AIAA 96-3232

Design Enhancement and Improved Post-Actuation Test Method for a 1/4" Normally Closed Pyro Valve

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Abstract

The NASA/JPL Cassini mission to Saturn will launch in October, 1997 and arrive at Saturn in the year 2004 with a 4 year mission to orbit the planet. The main propulsion thrust vector and attitude control for the spacecraft is supplied by the Cassini Propulsion Module Subsystem (C-PMS). This system will use numerous ordnance-actuated, normally-closed (NC) pyro valves to perform mission critical tasks over the 11 year mean mission duration (MMD).

The proper operation of this NC valve requires it to isolate fluid flow until commanded open. Once open, the valve must allow an unobstructed flow path and seal internally to prevent leakage external to the valve. This paper documents a design evolution to a qualified, Viking heritage design with improvements in design details that control external leakage to levels that support the planetary mission of this spacecraft. In addition, it addresses an improved post-actuation leak test technique, used to better detect gas leakage past the valve's primary metal-to-metal internal seal.

Introduction

The C-PMS has unique design requirements based on it's unique MMD (seven year cruise, eleven year total). Specific to this paper are two requirements that limit 1) the total spacecraft GHe external leakage to <1 x 10-3 scc/sec and 2) any single component to <1 x 10^{-6} scc/sec for the MMD. Considering the first NC pyro valve is actuated within days of launch, compliance to these requirements is critical for mission success.

For major burns, such as Trajectory Correction Maneuvers (TCMs) and Saturn Orbital Insertion (sol), a hi-propellant system consisting of Nitrogen Tetroxide (NTO) and Monomethyl-hydrazine (MMH) will be used. A monopropellant hydrazine (N2H4) system is used for attitude control.

Pressurization for the hi-propellant tanks is supplied by a 3,742 psig regulated helium system and attitude control by a separate blowdown hydrazine system with a one-shot 2,553 psig recharge tank. The C-PMS schematic is shown in **Figure 1.**

The C-PMS is a robust design with redundancy added whenever feasible. In April, 1994, a major design change was made to the functional schematic based on findings from the Mars Observer (MO) accident investigation. As a result, a number of additional NC pyro valves were added to prevent propellant vapors from migrating to critical components such as the regulator and high pressure latch valves. The helium pressurization system now uses a total of 25 pyro valves, 15 of them normally closed.

Cassini purchased NC pyro valves that had flown on many missions and therefore were considered to have "heritage".

Discussion

With the addition of each propulsion system component, the potential for external leakage increases. As a risk mitigating step, additional precautions were taken to ensure a leak free helium system. One of these was to test post actuated NC pyro valves for leakage in a manner that is not typically done, is more time consuming and more expensive. This process involves drilling into the housing, beneath the lower ram O-ring, instead of merely removing one of the initiators to test for primary metal-to-metal seal leakage.

