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ABSTRACT

Since no generally accepted guidelines exist on sizing booster charges to assure functional margins in pyrotechnically actuated devices, a study was conducted to provide an approach to meet this need. An existing pyrovalve was modified from a single cartridge input to a dual-cartridge input with a booster charge. The objectives of this effort were to demonstrate an energy-based functional margin approach for sizing booster charges, and to determine booster charge energy delivery characteristics in this valve. Functional margin was demonstrated by determining the energy required to actuate the valve through weight drop tests for comparison to the energy delivered by the cartridge and booster charge in firings in the modified valve. The results of this study indicated that this energy-based approach fully met the study objectives, showing its usefulness for this and possibly other pyrotechnic devices.

INTRODUCTION

In designing pyrotechnic devices, the pyrotechnic charge must be sized to deliver more energy than is required to assure that a functional margin (reference 1) is achieved. In order to determine functional margin and to accommodate known variations, described in reference 2, in the performance of gas-generating propellant charges, energy delivery must be measured in the device. Two approaches are generally used for providing energy-producing, pyrotechnic charges: (1) one or two cartridges with the full operating charge contained within the cartridge, and (2) one or two initiators to ignite a separate booster charge. Unfortunately, no generally accepted design guidelines exist on how to size the propellant charge in any configuration while assuring an acceptable functional margin. To address this issue, a research effort was conducted, using an Apollo pyrovalve, the same Apollo pyrovalve with a modification, and a steel test valve.

The objectives of this study were to determine the size of the booster charge needed to assure a functional margin for the operation of the Apollo pyrovalve, and to determine the energy delivery characteristics of the booster charge.

The proven functional margin test approach in reference 1 of comparing the energy required to function pyrotechnic mechanisms to the energy delivered by the pyrotechnic energy source was used in this investigation. Weight drop tests were used to measure the energy required to function the pyrovalve. A steel test valve was used to determine the effects of free volume within the valve and booster charge size, ignition, combustion, and energy delivery. The energy delivered by several select booster charge quantities was measured in the modified Apollo pyrovalve.

TEST HARDWARE

This section describes the valves, the cartridges and the booster charge material used.

Apollo pyrovalve

The "normally closed" aluminum Apollo pyrovalve is shown in figure 1. The fluid flow through the valve is blocked by the blind fittings. As the hot-gas output of the cartridge forces the piston downward, the piston blade shears off the nipples on the blind fittings (0.020-inch wall thickness). A continuation of the stroke aligns the port in the piston blade with the now-open fittings to allow fluid flow. Approximately 0.4 inch of stroke is required to fully open the valve. During this stroke, the tapered portion of the piston body engages a matching taper in the bore at approximately 0.2 inch. This engagement slows and stops the piston over the next 0.2 inch. The kinetic energy of the piston is

*Senior Pyrotechnic Engineer, AIAA Associate Fellow dissipated through friction and metal deformation of the cylinder wall. Since the cartridge used in this investigation was much smaller than the unit originally used on the mission, a port adapter and plug were employed to accommodate the large thread diameter and to eliminate the free volume introduced between the cartridge and piston.

Modified Apollo pyrovalve

The modified Apollo pyrovalve is shown in figure 2. A two-cartridge steel "Y" adapter was installed in the existing threads in the pyrovalve. Firing either or both of the cartridges would ignite the booster charge placed in the free volume. One of the cartridges was replaced with a piezoelectric pressure transducer, as shown, to monitor the working pressure within the valve as it operated. A portion of the internal free volume was reduced by installing the two cylinders in the cartridge bores and by extending the plug on the piston face. A free volume of 0.6 cubic centimeters was left to receive the varying amounts of propellant booster charge. Each 100 mg of the propellant occupied 0.10 cc, reducing the free volume as propellant was added. The bottoms of the cylinders in the cartridge ports were taped over to retain the propellant within the lower portion of the free volume during assembly. It should be noted that the use of the tape was a matter of convenience for this study. Steel foils, welded to the housing would be used in flight hardware to encapsulate and prevent contamination of the booster charge.

