AIAA
American Institute of Aeronautics and Astronautics

AIAA-2003-4930

CELEBRATING THE EVOLUTION OF FLIGHT
1903 TO 2003 ... AND BEYOND

39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
20 - 23 Jul 2003/ Huntsville, Alabama

MINIMUM IMPULSE THRUSTER VALVE DESIGN AND DEVELOPMENT

Richard L. Huftalen
Project Engineer
Moog, Inc., Systems Group

J. Morgan Parker
Technical Group Leader
Propulsion Flight Systems
Jet Propulsion Laboratory
California Institute of Technology

Andrea L. Platt
Product Engineer
Moog, Inc., Systems Group

George A. Yankura
Fluids Components Engineer
Propulsion Flight Systems
Jet Propulsion Laboratory
California Institute of Technology

ABSTRACT

The design and development of a minimum impulse thruster valve was conducted, by Moog, under contract by NASA's Jet Propulsion Laboratory, California Institute of Technology, for deep space propulsion systems. The effort was focused on applying known solenoid design techniques scaled to provide a 1-millisecond response capability for monopropellant, hydrazine **ACS thruster** applications. The valve has an extended operating temperature range of 20°F to +**350**°F with a total mass of less than 25 grams and nominal power draw of 7 watts. The design solution resulted in providing a solenoid valve that is one-tenth the scale of the standard product line. The valve has the capability of providing a mass flow rate of 0.0009 pounds per second hydrazine. The design life of 1,000,000 cycles was demonstrated both dry and wet. Not all design factors scaled as expected and proved to be the focus of the final development effort. These included the surface interactions, hydrodynamics and driver electronics. The resulting solution applied matured design approaches to minimize the program risk with innovative methods to address the impacts of scale.

Standard Thruster Valve Compared to Minimum Impulse Thruster Valve

INTRODUCTION

The minimum impulse thruster valve is a suspended armature, single solenoid design as depicted in Figure 1. The objective of the design effort was to scale a solenoid down to achieve the performance objectives and provide the benefits of a simple solenoid device. The design features include:

- Suspended armature (non-sliding fit plunger)
  - Eliminates seal wear during operation
  - Eliminates the particulate generation due to sliding fit
  - Provides demonstrated long life
- Single coil, single seat design
- AF-E-411 sealing Interface
- Equivalent square edge orifice of 0.14 mm (0.0055 inch)
- 105 ohm coil drawing a nominal 7.5 watts
- Minimal mass of less than 24 grams
- Fast response of 1.0 ms

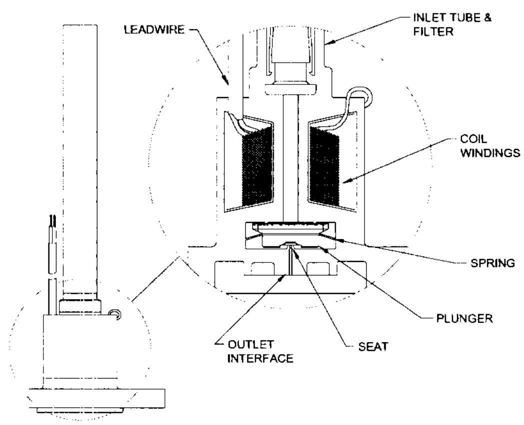


Figure 1. MI Thruster Valve Design

MAJOR DEVELOPMENT EFFORTS

During the spring of 2001, the Minimum Impulse Thruster (MI Thruster) valve development was nearing completion at the then contractor PerkinElmer Fluid Sciences. The development effort optimized the magnetic circuit and allowed the valve team to adjust to the scale of the valve, which was 1/10th of the existing production 1N monopropellant thruster valves. This adjustment required an increased awareness and sensitivity to detail to successfully build the valves. Two development valves were assembled and welded for test. The valves satisfied the operating performance objectives and mass targets. The development valves were run through a formal acceptance test procedure (ATP). During the ATP, a problem was discovered with GHe leakage at cold (-6.7°C) (non-operating) temperature. An evaluation of the seal stress and the elastomer, AF-E-411, material properties was pursued.