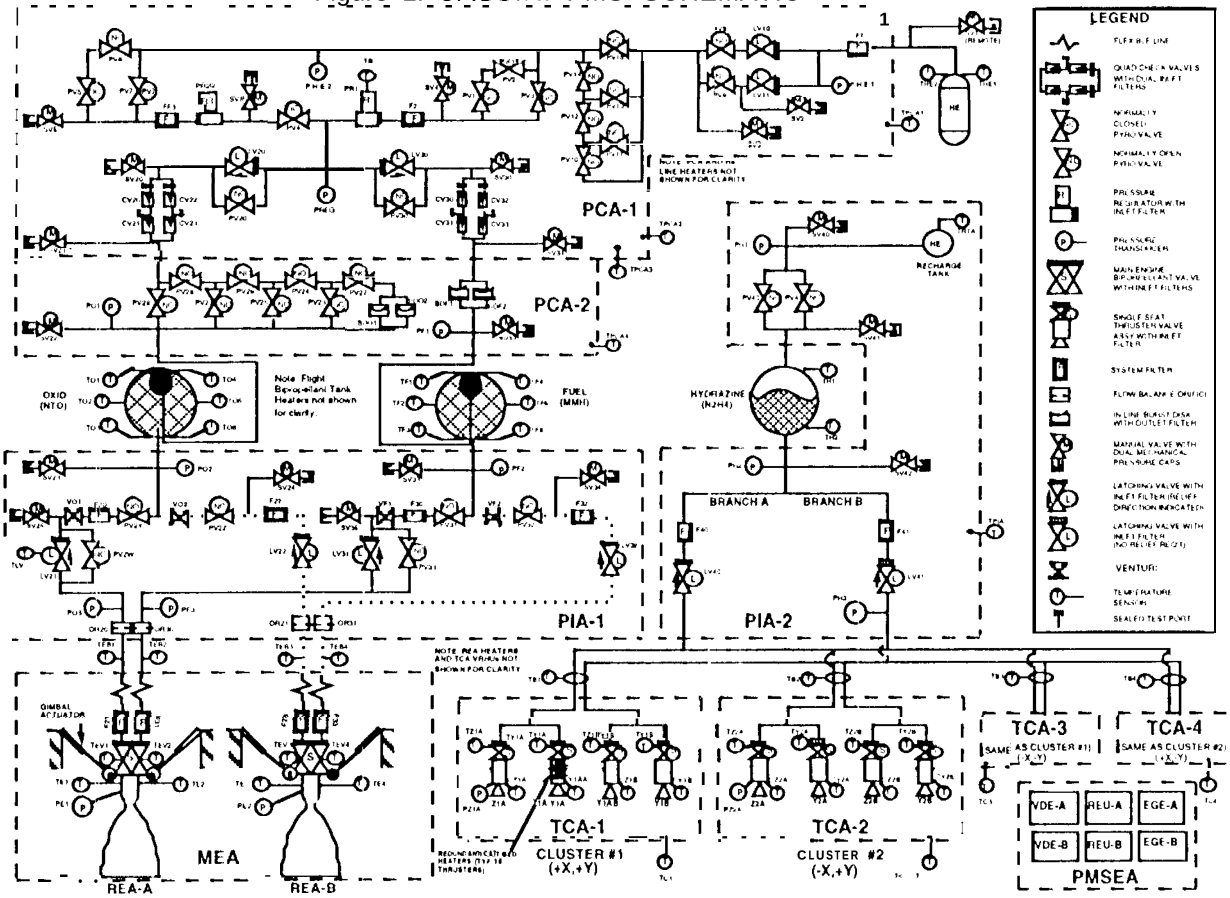
An investigation began after two successive C-PMS valve lots failed Destructive lot Acceptance Test (DLAT) in post-actuation external leakage. Since this valve design is dependent on piece part geometry, material properties and strict control to prevent contamination of the tapered seat, efforts focused on manufacturing or machining errors, inadequate piece part cleaning or inspections, and test set-up methods. Additional tests were performed to determine if the output of the NASA Standard Initiator (NSI), the electroexplosive device (EED) used to actuate the valve, may have produced more pressure (i.e., energy) than past lots.

The results of all testing reported herein are shown in **Table 1.** [Valve test references within this paper will be referred to by test number.]

Failure Investigation

As shown in **Table 1,** two of three of the first DLAT lot failed to meet the 1 x 10-6 scc/sec test

Figure 1: CASSINI PMS SCHEMATIC



criteria. The valve actuated by a single NSI (no.1) met the test requirement, while the two actuated using dual NSI's (no. 2 and 3) failed.

After finding a dimensional nonconformance in the bore of one of the failed valves from the first failed lot, all valves in the build lot were disassembled for further inspection. The subsequent discovery of improper rework by the housing manufacturer resulted in scrapping all housings in that lot.

The first of many valves (no. 4 and 5) actuated during the Failure Analysis (F/A) verified that remachining of the valve housings “to print” was still inadequate to prevent post-actuation leakage. Two more test firings, performed to determine the effects of the improper rework on valve operation, were inconclusive showing an in-tolerance valve (no. 6) to fail and an out-of-tolerance valve (no. 7) to pass the post-actuation leak test. It was determined during the post-actuation testing of valve number 6 that by drilling directly into the lower O-ring (no. 6A), instead of below it (no. 6B), the resulting leak test readings could vary by two orders of magnitude, As a result, future post-actuation radiographic inspections of the fired valves were used to measure the relative location of the lower O-ring to insure the hole was drilled below this seal.

