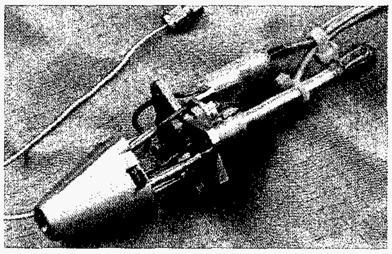
THE MINIMUM IMPULSE THRUSTER



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ABSTRACT

The Minimum Impulse Thruster (MIT) was developed to improve the state-of-the-art minimum impulse capability of hydrazine monopropellant thrusters. Specifically, a new fast response solenoid valve was developed, capable of responding to a much shorter electrical pulse width, thereby reducing the propellant flow time and the minimum impulse bit. The new valve was combined with the Aerojet MR-103, 0.2 lbf (0.9 N) thruster and put through an extensive Δ-qualification test program, resulting in a factor of 5 reduction in the minimum impulse bit, from roughly 1.1 milli-lbf-seconds (5 milliNewton seconds) to ~ 0.22 milli-lbf-seconds (1 mN-s). To maintain it's extensive heritage, the thruster itself was left unchanged. The Minimum Impulse Thruster provides mission and spacecraft designers new design options for precision pointing and precision translation of spacecraft.

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INTRODUCTION

Improving the current state-of-the-art minimum impulse bit capability of hydrazine monopropellant thrusters enables new design options for spacecraft including an alternative to reaction wheels for precision attitude control, and improved precision translation capability for rendezvous, docking, and formation flying. In addition to these new capabilities, benefits can include savings in propellant, prolonged thruster life, and for missions that can eliminate reaction wheels, savings in cost, system mass and power; benefits are mission dependent.

The MR-103 thruster was originally developed for the Mariner Jupiter/Saturn 77 (aka the Voyager missions) in the mid 1970s. From launch in 1977 until circa 1985, most of the Voyager thrusters operated at 10 msec pulses. Circa 1985, the yaw thrusters were commanded to operate at the valve's minimum electrical pulse width of 4 msec, in order to reduce thruster cycles, prolong thruster life and save fuel. The need for a valve capable of shorter pulse widths was recognized at that time. In 1998, JPL's Europa Project performed trade studies for using thrusters vs. reaction wheels to provide precision pointing. These and subsequent trade studies showed that the use of thrusters for precision pointing has significant advantages vs. reaction wheels, provided the minimum impulse-bit could be reduced sufficiently.

In order to reduce the minimum impulse-bit of a hydrazine thruster, it is necessary to reduce the amount of hydrazine fuel delivered to the thruster in a short pulse. This could be accomplished via changes in the thruster, or alternately, by developing a valve that opens faster and closes faster, enabling the valve to respond to a shorter electrical pulse width, thereby reducing the propellant flow time and the minimum impulse-bit. The Europa Project and the X-2000 [technology development] Project provided funding to develop such a valve, combine it with the "Voyager / Cassini" version of the Aerojet MR-103 (making <u>no</u> changes to the thruster), and perform a Δ-qualification test program of the thruster / valve combination. The new valve combined with the Aerojet MR-103 maintains all the previous capabilities and qualification heritage of the thruster, while providing new capabilities by virtue of a five-fold reduction in the minimum impulse-bit.

This paper will discuss some benefits and mission applications of the Minimum Impulse Thruster, and the Δ-qualification test program and results. The valve development is the subject of the AIAA=2003-4930 paper, "Minimum Impulse Thruster Valve Design and Development".

RESULTS AND DISCUSSION

Initial Work

JPL Propulsion performed in-house technology work while developing the requirements for the fast response valve, then issued a competitive RFP and selected/contracted EG&G Wright Valve Company in January 1999 to develop the valve. Shortly thereafter, EG&G Wright Valve Company was bought by Perkin Elmer Inc. JPL remained heavily involved in the valve development, performing some of the development and testing in-house. In June 2001, Perkin Elmer sold their aerospace valve product line to Moog Inc.,causing the contracted activities of the valve development to stop temporarily due to contractural technicalities. Approximately one year lapsed before the development was re-started with Moog. In August 2004, Moog delivered two flight acceptance-tested valves from the qualification lot to JPL. JPL delivered the valves to Aerojet, for an extensive Δ-qualification test program of the

Aerojet MR-103 thruster with the MI Thruster Valve. Aerojet's new designation for the Minimum Impulse Thruster is the MR-103M.

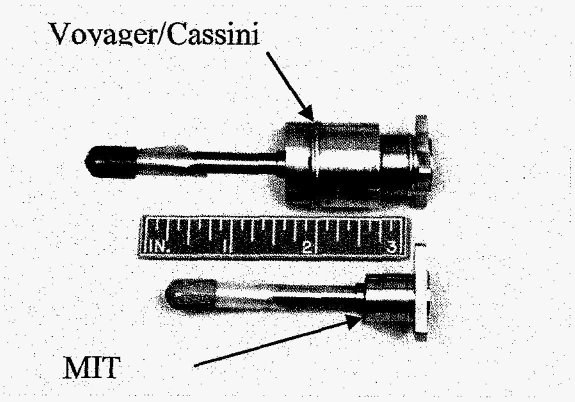

Figure 3. MIT Valve mass = 25 grams compared to 104 grams for the Voyager / Cassini valve

Figure 1 is a photo of the new Minimum Impulse Thruster Valve compared with the Voyager/Cassini Valve.

