EXTENDED DUTY CYCLE TESTING OF SPACECRAFT PROPULSION MINIATURIZED COMPONENTS

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Abstract

The objective of this study was to assess the functional performance of prototype miniaturized propulsion components for a spacecraft attitude control cold-gas propulsion system under flight design conditions. Greater than 60,000 cycles of testing over the temperature range of -?0 to + 70C were carried out on a breadboard system. The results provide confidence that components can be developed and qualified that will provide robust solutions for future deep space exploration mission requirements.

Nomenclature

I - current
P - pressure
T - thruster, temperature
t - time
V - valve, voltage

Introduction

Propulsion systems for new classes of miniaturized spacecraft for outer planet and deep space exploration will have to be lighter, use less power, and meet the greater life-times, duty cycles, and environmental extremes. In attempting to draw upon and extend technology originally developed for other applications for a long-term space probe to the planet Pluto, a major question mark is the ability of the technology to be extended to meet the above requirements. Prototype miniaturized propulsion components for a spacecraft attitude control cold-gas propulsion system had been developed earlier under a Pluto Fast Flyby Advanced Technology Insertion (ATI) program.[1] The objective of this study was to assess the functional performance of these components under the flight design conditions.

The study consisted of dynamic tests of the individual components and cycling tests, under ambient and flight design temperature conditions, of the components assembled into a breadboard cold-gas propulsion test system. Customized computer systems were used to actuate and pulse the latch- and thruster-valves and to acquire the measurement results (pressure, temperature, actuation voltage, and current draw). Acceptance tests were performed on the individual components at ambient temperature and at the test conditioning temperature prior to each cycling test to assess any degradation in performance with conditioning temperature and cycling.

Dynamic Tests

The prototype components, which were described in Ref. 1, are listed in Table 1:

The contract for the development and delivery of each component contained a set of prototype specifications and functional requirements, Tables 2-5. Each contractor was required to functionally test one of the delivered units to show compliance with the prototype requirements. In addition, each contract contained a set of flight design requirements, which included radiation (17 krad), temperature range (Tables 2-5), vibration (Table 6), and operational lifetime (9 years, rein). The contractors were not required to demonstrate qualification to these latter flight requirements. Instead, in their final reports they were to describe any potential design revisions or tests they felt would be required before doing so.

The service valve contractor elected to add dynamic testing to the required acceptance tests and S/N-1 successfully completed the flight design requirements.

Following delivery at JPL, holding fixtures were fabricated and one of each of the remaining components (S/N 002 in each case) was dynamically tested. The launch environment was better defined by this

Table 1. ATI Propulsion Components

Component	Manufacturer	Model No.	Serial No.	Functional Requirements
Service Valve	Futurecraft Corp.	505S8	-1 & -2	Table 2
Latch Valve	Moog, Inc.	51 X17(I	001 & 002	Table 3
Pressure Regulator	Moog, Inc.	50X7 13	001 & 002	Table 4
Cold Gas Thruster	Moog, Inc.	58x125	001 & 002	Table 5

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Table 2. Service Valve Prototype Functional Requirements

- Pressures:	0102.1 MPa (O to 300 Psi) operating (MEOP) 1.5 x MEOP proof 2.5 X MEOP burst
- Temperatures:	5 to 45° C (41 10 1 13°F) - prototype operating -20 to 70°C (-4 to 158°F) - flight non-operating
- Leakage:	uncapped, primary seal closed; 1x 10^{8} scc/s GN_2 (max) capped, seat open; 1x10^{5} scc/s GN_2 (max)

Life Cycle (open and close = 1 cycle) = 100 (min)

The "running torque", i.e. , torque on the actuation nut while opening or closing the valve, shall not increase more than 20% from the first 10 the 100th cycle.

Table 3. Latch Valve Prototype Functional Requirements

- Pressures:	0102.1 MPa (O to 300 Psi) operating (MEOP) 1.5 x MEOP proof 2.5 x MEOP burst
- operating Temperatures:	5 to 45°C (40 to 1 13°F) - prototype -20 in 70°C (-4 to 158"1') flight
- Flow rate:	2 sl/min. GN_2 max at 48.3 kPa (7 psia) inlet pressure and 14 kPa (2 psid) differential pressure
- Leakage:	internal; *0.01* see;/n,IrI. GN_2 (max) at 2.1 MPa (300 Psi) external; 1x1O ^{5} scc/min. GN_2 (max)
- Voltage:	28 ± 4 Vdc opening or closing
- Power;	15 W per coil (mm.) at 20°C (68°F)
- Response:	50 ms (max) with 24 Vdc opening or closing at 45°C (1 13°F)
- Cycle life:	5,000 total (min)

Table 4. Pressure Regulator Prototype Function al Requirements

- Pressures:		
	Inlet:	2.0/ to 0.345 MPa (300 to 50 Psi) operating 3.2 MPa (450 Psi) proof 5.2 MPa (750 Psi) burst
	Outlet:	34.5 kPa (5 Psi) ± 6% at 1.0 sl/min. flow rate, regulated " 48.3 kPa (7 Psi) max lock-up 2.07 Mpa (300 Psi) proof 3.5 Mpa (500 Psi) burst
- operating Tempt.ralures:		510 45°C (40 to 1 13°F) - prototype -20 to 70°C (-4 to 158°F) - flight
- Flow rate:		2 sl/min. GN_2 max at regulated pressure
- Leakage:		internal; 0.01 see;/njin GN_2 (max) at 2.1 Mpa (300 Psi) external; 1x 10^{5} scc/min. GN_2 (max)
- Cycle life:		15,000 regulated cycles (min)

time, and an analysis was performed to determine a revised set of qualification test levels for the panel-mounted propulsion module components (valves and regulators) and the strut-mounted cold gas thrusters. The revised levels are indicated in Table 7. Comparing the random vibration levels with the earlier flight design requirements, the thruster levels were unchanged and the final panel components level (0.5 g^2/Hz) was double the earlier requirement.