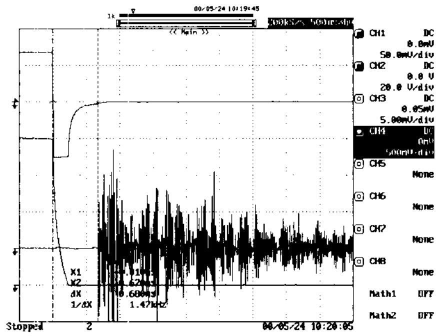
Per the TRW report 22539-6001-R0-00, *Space Shuttle Seal Material and Design Development for Earth Storable Propellant Systems*, the following are AF-E-411 material properties:

- Glass transition temperature of –51°C
- Capability to seal at less than –40°C when work is applied

The seal stress required, for gas isolation, increases as the temperature approaches the glass transition temperature.

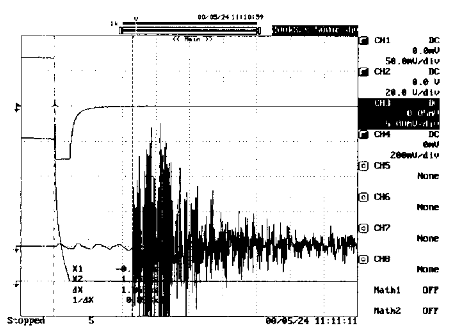
As the temperature is reduced, significant added seal stress is necessary to maintain seal integrity. The MI Thruster valve was modified to increase the seal stress and increase the seal compression into the seat geometry. These two design modifications provided acceptable cold leakage of 5.4E-04 scc/s GHe at –7°C (+1.5°F). When tested at +20, 0, -12°C the leakage was <1.0E-05 scc/s GHe.

After this initial ATP exposure, a 500,000 life cycle test was conducted as a pre-qualification confidence test with water as the test fluid. Water, rather than gas, is used as the test fluid in opening and closing response tests because it is the closest practical surrogate to hydrazine, and more accurately simulates the actual response times with hydrazine. The response measurements in liquid are significantly greater than the response times measured in gaseous nitrogen. This is depicted in the closing response times of the valve in gas compared to the closing response in liquid. As shown in the following response traces, it is the dynamic translation times that are impacted by the fluid.



Closing Response Trace From 28 vdc, 100 psig Gaseous Nitrogen

Total Closing Response of 0.680ms
0.565ms Electrical 83%
0.115ms Mechanical 17%



Closing Response Trace From 28 vdc, 100 psig H_2O

Total Closing Response of 1.165ms
0.565ms Electrical 48.5%
0.600ms Mechanical 51.5%

The closing response increased as a function of the number of cycles applied during the liquid cycle test. The closing response is the time from the end of the electrical signal to the time the valve is closed. The increase in closing response was significant as illustrated in Figure 2. This is undesirable, as the minimum impulse capability of the MI Thruster would degrade (increase) with life cycles. In addition to degraded minimum impulse capability, the performance analysis would become more difficult for propulsion and attitude control during mission operations.

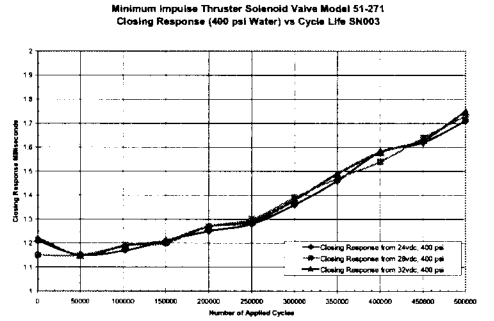


Figure 2. Closing Response as a Function of Applied Cycles

The valve was disassembled and inspected. No directly measurable variations were noted. The valve was re-assembled. Additional performance cycle tests were conducted and the closing response shift was found to be persistent. The problem was isolated to the effect of the contacting surface, in the open position, smoothing or polishing during cycling as illustrated in Figures 3, 4, and 5. As the metal contacting surfaces became smoother, the force required to pull them apart increased. This is commonly referred to as the "Johansen Block Effect". This effect is more pronounced when the surfaces in contact are immersed in liquid (as opposed to gas), and the effect increases as the surfaces become smoother and the film thickness is reduced. The response traces clearly isolated the event to the translation time of the response measurement and based on the pull-in current and drop-out current, there is no indication that the shift is caused by design margins.