BENEFITS AND MISSION APPLICATIONS

The Minimum Impulse Thruster has significant benefits for spacecraft requiring precision attitude control, or precision translation. Table 1 shows a comparison of test data at 400 psia inlet pressure between the 0.2 lbf MR-103H using the Voyager / Cassini valve, and the 0.2 lbf MR-103M (Minimum Impulse Thruster) using the new fast response valve. The Minimum Impulse Thruster demonstrated a reduction in minimum impulse bit by a factor of 5, from roughly 1.1 milli-lbf-seconds (5 milliNewton seconds) to ~ 0.22 milli-lbf-seconds (1 mN-s).

Comparison Parameter	Aerojet MR103H	MI Thruster Aerojet MR103M	Factor improvement
Thrust @ 350 psia	0.9 N	0.9 N	1 X
Envelope Volume	94 cc	55 cc	1.7 X
Valve Power	5 W/1W	7.1 W/2W	.6X
Catbed heater Pwr	1.9 W	1.9 W	1 X
Mass	195 g	160 g	1.2 X
Min. Impulse bit	5 mN-sec	1 mN-sec	5 X

Table 1: Comparison of the Minimum Impulse Thruster to the previous state-of-the-art.

Many spacecraft currently use reaction wheels for 3-axis control, and to date, reaction wheels have been the primary option for spacecraft requiring precision pointing. However, for some missions, thrusters can provide precision pointing with significant advantages vs. reaction wheels. The Minimum Impulse Thruster was baselined for JPL's Europa Orbiter as a backup to the reaction wheels, for Lockheed Martin's Pluto proposal (POSSE) as a replacement for reaction wheels, and on two of JPL's Discovery proposals as replacement for reaction wheels. JPL's Team X (mission feasibility quick study team) currently uses the Minimum Impulse Thruster in about 60% of all spacecraft designs due to its ability to provide 5 x improvement in minimum impulse bit while maintaining all the previous capabilities and qualification heritage of the MR-103 thruster.

A trade study for a "High Resolution Mars Reconnisance Orbiter" (HR_MRO) (not to be confused with the recently launched Mars Reconnisance Orbiter) demonstrates some benefits of the MIT used in place of reaction wheels. Here is an example of a large spacecraft in a high disturbance torque environment with tight pointing requirements. In this trade, the Minimum Impulse Thruster provides the same precision pointing capability, but with the added advantages of lower system mass, and lower peak power and average energy consumed compared to reaction wheels. The thruster system was also estimated to save ~ $1M in cost compared with the reaction wheel system.

Mission	Average Power (W-hours)		Peak Power (Watts)		System Mass Including propellant (kg)	
	RWA	MI Thruster	RWA	MI Thruster	RWA	MI Thruster
HR-MRO	20	.03	150	30	64	56

Table 2: Comparison of the MIT thruster system to reaction wheels for a HR-MRO study.

Reliability can also be a consideration in the trade between thrusters and reaction wheels. A number of spacecraft including Cassini have experienced cage instability, friction spikes, and oscillations with reaction wheels, degrading their precision pointing capability. Depending on mission requirements, a thruster system can often be expected to outlast wheels on long duration missions, and provide precision pointing with quiescent, vibration-free periods between pulses, benefiting instrument observations with demanding stability requirements. It should be noted that the outcome of any trade between the use of thrusters vs. reaction wheels depends on a number of factors including pointing requirements and disturbance torques for that particular mission.

A good example of how the Minimum Impulse Thruster could save propellant mass is exhibited by the Voyager spacecraft operations. Both Voyager spacecraft are still in operation, having reached the outer edges of the solar system a few years ago. The yaw thrusters fire in a two-sided deadband mode. From launch in 1977 until circa 1985, the yaw thrusters operated at 10 msec pulses, before switching to 4 ms pulses to reduce thruster cycles, prolong thruster life and save fuel. Operating at their minimum electrical pulse width of 4 milliseconds (msec) since ~ 1986, these thrusters fire approximately every 25 minutes. The MI Thruster could maintain the same deadband firing only every 125 minutes, or ~ 1/5 as often. Alternately, the Minimum Impulse Thruster could maintain a much tighter deadband if finer pointing were desired.

DELTA-QUALIFICATION TEST PROGRAM

The purpose of the test program was to demonstrate the flight qualification of the MIT. More specifically, to demonstrate that the combination of the new valve with the Aerojet MR-103 maintained all the previous capabilities and qualification heritage of the thruster, while providing new capabilities by virtue of reduced minimum impulse-bit.

The test program had to encompass typical MR-103 dynamic environments, hot-bias thermal hot-fire test environments, hot-fire performance characterization, and typical REA functional tests. Life testing was not needed because the thruster design already has sufficient qualified throughput and the valve was recently qualified on its own. However, >500,000 valve-thruster cycles in hot-fire were performed to substantiate the qualification of valve cycles in the flight environment. In accordance with aerospace standards (MIL-STD-1540C and MIL-HDBK-340A) a demonstration test was sufficient and appropriate to substantiate the delta-qualification of the new engine.