Steel test valve

The steel test valve, shown in figure 3, was used to better understand the ignition, combustion and energy delivery of the booster charge. It was designed to accommodate the "Y" adapter and the blind fittings to duplicate the Apollo valve interfaces. A heavy-duty steel housing was fabricated with no taper on the piston or the housing bore to allow for multiple reuses. The piston stroked approximately 0.7 inch before its bottom shoulder engaged the blind fitting. The initial conditions, prior to piston motion, that affected booster charge ignition and combustion in the "Y" adapter were the same between the two configurations; the housing materials and volumes were the same, as well as the initial resistance to stroke in shearing the nipples. An electrically grounded probe was installed on the piston blade to measure the velocity of the piston. As the probe contacted each of the electrically charged foil switches, an electrical impulse was recorded. The 0.140-inch stroke distance between adjacent switches, divided by the time interval required to traverse that distance, provided the average velocity for that specific portion of the stroke. This velocity was used to calculate the kinetic energy of the moving mass, which was the piston, plug and probe. The velocity of the mass was measured at a piston stroke displacement of 0.4 inch, which is the stroke required to open the Apollo pyrovalve. The kinetic energy at that point was used for performance evaluations.

Cartridge

The cartridge selected for this study was the NASA Standard Initiator (NSI)-derived Gas Generating Cartridge (NGGC), reference 3. This cartridge has the same body and electrical interface as does the NSI, but, depending on the application, has at least twice the output. The weight of the internal charge is 130 milligrams.

Booster charge

The booster charge selected for this study was an on-hand gun propellant, reference 4, composed of an 80/10/10 by weight mixture of nitrocellulose, nitroglycerine and other ingredients, respectively. It quickly generates a large volume of gases, consisting primarily of carbon monoxide, carbon dioxide, and water. The 0.04-inch diameter, 0.02-inch thick flakes were poured into the free volume of the valves. This material is not stable under thermal/vacuum conditions and is not recommended for application to aerospace missions.

EXPERIMENTAL AND ANALYTICAL PROCEDURES

This study was conducted in four steps: (1) tests to determine the energy required to function the Apollo pyrovalve; (2) tests to evaluate the performance of pyrotechnic charges in the steel valve; (3) tests to evaluate the performance of pyrotechnic charges in the Apollo pyrovalve; and (4) analysis to determine the functional margin achieved in the modified Apollo pyrovalve.

Tests to determine the energy required to function the Apollo pyrovalve

Dropping a weight (reference 1) onto the valve's piston (through an adapter pin that extends above the housing) provided a controlled input to determine the energy required to function the valve. The impacting weight simulates the dynamic output of the cartridge and booster charges. A load cell was positioned under the pyrovalve to measure the forces required to shear the nipples and complete the stroke to open the valve. The weight drop height was adjusted to determine the minimum energy required to accomplish the function. Tests were conducted (reference 5) at incremental input energies of 100 to 790 inch-pounds to understand the functional mechanisms of the valve. The data collected were the amount of stroke of the piston into the valve body taper engagement, versus energy input. This data was used to determine the energy induced by the output of the cartridge and cartridge/booster combination, as described in the subsequent section, "Tests to evaluate the performance of pyrotechnic charges in the Apollo pyrovalve."

Tests to evaluate the performance of pyrotechnic charges in the steel pyrovalve

A total of 14 functional tests, measuring velocity of the piston, were conducted in the steel pyrovalve. Four single-cartridge tests were conducted without the "Y" adapter (no internal free volume) to obtain a baseline. Ten were conducted with the "Y" adapter to better understand the ignition and combustion characteristics of the booster. These ten tests were conducted with the following booster charges:

No. of tests	Booster charge weight mg	Free volume cc
1	50	0.55
3	100	0.50
3	200	0.40
1	300	0.30
1	400	0.20
1	500	0.10

The kinetic energy achieved at 0.4 inch of stroke of the piston for each of these booster charges was used as the basis for performance comparison.

Tests to evaluate the performance of pyrotechnic charges in the Apollo pyrovalve

One single-cartridge test was conducted in the Apollo pyrovalve without the "Y" adapter to obtain a performance baseline. Due to a limited number of valve bodies, only 3 tests were conducted in the modified Apollo pyrovalve with the "Y" adapter:

No. of tests	Booster charge weight mg	Free volume cc
1	200	0.40
1	400	0.20
1	500	0.10

The mechanical energy delivered by the cartridge and booster charge combinations was determined by measuring the piston stroke in the taper engagement, and using the plot of "stroke versus input energy" derived from the weight drop tests, selecting the energy for a given measured stroke.

Analysis of functional margin

The functional margin, or excess capability to operate, of the Apollo pyrovalve was determined by comparing the mechanical energy delivered by the pyrotechnic charges to the mechanical energy required to fully open the valve. Functional Margin (reference 1) is defined as:

$$\frac{\text{Energy Delivered} - \text{Energy Required}}{\text{Energy Required}}$$

Where:

Energy Delivered = the energy delivered by pyrotechnic charges in firings in the Apollo pyrovalve.