Concurrent with the build of the second flight lot of valves, testing continued to better define the failure mechanism. One additional test firing (no. 8) was planned to determine the effects of a 2.0 msec stagger between initiator actuation (a test parameter based on a worst case output of C-PMS flight electronics). A mechanical failure of an initiator cable prevented this stagger, resulting instead in another successful single NSI actuated valve (no. 8A). Actuation of the second initiator days later (no. 8B) did not change the test results, indicating the effects of staggered initiation were likely secondary to the failure mechanism.

Table 1 PYRO VALVE LEAK TEST SUMMARY

Test No.	Valve lot - Serial No.	NSI (1) Lot Designator	Firing Temp (°c)	Qty Fired	Through-hole Leak Rate (2, 3) (scc/sec)	Notes, Comments and Failure Analysis (F/A) Results
1	1-018	MSK	-20	Single	1.0x10E-7	1st DLAT Firing
2	1-017	MSK	+ 70	Dual	7.2x10E-6	1st DLAT Firing; NSI's fired simultaneously
3	1-002	MSK	+70	Dual	>1 X10E-4	1st DLAT Firing; 2.0 msec stagger between NSI's
4	1-027	MSK	+70	Dual	1.1X10E-7	1st F/A Firing; 2 msec delay; Concave taper region
5	1-005	MSK	+ 70	Dual	**5.0x10E-5**	2nd F/A; 2 msec delay; Nominal taper region
6A	1-020	MSK	+70	Dual	1.4 x10E-7	3rd F/A; 2 msec delay; O-ring masked leak rate
6B	1-020	N/A	+70	N/A	**3.2x10E-5**	X-rayed valve, redrilled hole below O-ring
7	1-026	MSK	+70	Dual	1.6x10E-8	4th F/A; 2 msec delay; Re-machined taper to print
8A	SN22	MSK	+70	Single	0.4x10E-9	5th F/A; tech error - only 1 of 2 NSI's fired
8B	SN22	MSK	+70	Single	0.2x10E-9	Fired 2nd NSI days later; No further ram stroke
9	3-080	MSK	-20	Single	6.8x10E-9	2nd DLAT Series Firing
10	3-060	MSK	+ 70	Dual	**3.3x10E-1**	2nd DLAT; Bubble leak ; 1.2x 10E-8 thru NSI port
11	3-071	MSK	+70	Single	1.0x10E-8	2nd DLAT; Dual init.; bad cable - only 1 NSI fired
12	2-032	MSN	+70	Dual	**3.3x10E-3**	MGS Pre-DLAT; Dual simult.; Bubble leak test
13	2-049	MSN	+70	Dual	9.3x10E-2	MGS Pre-DLAT; Bubble leak test
14	2-039	(See note 4)	-20	Single	7.4x10E-8	6th F/A; Dual simult.; Ballistic press.= 14,500 psig
15	2-040	(See note 4)	+ 70	Dual	**>1x10E-4**	7th F/A; Dual simult.; No gross leak test done
16	1-003	(See note 4)	+ 70	Dual	1.6x10E-7	8th F/A; Dual simult.; Increased taper by 0.085"
17	3-063	120% (5)	-20	Single	1.0x10E-8	9th F/A; Rejected valve using single 120°A initiator
18	3-059	80% (6)	-20	Single	3.8x10E-8	10th F/A; Rejected valve using single 80% initiator
19	Viking	MSK	+70	Dual	1.2x10E-7	11th F/A; Dual simult.; Original Viking valve lot
20	No SN	120% (5)	+70	Dual	5.6x10E-7 (400) 1.2X10E-4(3800)	12th F/A; Dual simult.; Housing with 62Ksi yield 1st leak test done at 400 psig, 2nd at 3,800 psig
21	No SN	MSK	+ 70	Dual	2.4x10E-8 (400) 3.2x10E-8(3800)	13th F/A; Dual simult.; 62Ksi yield + longer taper 1st leak test done at 400 psig, 2nd at 3,800 psig
22	2-052	120% (5)	+70	Dual	5.6x10E-8(3800)	14th F/A; Dual simult.; 35Ksi yield + longer taper
23	4-095	MSK	+70	Dual	2.0x10E-8	Final DLAT (See note 7); Dual simultaneous init.
24	4-096	MSK	-20	Dual	1.0x10E-7	Final DLAT (See note 7)
25	4-092	MSK	+ 70	Single	1.8X10E-7	Final DLAT (See note 7)
26	4-090	MSK	-20	Single	5.0X10E-8	Final DLAT (See note 7)
27	4-105	120% (5)	+70	Dual	1.4x10E-8	Qualification of design modification
28	4-104	120% (5)	-20	Dual	2.0X10E-8	Qualification of new design
29	4-103	80% (6)	-20	Single	4.8x10E-8	Qualification of new design
30	5-139	MSK	+ 70	Dual	1.4x10E-8	Final DLAT (See note 7)
31	5-130	MSK	-20	Dual	2.6x10E-8	Final DLAT (See note 7)
32	5-116	MSK	-20	Single	2.8x10E-8	Final DLAT (See note 7)
33	5-138	MSK	+70	Single	1.2x10E-8	Final DLAT (See note 7)
34	5-125	120% (5)	+70	Dual	5.0x10E-8	Qualification of new design
35	5-134	120% (5)	-20	Single	2.8x10E-8	Qualification of new design
36	5-140	80% (6)	+70	Single	3.2x10E-8	Qualification of new design