Moog, Incorporated purchased the PerkinElmer space valve product line in the spring of 2001 and the development effort was placed on hold during the transition to the Moog facility. The development effort re-started at Moog in May 2002. The initial focus was to solve the Johansen Block Effect of the plunger transition in fluid.

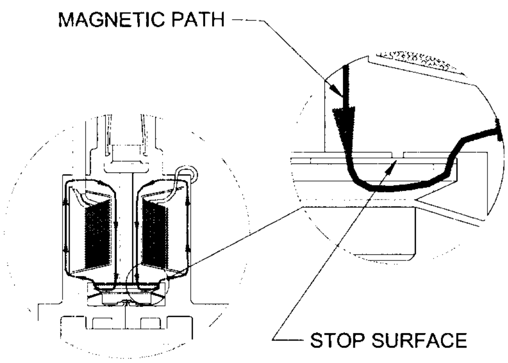


Figure 3. Plunger Energized and Resting on Mechanical Stop

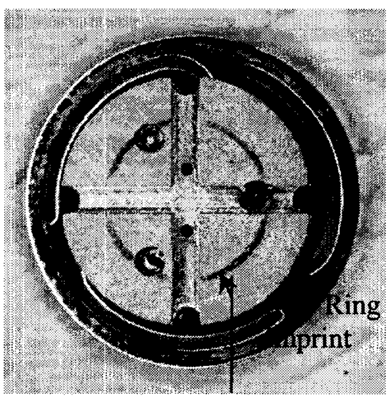


Figure 4. Plunger surface condition after 600,000 Cycles

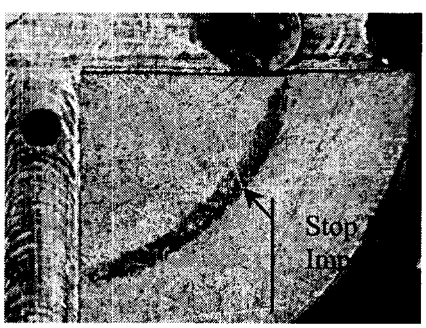


Figure 5. Minute surface smoothing on plunger contact area

Several potential solutions were identified that might reduce this Johansen Block Effect, and stabilize the resulting closing response over life cycles.

Investigation Paths

Three potential solutions were identified and isolated for further consideration. In the order of preference, the three areas are:

- Shot Peening Contact Surface
- Teflon Ring as Drop-Out Spacer
- Material Change for Non-Magnetic Stop Surface

Shot Peening

The preferred solution called for roughening one or both of the contact surfaces to reduce the Johansen Block Effect by a method commonly known as shot peening. This appeared to be the simplest solution in terms of cost, schedule, and impact to the valve design.

Teflon Drop-Out Spacer

The existing positive stop on the solenoid poleface consists of a non-magnetic 304L ring. Removing this raised surface on the ring and replacing it with a Teflon spacer ring may offer improvements due to this non-wetted material selection. Locating and securing the Teflon ring remained open as a design challenge. An experiment would be needed to evaluate the surface contact area necessary to minimize deformation as a result of plunger impacts to the ring. Increasing the surface contact area may impose further dynamic limits that would out weigh the benefits of the material properties. Evaluation would include a series of experiments to determine the optimum configuration. Further effort was postponed pending the evaluation of the shot peened surface treatment.

Change of Stop Material

Changing the existing 304L non-magnetic stop ring to a hardened material with a roughened surface may provide the wear resistance necessary to maintain the surface condition. Two materials were identified, A826 and MP35N.

A286 met most of the desired criteria with the exception of weldability to 430 stainless steel (SS). Several attempts were made to demonstrate that A286 could be welded to 430 SS. Initial results showed undesirable cracks and bubbles in the weld zones. The heat affected zones were also large in relation to the .050" wide non-magnetic ring. This large heat affect zone is undesirable because the material to be machined and hardened would have unknown properties due to the melting and mixing with the 430 SS.

