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FUNCTIONAL PERFORMANCE OF PYROVALVES

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Memorandums of Agreement with

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ABSTRACT

Following several flight and ground test failures of spacecraft systems using single-shot, "normally closed" pyrotechnically actuated valves (pyrovalves), a Government/Industry cooperative program was initiated to assess the functional performance of five qualified designs. The goal of the program was to improve performance-based requirements for the procurement of pyrovalves. 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 quantification of functional margins for each design. Experiments were conducted in-house at NASA on several units each of the five valve designs. The test methods used for this program measured the forces and energies required to actuate the valves, as well as the energies and the pressures (where possible) delivered by the pyrotechnic sources. Functional performance ranged widely among the designs. Blowby cannot be prevented by o-ring seals; metal-to-metal seals were effective. Functional margin was determined by dividing the energy delivered by the pyrotechnic sources in excess to that required to accomplish the function by the energy required for that function. All but two designs had adequate functional margins 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. 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 gases that drive an internal piston to shear off internal fittings to allow hydrazine flow. Two failure modes have occurred: (1) The combustion of the valve's titanium housing, causing the threads that retained the initiator cartridge to fail and the cartridge to be jettisoned by the valve's internal pressure at a velocity of over 600 feet/second, 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 hydrazine, and initiated a reaction, 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 was responsible for the loss of the Lockheed Martin Landsat 6 and NOAA 13, and is considered a possible cause for the Mars Observer spacecraft. All of these spacecraft employed essentially the same pyrovalve design.

Several questions have been raised about the design and development of pyrovalves: (1) What is the functional margin, or how well do these devices work, (2) how was the pyrotechnic charge "sized," and (3) how much "blowby" can be expected in pyrovalve designs. The Europeans reduced their main pyrotechnic charge, Hercules High Temp, by 60%, from 325 to 128 milligrams. Was this change justifiable? Was the functional margin affected? The manufacturer of Landsat 6 and NOAA 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 works (opens the flow) with an 85% charge, the implication is that it should work with a 100% charge. Conversely, if the valve doesn't burst with a 115% charge, it shouldn't burst with a 100% charge. Neither test provides a quantitative measurement of functional or containment margins.

The goal of the effort described in this paper was to improve performance-based requirements for the procurement of pyrovalves.

The objectives were:

1. Demonstrate improved test methods and logic for the functional evaluation of pyrovalves.
2. Quantify the blowby in 5 different pyrovalve designs.
3. Quantify the functional margin of these 5 different pyrovalve designs.

The approach for the test program, conducted in-house at NASA-LaRC, was to use the methods and logic in reference 1 to measure performance and to determine functional margins. The measurement of blowby required additional test methods.

The biggest challenge in the test program was to maximize the amount of data collected; only two valve types had sufficient units for an adequate evaluation. Some of the valve types had only four units.

PYROVALVES TESTED

The pyrovalves evaluated in this program were supplied by manufacturers (Scot and Conax) or were available in NASA inventory. Scot, Conax and Quantic provided design information. The following is a listing of pyrovalve types and the number available of each:

Manufacturer	Model Number	Manuf. Date	Test Units
Pyronetics	1456	2/74	18
Scot	6008200	8/91	14
Conax	1802011-01	8/61	4
Conax	1832-191	6/87	4
Quantic	1201B-02	2/70	6

Each valve design will be described, as well as the energy source used for its functioning.

Pyronetics - A cross sectional view of this design is shown in figure 1. The body is aluminum, 6061-T6. Fluid flow within the valve is prevented by blind nipples in aluminum fittings of the same alloy. The 0.55-inch diameter stainless steel actuating piston has dual o-ring seals. A taper has been machined in the piston, which engages a matching taper in the bore of the valve housing on stroking. A gas generating cartridge, the NASA Standard Initiator (NSI)-derived Gas Generating Cartridge (NGGC), reference 2, which has at least twice the output of the NSI, was used to power the piston stroke. A "Y" fitting with the NGGC in each leg of the "Y" for redundancy and a booster charge was also evaluated; this "Y" fitting introduced considerably more free volume in which the pyrotechnic charges burned to generate gas. The first portion of the stroke shears off the blind nipples. At approximately 0.19 inch of stroke, the tapers engage; the energy in the moving piston is then absorbed by deforming the cylinder wall. 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 0.4 inch.

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 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 reference 1, 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. With these handicaps, the efficiency of the o-rings to seal the working pressure from the pyrotechnic cartridge becomes questionable.

This investigation included an evaluation of performance with and without lubrication.

Scot - A cross sectional view of the Scot valve, qualified for venting air in the Harpoon missile, is shown in figure 2. The body is aluminum 2024-T351. Fluid flow within the valve is stopped by a single blind nipple in the aluminum fitting. The 0.31-inch diameter stainless steel actuating piston has dual o-rings. A Harpoon gas generating cartridge was used to power the piston stroke. The Harpoon cartridge contains about twice the same charge as the NSI ($Zr/KClO_4$). A piston stroke of 0.25 inch first shears off the nipple, then a through-hole in the piston blade is stroked into alignment with the fluid path in the fitting.

Conax - Two different designs were evaluated, as shown in figure 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 0.25-inch diameter 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 0.48 inch to trap the sheared diaphragm at the bottom of the stroke.

Model 1832-191 shears off a blind nipple in a stainless steel fitting to allow fluid flow around the actuating shaft of the piston.

Quantic - The cross sectional view of the stainless steel Quantic design, qualified for the Apollo program, is shown in figure 4. The 0.490-inch diameter piston has a single o-ring. Either cartridge provides sufficient energy to open the valve. As the piston strokes through 0.35 inch, the lower blade assembly shears off blind nipples on the fluid flow fittings; the two shoulders on the blade are staggered by 0.025 inch, so that the nipples shear sequentially. A hole through the blade aligns with the holes in the fittings on stroking. At 0.190 inch 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 (ASI) with a 60 mg booster charge of Hercules High Temp, an 80/20 RDX/nitrocellulose mixture. Since this charge was not available, the NGGC, reference 2, was used.

PROCEDURES

The effort was divided into four areas: Weight drop tests, test firings, blowby tests 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 weights on the actuating piston simulated the impulsive input of pyrotechnic charges. 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. Maximum possible input energies were determined by increasing the drop heights. One to ten-pound weights were dropped at heights to over 100 inches.

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. Pressure measurements were made, when possible, within the working volume. New nipples or diaphragms were installed for each firing in the steel mockup valves. The energy delivered by the pyrotechnic cartridges was calculated from measurements of the velocity of the actuating pistons at the completion of piston stroke; energy is $1/2 \, mv^2$. An effort was made to "size" a booster charge to assure sufficient energy delivery in a "Y" fitting in the Pyronetic valve. A final assessment of performance was made by examining the post-fire condition of the valves. That is, 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.

Blowby tests - Blowby was measured by evacuating the fluid flow path 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/atmosphere) and multiplying by 1,000 (1,000 cc/liter) yielded cubic centimeters in 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 determining 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. Two of these designs (Pyronetics and Quantic) contained an internal volume of air between the piston and fitting nipples that could not be evacuated for the test firing. Once the firing was made, this air was drawn into the fluid flow path. This volume was estimated and subtracted from the total amount of gas indicated during the firing.

Functional margin determinations - Functional margin was determined by dividing the cartridge-delivered energy in excess to that required to accomplish the function by the energy required to accomplish the function:

$$\text{Functional Margin} = \frac{\text{Excess Energy Delivered}}{\text{Energy Required to Function}}$$

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 versus time traces for weight drop tests for the two Conax and the Quantic designs are shown in figure 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 below.