The panel components assembly (PCA) and cold gas thruster were subjected to the. Table 7 sine. and random vibration test levels in each of their 3 principle axes, as shown schematically in Figure 1. The latch valve was tested in the closed position with 5 psi nitrogen at the inlet and a bubble meter tonne.:tcd to the outlet to monitor leakage, as shown in Figure 2. The pressure regulator and cold gas thruster were tested "dry".

Typical sine and random vibration sequences are shown in Figures 3 and 4. In each of the 3 principle axes tests the latch valve remained closed, with no indicated leakage, during the sine vibration, but abruptly unlatched to the open position during the random vibration. In Y and Z axe. tests (normal to the valve centerline) the unlatching appeared to occur when the test went to the maximum, 0.5 g^2/Hz

Table 5. Cold-gas Thruster Prototype Functional Requirements

- Pressures:	0 to 34.5 kPa (0 to 5 Psig) operating 2.07 kPa (300 Psi) proof 23.5 kPa (500 Psi) proof
Operating Temperatures:	-?0 to 45°C (-4 10113 °F) - prototype -45 to 70°C (-49 to 158°F) - flight
- Thrust Rating;	4.5 mN (0.001 lbf) ± 20% at 34.5 kPa (5 psig) GN_2 nominal inlet pressure
- Flow rate:	8 mg/s (0.0146 SCFM) GN_2 (max) at **34.5** kPa **(5** psig) and 20°C (68°F)
- Leakage:	internal; 0.01 scc/min. GN_2 (max) al 34.5 kPa (5 Psig) external; 1×10^{-5} scc/min GN_2 (max)
- Voltage:	?8 ± 4 Vdc operating ?0 Vdc (max) Pull-in at 45°C (113°F) 3 Vdc (rein) drop out at 45°C (113"1)
- Power:"	actuation;]0 W (max) at 28 Vdc and 20°((68" F) holding; 1 W (max) at 10 Vdc and 20°C (68°F)
- Response Time:	.<2.5 ms with ?4 Vdc from signal to full open or close at 45°C (113"P)
- Max. Continuous On-Time:	30s (min)
- Cycle life:	15,000 cycles (min)

Table 6. Vibration Design Requirements

Sinusoidal

FREQUENCY (Hz)	REQUIREMENTS
5 - 20	1.91 cm D.A. Displacement
20 - 100	15, (J g **010** peak

Design sweep rate: 2 octaves/minute (once up and down in frequency) in each of three orthogonal axes.

D.A. - Double Amplitude

Random

FREQUENCY (Hz)	REQUIREMENTS
20 - 80	+6 dB/octave
80 - 1100	0.25 g **2/Hz
1000 - 2000	-1? dB/octave
Overall	17.6 g rms

Design duration: 3 minutes/axis in each of three orthogonal axes

vibration magnitude. The valve was electrically re-closed after each test and the bubble meter showed no change in leakage rate. Further results will be discussed in the next section.

Thermal Cycling Tests

Breadboard Cold-Gas Propulsion Test System

A breadboard cold-gas propulsion test system was designed and assembled, and the Pluto AT1 spacecraft propulsion components were cycled a total of 60,000 times under ambient and design temperature conditions The system is shown schematically in Figure S and pictorially m Figures 6 and 7. The gas reservoir was pressurized to 300 psi, via manual valve V1, with nitrogen gas that had passed through a 0.4 micron high-capacity Millipore filter. The gas passed from the reservoir to the two cold gas thrusters through a system filter (2 micron effective, 10 micron absolute), latch valve V2 (S/N 002), pressure regulator, latch valve V3 (S/N 001), and line filter (10 micron effective, 25 micron absolute). A flow meter sensor was installed aft of the reservoir, but was not used for these tests since the flow rates of the individual thrusters had been previously calibrated by the manufacturer (0 34? SLPM at 5 psi inlet pressure). The two service valves, V4 and V5, were used as access ports to measure the leakage of valves V2 and V3 with the bubble meter

Nozzle plug fittings, shown installed in Figure 6, allowed the thruster valve leakage rates to be measured with the bubble meter or a

Table 7. Propulsion Component Vibration Qualification Test Levels

Sinusoidal Vibration

	Frequency (Hz)	Level
Cold-Gas Thrusters	5-28	0.75 in. D.A.
	28-44	30 g 0 pk
	44-100	15 g 0 pk
PCA Panel Components	5-20	0.75 in. D.A.
	20-100	15 g 0 pk

Vibrate in each of three orthogonal axes.
Sweep in one direction @ 2 octaves/minute.