Energy Required = the energy required to fully open the Apollo pyrovalve, as determined by weight drop tests.

In order to have a functional margin, the Energy Delivered must be greater than the Energy Required.

RESULTS

The results of this research are presented in the same sequence as the procedures section.

Energy Required to function Apollo pyrovalve

Typical force versus time plots for two different input energy levels from the weight drop tests (reference 5) are shown in figure 4. The first spike is the resistance to shearing the nipples in the blind fittings. An estimate of the internal pyrotechnic-generated pressure needed to shear these nipples was obtained by dividing the highest resistive force observed, approximately 1,700 pounds by the area of the 0.52-inch diameter piston to yield 8,000 psi. At least this much pressure is needed to shear the nipples. The oscillatory force indicates the engagement of the piston/cylinder tapers and stroking of the piston until it stops. The results of the weight drop tests (reference 5), shown in figure 5, indicate that the stroke in the taper engagement, versus energy input, was approximately linear. The energy required to fully open the valve at a 0.200-inch stroke in the tapered interface, based on a linear extrapolation, is 950 inch-pounds. Referring to the actuating forces in figure 4, virtually all of the energy consumed in stopping the piston occurs in the taper engagement. The energy consumed in shearing the nipples was only about 34 inch-pounds (0.02 inch, the wall thickness of the nipples, multiplied by the 1,700-pound peak force).

Performance of pyrotechnic charges in the steel pyrovalve

The kinetic energies (calculated from the measurements of the velocity the piston achieved at a stroke of 0.4 inch), versus booster charge weight and initial free volume are listed in table I and plotted in figure 6. In figure 6, the 5 data points collected in firing single cartridges, with zero free volume and without the "Y" adapter, are shown for convenience on the ordinate. The data with the "Y" adapter (lower curve) indicates a linear increase in energy delivered with an increase in booster charge and the corresponding decrease in free volume. This kinetic energy data in the steel pyrovalve should not be compared to the energy required to function the Apollo pyrovalve, a different mechanical operation. Figure 7 shows typical pressure versus time histories produced by the different booster charges. The 50-mg booster charge produced a pressure of 10,000 psi, which was unable to shear the nipples on the blind fittings. Thus, a better estimation of a threshold pressure to fail the nipples is greater than 10,000 psi, rather than the 8,000 psi estimate from the weight drop tests. Very rapid pressure rises occurred with larger charges. Also, the larger charges produced wider high-pressure pulses in transferring more energy to the piston. The times to reach the 0.7-inch limit of piston stroke for each charge are also shown in figure 7 to assist in describing functional performance.

Performance of pyrotechnic charges in Apollo pyrovalve - The mechanical-stroke energy data collected in these tests are listed in table I and shown in figure 6. The energy required to fully open the valve (950 inch-pounds, obtained from the linearly extrapolated weight drop test data, figure 5) is shown as the horizontal line. The firing of the single cartridge in the Apollo pyrovalve without the "Y" adapter is plotted on the ordinate, again for convenience. The three firings of the selected booster charges in the modified Apollo pyrovalve are also shown, resulting in a non-linear increase in energy with increase in booster charge and a corresponding decrease in free volume. The 500 mg booster charge delivered more energy (estimated at 1,050 inch-pounds, based on a linear extrapolation of the data in figure 5) than was required to fully open the valve. The pressure traces recorded in these three firings are shown in figure 8. The rapid pressure rises and peak pressures are comparable to those measured in the steel valve. The time for the piston to reach the limit of its stroke is no greater than 0.5 ms., based on the flattening of the pressure traces and on the data collected in the steel pyrovalve. The pressure rises after about 0.25 ms with the 400 and 500-mg booster charges indicate that some amount of the booster charge is still burning after the piston has stopped.

Analysis of functional margin

Of all the firings in the modified Apollo pyrovalve, the 500-mg booster charge was the only one that was able to fully open the valve. Based on an energy delivered of 1050 inch-pounds (extrapolation in figure 5), and an energy required of 950 inch-pounds, the functional margin for this firing was calculated to be 0.105.