Two flight configuration Rocket Engine Assemblies (REAs) were built and tested (S/N D1 and D2). The MR-103C thrusters used Shrunk Shell-405 25/30 mesh catalyst and a nozzle with a 200:1 expansion ratio. Each thruster had a catbed heater and catbed temperature sensor. The dual element catbed heater provided 1.9 watts per element at 28 vdc, 70±10°F. The MIT valve uses 7.1 watts at 28 vdc, 70±10°F. The catbed temp-sensor was a Platinum Resistance Temperature Device (RTD) with an ice-point reference (32°F) of 500 ohms.

A third REA (S/N D3) was assembled with special hardware not of the flight configuration. The valve was a bolt-together MIT valve with a seat that was not welded in place. The MR-103C thruster was an available engineering unit with prior hot-fire history, no chamber pressure (Pc) tube, and a large known leak in the Pc-tube tap location. This REA was used to subject the new valve design to testing and subsequently allow it to be easily dis-assembled for internal part inspection and assessment.

Figure MW1 presents the test flowplan for the MIT Delta-Qualification test program. All three engines were tested concurrently. Acceptance Test Procedures (ATP) typical for flight configurations were integrated as part of the Delta-Qual testing. Electrical and mechanical functional tests occurred without issue. All testing was conducted at Aerojet in Redmond, WA.

Figure MW2 shows the random vibration spectrum used. Vibration was conducted simultaneously on all three test units for three minutes in each orthogonal axis. This spectrum encompasses qual-level spectrums typical for this engine. The two flight configuration REAs had internal valve seat leakage monitored during the testing. Vibration was successful without indication of leaks.

Table MW1 presents the hot-fire tests conducted on the three REAs. The test blocks are divided into two parts designated by the relative chamber pressure (Pc). To minimize vacuum chamber breaks and test equipment modifications, all *High Pc Testing* was done first. *Low Pc Testing* was preceeded by a vacuum chamber break to make modifications to key test equipment. These test setup differences are explained in the next sub-section.

The engines were hot-fired differently because of different test objectives. D1 underwent the baseline set of tests necessary to characterize performance. All three engines underwent hot-bias steady-state testing that validated the MIT thermal model and demonstrated hot-restart capability. D2 underwent additional hot-bias testing in pulse-mode to further validate the MIT thermal model. In addition, D2 had ~500,000 pulses done to substantitate valve-thruster cycles during hot-fire. D1 and D2 had minimum impulse bit testing performed last, providing data for performance characterization and validating that the performance of D2 was not significantly affected by the large number of valve-thruster cycles. D3 underwent similar testing as D2. It did not undergo tests directed at Pc measurement because it lacked a Pc tube.

After completing hot-fire testing, the engines were decontaminated. Electrical functionals, mechanical functionals, and dimensionsional inspections were then done to validate the engines and their components were still in flight acceptance condition. All post-fire tests were acceptable.

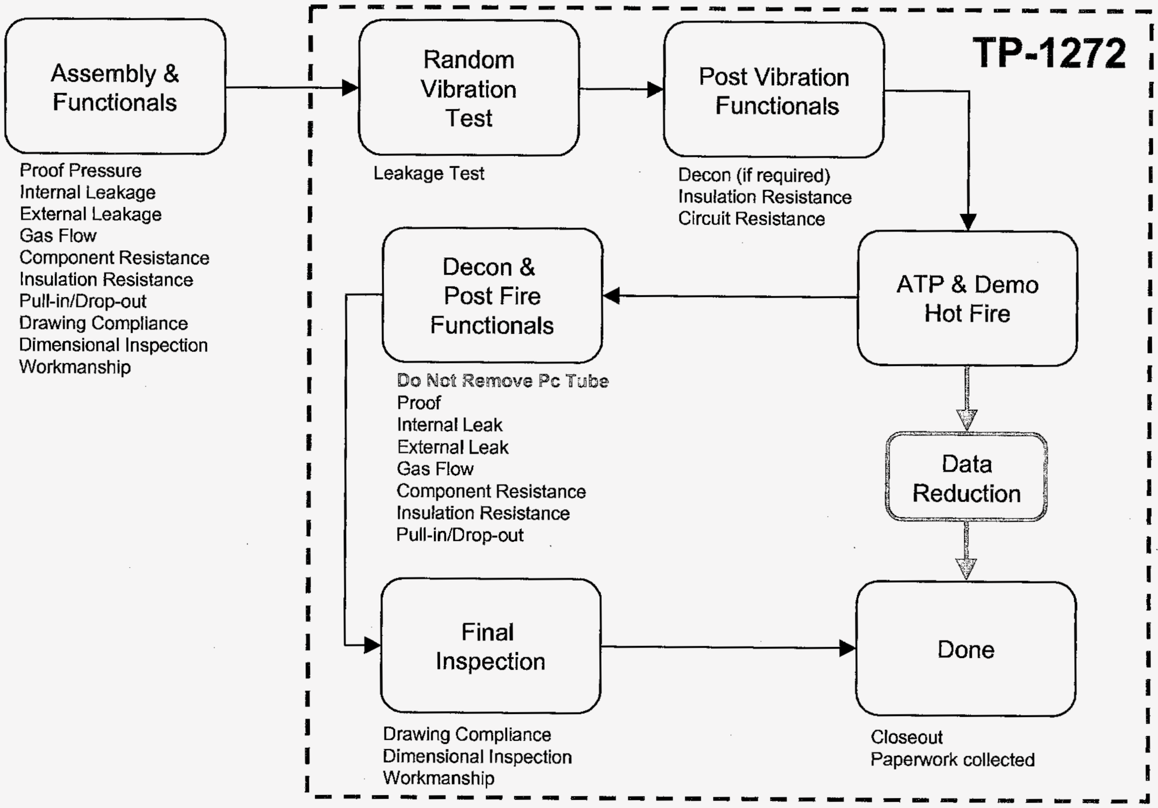

Figure MW1.Test flowplan for the MIT delta-qualification testing.