NOTES:
1. Unless otherwise noted, initiator is NASA part number SEB26100001-256.
2. Unless otherwise noted, helium leak testing @ 3,800 psig through a hole drilled below the lower O-ring.
3. Test no.s 10, 15, 16 were pressurized to 3,750 psig in alcohol; bubbles collected in graduated cylinder.
4. Did not use NSI; Used "NSI equivalent" (in 10cc closed bomb); Supplier part number 4704100.
5. Did not use NSI; Supplier part number 4704100-10 with output 20% higher than nominal NSI.
7. Did not use NSI; Supplier part number 4704100-3 with output 20% lower than nominal NSI.
8. Test no.s 23 through 36 used higher strength (62 vs. 33.7Ksi) housings with a 0.085" longer taper in housing.

Based on the testing to this point, the valve supplier recommended a design modification to increase the length of the tapered region. Without significant data on this modification, and biased toward product, the supplier was directed to proceed without the design change.

[Unknown at this time was a related post-actuation leak failure of a similar NSI actuated NC valve back in 1987. Five of six DLAT valves, three fired with a single NSI and three by dual simultaneous actuation, failed the test at 3,500 psig test pressure. Three of six still failed to meet the requirement at 250 psig test pressure This failure was attributed to a low material strength and the supplier had proposed the increase in taper length to their customer at that time. Again, the issue of heritage convinced them to retain their design and accept the hardware without modification.]

Following the second lot build, the subsequent DLAT revealed the same pattern of post-actuation leak failures. The valves actuated by a single NSI (no 9 and 11) sealed as required while the one powered by dual initiators (no. 10) failed.

A third lot of valves, built for another NASA/JPL program, was tested (no. 12, 13, 14 and 15) and experienced the same post-actuation leak test failure. Since their housings were made from the same material lot as the second C-PMS valves, the valves were scrapped and a new lot was built concurrently with the C-PMS build.

I-he dramatic leak rate of test unit number 10 lead to the conclusion that the material properties used to fabricate these housings were inadequate to absorb the energy imparted into the ram upon dual NSI actuation. Further investigation revealed an inconsistency on similar housing drawings with respect to the yield strength requirements.

Some housing drawings, including the C-PMS design, specified only ultimate tensile strength requirements while others called out minimum yield strengths from 40Ksi to 65Ksi, depending on the customers demands. It was determined the housings from the first C-PMS build, and the other NASA program lot, were manufactured from a lot of 304L with yield strength of approximately 34Ksi. However, previous successful valve lots used 304L and 321 stainless steel housings with yield strengths ranging from 31 .5Ksi to 64Ksi.

Based on testing to this point, it was concluded that higher material strength alone would not be sufficient to solve the problem. The program and supplier agreed to enhance the design 10 include a combination of higher material strength and longer taper region in the valve housing. A successful test (no. 16) of the proposed increase in taper length alone added confidence in this design approach, although the post-actutation radiograph revealed the ram had travelled through the tapered region, seating at the bottom of stoke.