CONCLUDING REMARKS

A research program was conducted on a modified Apollo pyrovalve to demonstrate a method for sizing booster charges to assure functional margins in pyrotechnic devices. A second objective was to determine booster charge energy delivery characteristics in this valve. The valve was modified from a single cartridge input to a dual-cartridge input with a booster charge. Test and analytical methods previously proven in evaluating other devices were adapted to this effort. Determining the energy required to function this pyrovalve and the energy delivered by the booster charge allows a calculation of functional margin. The "energy required" to function the valve was determined through weight drop tests on the actuating mechanism, while measuring the resistive forces during actuation. These measurements of resistive forces assisted in understanding the mechanics of operation in accomplishing the function. Repetitive test firings in a steel mockup of the pyrovalve, while measuring the pressure within the working volume and the kinetic energy delivered into the actuating piston, offered an improved understanding of the ignition and combustion of the booster charges. These tests not only gave direction in selecting the charges to be demonstrated in the final configuration valve, but also allowed a reduction in the number of units tested.

A number of performance effects were observed in this study. A rapid pressure rise and high pressures produce the highest efficiencies in transferring the energy from the burning booster charge to the actuating piston. The valve functions in less than 0.5 millisecond. Mockups of pyrotechnic devices are useful, but only tests in the final configuration hardware should be used to define specific performance. The cartridge used in this study (130-mg charge) had insufficient output to function the valve. In the modified valve, a booster charge of 200 mg was needed to match the energy delivered in the single-cartridge configuration, and a 500-mg charge was needed to fully open the valve. The booster charges overcame the adverse effect caused by the increase in the size of the working volume pressurized by the pyrotechnic charges. The 500-mg charge produced a functional margin of 0.105. This pyrovalve could be redesigned to be more energy efficient by stopping the actuating piston after the valve fully opened, rather than during the opening phase.

This work successfully demonstrates a method for sizing the booster charge necessary to generate a functional margin in a modified Apollo pyrovalve. The method should apply to, and be a useful tool for, design of other mechanisms.

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TABLE I. SUMMARY OF ENERGY MEASUREMENTS IN PYROVALVES

Energy Source	Initial Free Volume cubic centimeters	Performance inch-pounds	
		Steel	Apollo
Single cartridge (no "Y" adapter)	zero	276 185 230 - Avg. = 218 195 Std. Dev. = 49 205	690
Single cartridge (with "Y" adapter and booster, mg)			
50	0.55	0	
100	0.50	155	
100	0.50	221 - Avg. = 172	
100	0.50	140	
200	0.40	320	735
200	0.40	293 - Avg. = 295	
200	0.40	275	
300	0.30	492	
400	0.20	588	875
500	0.10	711	1,050

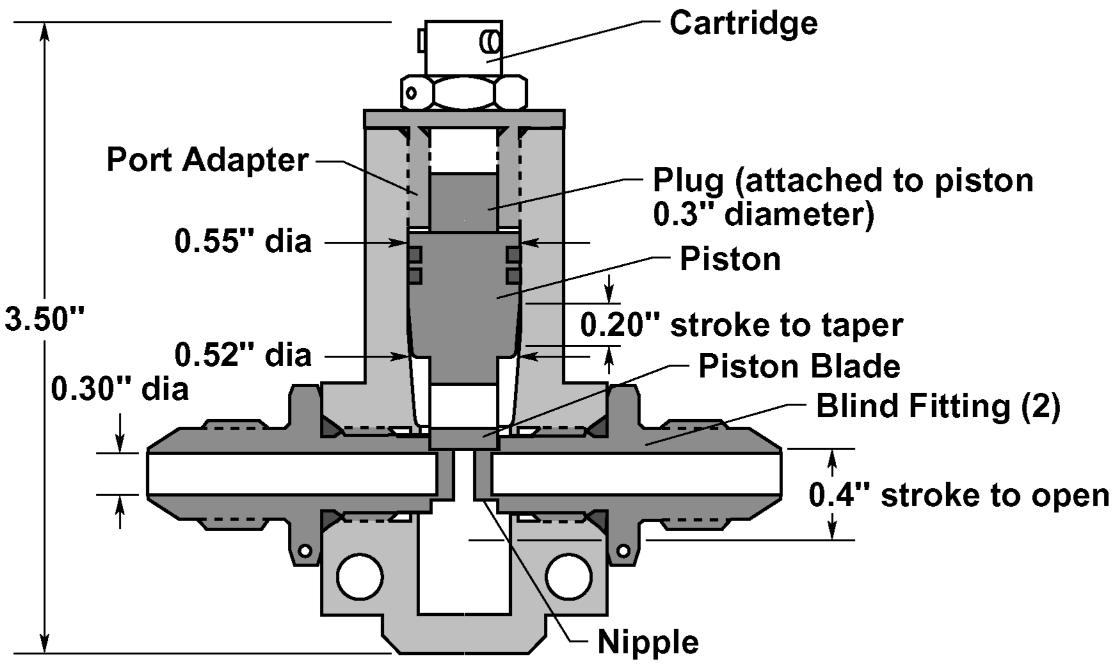

Figure 1. Cross sectional view of normally closed Apollo pyrovalve. The housing and fittings are aluminum.