Random Vibration

	Frequency (Hz)	Level
Cold-Gas Thrusters	20-80	+6 dB/octave
	80-1000	0.25 g^2/Hz
	1000-2000	-12 dB/octave
	Overall: 17.6 grms	
PCA Panel Components	20-80	+6 dB/octave
	80-400	0.25 g^2/Hz
	400-500	+9 dB/octave
	500-1000	0.50 g^2/Hz
	1000-2000	-12 dB/octave
	Overall: 22.8 grms	

Vibrate for three minutes in each of three orthogonal axes.

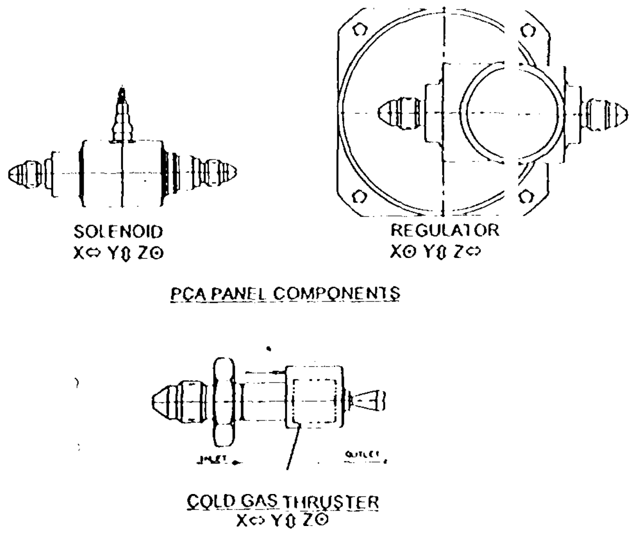

Fig. 1. Axis Definition and Accelerometer Location

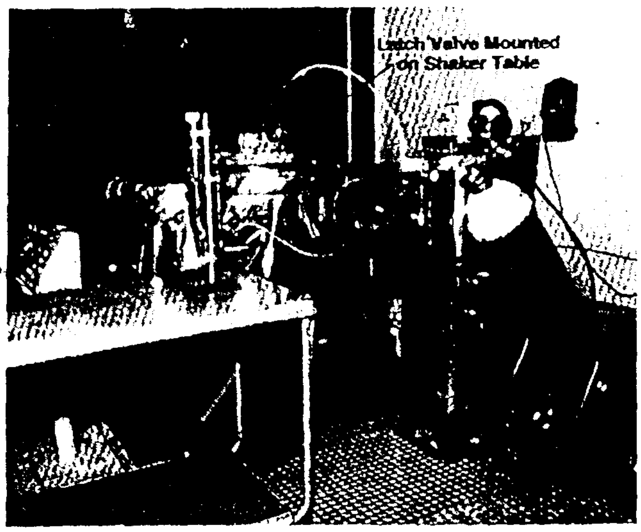

Fig. 2. Bubble Meter Setup for Latch Valve Shake Tests

helium leak detector. All components, tubing, and fittings were cleaned to the D2 level.

Beside leakage rates, measurements consisted of the reservoir pressure and temperature (P1 and T1), static pressure and temperature fore and aft of the pressure regulators (P2, T2/P3, T3), and the actuation voltage and current for the two thrusters (T1V, T1A, and T2V, T2A). P1 and P2 were Taber pressure transducers, P3 a short time response Statham transducer, and copper constantan thermocouples were used for all temperature measurements. Thruster current was determined by measuring the voltage drop across a 5 ohm resistor in the actuation circuit.

The breadboard system is shown installed in its temperature conditioning chamber in Figure 8. The test control and data acquisition system is shown in Figure 9. Actuation of the latch valves and pulsing of the two cold-gas thrusters was controlled by a LabView computer/power supply/valve driver system. The valve driver circuit, Fig 3 Cold Gas Thruster Sinusoidal Vibration Sweep, X Axis