The last attempt to weld A286 to 430 SS appeared to have been successful, at least in concept. This attempt, which was completed under contract with the Edison Welding Institute, involves a process called "projection welding", and will be the subject of a separate NASA JPL report in the near future.

MP35N met the criteria with the exception that its compatibility with hydrazine was unknown. A series of compatibility tests were designed specifically for this application and are being conducted by the NASA JPL Analytical Chemistry Group. Preliminary test results are promising.

SOLUTION

The shot peening consideration is particularly attractive because it offers the least impact to the existing design. The peened surface changes the characteristics of the surface film reducing the effect of the approaching and departing surfaces.

The shot peening was performed by bombarding the plunger's upstream surface per AMS-S-13165 with .012" diameter stainless steel shot. Two plungers were peened at two different pressures; 20 psi and 40 psi. The pressure used to propel the shot onto the surface, the distance from the shot nozzle to the surface, and the duration of bombardment controls the amount of peening. The force applied by the 20 psi process was .0063-.0067N. Shot peening also "work hardens" the upper layers of metal. This is desirable because it prevents the roughened surface from becoming smooth or polished with the repeated impact of the plunger contacting the fixed air gap stop over cycle life.

The 20 psi and 40 psi shot peened plungers were assembled into plunger assemblies and tested in SN003 and SN001 respectively. Baseline tests were performed, followed by cycle testing, with performance testing (opening response, closing response, pull-in, and drop-out) every 50,000 cycles until 1,000,000 cycles were completed on each unit. The results of these tests are shown in Figures 6 and 7. The closing response does not increase over the 1,000,000 cycles, but the standard deviation of SN003 data was higher than expected. This was attributed to the technician getting acquainted with the high degree of accuracy needed, and the measurement techniques and equipment available. The subsequent testing of SN001 validates this assertion, and shows a much smaller standard deviation for the closing response data, as well as a consistent value for closing response with cycle life.

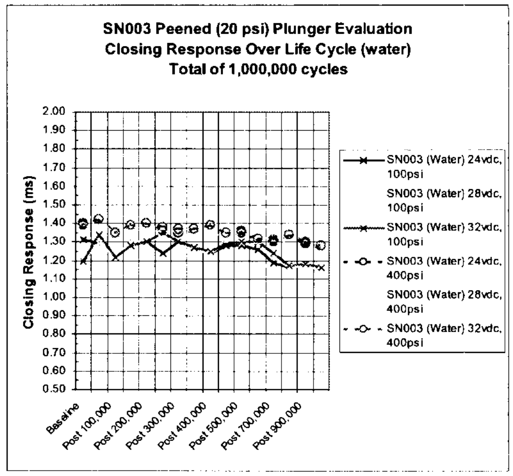


Figure 6. Closing Response Life Cycles with 20 psi Peened Plungers

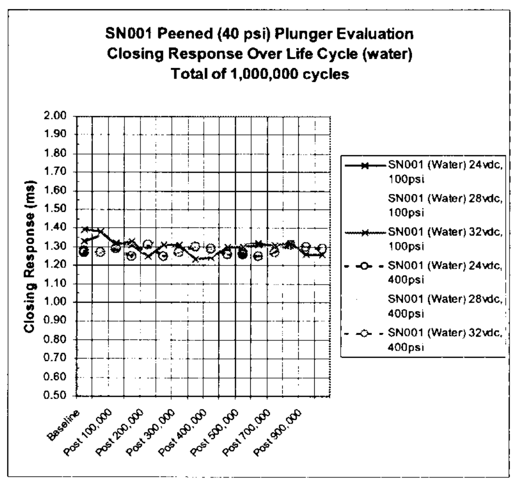


Figure 7. Closing Response Life Cycles with 40 psi Peened Plungers

Surface Interaction- Analytical Approach

Research into the physics of two surfaces approaching and retracting from each other located the works of F.P. Bowden and D. Tabor. Their research was published by University Press and titled "The Friction and Lubrication of Solids". A numerical simulation can be derived to simulate the affect of the surface interaction and the improvement achieved by peening as shown in Figures 8 and 9. The benefit of the surface change is understood and can be applied with confidence.

