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Functional Performance of Pyrovalves

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Following several ground test failures and flight failures of spacecraft systems using normally closed pyrotechnically actuated valves, a government/industry cooperative program was initiated to evaluate five flight-qualified designs. The goal of the program was to provide engineering information on functional performance to improve requirements for procurements. This information was to counter the generally held belief that the creation and operation of pyrotechnic devices is an art. Specific objectives included the demonstration of performance test methods, the measurement of blowby (the passage of gasses from the pyrotechnic energy source around the activating piston into the valve's fluid path), and the determination of functional margins for each design. The experimental results led to the following conclusions. 1) The test methods provided precise comparative measurements to document the wide range of functional performance of the valve designs. That is, the performance of each valve design was consistent, but the energies required to function the designs had a range of 50–1. 2) Blowby cannot be prevented by O-ring seals; however, metal-to-metal seals were effective. 3) Two of the five designs exhibited marginal performance because the valves did not fully open with the pyrotechnic cartridges evaluated.

Introduction

A NUMBER of failures have recently occurred in the use of single-shot, normally closed pyrotechnically actuated valves (pyrovalves) in spacecraft hydrazine-powered attitude control systems.[1] These pyrovalves, which were designed to prevent flow of hydrazine until actuation, are opened by electrically firing a pyrotechnic charge; this rapidly burning charge produces hot gases that drive an internal piston to shear off internal fittings to allow hydrazine flow. Two failure modes have occurred: 1) the burning of the valve's titanium housing threads allowed the initiator cartridge to be jettisoned by the valve's internal pressure at a velocity of over 200 m/s (600 ft/s) and 2) the blowby or venting of hot gases and hot particles from the burning pyrotechnic charge around the actuating piston, prior to O-ring seating; these gases/particles entered the fluid path of the valve and initiated a reaction in the hydrazine, which overpressurized and burst the system plumbing. The first failure mode occurred in a ground test in the European Space Agency Cluster Program. The second failure mode, as indicated by Lockheed Martin, was responsible for the loss of the Landsat 6 and Telstar 4. It was also considered by the Jet Propulsion Laboratory to be a possible cause for the loss of the Mars Observer spacecraft. All of these spacecraft employed essentially the same pyrovalve design.

Several questions have been raised from these current and past failures[2] about the design and development of pyrovalves. 1) How can the performance of pyrovalves be measured? 2) How much blowby can be expected in pyrovalve designs? 3) What is the functional margin, or how well do these devices perform?

As described in Ref. 2, the most frequent cause of pyrotechnic failures was the lack of understanding of how to measure performance and how pyrotechnic devices function. The generally held belief is that the creation of these devices is an art. There are no college engineering curricula for this technology. Few guidelines, such as Ref. 3, exist. As an example of typical pyrotechnic problems, the Europeans in the Cluster Program[1] reduced the main pyrotechnic charge, Hercules High Temp (an 80/20 RDX/nitrocellulose mixture), in their pyrovalve by 60%, from 325 to 128 mgs. Was this change justifiable? Was the functional margin affected? The manufacturer of Landsat 6 and National Oceanic and Atmospheric Administration 13 continue to use the full 325-mg charge. The current approach for demonstrating margins is to conduct go/no-go tests while changing the pyrotechnic load by ±15%. If the valve functions (allows fluid flow) with an 85% charge, the implication is that it should work with a 100% charge. Conversely, if the valve does not burst with a 115% charge, it should not burst with a 100% charge. Neither test provides a quantitative measurement of functional or containment margins.

The goal of this program was to provide engineering information on functional performance of these valves to improve requirements for procurements. The specific objectives were 1) to demonstrate improved test methods and logic for the functional evaluation of pyrovalves, 2) to quantify the volume of blowby in five different pyrovalve designs and assess the blowby debris produced, and 3) to quantify the functional margin of these five different pyrovalve designs.

The approach for the test program, conducted at NASA Langley Research Center, was to use the methods and logic in Refs. 3 and 4 to measure performance and to determine functional margins. That is, the energy required to function the valve was compared to the energy delivered by the pyrotechnic charge. Also measured were dynamic forces required to function the valves and pressures produced by the pyrotechnic charges. The measurement of blowby was accomplished by evacuating the internal volume of the valves and measuring the differential pressure produced in functioning the valve. The rise in pressure in a known volume allows a calculation of the amount of gas introduced.

A significant challenge in the test program was to obtain sufficient information from the limited number of units available. Few duplicate tests could be conducted to gain confidence in performance uniformity for the several different types of tests needed.