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 figure 6. The average sliding friction for lubricated o-rings was 16 pounds and or unlubricated o-rings, 140 pounds. 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 pyrovalves produced typical force versus time traces shown in figure 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 of 1,180 pounds at an 800 inch-pound input. This minimum value would provide a seal against 5,000 psi internal pressure (1,180 divided by the piston area of 0.236 square inch).

Test Firings - The "energy deliverable" values for each valve design are summarized in the functional margin section.

A number of pressure traces were obtained in firing certain valves that permitted measurements without affecting functional performance. Typical pressure traces recorded in several firings to establish a booster size in the Pyronetics valve with a "Y" adaptor are shown in figure 10. Figure 11 shows traces recorded for three different cartridge types in the Scot valve. Figure 12 shows pressure traces in the Quantic valve.

Blowby - The following table summarizes the blowby measured. The plumbing was configured, except where indicated, to evacuate both the inlet and outlet ports of the valves into a common manifold. Volumes are given in cubic centimeters at one atmosphere pressure.

Valve/Model	Cartridge	Total gas Volume	Est. free Volume	Blowby
Pyronetics/1456	NGGC	1.50, 1.48	1.00	0.50, 0.48
Scot/6008200	*NSI	0.37	0.08	0.29
	*NGGC	1.26	0.08	1.18
	*Harpoon	0.75, 1.01	0.08	0.67, 0.93
	Harpoon		0	0.18
Conax/1802011-01		0, **unknown	0	0, unknown
Conax/1832-191-01		0	0	0
Quantic/1201B-01	NGGC	6.13, 3.53	2.18	3.95, 1.35

* One fitting evacuated
** Fitting leaked, CO_2 detected

For the quantities of blowby shown, the Conax 1802011-01 and the Scot (second Harpoon firing) valves produced an indication of 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 primary gas generating material in the NSI and Harpoon cartridges, 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 6,000^{o}F) during the combustion. This hot gas quickly cools and condenses on the walls of the vacuum system plumbing, which prevents detection by the gas mass spectrometer. Some amount of blowby occurred in the second firing of the Conax 1802011-01 valve, because carbon dioxide was detected. This firing achieved a piston stroke that was much greater than the first firing (0.43 versus 0.24 of 0.48-inch total required). However, a leak in the plumbing to the valve opened after the firing and a quantitative measurement of blowby value could not be obtained.

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 residue were observed. The largest amount of debris was observed in the Scot valve, following firings with the large-output Harpoon cartridge; shavings up to 0.1 inch in length and residue to 0.01 inch occurred. The Conax diaphragm valves had shavings to 0.010 inch. The Quantic valve had shavings to 0.02 inch and residue to 0.005 inch.

Functional margin - The functional margins for each valve design are:

Manuf.	Model	Excess Energy	Energy Required	Functional Margin
Pyronetics	1456	1,192 (NGGC)	940	1.3
Pyronetics (performance in aluminum valve)	1456	650 (NGGC)	940	- 0.3
Scot	6008200	78 (NSI)	20	3.9
		83 (NGGC)	20	4.2
		127 (Harpoon)	20	6.4
Conax	1802011-01	552	1,035	- 0.5
Conax	1832-191-01	2,120	594	3.6
Quantic	1201B-01	355 (NGGC)	150	2.4
		226 (NSI)	150	1.5

A negative margin of 0.3 (0.7 of the energy required to fully open the valve) was observed in the Pyronetics valve in the blowby tests. That is, the stroke of the piston in the tapered interface (figure 8) was much less than would have been predicted by the firings in the steel test valve. The blowby firing produced a stroke of 0.144 inch (650 inch-pounds), while the firing in the steel valve indicated an energy value of 1,190 inch-pounds should have been produced (0.200 inch stroke). The Scot valve with the Harpoon cartridge has a very large functional margin; an adequate margin was provided by the NSI. The Conax model 1802011-11 valve also had a negative margin; the piston stroked only 0.24 of the required 0.48 inch. This corroborates the marginal performance predicted in the steel valve firing. The second Conax valve and the Quantic valve with the NGGC performed without incident.

The averaged results of pushout tests (in pounds-force) on each of the pyrovalve pistons after valve firings, compared to the retention observed in the weight drop test evaluation, are shown below:

	Test Firing	Weight Drop Test
Pyronetics	2120	1955
Scot	1911	130
Conax 180201-01	--	1150
1832-191-01	2350	--
Quantic	4785	2220

These values indicate that the pistons would be retained against thousands of psi internal pressures within the valve. For example, the Pyronetics valve with a piston area of 0.236 square inch can withstand an internal pressure of 9,000 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.

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. Five different pyrovalve designs were obtained from Industry and NASA inventories for experimental evaluation in-house at NASA. The goal of this effort was to improve performance-based procurement requirements for pyrovalves to avoid the failures encountered. Specific objectives were to provide test methods and logic to evaluate performance, measure the "blowby" of hot gasses from the pyrotechnic energy source around the actuating pistons of the five pyrovalve designs, and to quantify functional margins.

These five pyrovalve designs provided an excellent challenge to performance measurements, due to their wide range of performance. The test methods developed and applied in this program met this challenge by providing performance measurements on all aspects of valve performance. Weight drop tests, simulating the dynamics of pyrotechnic inputs, while measuring functional loads, indicated as little as 20 inch-pounds is required to function the Scot valve to over 1,000 inch-pounds for a Conax valve. For the Pyronetics valve, it was found that, contradictory to original assembly requirements, lubrication on piston o-rings and an interface seal produced consistent, acceptable performance. The energies delivered by the pyrotechnic cartridges in test firings in the valves were determined by measuring the velocities of the actuating pistons. Also demonstrated was the ability to tailor energy delivery through the use of booster charges.

The blowby tests revealed that single or dual o-rings in piston/cylinder configurations cannot prevent blowby. Some amount of hot gasses and particles will pass around o-rings before seating is achieved against cylinder walls. However, the metal-to-metal seal employed by Conax completely prevented blowby under conditions that were more severe than the o-ring-sealed 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 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 being inadequate. 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 NASA Standard Initiator (NSI), while reducing the pyrotechnically induced burst stress on the valve. The Conax model 1832-191-01 valve exhibited an adequate margin of 3.6, in spite of requiring a large energy value to stroke against the metal-to-metal seal. The 25 year old Quantic valve had a good margin of 2.4 in using the NSI-derived Gas Generating Cartridge (NGGC), but the NSI produced a margin of only 1.5. The 22 year old Pyronetics valve was marginal (1.3) with the NSI-derived Gas Generating Cartridge (NGGC); a firing in the aluminum flight valve indicated a negative functional margin of 0.3, half the energy measured in the steel test unit. That is, this energy level would have opened the valve, but would not have been sufficient to stroke the piston sufficiently to align an internal port to allow unrestricted fluid flow. This reduction in performance can be attributed to the additional heat loss to the aluminum. The 35 year old Conax model 1802011-01 valve also was inadequate with a negative margin of 0.5; this valve opened, but did not fully stroke as designed.

Based on the results of this investigation, sufficient test information and analyses have been provided to justify the modification of pyrovalve procurements to require quantification of performance and functional margins.

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2. Bement, Laurence J.; Schimmel, Morry L.; Karp, Harold and Magenot, Michael C.: Development and Demonstration of an NSI-Derived Gas Generating Cartridge (NGGC). Presented at the 1994 NASA Pyrotechnic Systems Workshop, Albuquerque, New Mexico, February 8 and 9, 1994.

