DETERMINATION OF PYROTECHNIC FUNCTIONAL MARGIN

by

Laurence J. Bement
NASA Langley Research Center
Hampton, VA

Morry L. Schimmel
Schimmel Company
St. Louis, MO

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SUMMARY

Following the failure of a previously qualified pyrotechnically actuated pin puller design, an investigation led to a redesign and requalification. The emphasis of the second qualification was placed on determining the functional margin of the pin puller by comparing the energy deliverable by the pyrotechnic cartridge to the energy required to accomplish the function. Also determined were the effects of functional variables. This paper describes the failure investigation, the test methods employed and the results of the evaluation, and provides a recommended approach to assure the successful functioning of pyrotechnic devices.

INTRODUCTION

Although pyrotechnic devices accomplish critical mechanical functions in aerospace systems, little effort has been applied to understand how well they perform (their functional margin). These devices are single-shot and costly, so the number of component tests (development, qualification and lot acceptance) and the number of system-level functional tests are minimized. Furthermore, there are few generally accepted margin tests to assist in enhancing this understanding. Consequently, many programs enter flight operations with only a "go/no-go" definition of pyrotechnic performance; that is, in testing the device the only data collected were that the device either did or did not function. This lack of testing and performance definition has led to costly failures on two current programs. The Hipparcos astronomy satellite utilized through-bulkhead initiators to ignite a rocket to achieve a circular orbit. Failures of the initiators left the satellite in an eccentric orbit, which reduced the effectiveness of the mission (references 1 and 2). The Tri-Services stealth missile utilizes pyrotechnic devices "to blow the cover off the radar-evading missile when it's dropped from a bomber, allowing its wings to unfold and its engine to start," (reference 3). These devices have contributed to three flight failures, and have delayed funding on the $15 billion program, (references 3 and 4). The purpose of the effort described in this paper was to improve the of understanding how pyrotechnic devices work by demonstrating a method for measuring the performance margin of a pyrotechnically actuated pin puller for use on the NASA's Halogen Occultation Experiment (HALOE) instrument, which is on an orbital spacecraft.

Performance of cartridge-actuated devices, such as the pin puller, is influenced by a number of parameters. These include: composition of the gas-generating charge; the volume, shape and material into which the cartridge is fired; and the work to be accomplished within the device. As described in reference 5, designers have generally tried to use the peak pressure achieved by cartridges in a closed bomb, that simulates the initial volume in the device, as measure of performance. With this peak pressure and past experience, designers then use a "cut and try" approach to size the cartridge's charge for use in the actual device. When the device is fired, the usual approach is to document whether it did or did not accomplish the desired function.

This paper raises and addresses two very important questions:

1. How could devices that passed qualification fail to perform?
2. What can be done to minimize the risk of flight failures?

The approach for this paper was to follow the history of the HALOE pin puller to address these questions and describe how it: 1) was qualified for and successfully performed on a planetary landing mission, 2) experienced failures on a second intended application, 3) was subjected to an extensive failure analysis, and 4) was redesigned, functionally evaluated, including analysis of functional margin, and requalified for use on the HALOE instrument.

PIN PULLER DESCRIPTIONS

Two pin puller designs for different applications, as shown in figures 1 and 2, were evaluated in this effort. The Viking application was to release an antenna on the surface of Mars, and the HALOE application was to release a gimbal interface in Earth orbit. Both pin pullers had the same basic design: a 0.25-inch diameter pin was withdrawn just over a half inch, by firing either of two cartridges. The cartridge output vented through a 0.100-inch diameter opening out of the port to pressurize the pin side of the piston. The shear pin failed at approximately 80 pounds static force. Redundant o-rings were used on both the pin and the piston and lubricated with medium consistency silicone grease. A deep-drawn, 0.15-inch long, 0.010-inch wall thickness, 302 stainless steel energy-absorbing cup (labeled shock absorber in figure 1 and energy absorbing cup in figure 2) crushed on impact into the cap to remove the excess energy from the pin/piston and prevent rebound. The following describes the features that were unique to each pin puller.

Viking Pin Puller

The body and cap were manufactured from 6061-T6 aluminum as a weight consideration and to allow the cap to be welded to the body, (figure 1). The aluminum had a chemical chromate coating both internally and externally for oxidation protection. A molybdenum disulfide coating was applied to the pin as a dry lubricant. The energy absorbing cup had a height of 0.150 inch. The cartridge used, the Viking Standard Initiator (VSI), is a clone of the NASA Standard Initiator (NSI). The NSI was qualified for the Apollo and Space Shuttle programs. Both cartridges use 114 mg of zirconium/potassium perchlorate as the output charge.