As the final phase of the F/A, another series of valves were tested to validate the proposed modification. Tests 17 and 18, using the 34Ksi housings, repeated the single initiator actuations. A secondary test (no. 19) was performed using a valve from the original Viking program along with dual simultaneous “MSt<” initiators. The success of this test indicated the NSI’s were secondary to the failure mechanism. Test firing number 20 was successful using a housing with 62Ksi strength. Two more tests (no. 21 and 22) verified the design approach.

A combination DLAT and Qualification program was initiated to validate the flight hardware. All test conditions were proposed, as well as over and under charged initiation to satisfy margin. The successful results of these tests are documented in **Table 1.**

NSI Characterization Testing

The Cassini program will rely on this NC pyro valve to perform mission critical functions. That, coupled with the high rate of post-actuation leakage failures following dual initiator firings, made it necessary to test the NSI’s to determine their output in comparison to previous flight lots of initiators. The NSI’s reserved for use on C-PMS were built in March, 1992 under the lot designator “MSK.

Lockheed Martin, formerly Martin Marietta, developed a Dynamic Test tool (DTt) to measure the relative energy output from the NSI and have data from 5 previous flight lots.(1)

A population of 19 each of the Cassini “MSK” NSI’s were fired in the DTt and results showed an average of 44.5 ft-lbs of energy output with a standard deviation of 3.74 ft-lbs. This is approximately 5 to 14 % higher than previous lot energy outputs shown below in **Table 2.**

Table 2 NSI Lot Energy Outputs

NSI Lot	Energy Output	Std.Dev.	Date of Manufacture
XPA	40.57 ft-lb	1.15 ft-lb	9/84
XPC	42.26 ft-lb	2.73 ft-lb	11/84
XPG	40.12 ft-lb	2.59 ft-lb	3/85
XPJ	40.69 ft-lb	1.73 ft-lb	5/85
XRY	38.22 ft-lb	1.30 ft-lb	10/89
MSK	44.50 ft-lb	3.74 ft-lb	3/94

These data would indicate that the higher output from this lot of NSI's could have contributed to the DLAT post-actuation leak test failures, As mentioned earlier, all of the single NSI actuated valves passed the post-actuation leak test, the "worst" unit leaking at a rate equal to 1.0×10^{-7} scc/sec while pressurized to 3,800 psig. The valves failed to seal when dual NSI's were fired.

It was determined during the F/A that proper operation of the valve is dependent upon, among other things, the yield strength of the housing. One postulated failure mechanism involved a scenario where the dual initiators produced an excessive ballistic pressure for the relatively low material yield strength to absorb, accelerating the ram through the critical tapered region and rendering the metal-to-metal seal ineffective. The rate of failure in the dual initiator mode would indicate this was the case.

In compiling the supplier data from previous NC valve single initiator actuations, it was evident that this lot of NSI's was not producing peak pressures higher than had been recorded since the original Viking valves used the Viking Standard Initiator (VSI). The following table shows examples of average peak ballistic pressures, from a single initiator, recorded during the actuation of NC valves using both the VSI and NSI. The data presented below was taken from supplier ATP data sheets.

Initiator Lot Designator	Quantity of NC Valves	Avg. Peak Ballistic Pressure* in a NC Pyro Valve (psig)
04 (VSI)	10	8,490
06 (VSI)	4	10,155
XPF (NSI)	2	4,370
UBL (NSI)	2	7,690
MBJ (NSI)	2	13,140
MSK (NSI)	**6**	**13,920**
MBW (NSI)	3	14,090
MCB (NSI)	2	14,520

Though not an exhaustive nor even scientifically significant data body of ballistic pressure, it does indicate that NSI lot "MSK", planned for use on the C-PMS, does not seem to produce excessive ballistic pressure. Since none of the initiators shown, with the exception of "MSK", were ever tested in the DTt, no quantifiable conclusion can be reached without further tests.