Closing Response Liquid Film Impact Evaluation Model 51-271:

Reference: F.P. Bowden and D. Tabor's "The Friction and Lubrication of Solids", Oxford University Press

$R := \frac{0.074}{2.}$ inch, Equivalent Stop Ring Surface Radius

$h_2 := 0.0038$ inch, Initial Film Thickness

$h_1 := 0.000125$ inch, Final Film Thickness

$Rate := 12$ lbs/in, Spring Rate

$F_{spg} := .030$ lbs, Spring Preload

$\eta := 1.005 \cdot (0.0000001453)$ (lbf sec/in^2), Fluid Viscosity at 68 °F

$$t_{12} := \left[\frac{(3 \cdot \pi \cdot \eta \cdot R^4)}{4 \cdot [F_{spg} + Rate \cdot (h_2 - h_1)]}\right] \cdot \left[\left(\frac{1}{{h_1}^2}\right) - \left(\frac{1}{{h_2}^2}\right)\right]$$

$t_{12} = 0.00056$ seconds, impact to translation total time due to liquid film thickness

Figure 8. Closing Response Impact due to Liquid Film Impact

Closing Response Liquid Film Impact Evaluation Model 51-271:

Reference: F.P. Bowden and D. Tabor's "The Friction and Lubrication of Solids", Oxford University Press

$R := \frac{0.074}{2.}$ inch, Equivalent Stop Ring Surface Radius $i := 8000 .. 12000$

$h_2 := 0.0038$ inch, Initial Film Thickness

$h_{1_i} := \frac{1}{i}$ inch, Final Film Thickness

$Rate := 2$ lbs/in, Spring Rate

$F_{spg} := .030$ lbs, Spring Preload

$\eta := 1.005 \cdot (0.0000001453)$ (lbf sec/in^2), Fluid Viscosity at 68 °F

$$t_{12_i} := \left[\frac{(3 \cdot \pi \cdot \eta \cdot R^4)}{4 \cdot [F_{spg} + Rate \cdot (h_2 - h_{1_i})]}\right] \cdot \left[\left[\frac{1}{(h_{1_i})^2}\right] - \left(\frac{1}{{h_2}^2}\right)\right]$$

seconds, impact to translation total time due to liquid film thickness

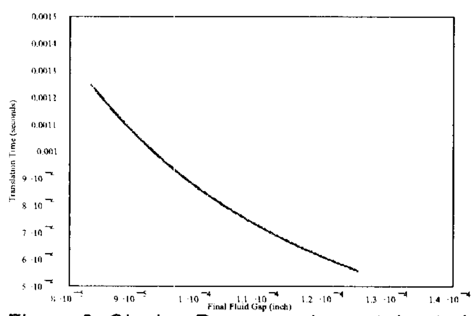


Figure 9. Closing Response Impact due to Liquid Film Impact and Improved Surface Finish

Understanding the impact of the fluid film and the surface finish is important. With the numerical prediction defined, the design model has been revised to reflect the impact to the valve response characteristics. The next generation of high-speed solenoid valves will benefit from the experience by enabling the designer to accurately reflect the impact of scale and predict the behavior of the solenoid valve.

Disassembly and Inspection

After the million-cycle test, the valves were disassembled and the plunger contact surfaces were photographed as shown in Figures 10, 11, 12, & 13. The resulting wear was dramatically reduced which is reflected in the acceptable cycle life performance.