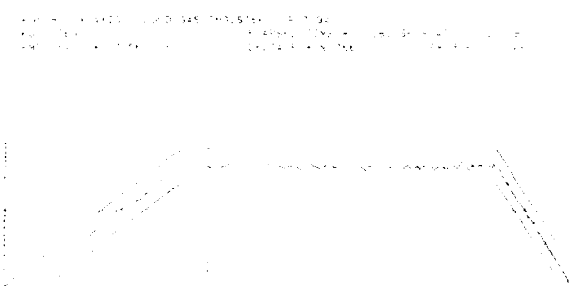

Fig 4 Cold Gas Thruster Random Vibration Sweep, X Axis

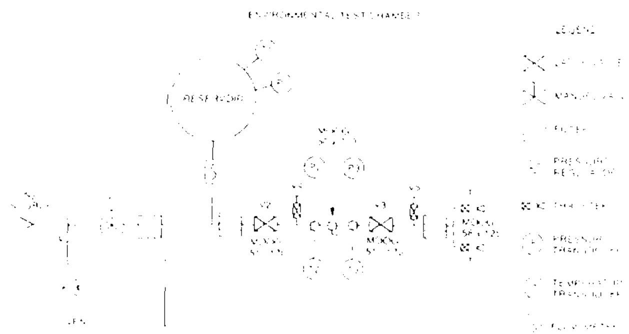

Fig. 5. ATI Breadboard Test System

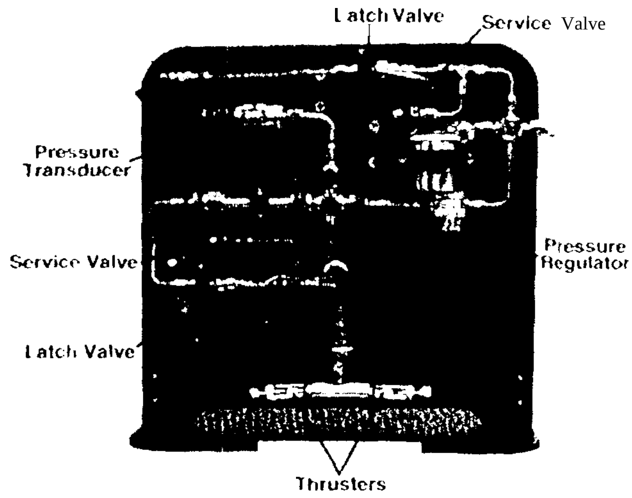

Fig. 6. Breadboard Cold-Gas Propulsion Test System - Front View

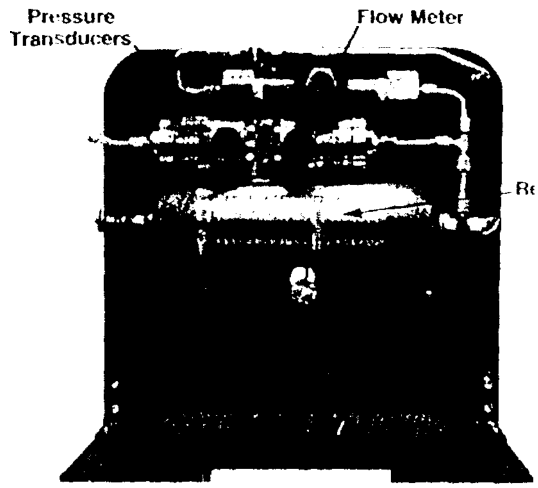

Fig. 7. Breadboard Cold-Gas Propulsion Test System - Rear View

shown schematically in Figure 10, was a simplified version adapted from plans provided by the latch valve and thruster manufacturer.

The data acquisition system was a second LabView computer operating at two sampling rates. The thruster valve voltage and current and the regulated pressure, P3, were each sampled approximately 40 times a second, the balance once a minute. A digital oscilloscope was also used to periodically record the thruster valve voltage and current trace pulses for opening response-time determination.

Test Procedure

The breadboard system was cycled at ambient temperature and the preliminary flight requirement temperatures of -20°C and +70°C. The order of the testing was as shown in Table 8.
Basically, what was felt to be the most critical of the ATI miniaturized components acceptance tests were performed at ambient temperature and at the test conditioning temperature prior to each cycling test. Table 9 shows the order of these acceptance tests.

Test Results

The predicted thruster duty cycle had increased considerably beyond the prototype functional requirement of 15,000 cycles. As indicated previously, the two thrusters were pulsed a total of 60,000 times (an FY'94 representative duty cycle): 10,000 at ambient temperature, 15,000 at -20°C (-4°F), 15,000 at 70°C (158°F), and 20,000 at ambient. The thrusters were pulsed at a period of 1 second: 100 ms on, 900 ms off - an impulse bit of approximately 4.4 x 10^{-4} N-s. In pre-test check-out of the breadboard system, it was discovered that the S/N 002 pressure regulator had been affected by the vibration testing it

Fig. 8. Test System Installed in Temp. Conditioning Chamber

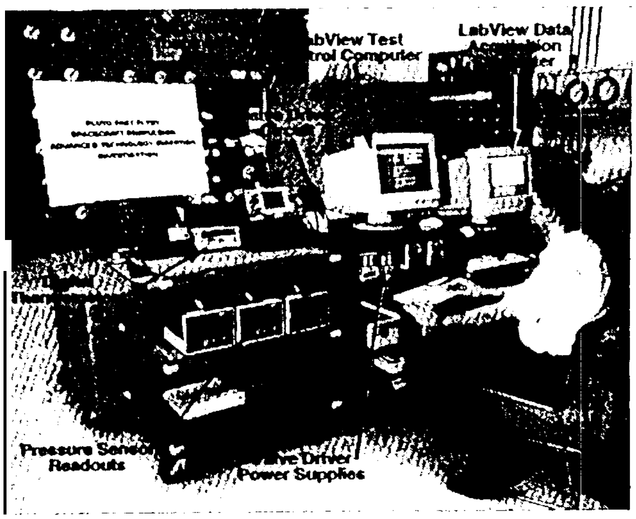

Fig. 9. Test Control and Data Acquisition System

bad undergone. It would not open (remained in the lock-up position) to allow gas flow through it. It was removed from the breadboard system and the non-vibrated S/N 001 regulator installed and used in the subsequent tests.

The latch valve internal leakage measurement results are listed in Table 10. No measurable leakage (NML) could be detected for either latch valve before or after the first 10K ambient temperature cycles. At -20°C V2, which had been dynamically tested, would not open. Raising the temperature back to 20°C allowed the valve to be opened. The amend latch valve, V3, had a gross leak at -20" C which exercising the valve didn't correct. At the subsequent ambient acceptance test V2 could not be closed, and it remained in the open position for the. balance of the test program. No measurable leakage was detected for V3 here and for the balance of the test series.