Viking/Cassini Test Technique

Depending on the application and/or function of a NC pyro valve in any given propulsion system, the test method chosen to determine post-actuation internal leakage can and will vary. Post-actuation external leakage from the pressurized flow tube, past the seated ram into the ballistic cavity, can over time, result in external loss of pressurant, fuel, or both. If this occurs, system degradation or total mission loss is conceivable.

Figure 2 shows the typical pre-actuation state of the C-PMS NC pyro valve design. Since these devices do not lend themselves to be functionally tested before flight, the aerospace industry has adopted the random sampling of these valves, such as is done in a DLAT. One or more valves may be exposed to projected flight environments then actuated in a flight condition. This "Test as you Fly" approach is the only means of determining hardware integrity prior to actual system operation. It is incumbent upon the engineer to determine if the hardware performed in accordance with the design specification.

Typically, in the case of a dual initiated valve, post-actuation external leakage testing is done simply by removing one of the two initiators, pressurizing the flow tube with helium, and "sniffing" to detect and measure helium leaking past the ram. Measurements can be obtained using a hand held gas detecting probe in the hermetic confines of a bell jar, **Figure 3** shows the typical pre-actuation state of the C-PMS NC pyro valve.

The problem with this leak test method is twofold. First, the two ram O-rings, designed to react and contain the NSI ballistic gasses during actuation, are still viable sealing surfaces after the ram has stroked and seated in the tapered portion of the housing. Second, unless the fluid medium has degraded the O-ring material, or permeation occurs, these O-rings could conceivably maintain a seal beyond MMD of the system.