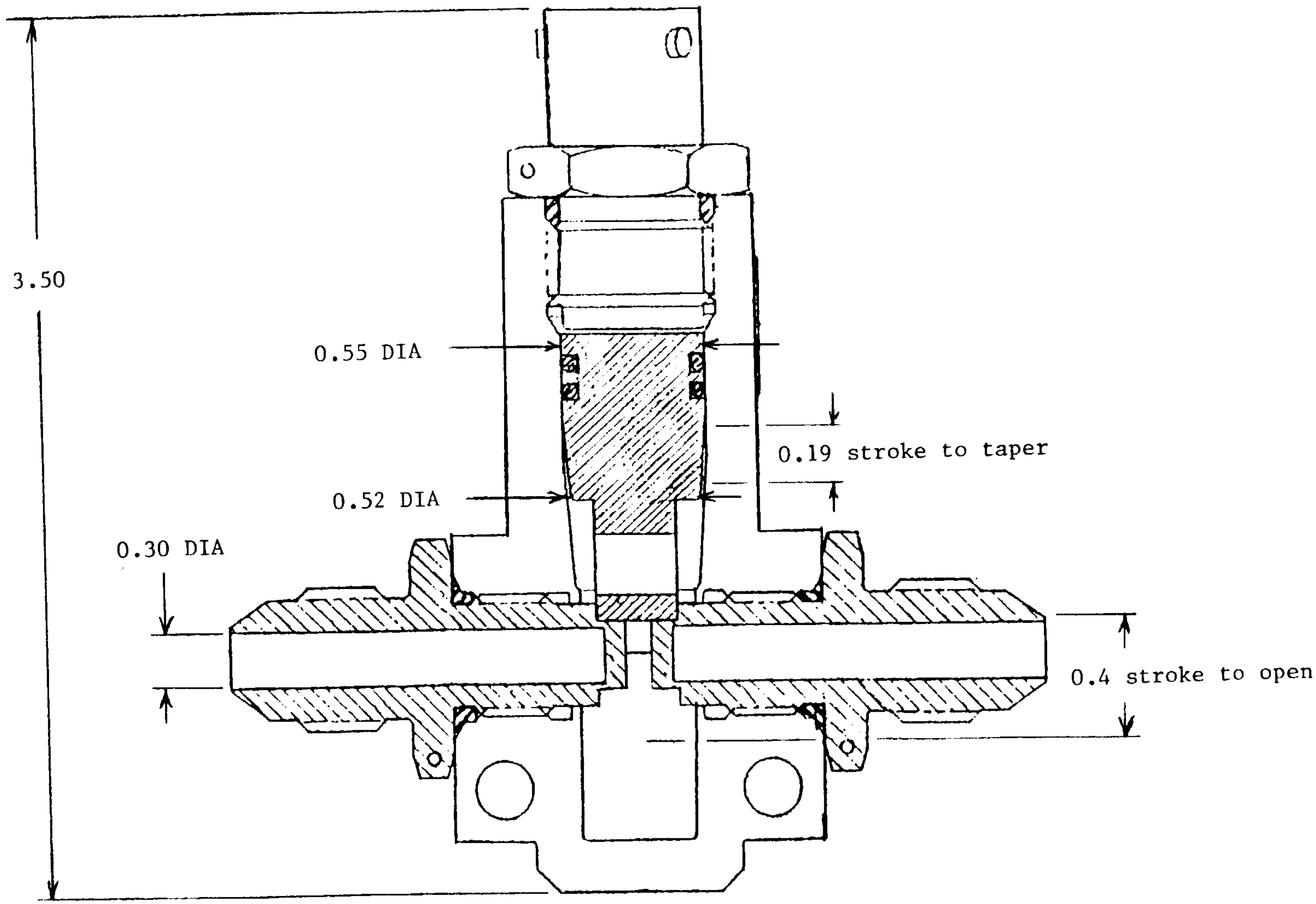

Figure 1.- Cross sectional view of Pyronetics pyrovalve. The body and fluid fittings are aluminum.

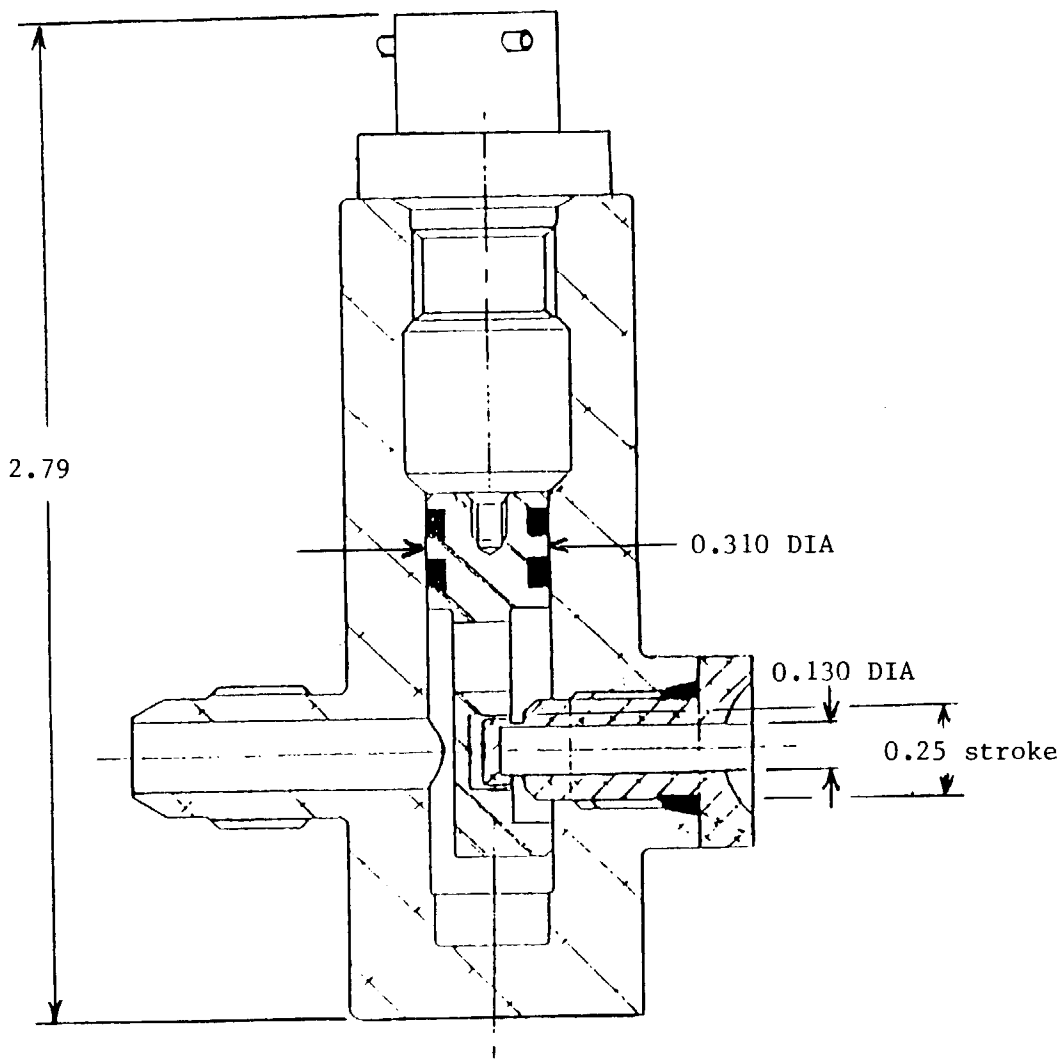

Figure 2.- Cross sectional view of Scot pyrovalve. The body and outlet is aluminum.