Pyrovalves Tested

The pyrovalves evaluated in this program were supplied by manufacturers or were available in NASA inventory. Design information was made available on some of the valves. Table 1 is a listing of pyrovalve types and the number available of each. Each valve design will be described, as well as the pyrotechnic energy source used for its functioning.

Pyronetics

A cross-sectional view of this design is shown in Fig. 1. The body is aluminum, 6061-T6. Fluid flow within the valve is prevented by nipples in blind aluminum fittings of the same alloy. The stainless-steel actuating piston has dual O-ring seals. A taper has been machined in the piston, which engages a matching taper in

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the bore of the valve housing on stroking. The hot gas produced on firing the cartridge drives the piston down the bore. The first portion of the piston stroke shears off the nipples on the blind fitting. At approximately 0.48 cm (0.19 in.) of stroke, the tapers engage; the energy in the moving piston is then absorbed by deforming the cylinder wall to stop the stroke of the piston. A through hole in the piston blade that shears the nipples is stroked into alignment with the fluid path in the fittings at a stroke of 0.64 cm (0.4 in.).

Table 1 Pyrovalve types and number available

Manufacturer	Model number	Manufacture date	Test units
Pyronetics	1456	2/74	18
Scot	6008200	8/91	14
Conax	1802011-01	8/61	4
Conax	1832-191-01	6/87	4
Quantic	1201B-02	2/70	6

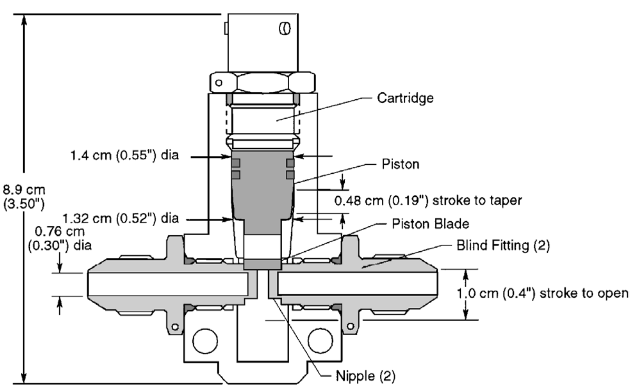

Fig. 1 Cross-sectional view of Pyronetics pyrovalve; body and blind fittings are aluminum.

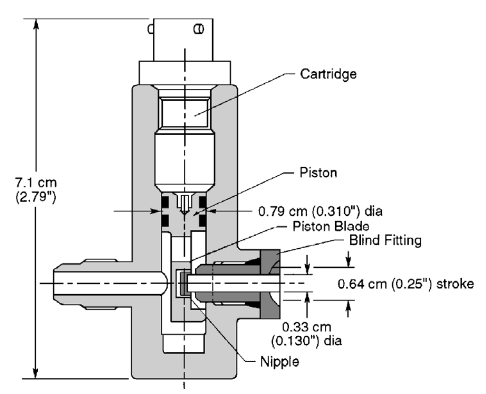

Fig. 2 Cross-sectional view of Scot pyrovalve; body and blind fittings are aluminum.

Because the type or performance of the original flight gas generating cartridge was not available, the NASA Standard Initiator- (NSI-) derived Gas Generating Cartridge (NGGC)[5] was used. This cartridge has at least twice the output of the NSI.

The original assembly procedures for this valve required that no lubrication be used on the O-rings. Any lubrication in this area would migrate onto the tapered interface and reduce the degree of seizing of the piston in the bore. This seizing was believed to be necessary to prevent the valve's fluid pressure from dislodging the piston, allowing a leak path into the cartridge's combustion volume. However, as described in Ref. 4, unlubricated O-rings introduce several functional problems. The dry O-rings produce considerable friction against the cylinder wall, roll on their axes tearing out material, and cause a considerable increase in energy consumed in stroking the piston. These conditions result in questionable efficiency of the O-rings to seal the working pressure from the pyrotechnic cartridge.

This investigation included an evaluation of performance with and without lubrication. The O-rings and tapered interface were fully lubricated, using a nonflight, silicone-based lubricant.

Scot

A cross-sectional view of the Scot valve, qualified for venting air in the Harpoon missile, is shown in Fig. 2. The body is aluminum 2024-T351. Fluid flow within the valve is prevented by a single nipple in the blind aluminum fitting. The stainless-steel actuating piston has dual O-rings. A Harpoon gas generating cartridge was used to power the piston stroke. The Harpoon cartridge contains a charge of titanium hydride/potassium perchlorate. A piston stroke of 0.64 cm (0.25 in.) first shears off the nipple, and then a through hole in the piston blade is stroked into alignment with the fluid path in the fitting to allow fluid flow.