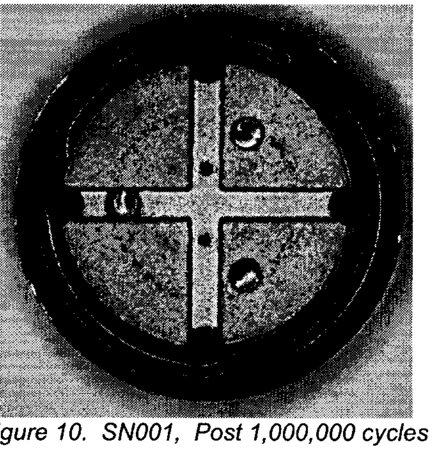


Figure 10. SN001, Post 1,000,000 cycles Plunger Minor Surface Wear (40 psi Peening)

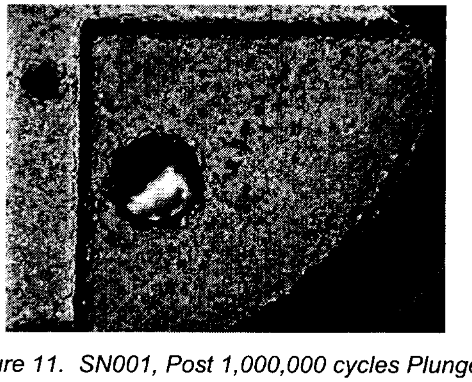


Figure 11. SN001, Post 1,000,000 cycles Plunger Minor Surface Wear (40 psi peening)

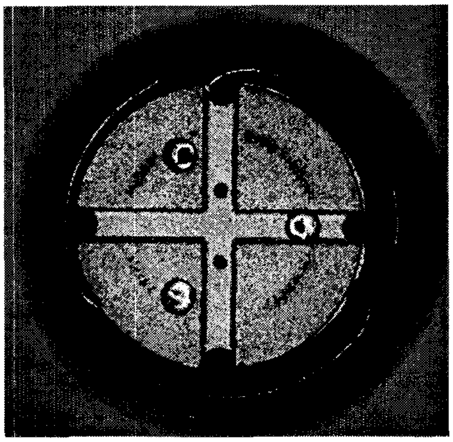


Figure 12. SN003, Post 1,000,000 cycles Plunger Minor Surface Wear (20 psi peening)

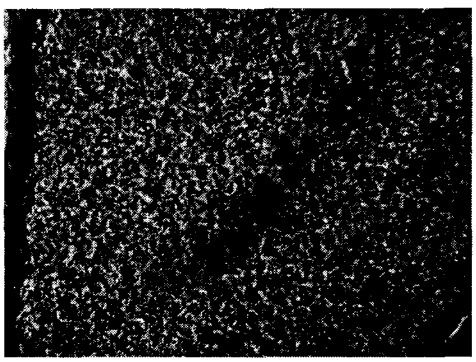


Figure 13. SN003, Post 1,000,000 cycles Plunger Minor Surface Wear (20 psi peening)

The 20 and 40 psi peened surfaces both provide consistent and stable closing response characteristics as a function of life cycles. The 20 psi shot peened plunger appears the best when visually inspected and has been incorporated into the final plunger design.

Valve Driver Suppression Network Selection

Closing response is adversely impacted by a low Zener diode clipping voltage. An evaluation was conducted by varying the suppression network clipping voltage and measuring closing response.

The existing valve driver circuits had switching noise which impacted the accuracy and repeatability of the performance measurements. An optically isolated driver circuit was designed to simulate the spacecraft valve driver and provide a minimal noise-switching device. The driver circuit is appropriate for automated test data acquisition system interfacing. The circuit is provided in Figure 14.

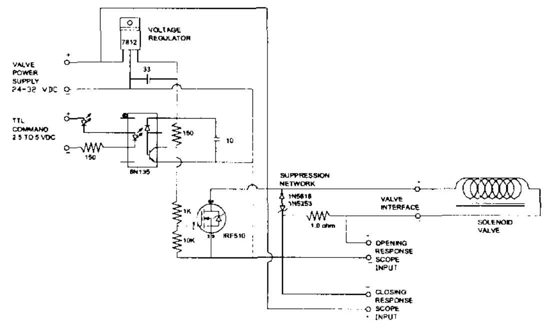


Figure 14. Optically Isolated Valve Driver Circuit

Use of the circuit allowed repeatable measurements with minimal switch noise. The selection of the spacecraft valve suppression network directly impacts the closing response of the valve. The time required to collapse the magnetic field is proportional to the Zener diode clipping voltage as shown in Figure 15. For optimal spacecraft operation a 26 vdc clipping diode was selected for the suppression network.