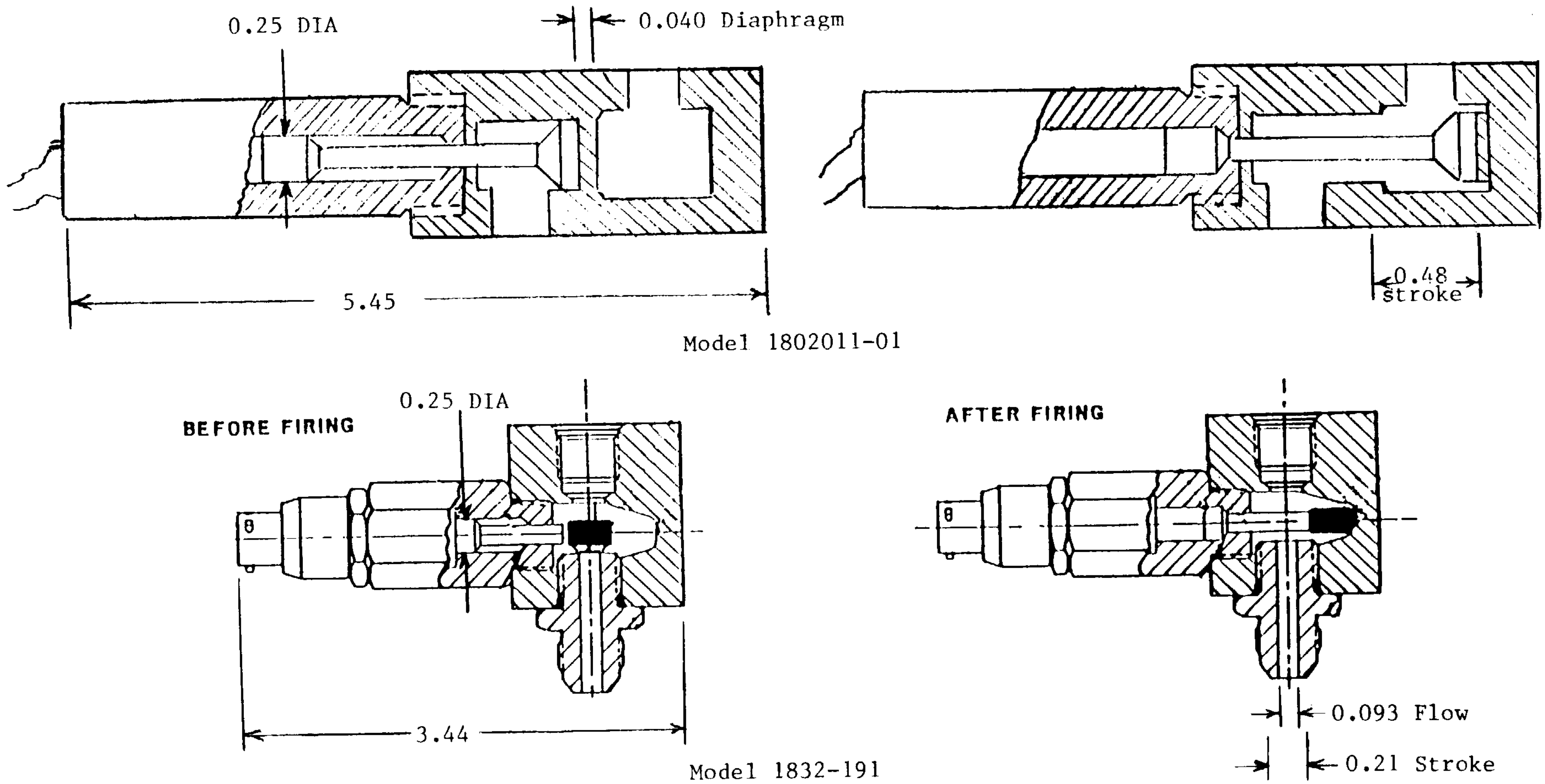

Figure 3.- Cross sectional view of Conax pyrovalves. The bodies are aluminum.

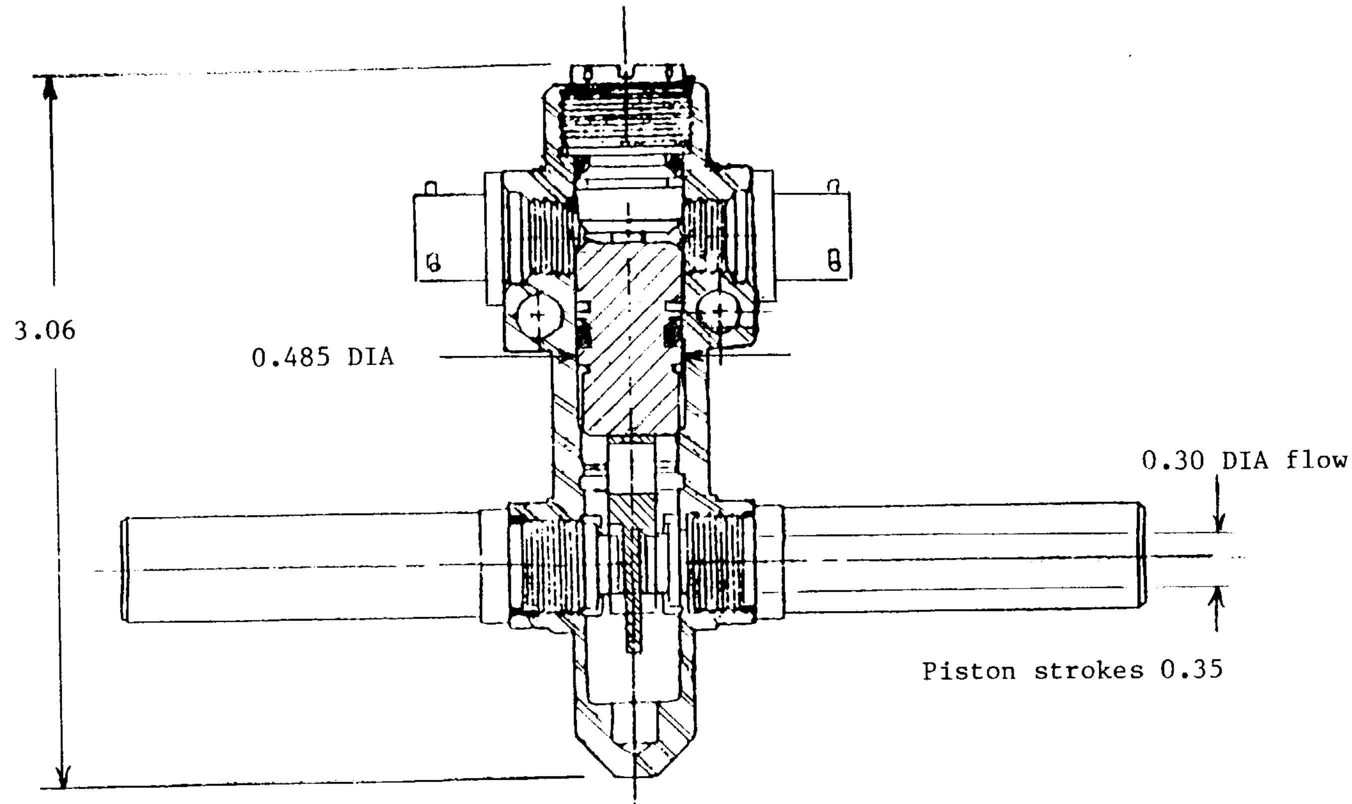

Figure 4.- Cross sectional view of Quantic pyrovalve. The body and fluid fittings are stainless steel.

