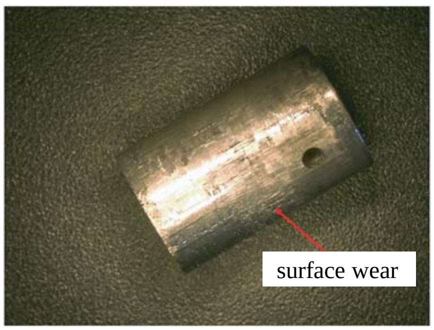


Figure 9. Solenoid actuated valve applied voltage and current draw, showing the characteristic current and voltage waveforms at valve failure.

a) 

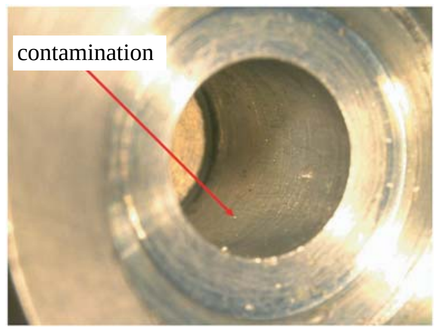
b) 

Figure 10. Solenoid actuated valve a) plunger slideing surface wear and b) plunger bore contamination after failure.

between the stainless steel plunger and the stainless steel bore, given that this combination of materials does not have a high galling resistance. No specific design considerations were implemented to address this high cycle life aspect of the design. Traditional high cycle life valve requirements, such as those implemented in attitude control thruster valve applications, were met. It is recommended that evaluation of low galling materials be performed for long life high cycle in-space propulsion system applications. Design modifications focused on reduction of wear, contact loads, and friction, should also be considered.

VII. Conclusions

Two types of valves, a piezo valve and a solenoid actuated valve, are under evaluation for application on gas-fed pulsed electric thrusters. Both valve types were tested for performance, with both demonstrating the ability to throttle flow rate while achieving leakage rates of less than 10^{-3} sccs of He early in their lifetime. Additionally, the solenoid actuated valve was evaluated over a one million cycle test to demonstrate valve lifetime.

The piezo valve has demonstrated the ability to vary the flow rate by adjusting the amount that the valve is open. Calibration tests on the piezo valve shows the ability to control the flow rate over a wide range from 0 to $\sim$10 mL/s. Tests were performed with opening durations between 10 and 20 ms, with the valve drawing 0.51 mW of power at 100 V while opening and closing in 100 μs or less. Future efforts will focus on demonstrating the ability of the valve to achieve the requirements for design lifetime.

The solenoid actuated valve has demonstrated performance that meets most of the valve requirements at beginning of life. The closing time was slower than the opening time, but it is thought that this could be improved in later iterations with a more optimized magnetic circuit and pulse driver. The valve operated from roughly 10-40 scim (2.7-

11 mL/s), with the flow rate adjusted by the pressure applied to the gas feed port. In life testing, the valve achieved one million cycles before it started failing to cycle. It was determined that there was excessive wear of the valve plunger sliding surface, causing the plunger to bind. The valve seat appeared to still be performing well when this failure occurred, and it is thought that using low galling materials will help mitigate the binding failure mode in future iterations of the valve.

Acknowledgments

The WASK Engineering work was funded through a 2014 NASA Phase 1 SBIR under contract NNX14CM33P. The NASA-MSFC effort was funded through the In-Space Propulsion Project of the Game-Changing Development (GCD) Program of NASAs Office of the Chief Technologist.

References

[1] Frisbee, R.H., "Evaluation of High-Power Solar Electric Propulsion Using Advanced Ion, Hall, MPD, and PIT Thrusters for Lunar and Mars Cargo Missions," in *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Sacramento, CA (2014). AIAA 2006-4465.

[2] Martin, A.K., Dominguez, A., Eskridge, R.H., Polzin, K.A., Riley, D.P., and Perdue, K.A., "Design and Testing of a Small Inductive Pulsed Plasma Thruster," in *34th International Electric Propulsion Conference*, Hyogo-Kobe, Japan (2015). IEPC 2015-050.

[3] Polzin, K.A., "Comprehensive Review of Planar Pulsed Inductive Plasma Thruster Research and Technology," *J. Propuls. Power*, vol. 27, no. 3, pp. 513–531 (2011).