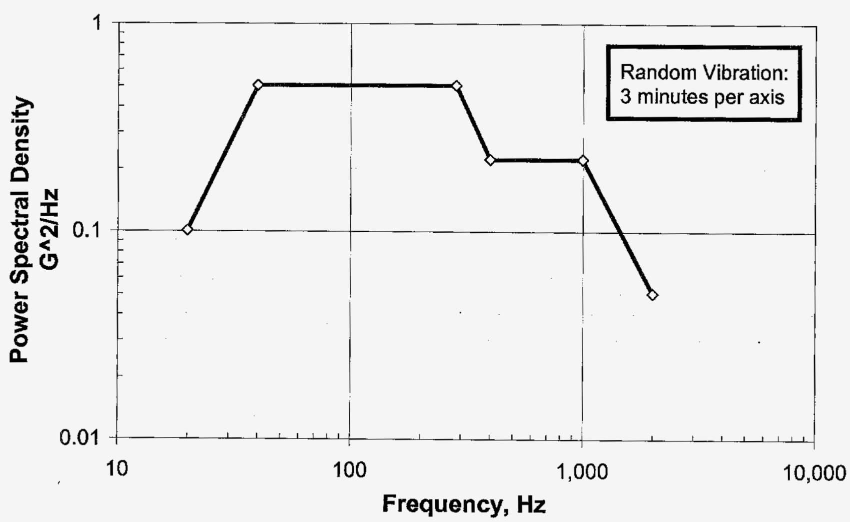

Figure MW2. Random vibration spectrum used for the MIT delta-qualification.

Table MW1:
Hot-Fire Test Descriptions

Test	Description / Purpose	S/N D1	S/N D2	S/N D3
High P_c Testing				
ATP-H *	Conduct a thorough firing similar to a production Acceptance Test Procedure (ATP).	X	X	
SOH-1 *	State-Of-Health (SOH) to provide health snapshot. A subset of ATP-H.			X
SS-Eq-34vdc	Steady-state to thermal Equilibrium at 34 vdc in the hottest predicted flight environment. Followed by steady-state hot-restart at peak soakback, followed by pulse-mode hot-restart at peak soakback. Validate successful operation at hottest conditions, predicted by thermal model to occur in hot-bias environment at steady-state soakback.	X	X	
PM-Eq-34vdc	Pulse-mode to Thermal Equilibrium at 34 vdc in the hottest predicted flight environment. Followed by finding peak soakback and validating it is lower than that from SS-Eq-34vdc. Validate thermal model prediction that hot-bias soakback is worst at steady-state. Repeat hot-restarts if a worst duty cycle is found. (None was).		X	X
SOH-2 *	State-Of-Health (SOH) to provide health snapshot. A subset of ATP-H.	X	X	X
500k	Subject engine to ~500,000 rapid pulses to validate acceptable operation during and after. Conducted at various on times, off times, duty cycles, and feed pressures to provide additional pulse-mode performance data.		X	X
Delta-H *	Delta characterization of pulse-mode performance at High Pc compared to standard MR-103 engines. Conducted at various on times, off times, duty cycles, and feed pressures.	X	X	X
SOH-3 *	State-Of-Health (SOH) to provide health snapshot. A subset of ATP-H.	X	X	X
Low P_c Testing				
PMap-L	Performance Map at Low Pc. Characterize Limit Duty Cycle pulse-mode performance at various minimum pulse widths at various feed pressures and various pre-heated catbed temperature conditions. Find minimum impulse bit.	X	X	

* Sightglass measurements were done at the beginning and end of pulse-mode sequences to provide data for both transient and equilibrium specific impulse.

HOT-FIRE TEST EQUIPMENT

Hot-fire was conducted inside Vacuum Chamber #6 at Aerojet in Redmond, WA.

To achive the thermal conditioning required for the hot-bias testing, a new firing fixture and fuel manifold were used that together provide a broad range of thermal control for both incoming hydrazine propellant and the rocket engines themselves. Catbed heaters, firing fixture heaters, and valve voltage were used to create the hot-bias environment. To simulate flight mounting, thermal spacers were used to mount the REAs to achieve thermal conductivity of ~0.04 W/°C. Thermocouples were used to measure temperature on a variety of engine and test locations.

Data acquisition and control were provided by Aerojet's standard setup. JPL supplied equipment for the valve drivers. The drivers had 30 vdc suppression, and were optically isolated and designed to minimize opening response delays. *High Pc Testing* was conducted with the standard mechanical setup, e.g. the standard fuel system, 3/8" or .01" sightglass, and a Druck 500 psia chamber pressure transducer.

Low Pc Testing was conducted with a special setup. A greatly simplified fuel system was built to maximize fuel system hardness and data integrity by minimizing complex plumbing, gas traps, and heat sources. A miniature sightglass with an inner diameter of 0.013 in. (0.33 mm) was used to measure propellant mass per pulse. The sightglass was sectioned and measured post-test to determine / validate its precise scale factor.