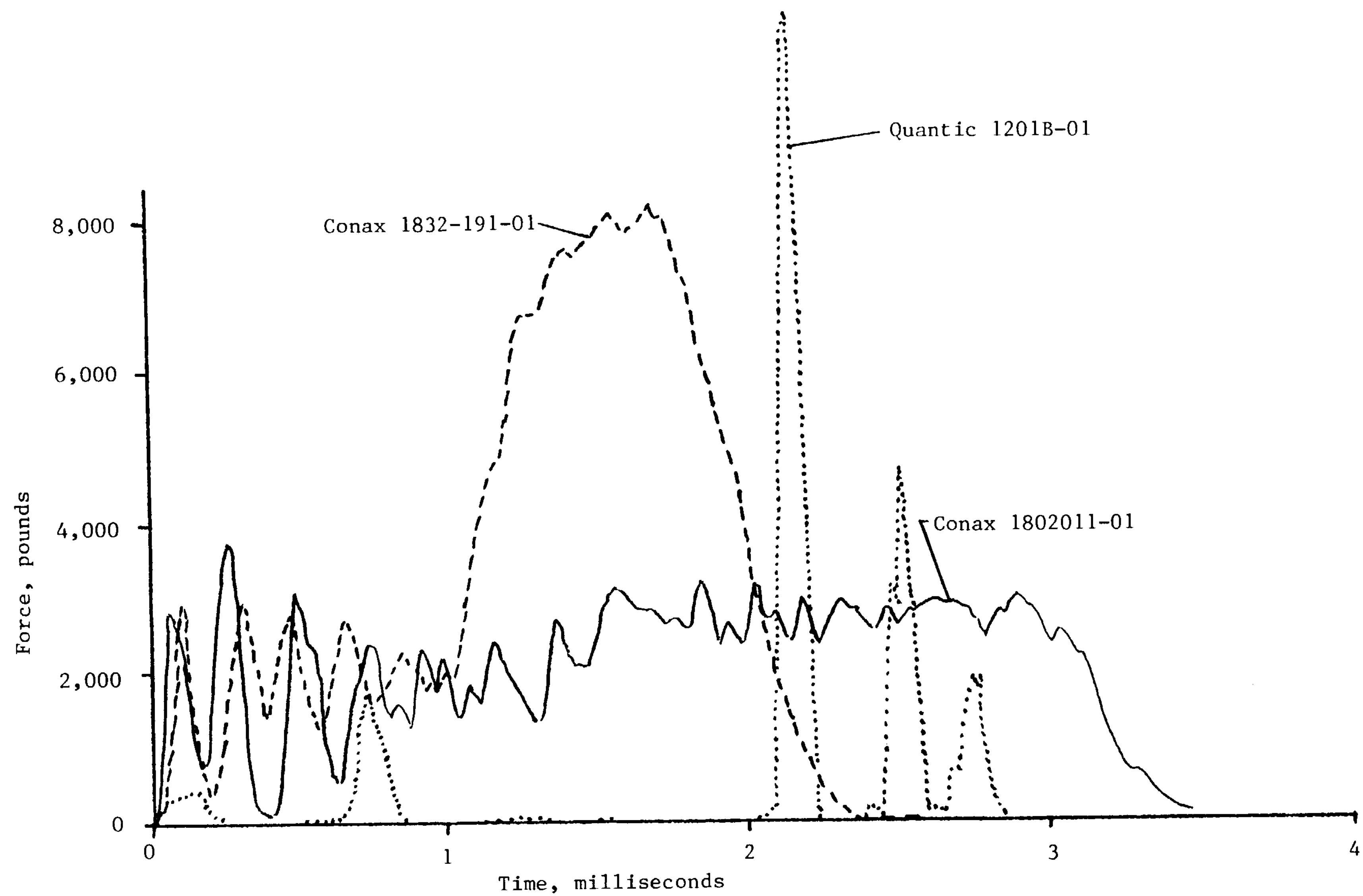

Figure 5.- Force versus time plots for weight drop tests on the pyrovalves indicated.

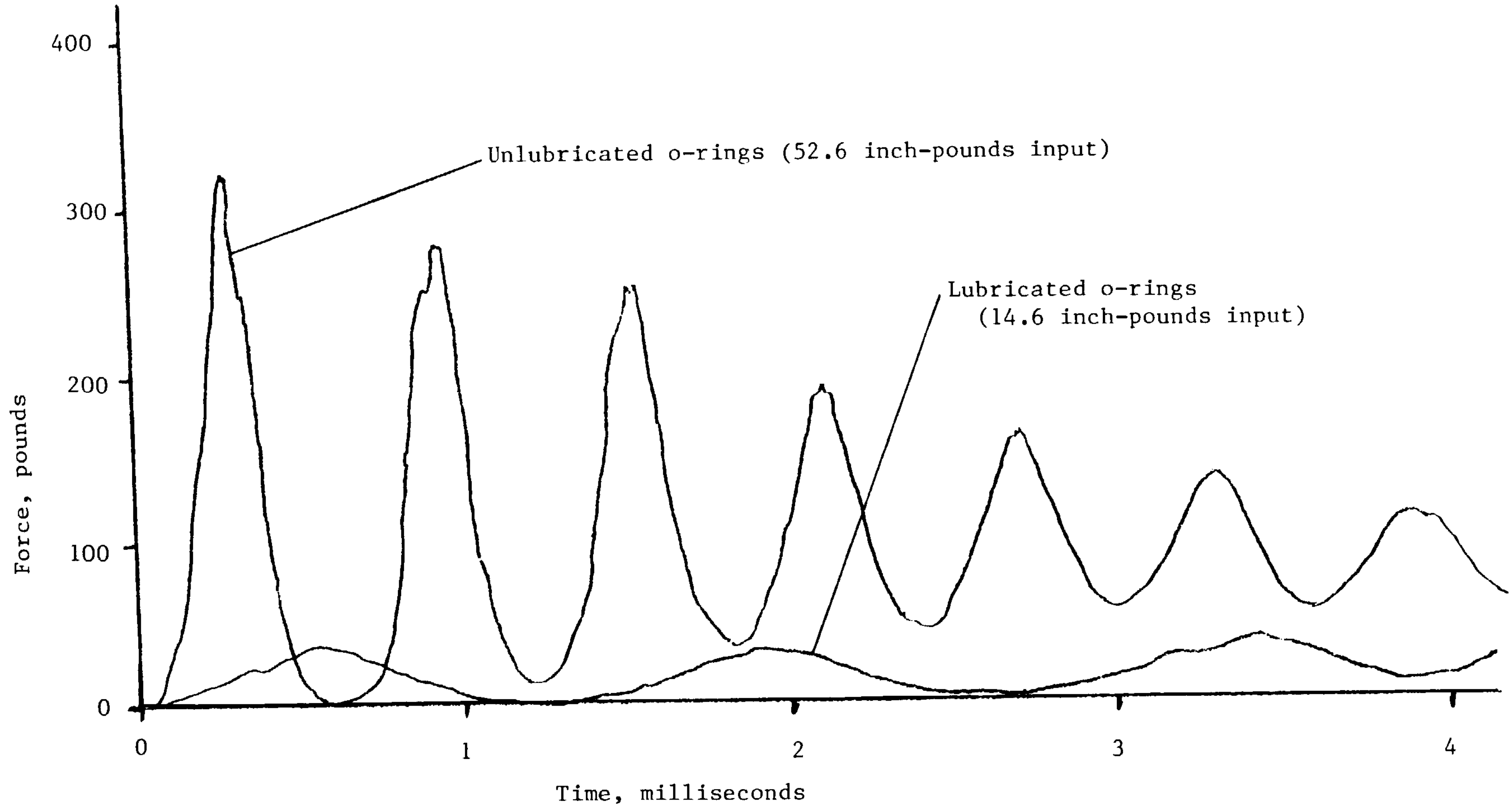

Figure 6.- Force versus time plots for weight drop tests on a steel Pyronetics test valve, unlubricated and lubricated o-rings.