Conax

Two different designs were evaluated, as shown in Fig. 3. Both designs employ a metal-to-metal seal between the stainless-steel actuating piston and the aluminum (2024-T351) housing bore. That is, the 0.64-cm- (0.25-in.-) diam pistons are oversized, relative to the bore; as the piston strokes, the cylinder bore is deformed to maintain a seal against the pressure produced by the energy source. Both designs utilize a primary explosive, diazodinitrophenol, in their activating cartridges. Primary explosives deliver considerably more energy more quickly than the gas-generating materials used in the other pyrovalve designs.

Model 1802011-01 requires the shearing of a diaphragm, machined in the valve body, to allow fluid flow around the actuating shaft of the piston. The piston is designed to stroke 1.22 cm (0.48 in.) to trap the sheared diaphragm at the bottom of the stroke. This cartridge was assembled in 1961; the effects of aging on this material is not known.

Model 1832-191-01 shears off a nipple in a blind stainless-steel fitting to allow fluid flow around the actuating shaft of the piston. The nipple is also trapped at the end of the stroke.

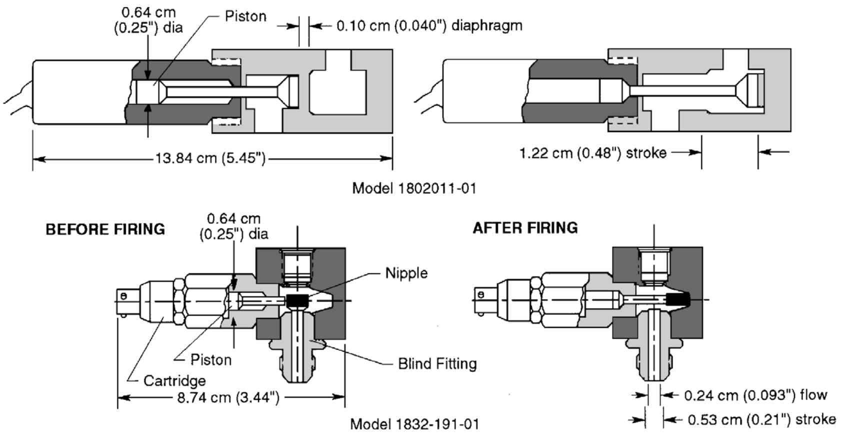

Fig. 3 Cross-sectional view of Conax pyrovalves; bodies and blind fittings are aluminum.

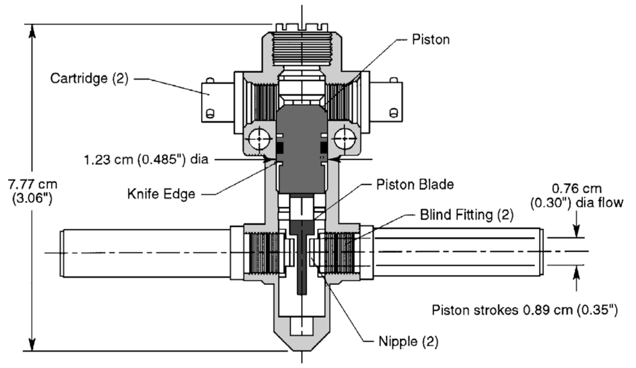

Fig. 4 Cross-sectional view of Quantic pyrovalve; body and blind fittings are stainless steel.

Quantic

The cross-sectional view of the stainless steel Quantic design, qualified for the Apollo program, is shown in Fig. 4. The piston has a single O-ring. Either cartridge provides sufficient energy to open the valve. As the piston strokes through 0.89 cm (0.35 in.), the lower blade assembly shears off nipples on the blind fluid flow fittings; two shoulders on the blade are staggered by 0.065 cm (0.025 in.) so that the nipples are engaged and shear sequentially. A hole through the blade aligns with the holes in the fittings on stroking. At 0.48 cm (0.190 in.) of stroke, a circumferential knife edge on the piston body engages a reduced diameter shoulder in the piston's bore. This knife edge cuts and curls the shoulder material into a cavity in the piston to decelerate the moving mass in a controlled manner. This cutting mechanism, in addition to the lower portion of the piston wedging into the bore, prevents valve fluid pressure from dislodging the piston and allowing a leak path into the cartridge's combustion volume.

This valve was designed to use the Apollo Standard Initiator with a 60-mg booster charge of Hercules High Temp, an 80/20 RDX/nitrocellulose mixture. Because these materials were not available, the NGGC[5] was used.