To improve chamber pressure resolution for the short pulses, a Druck 15 psia chamber pressure transducer was used with a special low-volume fitting. These transducers were wrapped with line heaters and heated to 200°F during calibration and use. The line heaters were also wrapped around the Pc-tubes and adapters during use.

MINIMUM IMPULSE DATA REDUCTION

Thrust stands have not been used for MR-103 engines since the early 1990s when thrust stand performance mapping was done. Steady-state thrust and specific impulse were emperically related to chamber pressure and flowrate. Pulse-mode impulse bit was emperically related to chamber pressure and its integration time. Throat area and temperature are also used in both. By freezing the design and performing adequate throat inspection to ensure discharge coefficient was constant, direct thrust measurements were no longer needed. A standard method of MR-103 data reduction was developed.

However, the MIT engine is capable of much smaller impulses than was feasible in the 1990s. The operating conditions, environmental conditions, valve response characteristics, chamber pressure magnitudes, and overall pulse shapes are different that those where the emperical relationships were characterized. Furthermore, the variability and magnitude of impulse long after the valve closes is significant for the MIT's minimum impulses.

Thus, a new data reduction technique for minimum impulses was developed to provide the best estimate possible for impulse bit. The methodology combined extrapolation of the standard MR-103 performance equations with longer integration times of chamber pressure to include the tailoff impulse in the measurement. All parameters used in this analysis were reported with the intent that they could be easily re-evaluated if future thrust stand testing and/or analysis were to occur and yield improved emperical relationships.

HOT-FIRE TEST RESULTS

Table MW2 summarizes the overall cumulative test results from the flight configuration engines. All testing was successful. Post hot-fire functional tests and inspection validated the engines and components were still in flight acceptance condition. *State-Of-Health (SOH)* tests validated that performance did not change throughout testing. Results are extensively documented in Reference 3.

Table MW2. Cumulative Hot-Fire Operation Summary

Engine	Cumulative Total Impulse		Cumulative Pulses	Cumulative Run Time (min)
	(Lbf-s)	(N-s)		
D1	1,915	8,518	4,994	154
D2	5,161	22,957	515,619	420

ATP-H provided a baseline of performance for future production ATPs. It also provided the nominal steady-state equilibrium beginning of life performance curves presented in Figure MW3. The thrust curve is slightly lower for the MR-103M than prior MR-103 configurations because the MIT valve has slightly more liquid pressure drop than previous valves.

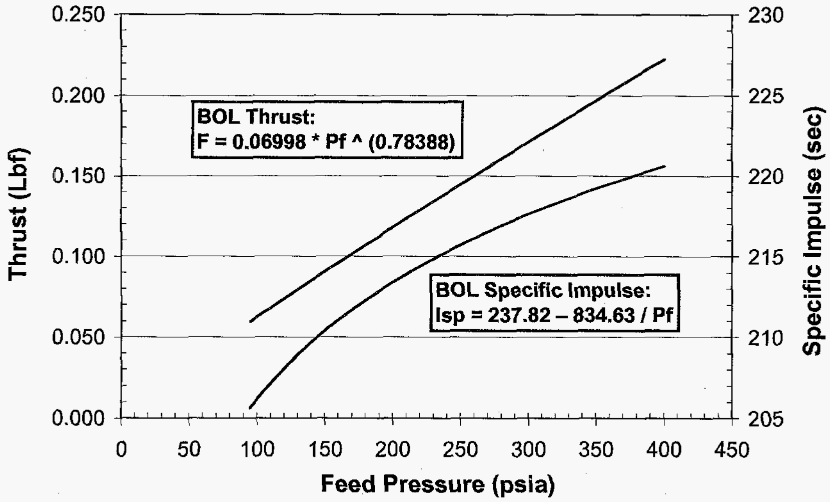

Figure MW3. Beginning-Of-Life (BOL) steady-state performance for the MIT.

The hot-bias testing (*SS-Eq-34vdc* and *PM-Eq-34vdc*) validated the thermal model's hot-bias prediction capability and that the worst case valve soakback temperature occurs after steady-state operation. Peak valve seat temperature was ~245°F and peak valve body temperature was ~255°F. Restarts at peak temperatures verified hot-restart capability with acceptable performance and without any permanent change to performance.

The *500k* and *Delta-H* tests were high impulse pulse-mode sequences. The *500k* test successfully cycled the valve in a hot-fire environment for >500,000 pulses without affecting operation or performance. The *Delta-H* tests supplemented this with transient and equilibrium data, measuring propellant usage for both. The resulting broad data set will permit characterization of high impulse pulse-mode performance at a variety of feed pressures, duty cycles, and on-off time combinations.

The *PMap-L* test block was the most important hot-fire testing of the MIT delta-qualification. The primary purpose of this testing was to characterize the minimum impulse capability of the MIT. Getting a sufficiently hard fuel system in the new fuel cart proved to be the largest test challenge. Throughout testing, modifications were made until trapped gas could be avoided. Subsequent analysis showed that only the sightglass deflections were affected by the fuel system softness. Thus, a larger set of data is available for the evaluation of impulse bit than for specific impulse. Table MW0 shows the quantity of pulses tested for each engine at each test condition.

Table MW0

Minimum Impulses Conducted for *PMap-L*.