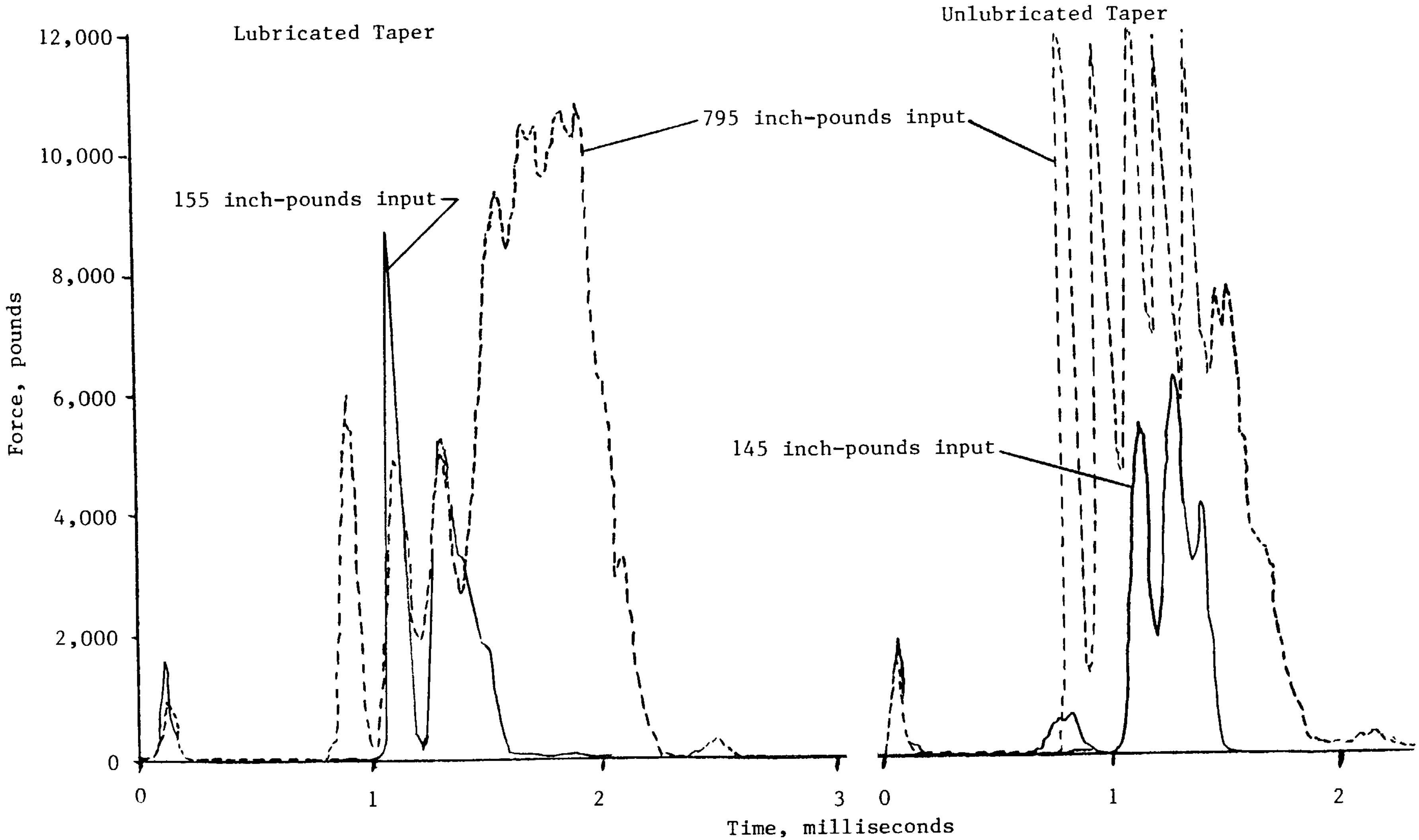

Figure 7.- Force versus time plots for weight drop tests on Pyronetics pyrovalves, lubricated and unlubricated tapered interfaces.

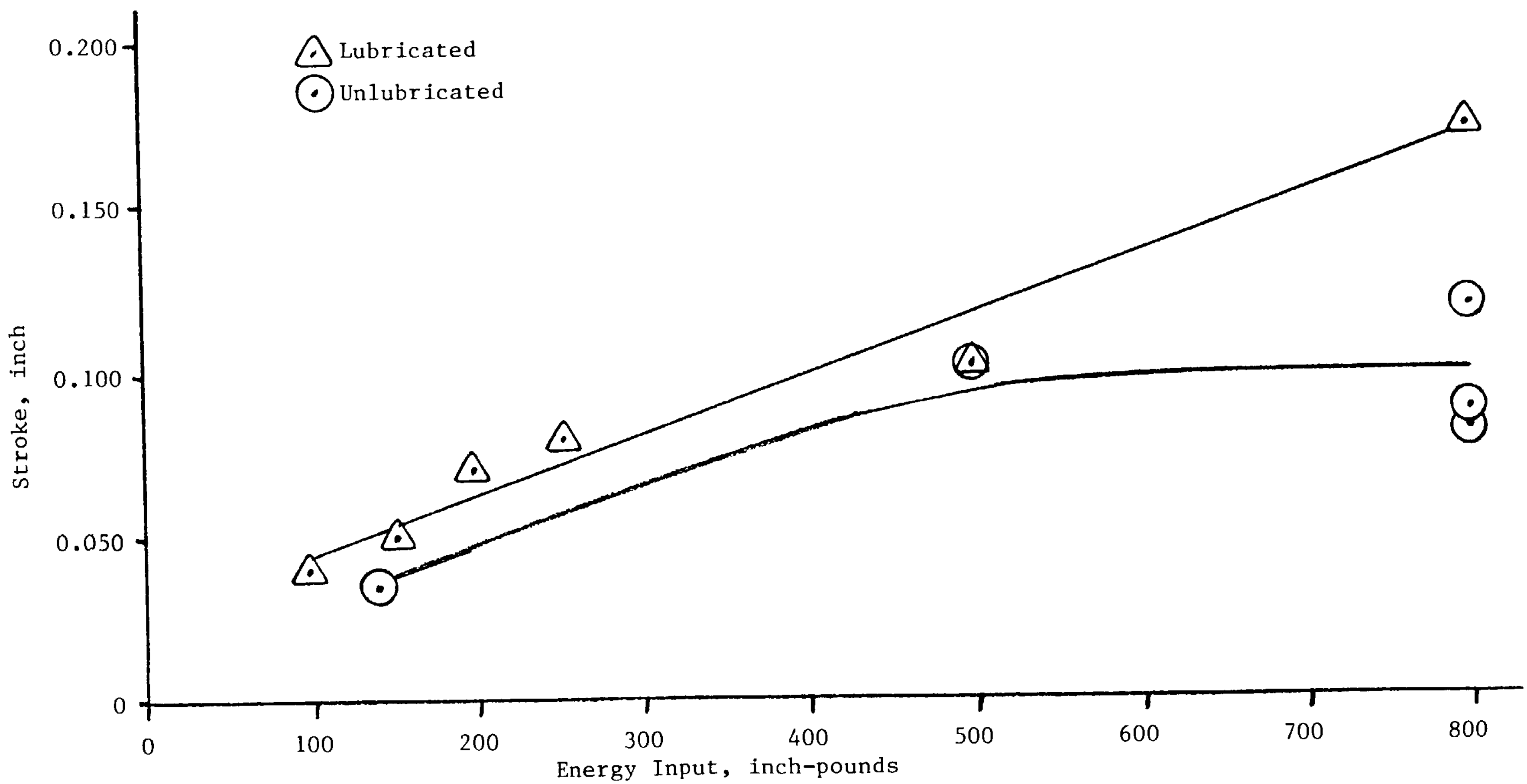

Figure 8.- Stroke in tapered interface of Pyronetics pyrovalve versus energy input with and without lubrication.