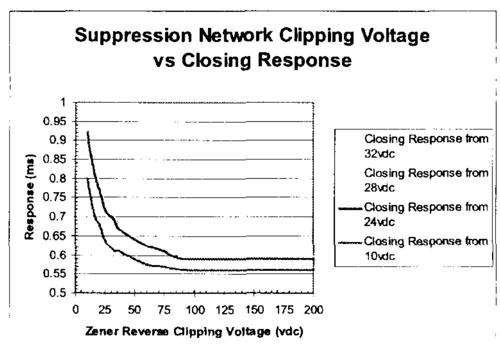


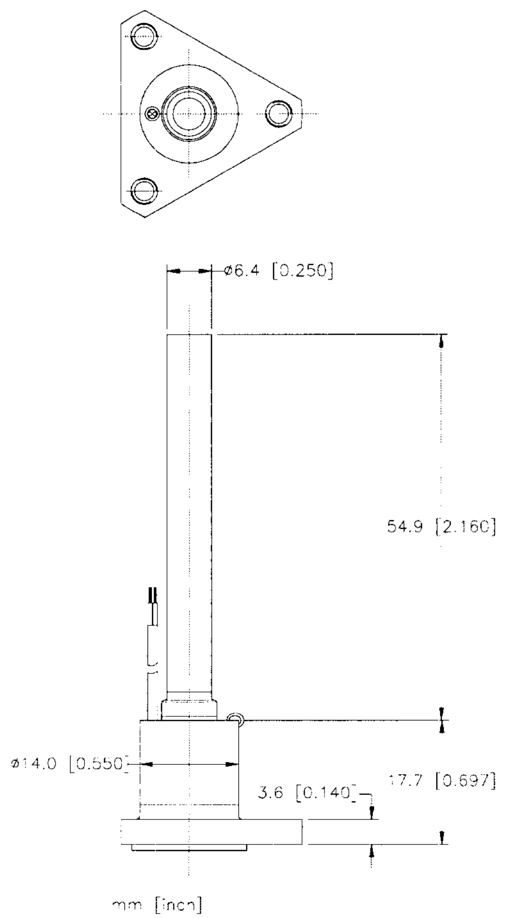
Figure 15. Suppression Network Diode Selection and Impact to Closing Response.

CONCLUSION

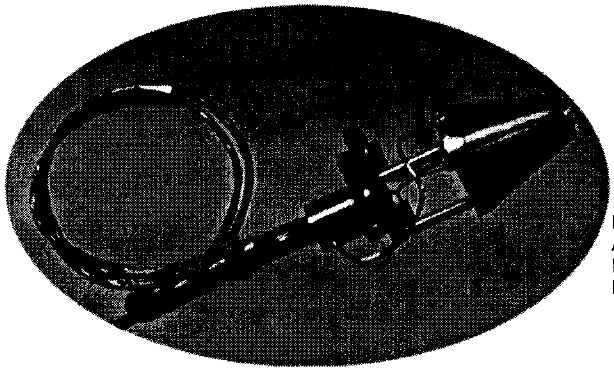
The development of a high performance miniature solenoid valve challenged the current design models and required additional understanding of the translational relationships of the device. Historically, the small variation due to surface interactions represented a small portion of the total response characteristics. With a significantly faster response capability, the percent impact due to surface interactions became significant. A 0.5 millisecond dynamic response with a 0.5 millisecond electrical response as compared to a typical propellant valve with a 0.5 millisecond dynamic response and a 10 millisecond electrical response. Abrading the mating surface reduced the impact of surface interaction and maintained the surface stability over life cycles.

The last challenges encountered from the development effort are closed, allowing qualification and production to continue. The completion of the effort is scheduled for the late summer of 2003.

The research described in this (publication or paper) was partially carried out at the Jet Propulsion laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.