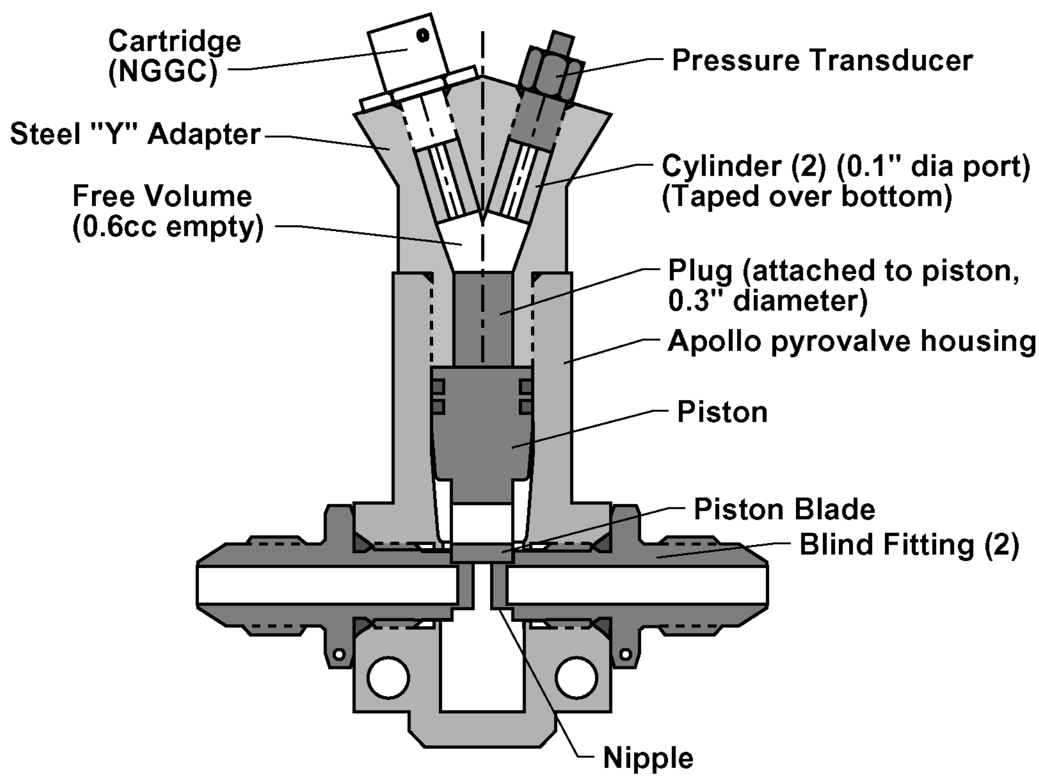

Figure 2. Cross sectional view of Apollo pyrovalve modified to accept two inititators. The pressure transducer was installed in the second port to measure activation pressure.