Procedures

The effort was divided into five areas: weight drop tests, test firings, blowby tests, posttest evaluations, and functional margin determination. The O-rings in the Pyronetics and Quantic valves were replaced with new O-rings for this effort.

Weight Drop Tests

Impacting falling weights on the actuating pistons of each valve provided a highly controlled simulation of the impulsive input of pyrotechnic charges. Total energy input was the drop height multiplied by the weight of the falling mass. The forces required to stroke the pistons during the impact were measured with high-response (80-kHz) piezoelectric load cells. The minimum energy required to accomplish the function was determined by reducing the drop heights until the valve failed to function. Higher input energies were tested by increasing the drop heights to match the cartridge input levels. Weights of 0.453–4.53 kg (1–10 1b) were dropped at heights to over 2.5 m (100 in.). A special series of tests were conducted on the Pyronetics valves to compare the forces in stroking and the amount of stroke with and without lubrication on O-rings and the tapered piston interface.

Test Firings

Functional tests were made in steel mockup valves (without piston capture mechanisms) and flight valves to determine the energy delivered by the pyrotechnic cartridges. Steel mockup valves, which duplicated the internal dimensions of each valve design, were used for repetitive testing. Measurements were made of the working pressure from the cartridges, when possible, without affecting internal volumes and functional performance. For example, a port was installed perpendicular to the thrust axis of the Scot valve to install a flush-mounted pressure transducer. A transducer was installed in the opposite port from the initiator in the Quantic valve. The Pyronetics valve could not accommodate a transducer without affecting the internal free volume, and the output of the Conax valve cartridge, containing a primary explosive, far exceeds the monitoring capability of piezoelectric transducers. The steel pistons from each valve design were used. An O-ring was installed on the Conax pistons to allow an energy measurement without the drag of the metal-to-metal seal. New blind fittings/nipples or diaphragms were installed for each firing in the steel mockup valves; this duplicated the initial resistance of the piston against stroking and ensured that the combustion characteristics of the cartridge propellant were duplicated.

The energy delivered by the pyrotechnic cartridges was calculated from measurements of the velocity of the actuating pistons at the positions of piston stroke completion in the flight valves; kinetic energy is $\frac{1}{2}mv^2$, where m is the mass that moves to accomplish the function. The velocity v for this calculation was the velocity achieved by the moving mass at the position where the valve would have fully opened in the flight configuration. To measure velocity, an electrically grounded probe was mounted in the bore side of the piston. As the probe stroked, six electrically charged aluminum foil switches [spaced at 0.355 cm (0.140 in.)] were sequentially contacted. The electrical discharges at each contact were recorded on a high-speed tape recorder to provide a measurement of the time intervals between contacts. Velocity was determined by dividing the known distance by the time intervals.

Blowby Tests

Blowby volume was measured by evacuating the fluid flow path to 1×10^{-6} torr or less and functioning the valve. A pressure increase within the fluid flow path and the known volume evacuated allowed a measurement of blowby gasses in torr-liters. Dividing this value by 760 (760 torr/atm) and multiplying by 1000 (1000 cm^3/l) yielded cubic centimeters at one atmosphere. The critical sensor to this test was the pressure transducer, Granville–Phillips 275 Convectron gauge, which was able to measure pressure from 0.001 to 1000 torr. One or two blowby tests were conducted on each valve design to measure the quantity and type of gases, as well as to determine the blowby debris produced. The blowby gas was analyzed with a gas mass spectrometer. The blowby debris, which was examined microscopically, was obtained by rapping the valve body with the axes of the flow tubes over a clean dish. The Pyronetics and Quantic designs contained an internal volume of air between the piston and blind fitting nipples that could not be evacuated for the test firing. Once the firing was made and the nipples sheared, this air was drawn into the fluid flow path. This internal volume was calculated and subtracted from the total amount of gas indicated during the firing. New O-rings were installed for the Pyronetics and Quantic valve firings.

Posttest Evaluation

A final assessment of performance was made by examining the postfire condition of the valves. The valves were helium leak checked at 2 atm of pressure. The amount of stroke achieved by the actuating piston and the forces required to push out the seated pistons were compared to the data collected through weight drop tests.

Functional Margin Determinations

Functional margin was determined as follows:

$$\text{functional margin} = \frac{\text{energy delivered} - \text{energy required}}{\text{energy required}}$$

$$\text{or} \quad \frac{\text{excess energy delivered}}{\text{energy required}}$$

where energy delivered is the kinetic energy delivered by the cartridge to the piston and energy required is the energy required to function the valve.