HALOE Pin Puller

This body and cap were manufactured from 15-5 stainless steel; no coatings were required. The pin/piston used an electrodeposited nickel/Teflon coating as a dry lubricant. To assure lubrication of both the o-rings and the pin/piston bores, the o-rings were generously lubricated before installation and the pin/piston assembly was stroked six times through its limits in the body, followed by a force measurement to verify low friction levels. An o-ring was used to seal the cap to allow reusability. The units were disassembled and cleaned after each firing. The cap was extended to allow a larger volume to accommodate the potential for blowby and gaseous compression in the stroke of the piston. The energy absorbing cup height was increased to 0.250 inch to provide a greater energy absorbing capability than that in the Viking pin puller.

TEST APPARATUS

The pin puller was evaluated in three basic test configurations: tests to determine the energy required to stroke, tests to measure and compare NSI output, and functional tests.

Energy Required to Stroke

To determine the energy required to stroke, a drop test rig was employed to drop 1, 2 or 3-pound steel weights onto the vertically oriented pin puller. The total energy input was determined by multiplying the drop weight by the drop height to obtain a value in inch-pounds. The rebound height of the drop weight was monitored and found to be negligible, less than 2 percent. Small weights and large drop heights were selected to simulate the dynamics of an actual firing. Drop tests completed the stroke in 2 milliseconds, while an actual firing required 0.5 millisecond. The measured energies required to stroke the pin puller are conservative, because impact losses were not considered.

Cartridge Output Comparisons

The pin puller was fabricated with a steel body and adapted to an energy sensor to measure cartridge output, as shown in figure 3. On functioning, the pin puller's piston/pin stroked against crushable honeycomb that was cut and calibrated to present about 300-pound force resistance throughout the stroke. The amount of stroke achieved during the firing, multiplied by the crush strength, provided an energy measurement in inch-pounds.

Functional Tests

Functional tests of the flight-configuration pin pullers were usually conducted in fixtures that induced no resistance to the stroke of the pin, (a non-system test). However, a number of tests were conducted, described later, using actual spaceflight hardware and interfaces, (a system test).

PROCEDURE

The approach used in this effort was to compile the history of this pin puller design from its application on the Viking program to Magellan failures, through a HALOE-sponsored failure investigation, to the HALOE redesign, functional evaluation, and requalification.

Viking History

The records for the Viking mission were studied to document the approach for development, including functional demonstration, qualification and system testing.

Magellan Selection/Failures

The records of the Magellan project's experience with the Viking pin puller design were compiled. Fortunately, the same prime contractor, Martin Marietta, developed both the Viking and Magellan spacecraft, allowing technical continuity to be maintained.

HALOE Failure Investigation

The HALOE project office had chosen to use residual Viking pin pullers from the original manufactured lot in their system. It was imperative that the Magellan failures be resolved, prior to incorporating the Viking pin puller into the HALOE instrument. The approach for this failure investigation was to examine pin pullers that had been functioned in past tests, determine the functional parameters that affected performance, and determine functional margin of this design. The goals of the HALOE investigation were to determine if the Viking pin puller could be used, and if not, compile information to assist in the redesign.

Post-test examination - Four pin pullers previously used in LaRC HALOE system-level tests were x-rayed and dissected for visual inspection by removing the caps and cutting the bodies on their longitudinal axes on the centerline, perpendicular to the view shown in figure 1, to expose the piston and pin bores.

Evaluation of functional parameters - Evaluated were the effects of friction of the piston/pin o-ring interfaces, the performance of the energy absorbing cup, and the variation in output performance of the NSI. The drop test fixture was used to determine the energy required to overcome the shear pin and stroke the piston/pin with different levels of lubrication. Drop test energies were further increased to measure the crush characteristics of the energy absorbing cups. The honeycomb energy test fixture was used to determine the output performance of the VSI and two candidate NSI lots. Performance enhancement tests were conducted to improve combustion efficiency of cartridge loads, using VSIs with a 0.075-inch throat-diameter, epoxy nozzle (cast into the output cup of the VSI), and bonding 20 mg of BKNO3 in the output cup of the VSI. A dual VSI firing was conducted to determine a maximum output energy production. (The normal mode of operation is to fire a single cartridge). A reusable, steel-bodied test unit, identical to the aluminum body, was manufactured for this series of tests, instead of using new aluminum bodies for each test. A Viking flight unit was also tested in the honeycomb energy test fixture.

HALOE Redesign/Functional Evaluation/Requalification

The goals for the redesign were: 1) that the energy deliverable by the NSI be at least three times that required to withdraw the pin, 2) that all functional parameters be controlled, 3) that the pin puller performance be evaluated in worst-case, system-level tests, and 4) that the environmental qualifiction effects on performance be minimal.