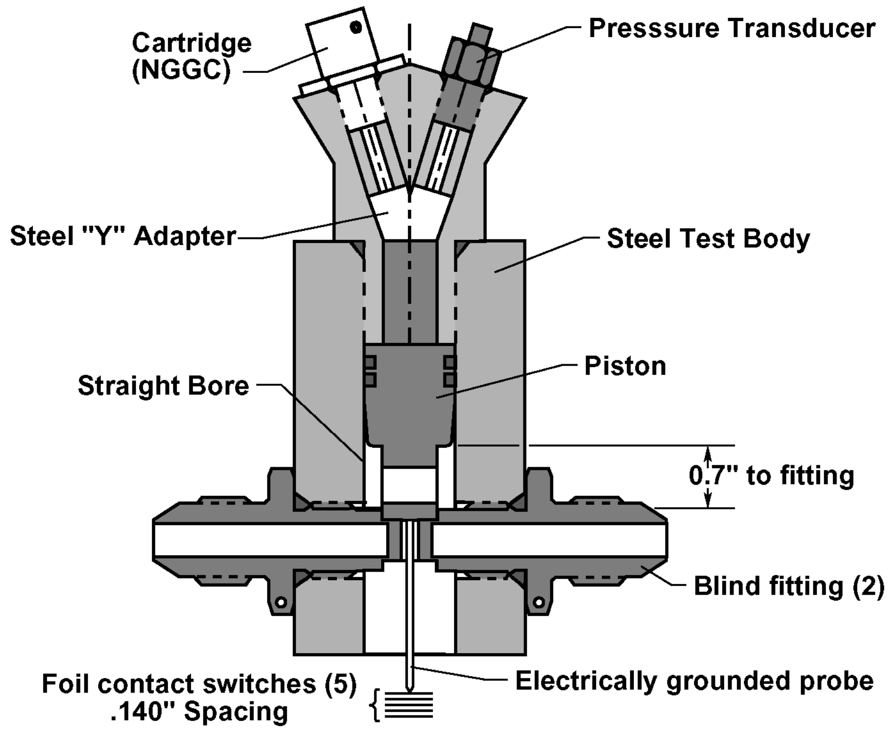

Figure 3. Cross sectional view of steel test pyrovalve used to measure the velocity of the piston in opening the valve.

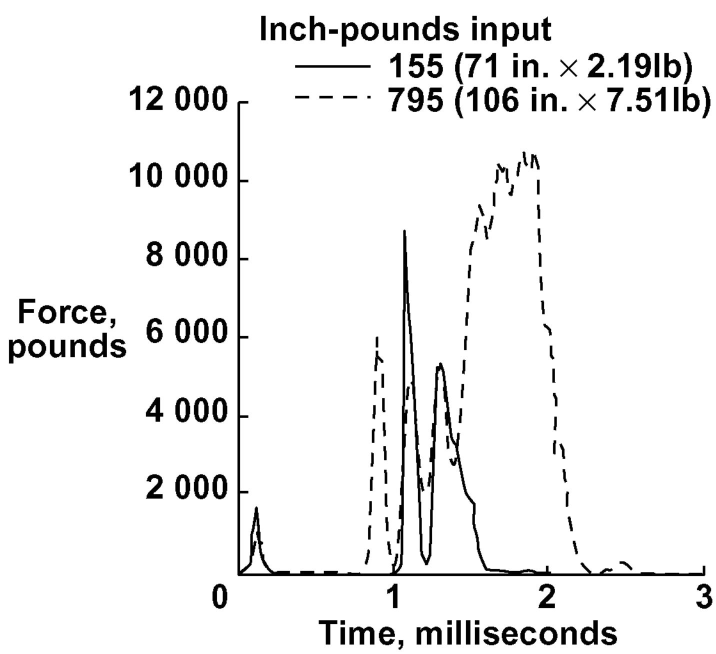

Figure 4. Force versus time traces for weight drop tests on Apollo pyrovalve.