Results

The results of the experimental program are presented here in the same order as presented in the Procedures section.

Weight Drop Tests

Typical force vs time traces for weight drop tests for the two Conax and the Quantic designs are shown in Fig. 5. The minimum energy-required values to function the valves (shear the nipples or diaphragms and stroke to fully open the fluid flow within the valve) are summarized in the functional margin section.

To evaluate the effects of lubrication in the Pyronetics valve, weight drop tests were conducted with and without lubrication under the same conditions. The sliding frictional forces are shown in Fig. 6. The average sliding friction for lubricated O-rings was 71 N (16 lb) and for unlubricated O-rings, 622 N (140 lb). Unlubricated O-rings were badly torn, when the piston was removed from the bore. The evaluation of the effects of lubrication on the tapered interface between the piston and the cylinder bore in Pyronetics valves produced typical force vs time traces shown in Fig. 7. Although different, these traces do not show the effect that lubrication had on the seating of the interface. Figure 8 shows the amount of stroke induced in the lubricated and unlubricated tapered interface with increasing energy input. Figure 9 shows the effect of lubrication on the pushout forces of the piston/cylinder tapered interface. Although all units exhibited no leakage, the lubricated interface exhibited a minimum pushout force of 5250 N (1180 lb) at a 90-J (800-in.-lb) input. This minimum value would provide a seal against 34.5 mPa (5000 psi) internal pressure (pushout force, divided by the piston area).

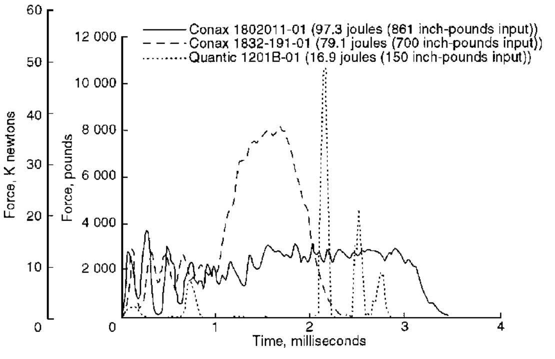

Fig. 5 Force vs time plots for weight drop tests on Conax and Quantic pyrovalves.

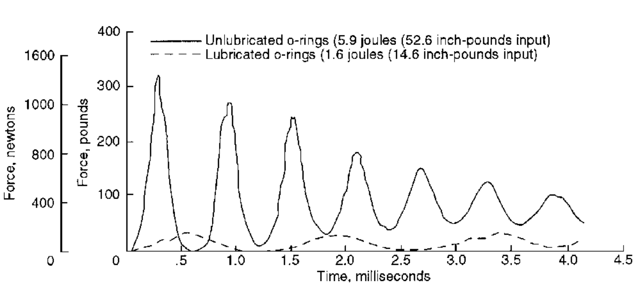

Fig. 6 Force vs time plots for weight drop tests on a steel Pyronetics test valve, unlubricated and lubricated O-rings.

The force/time traces for each of these valve designs (Figs. 5–7) are unique. Each can be interpreted to recognize the forces required to accomplish each function. In Fig. 5, the sliding friction of the metal-to-metal seals in the two Conax designs were very similar, averaging 8900 N (2000 lb) of force for the entire stroke. Figure 6 shows a dramatic difference between lubricated and unlubricated sliding friction in the Pyronetics valve. In Fig. 7, the first force spikes occurred as the nipples in the Pyronetics valve were sheared, and the following loads occurred as the tapered piston engaged the tapered bore. Significantly higher forces occurred in the unlubricated condition; the lubricated interfaces slid more easily as the energy from the moving piston was transferred to expanding the aluminum bore of the valve body; the unlubricated surfaces caused energy absorption in tearing the metal in the bore, rather than as much expansion of the bore. The amount of stroke that occurred in the Pyronetics valve (Fig. 8) indicates that with the unlubricated piston no amount of input energy could fully open the valve.

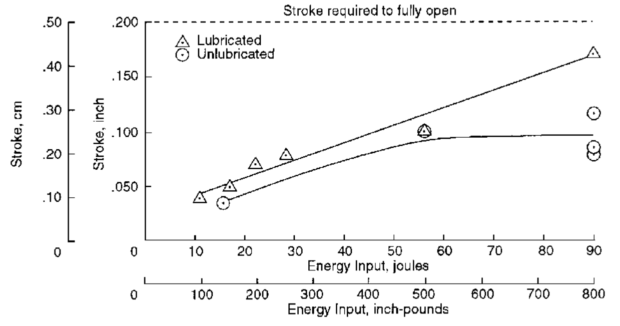

Fig. 8 Stroke in tapered interface of Pyronetics pyrovalve vs energy input with and without lubrication.