Minimum Impulse Thruster Valve Performance Summary



Minimum Impulse Thruster
Aerojet MR-103M 1N Rocket
Engine Assembly with Moog
Model 51-271 Solenoid Valve

The MI Thruster incorporates a new fast valve, developed by JPL via contract with Moog Inc. In Aug,'01, the MI Thruster demonstrated the smallest impulse bit ever achieved by a hydrazine thruster during a test at Aerojet Redmond Rocket Center. A 1.4 millisecond pulse was approximately 1 milliNewton-second (1 mN-s). This is ~ 5 times smaller than the smallest impulses produced by the Voyager / Cassini 0.9 N thruster.

Benefits & Applications

The MI Thruster takes precision attitude control a big step forward. The 5 X reduction in minimum impulse enables:

- tighter deadband pointing
- less fuel used (wet mass savings)

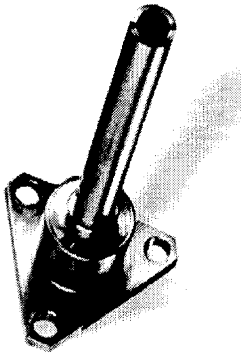
The MI Thruster saves dry mass:

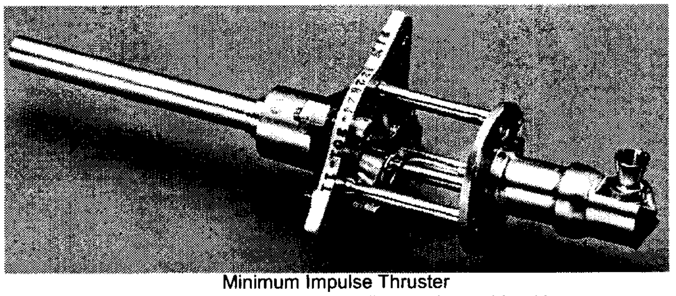
- The MI Thruster valve is only 1/4 the mass of the Voyager / Cassini valve (25 grams vs. 104 grams)

The MI Thruster is easily added to any existing hydrazine system, (e.g. a dual mode bipropellant, or a monopropellant hydrazine system)

Comparison Parameter	Voyager/Cassini Current SOA	MI Thruster
Thrust	0.9 N	**0.75 N**
Envelope Volume	94 cc	**55 cc**
Power	7 W	**8 W**
Mass	195 g	**116 g**
Min. Impulse	5,000 μN·sec	**1000 μN·sec**
Pointing Stability Europa Type S/C	1000 μrad/sec	**200 μrad/sec**

Minimum Impulse Thruster





Minimum Impulse Thruster
Aerojet MR-103M 1N Rocket Engine Assembly with
Moog Model 51-271 Solenoid Valve

Moog Model 51-271 Solenoid Valve

Primary Design Features

- Suspended Armature
- Minimal mass <24 grams
- <1 ms response
- >1,000,000 cycle life (wet or dry)
- Extended operating thermal range
- Successfully hot fired at Aerojet Redmond Rocket Center
- Component Qualification Fall 2003

Valve Performance Map

Media:	Gas, Nitrogen		Water	
Condition:	100 psi (6.9 bar)	400 psi (27.6 bar)	100 psi (6.9 bar)	400 psi (27.6 bar)
Parameter				
Pull-In Current	0.076 amp	0.081 amp	0.086 amp	0.071 amp
Drop-Out Current	0.063 amp	0.068 amp	0.091 amp	0.067 amp
Opening Response				
24 vdc	0.790 ms	0.845 ms	1.025 ms	1.160 ms
28 vdc	0.715 ms	0.775 ms	0.965 ms	1.050 ms
32 vdc	0.675 ms	0.715 ms	0.910 ms	0.945 ms
Closing Response				
From 24 vdc	0.490 ms	0.520 ms	0.820 ms	0.825 ms
From 28 vdc	0.505 ms	0.520 ms	0.830 ms	0.830 ms
From 32 vdc	0.505 ms	0.530 ms	0.830 ms	0.835 ms

Gaseous Helium Leakage

Internal: <1.0E-07 scc/s GHe at 15 and 600 psid

External: <1.0E-07 scc/s GHe at 600 psid