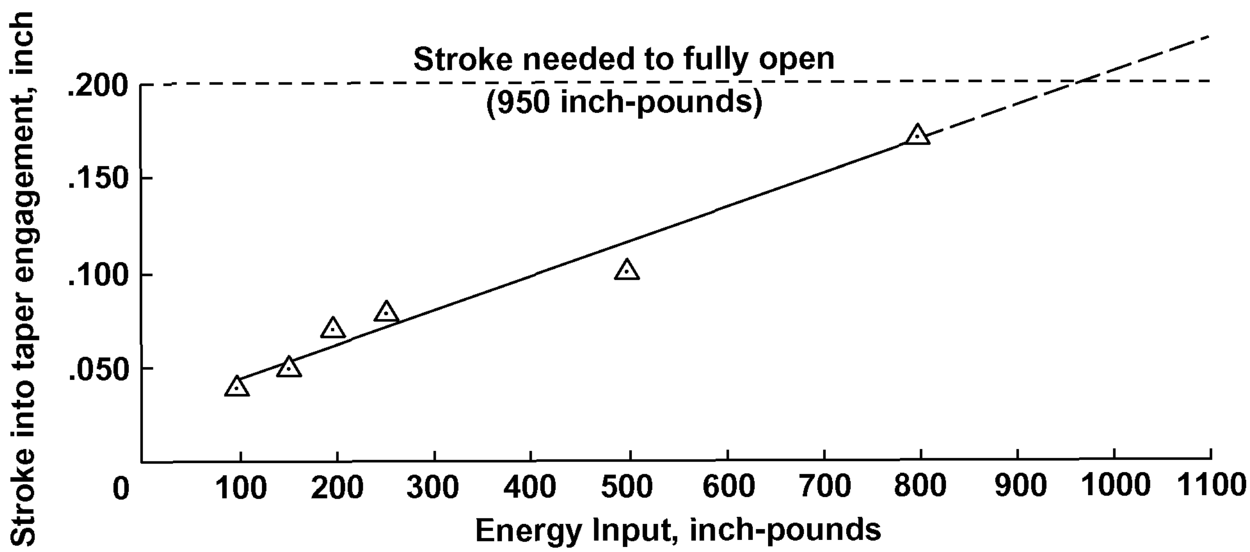

Figure 5. Weight drop test stroke into the taper engagement versus energy input in the Apollo pyrovalve.

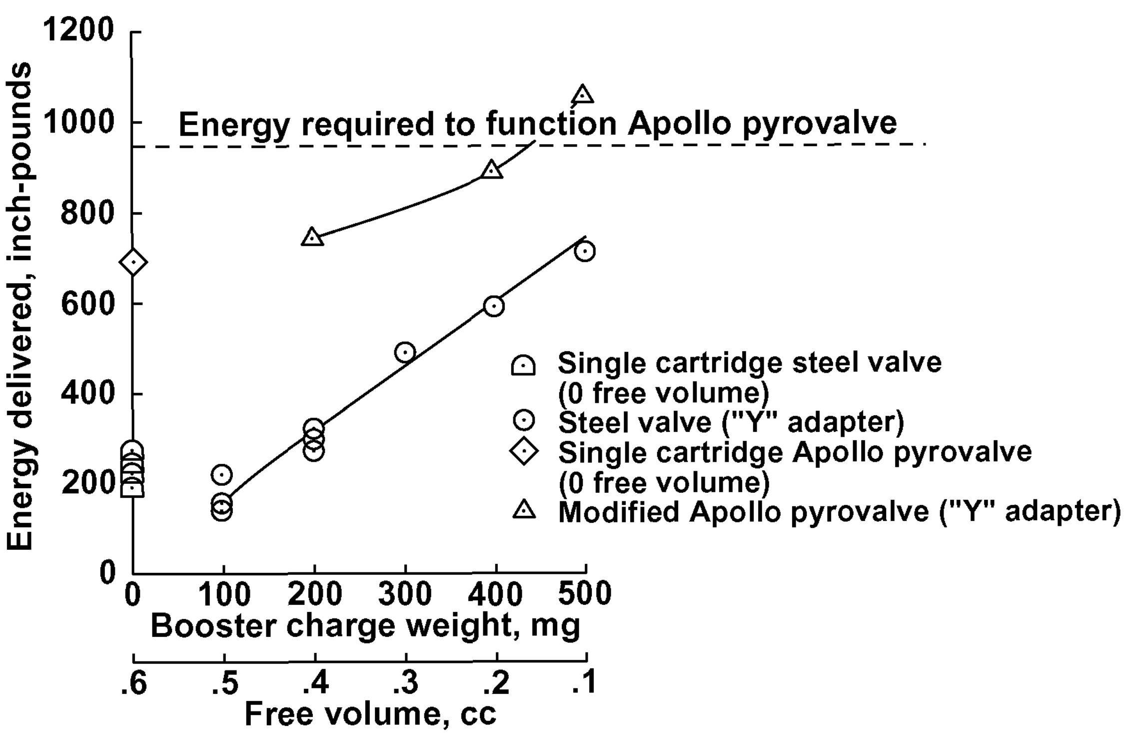

Figure 6. The energy delivered versus booster charge weight and free volume of aluminum and steel pyrovalves.