The internal leakage measurement results for the two cold gas thrusters are shown in Table 11. T2, which was dynamically tested, showed no measurable leakage throughout the test series. Helium leak checks before and after yielded 3.2 x 10^9 and 2.0 x 10* see/s, respectively. T1 developed a detectable leakage - 6 to 7 x10^3 scc/min.

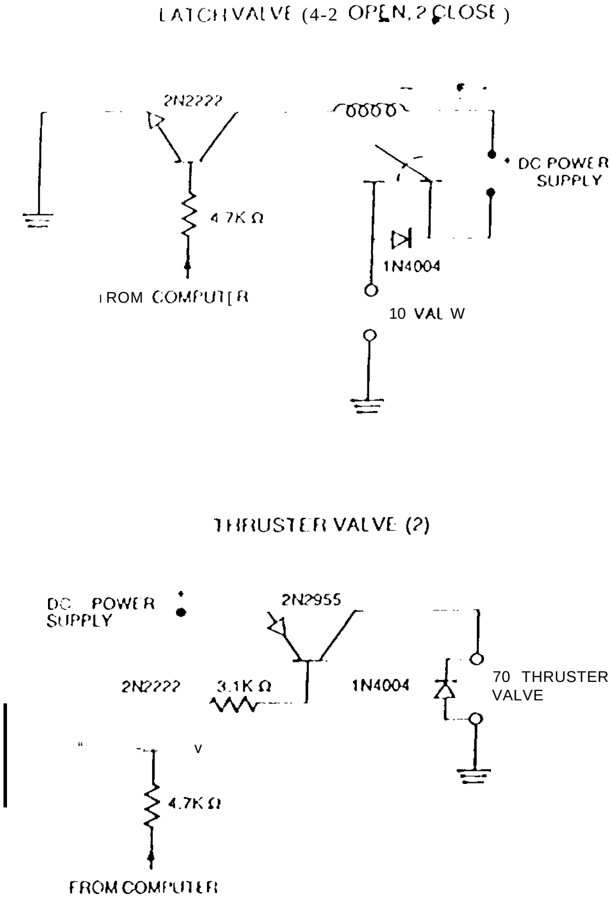

Fig. 10. Valve Drive Circuit

GN_2, still below the prototype technical specification value of 10^2 scc/min. GN_2 - over the final 20K ambient temperature cycles.

The pull-in and drop-out voltages (Table 12), measured to ±1V, for the two thrusters showed little or no deviation over the span of the test series

Table 8. Testing Order

1. Ambient Temperature Test
   - a. Component Acceptance Tests
   - b. Thruster Cycling (1 OK)
2. Cold Conditioning emperature Test (-20°C)
   - a. Component Acceptance Tests - Ambient Temperature
   - b. Component Acceptance Tests - -20°C
   - c. Thruster Cycling (1 SK)
3. Hot Conditioning-Temperature Test (70°C)
   - a. Component Acceptance Tests - Ambient Temperature
   - b. Component Acceptance Tests - 70°C
   - c. Thruster Cycling (1 SK)
4. Repeat Ambient Temperature Test
   - a. Component Acceptance Tests - Ambient Temperature
   - b. Thruster Cycling (20K)
   - c. Component Acceptance Tests - Ambient Temperature

Table 9. Order of Component Acceptance Tests

1.	Measure leakage of latch valve V? (bubble meter) over period of 10 minutes.
2.	Measure leakage of latch valve V3.
3.	Measure leakage of thruster T1.
4.	Measure leakage of thruster T2.
5.	Measure pull-in and drop-out voltage of thruster T1
6.	Measure pull-in and drop-out voltage of thruster T2
7.	Record regulator pressure leakage over period of 1/2 to 1 hours
8.	Measure regulator regulation band, with two thrusters pulsing, over inlet pressure range of 300 to 50 psi.

Table 10. Latch Valve Internal Leakage Results

Functional Requirement: 0.01 scc/min. GN_2 (max) at 2.1 MI's (300 Psi)

	Moog Acceptance	10K cles			15K		15K	20K
	admin. G N_2	Amb.	Amb.	-4°F	Amb.	158°F	Amb.	Amb.
V2 (**300** Psi)	6.67x1(P	NML	NML	NML (wouldn't open)	Stuck in open position	-	. .	. .
V3 (5 Psi)	**0.0** (300 Psi)	NML	NML	Gross leak	NML	NML	NML	NML

NMI - No Measurable Leakage

Table 11. Thruster Valve Internal Leakage Results

Functional Requirement: 0.01 scc/min. GN_2 (max) at 34.5 kPa (5 Psig)

	Moog Acceptance	10K cles			15K		15K	20K
	scc/min. GN_2	Amb.	Amb.	-4°F	Amb.	158°F	Amb.	Amb.
T1	1.0x10⁴	NML	NML	NML	NML	NML	NML	7. MX103 6.0x10⁻³
T2	7.4X1O$	NML 3.2x1 (19 scc/s He	NM1.	NML	NML	NMI	NML	NML 2.0?.10' scc/s He