Tc (°F)	PW (ms)	Number of Pulses at each Feed Pressure (psia)												
		D1						D2						All
		400	320	240	180	100	All	400	320	240	180	100	All	
~325	1.7	6		7			13	6		7			13	26
	2.3	5		5		4	14	5		5		4	14	28
	2.9	11	4	15	4	15	49	11	4	15	4	15	49	98
	3.5	13	3	23	2	17	58	10	3	15	4	12	44	102
	4.1	7		17		11	35	5		8		8	21	56
	5.6	1		1			2	1		1			2	4
	7.1	13		16		9	38	13		13		8	34	72
	8.1	13		16		9	38	13		13		8	34	72
	10.1	10	4	15	4	11	44	8	4	15	4	11	42	86
	12.1	10	4	15	4	11	44	8	4	15	4	11	42	86
	16.1	1		1			2	1		1			2	4
Subtotal		90	15	131	14	87	337	81	15	108	16	77	297	634
~450	1.7	5		6			11	5		6			11	22
	2.3	4		8		4	16	4		8		4	16	32
	2.9	9		17		9	35	9		17		9	35	70
	3.5	10		22		11	43	8		17		8	33	76
	4.1	5		13		6	24	5		12		6	23	47
	5.6													
	7.1			4		5	9			4		5	9	18
	8.1			4		5	9			4		5	9	18
	10.1	5	5	5		1	16	4	5	5		1	15	31
	12.1	5	5	5		1	16	4	5	5		1	15	31
	16.1													
Subtotal		43	10	84		42	179	39	10	78		39	166	345
~520	1.7	5		6			11	5		6			11	22
	2.3	4		8		4	16	4		8		4	16	32
	2.9	9		17		9	35	9		17		9	35	70
	3.5	10		22		11	43	8		17		8	33	76
	4.1	5		13		6	24	5		12		6	23	47
	5.6													
	7.1			4		5	9			4		5	9	18
	8.1			4		5	9			4		5	9	18
	10.1	5	5	5		1	16	4	5	5		1	15	31
	12.1	5	5	5		1	16	4	5	5		1	15	31
	16.1													
Subtotal		43	10	84		42	17	39	10	78		39	16	345

						9						6	
Total	17 6	35	29 9	14	17 1	69 5	15 9	35	26 4	16	15 5	62 9	132 4

Minimum impulse performance was characterized at feed pressures from 100-400 psia with commanded pulse widths of 1.7-16 msec. All pulses were Limit Duty Cycle (LDC) using the catbed throat temperature plus a 60-second "hold time" as the trigger. This was typically repeated multiple times at each test condition. This technique minimized the affect of environmental variables on performance and maximized pulse-to-pulse repeatability.

Tests were conducted at three different catbed chamber / throat temperatures. Using the MR-103M thermal model and Cassini history, these temperatures represented the catbed temperature in-flight at the cold-bias condition resulting from one catbed heater element on at 28 vdc (~325°F), two catbed heater elements on at 28 vdc (~520°F), and one condition in-between (~450°F).

To assist with minimum impulse performance evaluation, a spreadsheet was created to facilitate easy analysis and presentation of the data. The file provides an easy way for parameters to be analyzed against each other and the results tabulated and plotted in two ways. First, they can be presented in terms of constant feed pressure by selecting which catbed temperature data to include (individual or all). Second, they can be presented in terms of constant catbed temperature by selecting which feed pressure data to include (individual or all). The spreadsheet also provides a way to remove pulses from evaluation for test related reasons of poor sightglass measurement, poor chamber pressure measurement, or both.

The minimum repeatable impulse bit found from the testing was ~210 μlbf-s (934 μN-s) for engine D1 and ~150 μlbf-s (667 μN-s) for engine D2. These occurred at a commanded pulsewidth of 1.7 msec with a chamber temperature of ~325°F. Figures MW4 and MW5 provide the propellant usage and impulse bit, respectively, as functions of feed pressure and pulsewidth for this chamber / throat temperature. The latter chart was analyzed with multi-variate regression to create the contour plot in Figure MW6.

The relationship of characteristic impulse times is presented in Figure MW7. The chart plots the time to reach half the impulse against the time to reach centroid. As the data shows, these two parameters have a linear relationship regardless of chamber temperature, feed pressure, or pulse width.