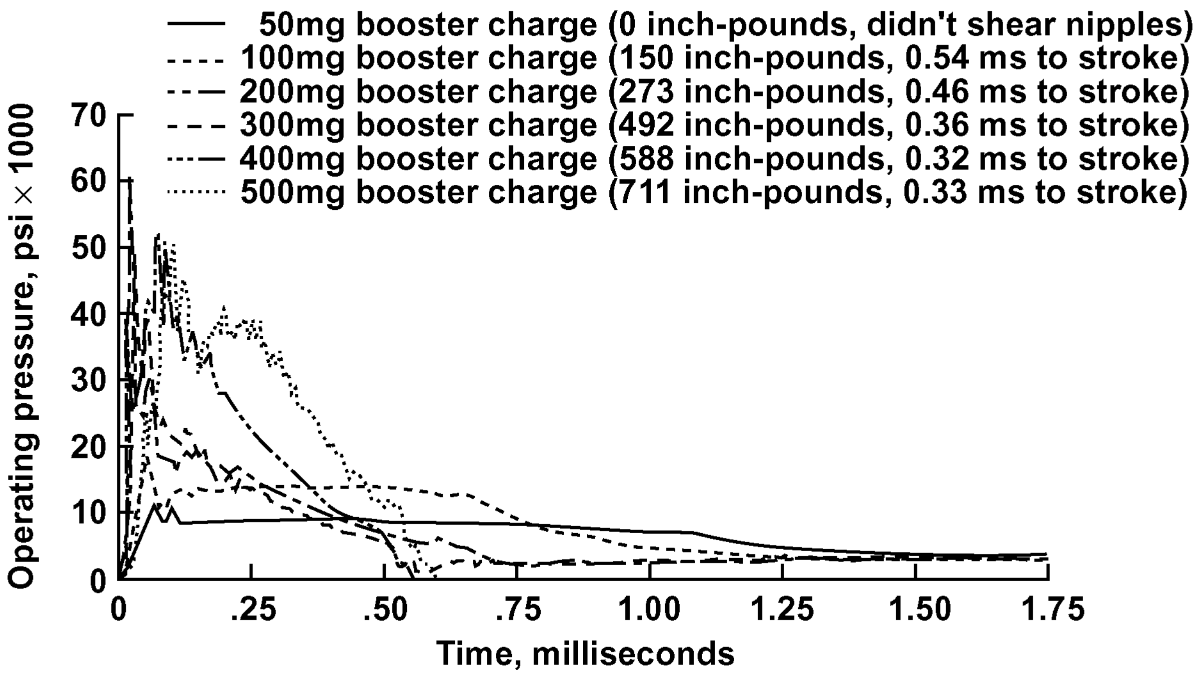

Figure 7. Typical presure versus time histories of the booster charges tested in the steel pyrovalve. The times listed indicate when the piston reached 0.7 inch in its stroke.

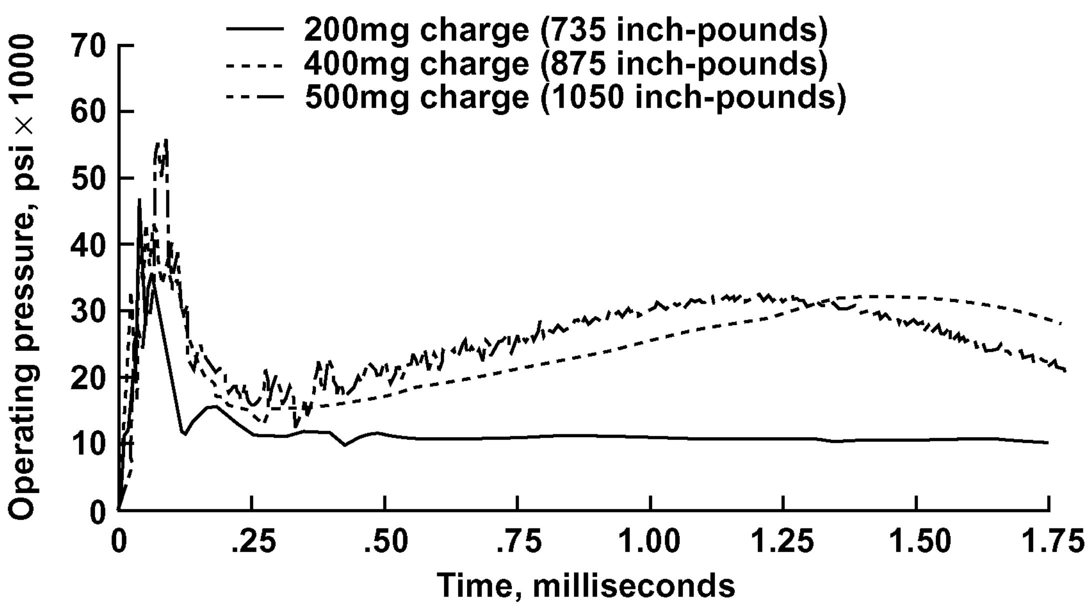

Figure 8. Pressure versus time histories of the booster charges tested in the Apollo pyrovalve.