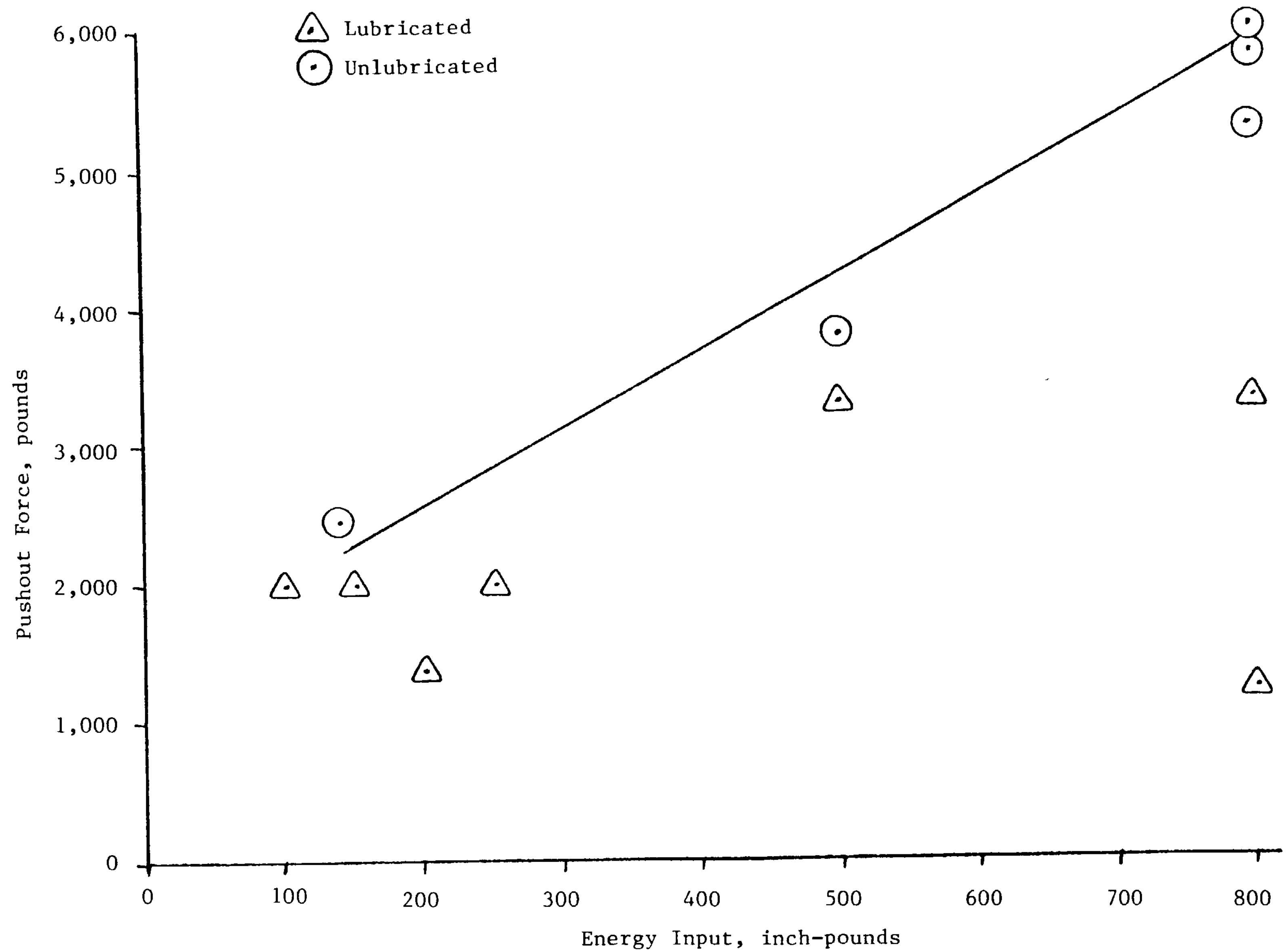

Figure 9.- Pushout forces of tapered interface in Pyronetics pyrovalve versus energy input with and without lubrication.

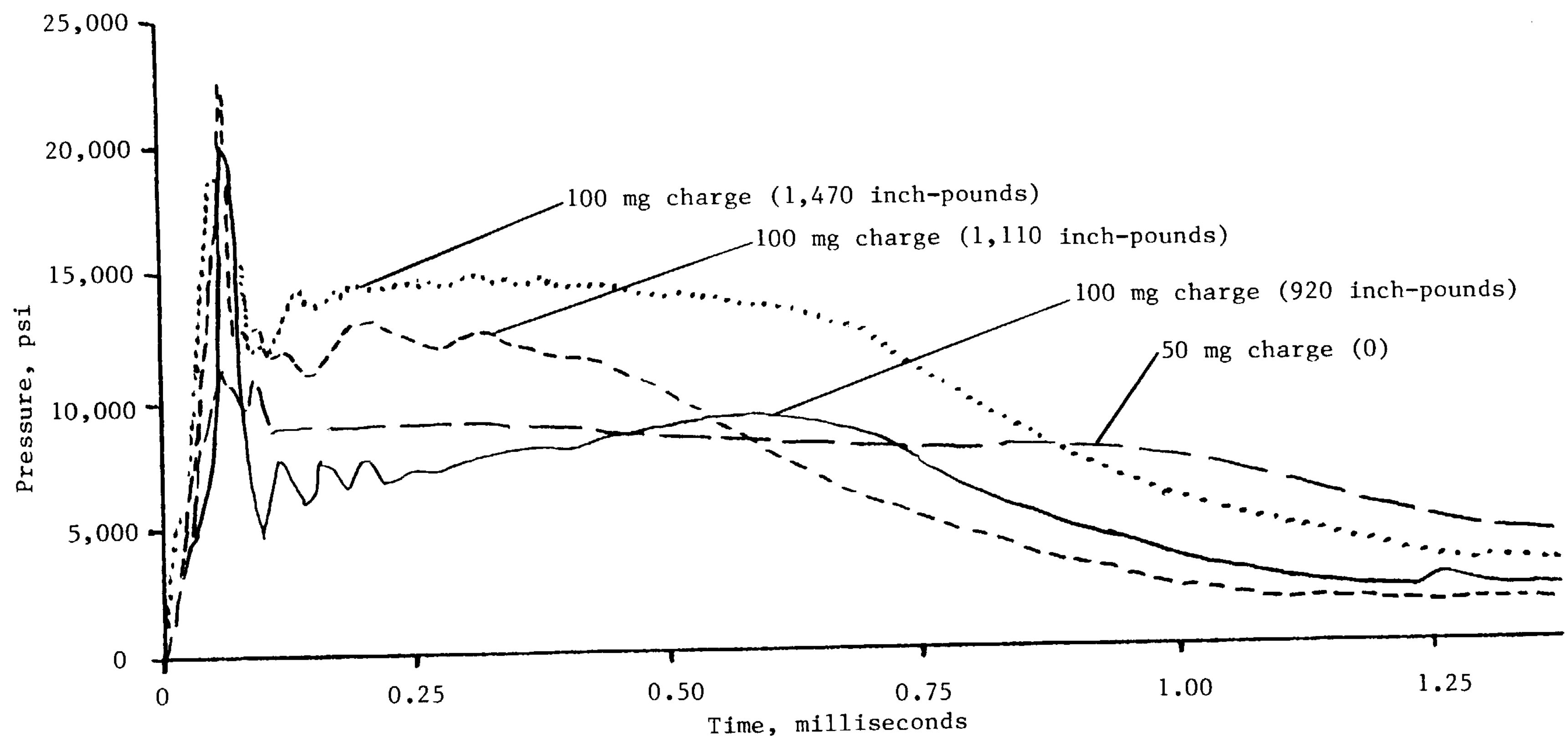

Figure 10.- Pressure traces recorded in sizing the booster charge for the Pyronetics pyrovalve. Energy values shown are excess to that required to function the valve, excluding piston seating.