Once the design was selected, a total of 18 pin pullers were manufactured in a single lot. Of the total, 2 units were subjected to repeated test firings (refurbished after each) for functional evaluations, 10 units were subjected to an environmental qualification, and 6 units were set aside for system tests and flight. The 2 units were used to evaluate the energy required to stroke and to size the height of the energy absorbing cup, as well as providing data on the energy delivered by the NSI. On completion of all firings, the energy delivery data were analyzed to determine the pin puller's functional margin.

RESULTS

The results obtained in this effort are presented here in the same order as in the Procedures section.

Viking History

The Viking pin puller progressed through development, environmental qualification, and system demonstration.

The functional margin demonstration consisted of measuring and comparing the pressure in the working volume of the pin puller produced by fully loaded VSIs to the pressure produced by VSIs in which a percentage of the propellant load had been removed (off-loaded). Reference 6 specifies the requirements of using off-loaded cartridges to demonstrate functional margin. Since the pin puller was still able to function with half the expected peak pressure, a functional margin of two was assumed. System-level frictional tests were successfully conducted. Seven units successfully passed environmental qualification. All of the approximately 150 units tested in the Viking program successfully functioned. None of the units were subjected to a post-test dissection evaluation.

Magellan Selection/Failures

Based on the success of the Viking program, the Magellan program selected this pin puller to release the spacecraft's solar panels. At least two lots of pin pullers were manufactured by the original supplier and to the original drawings for the development effort. Two NSI lots were used during development; NSI lot XPJ was selected for flight.

Early in the program, a functional failure occurred, as reported in reference 7. The pin had stroked approximately half the required distance. The force required to push the pin to the end of its stroke was approximately 50 pounds. An inspection revealed that the NSI port had not been chemical chromate coated, as required by drawing. Additional firings of deliberately uncoated units, and properly coated units showed that coated units produced consistently higher peak pressures, so the failure was considered resolved.

Within three more firings a second failure occurred. In this failure the pin stroked less than 0.02 inch. The dissection revealed that the web (defined in figure 1) in the port into which the NSI was fired was deformed and had gripped and locked the piston into place. This pin puller design was then abandoned in favor of another previously qualified design. There was no failure resolution.

HALOE Failure Investigation

The objective of this effort was to inspect recently fired units and to evaluate the functional parameters of the Viking pin puller. These firings were made with NSI lot XPJ.

Post-test examination - An x-ray examination revealed that the pin puller bores on all the Viking units had been drilled off-center by as much as 0.009 inch, thus causing the webs to vary by that amount. On removing the caps from the bodies of three pin pullers that had been fired with a single NSI, two units had not fully stroked to contact the end cap, and the third had just contacted without appreciably deforming the energy absorbing cup to achieve the locking function. The fourth unit had been fired in a non-standard mode with two simultaneously initiated NSIs. The energy absorbing cup in this unit was completely flattened. The cylinder bores indicated no appreciable web deflection in the NSI port bottom, and only minor scuffing on the walls. There were no obvious indications of blowby around the o-ring seals.

Evaluation of functional parameters - This test series included input energy drop tests and honeycomb crush energy output tests.

Drop tests conducted with well-lubricated o-rings indicated that approximately 25 inch-pounds were required to fail the shear pin (5 inch-pounds), stroke the piston/pin (static friction forces of 3 to 5 pounds) and lock it by slightly deforming the energy absorbing cup. Tests without lubrication required over 100 inch-pounds to stroke (static friction forces of 50 pounds). The o-rings actually had rolled up on their axes and had chunks of material torn from their bodies.

The results of drop tests to determine the crush characteristics of the energy absorbing cups are summarized in figure 4. The amount of crush increased linearly with both the initial (I series) 0.150 and a new procurement of 0.250-inch deep cups (DC series).

The results of the cartridge output series are shown in table I (reference 8). The NSI lot XPJ produced the highest and most consistent energy output, averaging 127 inch-pounds, with a standard deviation of 20 inch-pounds. The VSI with 99 and 21 inch-pounds, respectively, was the second highest and consistent. However, the NSI lot XDB exhibited a low and highly erratic output; the average was 53 inch-pounds with a standard deviation of 49 inch-pounds. The maximum was 137 inch-pounds and the minimum was 19.

The performance enhancement tests, table II, indicate considerably improved performance. The epoxy nozzles produced a 100 inch-pound increase in energy output in both the VSI and the NSI lot XDB. The BKNO3 charge produced an increase that was greater than 200 inch-pounds. The dual-VSI firing produced an increase that was greater than 200 inch-pounds.

Severe blowby was visually observed at all o-ring interfaces during the single firing of an NSI lot XPJ in a Viking pin puller. This unit had been previously drop-tested to measure its state of lubrication and reset to its original position. In the firing, the piston/pin stroked less than 0.020 inch and the web deformed and locked the piston, as had been experienced in the second Magellan failure. An examination revealed that a possible cause of the blowby was that the chemical chromate coating had rubbed off and adhered to the surface of the o-rings, preventing contact with the piston bore. The molybdenum disulfide coating had also likely wiped off of the pin and deposited on the pressure side of the pin's o-ring interface, preventing sealing. The previous drop test likely further aggravated these conditions.