NMI. No Measurable Leakage

Table 12. Thruster Valve Pull-In and Drop-Out Voltages

Functional Requirements:

Pull-in; 20 Vdc (max) at 45°C (113°F)
Drop-out; 3 Vdc (min) at 45°C (113°F)

		Moog Acceptance						
		10K cycles		15K		10K	20K	
		70°F	Amb.	-4°F	Amb.	158°F	Amb.	Aml
T1	Pull-in, V	13.3	15±1	15	15	15-16	16	15
	Drop-out, V	4.3	4	5	4-5	5	4	5
T2	Pull-in, V	14.6	15	16	16	16	16	15
	Drop-out, V	7.3	8	7	8	9	9	8-9

Figure 11 shows voltage and current pulse traces for the two thruster valves - taken at the conclusion of the **60,000 cycles, but essentially** unchanged throughout the series. Table 13 shows representative actuation voltage, current draw, and power values for the respective conditioning temperature cycles. The excitation voltage was held at the thruster manufacture.r's acceptance test value of 23-24 volts. As shown, the current drawn by the two thrusters increased at -20°C and decreased at 70°C.

The opening response time (time delay from energizing to opening of thruster valve) for the two thrusters is indicated by the inflections in the high sweep-rate voltage and current traces in Figure 12. These sweeps were also taken near the. conclusion of the 60,000 cycles. The results for the respective conditioning temperature cycles are tabulated in Table 14. The opening response times were $\leq$ 1ms throughout the test series and the final values were essentially identical to the manufacturer's acceptance test results. Valve closing response times for the latter were _< ?S0 ms.

The results of the pressure regulator lock-up leakage tests are tabulated in Table 1S. 1 he initial acceptance test showed a drop in the lock-up pressure, 3'3. of 0.03 psi (0.7S%) over a period of 1 hr., indicating that the outlet line fittings leakage exceeded that.Of the **regulator.** The high values for the pre-70° C ambient temperature tests are probably attributable to the pressure transducer not being adequately warmed up. I he lock-up pressure rose 0.3 psi, a 5.7 % increase, m 15 min. at the pm-test 70°C temperature condition, indicating a definite leak. The post-70° C acceptance test at ambient temperature showed 00 change over 3(I min. The final acceptance test showed a low 0.03 psi (0.5 S%) **drop over a** period of 2 hr.

The lock-up/regulated pressures with the two thrusters cycling, measured over a regulator supply pressure, range of 300 to 50 psi, are tabulated in Table. 16. The regulated pressure results, plotted in Figure 13, fell within the technical specification of 5 ± 0.3 psi. A standard deviation of ± 0.03 psi over the 250 psi range in inlet pressure was determined for the most complete data sets.