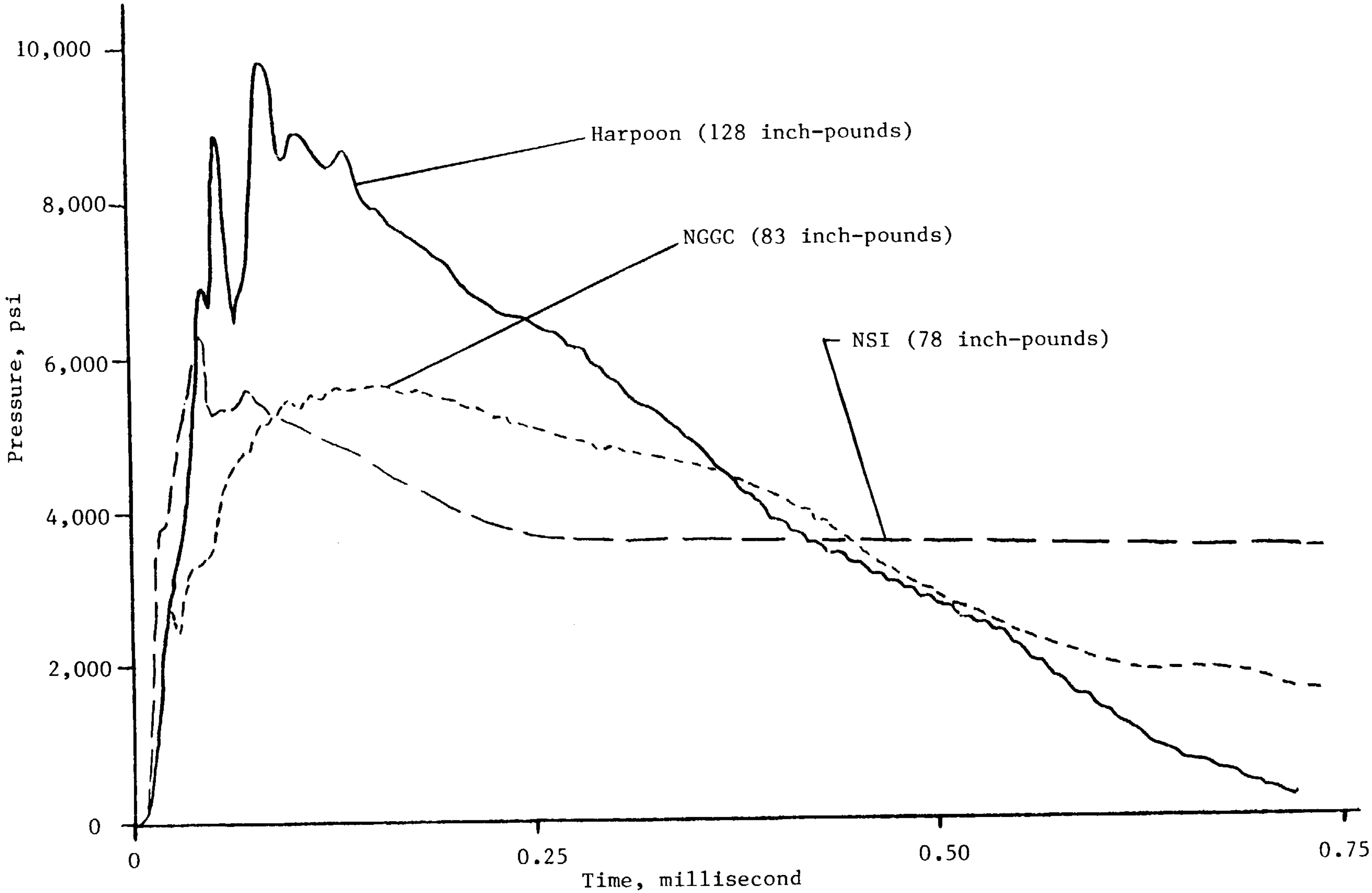

Figure 11.- Typical pressure traces recorded in the Scot pyrovalve, using the cartridges shown. Energy values shown are excess to that required to function the valve.

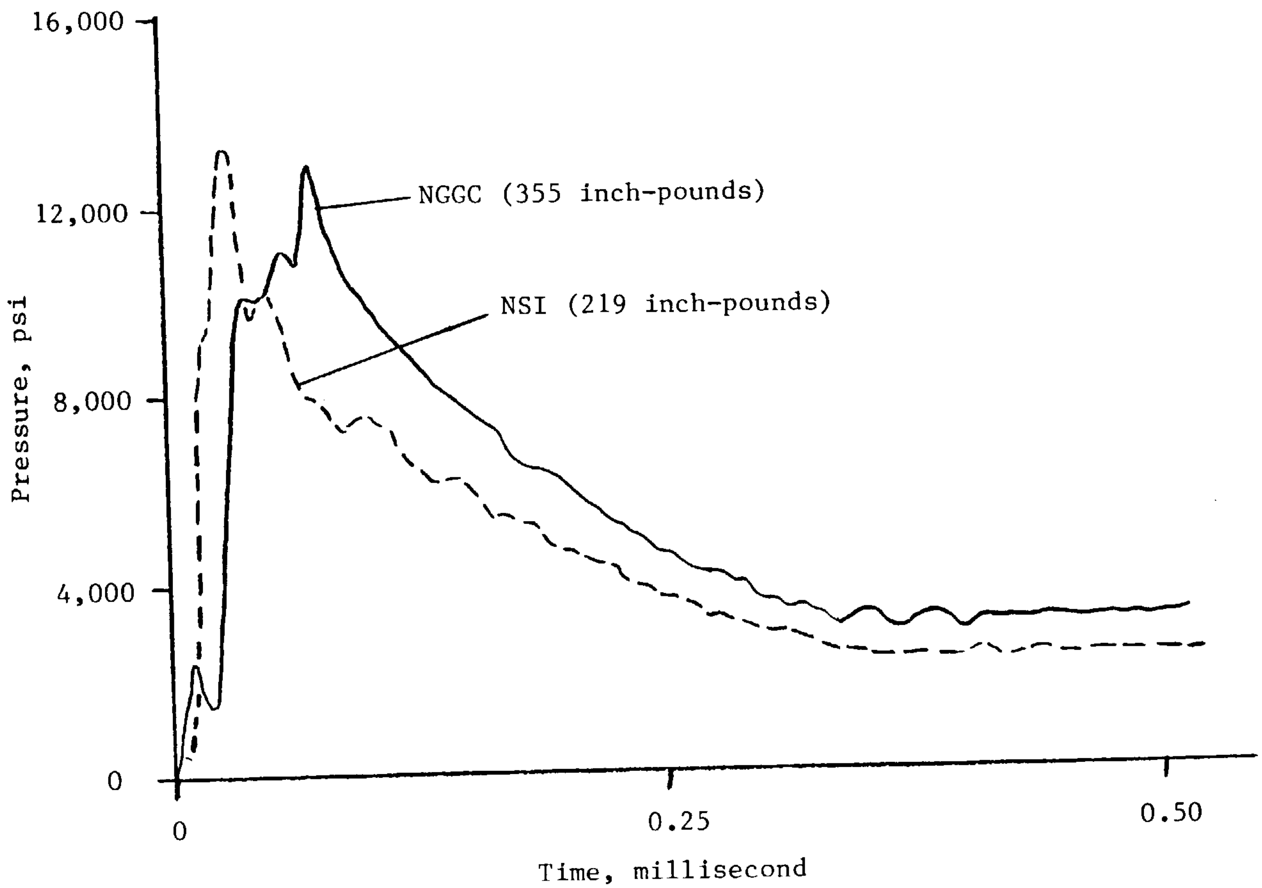

Figure 12.- Typical pressure traces recorded in the Quantic pyrovalve, using the cartridges shown. Energy values shown are excess to that required to function the valve.