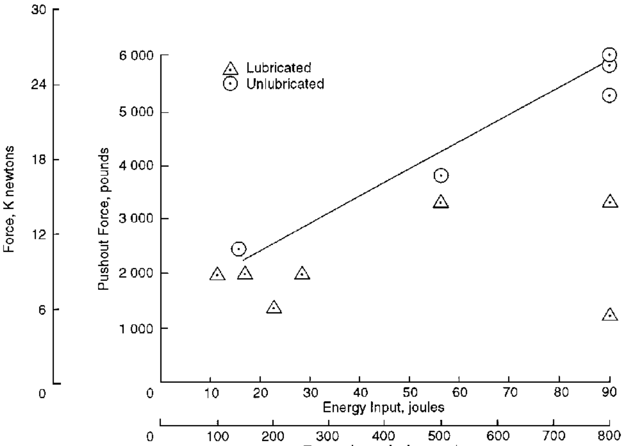

Fig. 9 Pushout forces of tapered interface in Pyronetics pyrovalve vs energy input with and without lubrication.

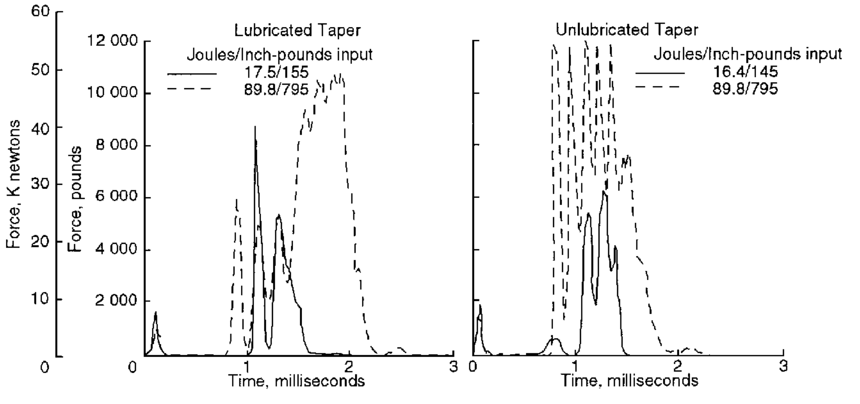

Fig. 7 Force vs time plots for weight drop tests on Pyronetics pyrovalves, lubricated and unlubricated tapered interfaces; no O-rings were used.

Table 2 Blowby volume measurements

Valve/model	Cartridge	Total gas volume, cm^3, 1 atm	Calculated internal volume, cm^3	Blowby volume, cm^3, 1 atm
Pyronetics/1456	NGGC	1.50, 1.48	1.00	0.50, 0.48
Scot/6008200	NSI[a]	0.37	0.08	0.29
	NGGC[a]	1.26	0.08	1.18
	Harpoon[a]	0.75, 1.01	0.08	0.67, 0.93
	Harpoon	0.18	0	0.18
Conax/1802011-01		0, unknown[b]	0	0, unknown
Conax/1832-191-01		0	0	0
Quantic/1201B-01	NGGC	6.13, 3.53	2.18	3.95, 1.35

[a]One fitting evacuated. [b]Fitting leaked.

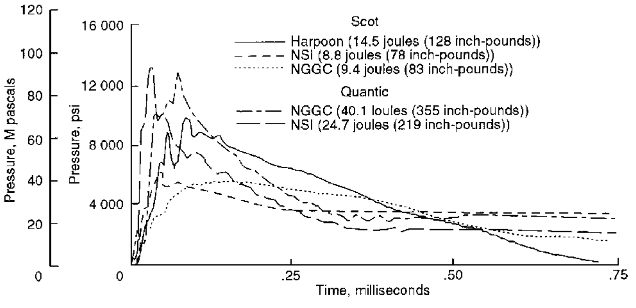

Fig. 10 Typical pressure traces recorded in the Scot and Quantic steel pyrovalves, using the cartridges shown; energy values shown are excess to that required to function the valve.

Test Firings

The energy delivered values for each valve design are summarized in the Functional Margin section.