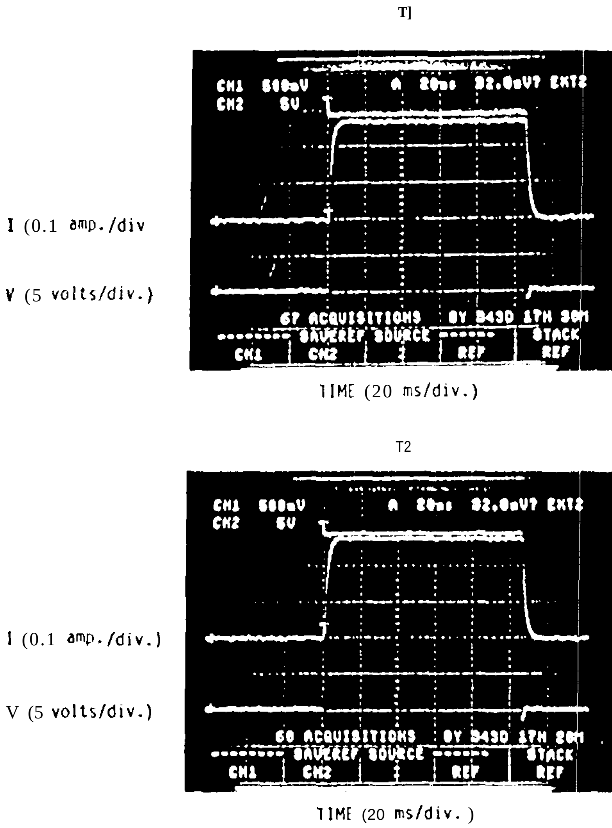

Fig. 11. Thruster Valves Voltage. and Current Pulse Traces

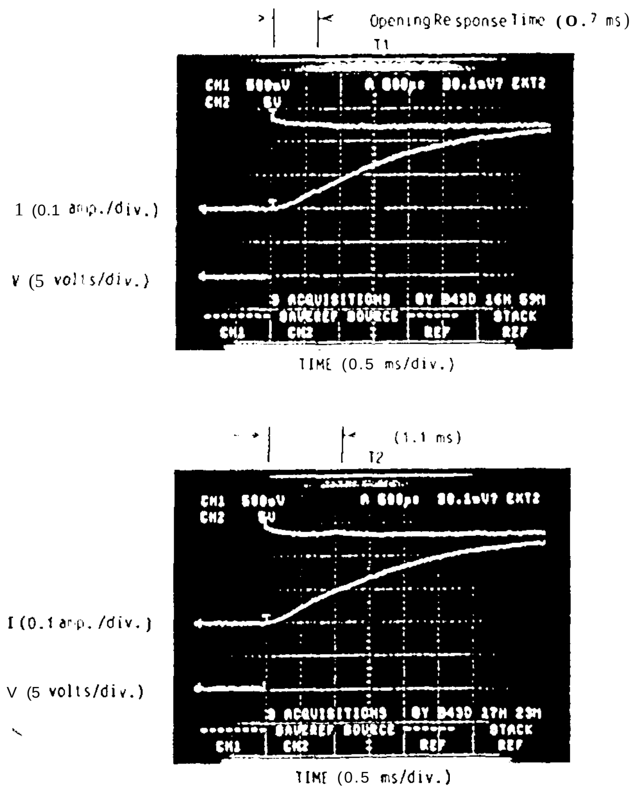

Fig. 12. Thruster Valves Opening Response Times

Table 13. Thruster Valve. Actuation Power at 23-24 Vdc Excitation Voltage

Functional Requirement: 10W (max) at 28 Vdc and 20°C (68°F)

		Moog Acceptance 70°F	10K cycles Amb.	15K -4°F	15K 158°F	20K Amb.
T1	Voltage, V	?4	23	23	23	24
	Current, A	0.28	0.26	0.29	0.24	0.27
	Power, W	6.27	5.41	6.72	4.61	5.83
T-2	Voltage, V	?4	23	23	23	23 24
	Current, A	0.28	0.26	0,?9 0,30	O 24	0.26 0.28
	Power, W	6.27	5.41	6.72-7.20	4.61	5.41 6.27

Table 14. Thruster Valve Opening Response Time

Functional Requirement: ≤2.5 ms with 24 Vdc at 45°C (113°F)

	Moog Acceptance	10K cycles	15K	15K	20K
	70°1	Amb.	-4°F	158°F	Amb.
T1	0.66 ms	< 1	< 1	< 1	0.7
T2	1.06	~ 1	- 1	~ 1	1.1

Table 15. Pressure Regulator Lock-up Leakage Test Results

Functional Requirement: 0.01 scc/min. GN_2 (max) at 2.1 MPa (300 Psi)

	P3, Psig						
	10K cycles		15K		15K		20K
Time, min.	Amb.	Amb.	-4°F	Amb.	158°F	Amb.	Amb.
0	5.36	5.35	5.38	7.2?	5.30	5.31	5.43
7			5.37		5.46		|
15	5.35	5.34	5.34	7.20	5.59	5.31	
30	5.34			7.20		5.31	|
45	5.33						|
60	5.32						|
|							|
1?0							5.40
Net Reg. Leakage	...	..		...	Leaking	-	..

Table 16. Pressure Regulation Band Test Results
S/N 001

Functional Requirements:
Lock-up; 7 Psi (max)
Regulated; 5 ± 0.3 Psi at 1.0 sl/min

	P3, Psig Lock-up/Regulated at 0.7 sl/min					
	10 cycles	15K		15K		20K
P2, Psi	Amb.	-4°F	Amb.	158°F	Amb.	Amb.
300	5.2915.19	5.3315.??	5.32/5.20	5.20/5.13	5.?715.22	5.31/5.22
2.50	5.31/5.21	5.38/5.26				
200	5.3315.23	5.40/S.?8	5.3415.23	5.2?15.17	5.?915.22	5.33/5.23
150	5.34/5.24	5.411s. ?9				
100	5.35/5.26	5.41/5.30	5.3515.24	5.23/S.17	S.311S.20	5.35/5.25
so	5.3615.28	5.40/5.31		5.2415.17	5.31/s. ?1	5.3 S15.26
Mean	5.3315.24	5.39/5.28				
Std. dew.	30.026140.033	± 0.031/j 0.033				

The decrease in the regulated pressure with increasing temperature is as was observed in the manufacturer's acceptance tests.

Summary

Dynamic testing of one of each component resulted in unlatching of the latch valve at the maximum random vibration level of 0.5 g^2/Hz (double the prototype flight design requirement). and the pressure regulator would not open following testing. The breadboard cold-gas propulsion test system with the second, unshaken regulator was cycled 60,(X)0 times (prototype functional requirement - minimum of 15,000 cycles): 10,000 at ambient temperature, 15,000 at each of the flight design temperatures of -20°C and 70" C, and 20,000 at ambient temperature. The following problems were encountered (1) the shaken latch valve would not open at -20°C and later failed in the open position; (2) the second, unshaken latch valve exhibited gross leakage at -20°C, probably not fully closing, and (3) the pressure regulator leaked about + 0.02 psi/min. in the lock-up condition at 70°C. Other than an increase in leakage (still within spec) of one thruster valve over the final 20,000 cycles, the performance of the two cold-gas thrusters remained essentially unchanged throughout the 60,000 cycle test series.