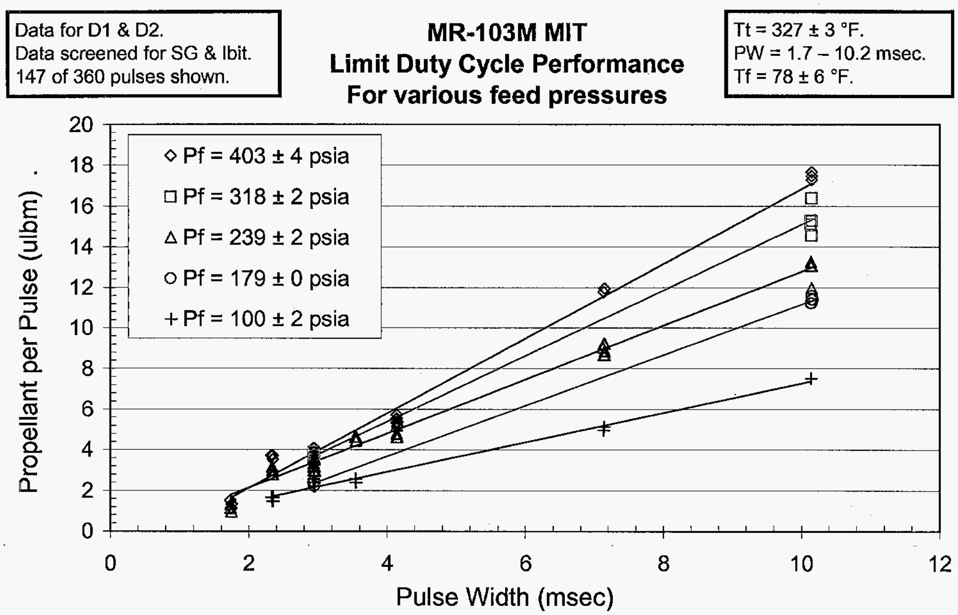

Figure MW4. LDC propellant usage as a function of pulsewidth and feed pressure with a chamber temperature of ~325°F (one catbed heater element in a cold-bias environment).

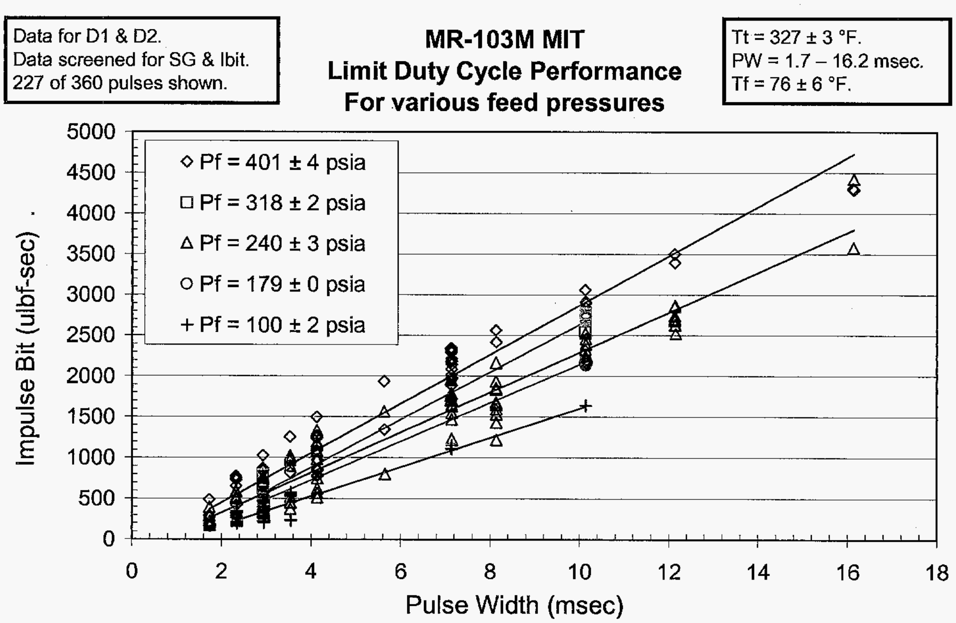

Figure MW5. LDC impulse bit as a function of pulsewidth and feed pressure with a chamber temperature of ~325°F (one catbed heater element in a cold-bias environment).

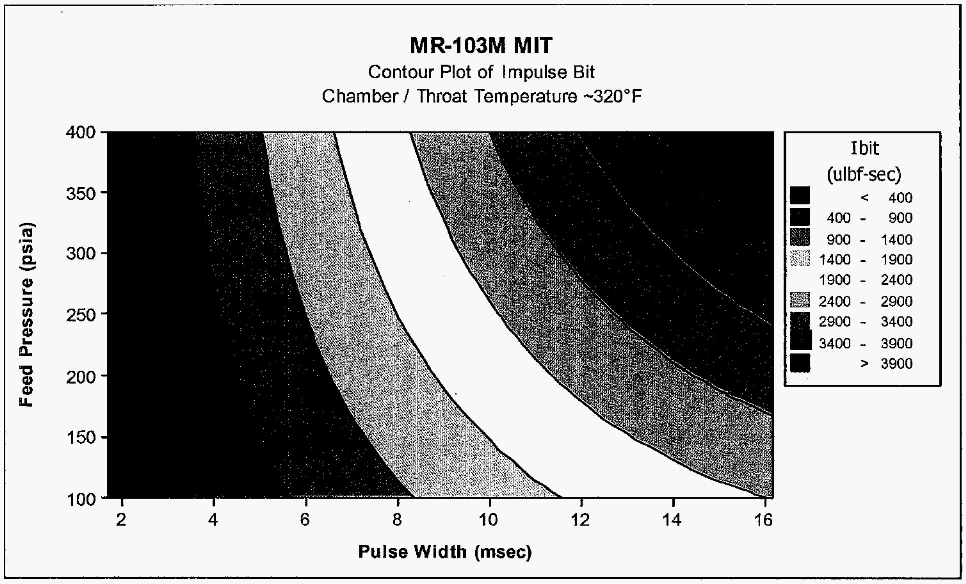

Figure MW6. Contour plot for LDC impulse bit as a function of pulsewidth and feed pressure with a chamber temperature of ~325°F (one catbed heater element in a cold-bias environment).