The pressure traces obtained in firing steel test valves are shown in Fig. 10: three different cartridge types in the Scot valve and two cartridges in the Quantic valve. These pressure traces are unique to the pyrotechnic materials and the configurations in which they are fired. Combustion characteristics[3] and energy delivery are affected by the pyrotechnic materials, the size and shape of the combustion volume, and the housing material. The size of the volume consumes energy in pressurization (volume multiplied by pressure yields units of energy). The area and material in contact with the extremely hot (over 6000°C) burning gases act as heat sinks, reducing the temperature and pressure of the hot gases, which in turn affect burn rate. As the amplitude and duration of the pressure pulses created in the valves increase, the energy delivered increases. When the pressure drops to zero, the piston has cleared the bore of the valve. When the pressure remains constant, the piston has stopped against the blind fitting(s).

Blowby

Table 2 summarizes the blowby volumes measured. The plumbing was configured, except where indicated, to evacuate both the inlet and outlet ports of the valves into a common manifold. Total gas volume was the value in cubic centimeters at 1 atm, measured from the firings; subtracting the calculated internal volume from this value provides the blowby volumes.

For the quantities of blowby shown, one of the Conax 1802011-01 and the Scot (second Harpoon firing) valves produced an indication of a carbon dioxide combustion product. Gaseous combustion products, such as carbon monoxide and carbon dioxide, require organic fuels. No permanent gases are produced by gas generating materials that contain metal fuels with metal-oxide oxidizers. For example, the gas generating material in the NSI, zirconium fuel and potassium perchlorate oxidizer, yield a primary combustion product of zirconium oxide. This material can only be a gas during a vapor phase, when it is extremely hot (about 6000°C) during the combustion. This hot gas quickly cools and condenses on the walls of the vacuum system plumbing. The firing of the Conax 1802011-01 valve that experienced blowby achieved a piston stroke that was much greater than the first firing, 1.1 vs 0.61 cm (0.43 vs 0.24 in.) of the 1.22 cm (0.48 in.) total required. However, a leak in the plumbing to the valve opened after the firing and a quantitative measurement of blowby volume could not be obtained.

Table 3 Pushout forces, newton/pound

	Test firing	Weight drop test
Pyronetics	9,430/2,120	8,700/1,955
Scot	8,500/1,911	578/130
Conax 180201-01	——	5,120/1,150
1832-191-01	10,450/2,350	——
Quantic	21,280/4,785	9,880/2,220

All of the valve designs introduced some debris in the valve fluid flow path. Shavings were created in shearing the nipples and diaphragms, and in all but the Conax valves, pieces of combustion residue products were observed. The largest amount of debris was observed in the Scot valve, following firings with the large-output Harpoon cartridge; shavings up to 0.25 cm (0.1 in.) in length and residue particles to 0.025 cm (0.01 in.) occurred. The Conax diaphragm valves had shavings to 0.025 cm (0.010 in.). The Quantic valve had shavings to 0.05 cm (0.02 in.) and residue particles to 0.013 cm (0.005 in.).

Posttest Evaluation

The averaged results of pushout tests on each of the pyrovalve pistons after valve firings, compared to the retention observed in the weight drop test evaluation, are shown in Table 3.

These values indicate that the pistons would be retained against millions of pascals (thousands of pounds per square inch) internal pressures within the valve. For example, the Pyronetics valve with a piston area of 1.52 cm^2 (0.236 $in.^2$) can withstand an internal pressure of 62 MPa (9000 psi). Although pushout measurements were not made on the Conax 1802011-01 after firing and the 1832-191-01 after the weight drop test, the similarity in sliding friction would imply roughly equal results. The resistance to pushout in actual firings was always superior compared to the weight drop tests.

Functional Margin

The functional margins for each valve design are shown in Table 4. A considerable disparity exists between the performances measured in the steel mockup and aluminum Pyronetics valves with identical cartridges. This can be explained by recognizing that two completely different measuring techniques were employed. The steel unit measured the velocity of the moving mass as it passes the distance needed to complete the stroke to open the valve. Furthermore, the steel unit allowed the piston to stroke farther (well beyond the stroke needed for full actuation) than is possible in the aluminum unit. Consequently, the combustion characteristics achieved are considerably different; although aluminum absorbs more heat than does steel to reduce burn rate, the pyrotechnic materials from the cartridge burn much more rapidly and completely to deliver more energy in the smaller volume presented by the aluminum valve. The energy imparted into the piston beyond stroke completion in the steel valve is wasted. Both measurements indicate a negative functional margin. That is, the NGGC has insufficient energy to fully open the Pyronetics valve design.