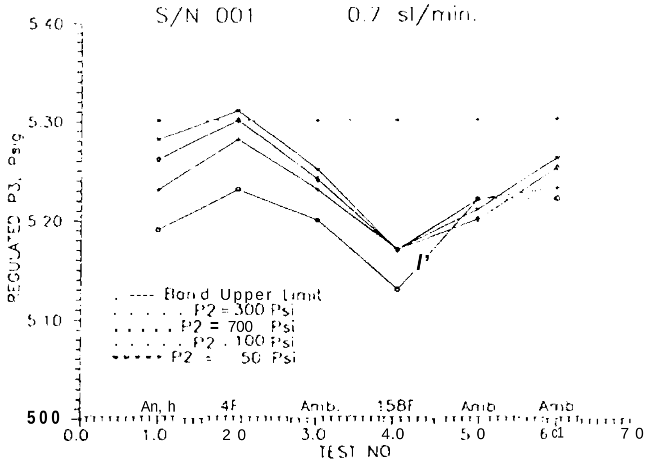

Fig. 13. Regulation Band Test Results

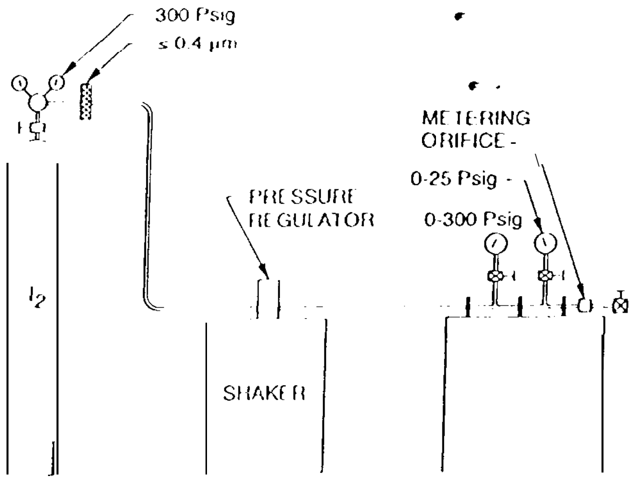

Fig 14. Dynamic Test Set-Up for Modified Pressure Regulator

Diagnosis and Modification

The prototype latch valves and pressure regulators were returned 10 the manufacturer for examination.

Latch Valve

The shaken latch valve was first checked at room temperature. Opening and closing performance was normal and leakage was measured to within specification. The valve was then tested in a thermal chamber. The test consisted of cycling the valve cope and closed data frequency of 1 Hz while lowering the temperature from 29°C (75°F) to -18°C (0°F) and returning to 24°C. The valve operated normally during the temperature descent to about -7" C. At -9° C the valve began to operate erratically, appearing to operate at only one-half its stroke. At -15°C the unit barely closed, and at -18°C it from in the open position, substantiating the JPL cold temperature failure. During ascending temperature, erratic operation resumed at -7°C arrd normal operation at 10"C.

Disassembly of the valve revealed longitudinal wore marks on the inner surface of the valve poppet Vespel sleeve. Measurement of the parts showed them to be within tolerances, but towards the minimum clearance. The sleeve was refurbish by reaming the I.D. to the high side of the diametral tolerance. Following reassembly. the valve was re-tested in a manner similar to the initial failure substantiation test, down to a temperature of -23°C. The valve operated normally throughout the test.

Pressure Regulator

Examination of the shaken regulator revealed that the "ny-lock" thread locking mechanism for the spring adjustment nut had allowed the nut to move slightly, enough 10 prevent the regulator from opening. A positive thread locking mechanism was designed and implemented. Dynamic testing of the modified regulator was repeated at JPL using the test configuration shown schematically in Figure 14. 1 able 17 lists the lock-up and regulated pressure values measured between each shaker test. The approximately 5 % shift in regulated pressure would be acceptable

Conclusions

There appear to be no technical obstacles in miniaturizing passive propulsion components like service valves, with resultant considerable weight savings

The miniaturization of latching type valves increase-s the challenge of balancing the actuating and latching forces to hold the valve armature in the last commanded position, and of maintaining adequate diametral clearance between any sliding parts, under all dynamic and thermal environmental conditions.

A miniaturized prototype pressure regulator demonstrated the ability to meet a narrow regulated pressure band (±5 %) at low outlet pressure, 34.5 kPa (5 psig), and flow, 0.35 SLPM, conditions over a wide range of inlet pressure and conditioning temperature.

1 he small internal displacements in low outlet pressure/flow rate mechanical-type pressure regulators increase their susceptibility to malfunction under dynamic environmental conditions. Slight dislocations of the internal mechanisms will alter their operating performance, i.e., ability to meet the functional requirements. Electronic "bang-bang" type systems should continue to be developed as an alternative pressure regulation, approach.

A robust cold-gas thruster valve-seal design has been developed that demonstrated low leakage, operating repeatability, arrd high operating cycle life.

Acknowledgments

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References

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Table 17. Post-Dynamic Testing Pressure Regulation Test Results, Modified Regulator S/N 002

Functional Requirements:
Lock-up; 7 Psi (max)
Regulated; 5 ± 0.3 Psi at 1.0 sl/min.

Description	P_{inlet} = 300 Psig T = ambient P_{outlet}, Psig Lock-up/Regulated at 1-1/4 sl/min.
Pre-test	5.00/4.75
Y axis sine vibration	5.00 / 4.75
Y axis random vibration	5.00 / 4.75
Z axis sine vibration	5.00 / 4.75
Z axis random vibration	4.90 / 4.55
X axis sine vibration	4.90 4.55
X axis random vibration	4.80 4.55