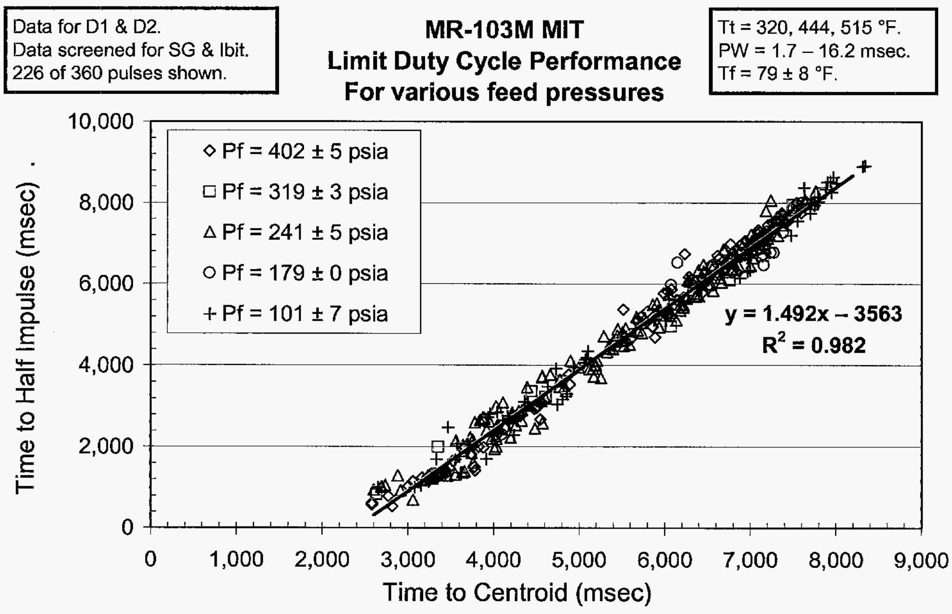

Figure MW7. Linear relationship of characteristic pulse times.

SUMMARY AND CONCLUSIONS

The Minimum Impulse Thruster significantly improves the state-of-the-art minimum impulse capability of hydrazine monopropellant thrusters, with a factor of 5 reduction in the minimum impulse bit, from roughly 1.1 milli-lbf-seconds (5 milliNewton seconds) to ~ 0.22 milli-lbf-seconds (1 mN-s). The robust Δ-qualification test program has demonstrated that the new valve combined with the Aerojet MR-103 maintains all the previous capabilities and qualification heritage of the thruster. The Minimum Impulse Thruster provides new design options for spacecraft, including an alternative to reaction wheels for precision attitude control, and improved precision translation capability for rendezvous, docking, and formation flying. In addition to these new capabilities, benefits can include savings in propellant, prolonged thruster life, and for missions that can eliminate reaction wheels, savings in cost, system mass and power; benefits are mission dependent.

FUTURE WORK

As was mentioned earlier, the Δ-qualification testing of the Minimum Impulse Thruster was not performed on a thrust stand. Instead, chamber pressure and flowrate were measured and emperically related to steady-state thrust and specific impulse. Pulse-mode impulse bit was emperically related to chamber pressure and its integration time. Because the Minimum Impulse Thruster is capable of much smaller impulses than was feasible when these emperical relationships were developed, it would be desirable to perform testing on a thrust stand capable of measuring the minimum impulse bit as well as steady state thrust, and correlate back to the Δ-qualification test data. The data reduction was performed with this possibility in mind, and parameters used in the analysis were reported with the intent that they could be easily re-evaluated if future thrust stand testing and/or analysis were to occur and yield improved emperical relationships. There is currently no funding to perform testing of the Minimum Impulse Thruster on an appropriate thrust stand, but the assest are available should funding become available.

There are two paths to reducing minimum impulse. The path chosen for the Minimum Impulse Thruster was to develop a valve that opens faster and closes faster, enabling the valve to respond to a shorter electrical pulse width, thereby reducing the propellant flow time and the minimum impulse-bit. An alternate path involves a new thruster specifically designed for smaller thrust and impulse. JPL has a small technology effort funded by the Mars Technology Program who's goal is to demonstrate proof of concept of a Hydrazine milliNewton Thruster, and develop this technology to pre-qualification status (funding permitting). The goals of the Hydrazine milliNewton Thruster are roughly 5 milli-lbf (22 mN) thrust and 10 micro-lbf (45 microNewton seconds) impulse.

REFERENCES

MIL-STD-1540C
MIL-HDBK-340A
"Minimum Impulse Thruster Delta Qualification Test Report", Aerojet Report No. 2004-R-2577, prepared by Aerojet for JPL.

Or...
Aerojet Test Report No. 2004-R-2577, Minimum Impulse Thruster Delta-Qualification Test Report.

GLOSSARY

General Comments from Mike:

- some sentences are very long.
- Aerojet REA model numbers are hyphenated (MR-103 not MR103). To avoid MS Word from breaking this hyphen between lines use "control" while tying the hyphen.
- Table MW1 fits onto one page perfectly when sized for JANNAF settings.
- I changed the nominal temperatures to reflect what we actually got. (320 to 325, 444 to 450, 515 to 520).
- I changed the nominal pulsewidth to reflect what we actually got (e.g., 1.6 to 1.7)
- I'm not too worried about length of the paper. They request "try no more than 10". But having more due to large tables isn't a bad thing.
- If length is an issue, consider removing my last two figures.