The Scot valve with the Harpoon cartridge has a very large functional margin. As observed in the Pyronetics valve, the energy

Table 4 Functional margin analysis (energy in joules/inch-pounds)

Manufacturer	Model	Energy delivered	Energy required	Functional margin
Pyronetics (performance in steel mockup)	1456	25/218 (NGGC)	106/940	−0.77
Pyronetics (performance in aluminum valve)	1456	78/690 (NGGC)	106/940	−0.27
Scot	6008200	11.1/98 (NSI)	2.26/20	3.90
		11.6/103 (NGGC)	2.26/20	4.15
		16.6/147 (Harpoon)	2.26/20	6.35
Conax	1802011-01	77.7/688	117/1035	−0.34
Conax	1832-191-01	251/2220	67/594	2.73
Quantic	1201B-01	57/505 (NGGC)	17/1502.36	
		42/376 (NSI)	17/150	1.50

measured in the Scot steel mockup should be less than would be delivered in the aluminum valve. The piston in the aluminum valve bottoms shortly after fully opening to allow for more rapid and complete combustion of the cartridge propellant. An adequate margin was provided by the NSI.

One of the Conax model 1802011-11 valves also had a negative margin; the piston stroked only 0.61 cm (0.24 in.) of the required 1.22 cm (0.48 in.). This corroborates the marginal performance predicted in the steel valve firing. Because primary explosives detonate rather than burn, the energy delivered is less affected by the amount of piston stroke and heat sinks than is propellant. Although not a part of this study, the output of the cartridge could have been affected by its age of 35 years. The second Conax valve (model 1832-191) and the Quantic valve with the NGGC performed with good functional margins.

Conclusions

In response to a number of spacecraft failures that occurred when single-shot, normally closed, pyrotechnically actuated valves (pyrovalves) were functioned, a government/industry cooperative investigation was conducted. An experimental evaluation of five different models of pyrovalves provided test methods, logic, and performance information to allow for design and development on an engineering basis, rather than to use the perception that it is an art. The specific objectives met for each pyrovalve model were 1) measurements of the energy and force required for actuation, as well as the energy delivered by the respective pyrotechnic cartridge(s); 2) the amount of blowby (hot gasses from the pyrotechnic cartridges escaping around piston-to-cylinder interfaces on actuation); and 3) functional performance margins.

These five pyrovalve designs provided an excellent challenge to performance measurements, due to their wide range of performance. One valve design operated with as little as 2.26-J (20-in.-lb) input energy, whereas another required 117 J (1035 in.-lb). The dynamic force measurements recorded during valve functioning allowed for interpretation of mechanical events and energy consumption. For example, it was found that lubrication was needed on piston O-rings and on interface seals in the Pyronetics valve (contradictory to original assembly requirements) to achieve consistent performance and to allow the valve to fully open. The energy and pressure produced by the various cartridges in their respective valve designs provided for an improved understanding of how energy is transferred from the burning gases to the pistons. For example, a rapid pressure rise delivers more energy to these small-mass, short-stroke pistons. Although the use of steel, rather than aluminum, in valve test bodies contradicts the importance of testing only the flight configuration, it was found that for these tests the energy measured in the steel test bodies was conservative (less than that produced in aluminum).

Functional tests revealed that blowby cannot be prevented by single or dual O-rings in pyrotechnically actuated piston/cylinder configurations. That is, some amount of hot gasses and particles will pass around O-rings before seating is achieved against cylinder walls. However, the most recent metal-to-metal seal employed by Conax completely prevented blowby under conditions that were more severe than those occurring in the other valve designs. That is, the pyrotechnic charge used by Conax, a primary explosive, produces a much faster pressure rise and much higher pressure levels than do the gas generating charges employed in the other valve designs.

Functional margin was obtained by dividing the energy delivered by the pyrotechnic cartridge that was in excess to that required to function the valve by the energy required to function the valve. Functional margins varied from some valve designs being overpowered to others not having the ability to fully open. The Scot design was considerably overpowered with a margin of 6.4, using the cartridge required by a customer. In fact, an ample margin of 3.9 could be provided by the NSI, while reducing the pyrotechnically induced stresses due to excess pressure and heat in the valve. The Conax model 1832-191-01 valve exhibited a margin of 2.7, in spite of requiring a large energy value to stroke against the metal-to-metal seal. The Quantic valve had a good margin of 2.4 in using the NGGC, but the NSI produced a margin of only 1.5. The Pyronetics valve, even with lubrication, would require a higher performance cartridge than the NGGC to fully open. The cartridge used in the old Conax model 1802011-01 valve also could not fully stroke as intended. A postfunctional evaluation of the valves, including helium leak tests and piston pushout tests, provided additional corroboration of successful performance.

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