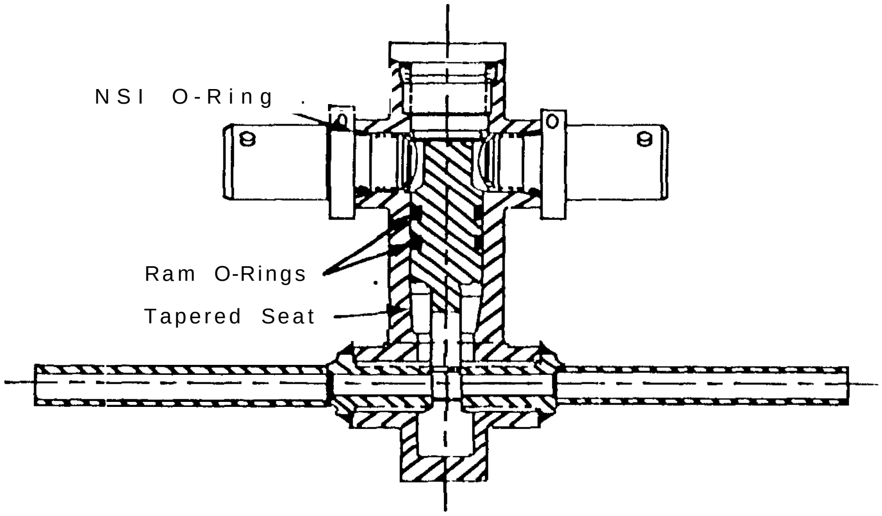


Figure 2 Pre-Actuated Normally Closed Pyro Valve

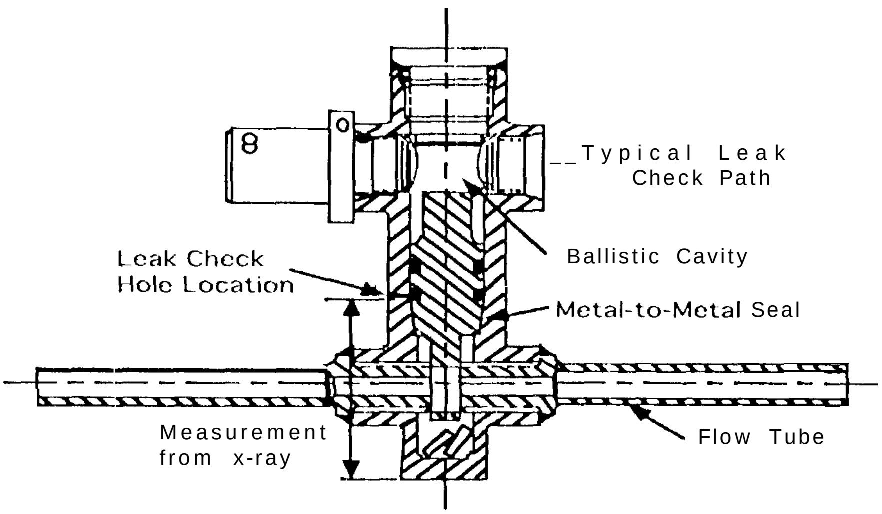


Figure 3 Post-Actuated Normally Closed Pyro Valve

For most short duration (l-3 years), Earth orbiting, low pressure propulsion systems, this test method may be satisfactory. If however, internal leakage is of major concern, as it was for the original Viking Landers and will be for any planetary mission, it is critical that the internal leakage be measured as accurately as possible. The test method described herein is a derivation of that developed during the original Viking pyro valve test program.

This test method requires a number of inspections and accurate measurements prior to measuring leakage. Following actuation, a radiographic inspection of the valve will determine the exact position of the lower O-ring groove of the ram relative to a defined, external reference frame; in this case the bottom of the valve housing.

Once this dimension is known, a small hole (e.g., 0.040" dia) can be precisely drilled into this gland -below the O-ring. The valve is now configured such that, once the flow tube is pressurized, the actual leakage past the metal-to-metal seal can be measured without the dual O-rings impeding or masking the actual leakage rate. Data from test number 5 is an example of how, in one case, drilling into the O-ring instead of below it can distort the actual leak rate. Test number 10 confirmed the difference in leak rates as tested through the initiator port, versus through a properly drilled hole just above the seal, can differ by many orders of magnitude.

In every case a calibrated leak detector was used with the valve pressurized in an evacuated bell jar. The C-PMS nominal test pressure was 3,750 psig, but it was observed that leak rates obtained by any test method are heavily influenced by the flow tube test pressure (no. 20 and 21). It is important to always test using the maximum expected operation pressure (MEOP) of the system. The difference in leak rates between an arbitrary test pressure and system MEOP could be enough to violate system acceptance test criteria.

Conclusions

1) There have been a number of design changes in this NC pyro valve since it was originally qualified for Viking. The extent to which those changes affected the valve's performance is still not fully understood.

2) Contributors to the post-actuation leakage failure experienced on the C-PMS hardware included low housing material yield strength, NSI output and machining errors. Other possible causes include piece part contamination, inadequate cleaning agents (a result of changing EPA standards).

3) 1 he use of a specified material yield strength and 0.080" increase in the length of the housing taper has been qualified.

4) The current lot of NC pyro valves are qualified to meet the C-PMS flight requirements.

Recommendations and Comments

1) Since NSI outputs vary from lot to lot, the designated flight lot should be incorporated into testing the flight hardware.

2) Dual, simultaneous actuation of NSI's in this type of 1/4" NC pyro valve design should be avoided if system constraints do not require such actuation.

3) Design heritage is not always fool-proof. A thorough examination should be made of flight hardware prior to system application.

4) The test methods used to determine the actual leakage past the metal-to-metal seal should be incorporated into the DLAT of future flight hardware where component external leakage is a critical design parameter. The data obtained from those tests should be compared with system parameters to determine system test success criteria.

5) The test methods described in this paper for the 1/4" pyro valve will apply to any size pyro valve of similar design.

Acknowledgments

We greatly appreciate the work and assistance from Mr. Ralph Eberhardt, Mr. Robert Berry, Mr. Albert Hertz, and Mr. Harold Thompson of Lockheed Martin, Mr. Carf Guernsey of JPL and Mr. Dan Frederick and Mr. Prakash Tripathi of OEA Aerospace, Inc.

1 he work described in this paper was carried out by Lockheed Martin Flight Systems and OEA Aerospace, Inc. under the Cassini Propulsion Module Subsystem contract with the Jet Propulsion Laboratory/NASA.

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1. Butterfield, N. J., "Dynamic Output (Energy) Available from the NASA Standard Initiator," Martin Marietta Aerospace Group Technical Note TN-1009-92, October 1992.

2. OEA Aerospace, Inc., "Failure Analysis Report for Cassini Valves", document number 60-1430-34, October 1995.