In summary, the aluminum-bodied test series revealed that a considerable increase in energy required to stroke could be expected with less lubrication on o-ring interfaces. The chemical chromate and molybdenum disulfide coatings reduced the sealing reliability of o-ring interfaces. The aluminum body had a sensitivity to deformation. The steel-bodied test series revealed considerable output variation among VSI and NSI lots and that the combustion efficiency of all lots could be significantly enhanced by using an epoxy nozzle and an external BKNO3 booster charge. Also, the steel body exhibited none of the sensitivities to sealing or metal deformation. Finally, the use of a steel body met the requirement that the NSI energy output (127 inch-pounds for lot XPJ) was at least three times the energy required to stroke (25 inch-pounds).

HALOE Redesign/Functional Evaluation/Requalification

Based on the results of the failure investigation, the project office decision was to proceed with a steel-bodied configuration.

<u>Energy required to stroke tests</u> - Drop tests revealed that the 25 inch-pound energy requirement to stroke and lock the piston and the cup crush characteristics were the same between pin puller designs.

<u>Energy delivered by the NSI tests</u> - The energies measured in all functional tests of the HALOE pin puller are shown in table III. Energy delivery measurements were obtained in each firing by measuring the amount of crush occuring in the energy absorbing cups. The cup crush calibration of energy input versus cup crush (figure 4) was obtained from drop tests. Note that for tests 1 through 9, using the 0.154-inch

energy absorbing cup, the energy deliveries are greater than 120 inch-pounds. This is because all cups were fully crushed. This situation was not determined until late in the series, when in the dual cartridge firings (tests 8 and 9) the piston was deformed, even though the cup crush did not increase. Therefore, a 0.250-inch cup was selected. Accurate energy deliveries are shown in tests 10 through 15. The environmentally tested units, tests 16 through 25, produced comparable energy levels, excluding tests 17 and 18. A sympathetic initiation of the second cartridge (not an NSI) occurred in the opposite port in test 17. This second cartridge did not have sufficient thermal insulation to prevent such an initiation. Test 18 was a deliberate dual-NSI firing to determine the pin puller's pressure containment capability at +200 F under vacuum; the piston deformed as the cup bottomed out, but no venting occurred. The five pin pullers fired in the system tests produced significantly lower energy outputs than tests 10 through 25, which was attributed to pin loading.

<u>Functional</u> <u>margin</u> <u>analysis</u> - The functional margin for pyrotechnic devices is defined as follows:

$$\text{Functional Margin} = \frac{\text{Energy Deliverable} - \text{Energy Required}}{\text{Energy Required}}$$

Energy Deliverable is the average energy produced by the cartridge through firings under test conditions that are identical to the flight configuration.

Energy Required is the average energy required to function the device, measured through drop tests with flight hardware.

Therefore, Functional Margin is a ratio of the energy in excess of that required to accomplish the function to the energy required to accomplish the function. For the HALOE pin puller:

$$\text{Functional Margin} = \frac{165 - 25}{25} = 5.6$$

The average energy deliverable by the NSIs in the system tests was 165 inch-pounds. The energy required to stroke the piston was determined to be 25 inch-pounds in the drop tests.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations in regard to the two questions raised in the introduction are:

1. How could devices that passed qualification fail to perform?

For the Viking pin puller design, there was an inadequate demonstration of functional margin. That is, not enough information had been obtained on the influence of functional variables and how much energy was consumed by these variables in accomplishing the function. The Magellan failures occurred when production variables reduced the pin puller's performance below its functional threshold: 1) sliding friction increased, 2) o-rings seals were poor, 3) the combustion efficiency of the NSI was reduced, and 4) the aluminum housing deformed.

2. What can be done to minimize the risk of flight failures?

   Functional margin should be determined, comparing "energy deliverable" by a cartridge to the "energy required" for the device to function. The "energy deliverable" by the cartridge should be measured by firings in the actual device. "Energy required" should be determined by drop tests on the actual device.

A further conclusion is that the changes made to the pin puller design, specifically using steel instead of aluminum and using a more durable dry coating on the pin, significantly improved functional performance.

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TABLE I - ENERGY OUTPUT COMPARISONS OF VSI AND TWO NSI LOTS IN STEEL TEST PIN PULLER ENERGY SENSOR CONFIGURATION.

Ser. No.	Energy in-lb
Viking Standard Initiator, Lot No 13-32275, Mfd in 1972	
0500391	85
0500372	95
0300141	119
0300088	92
0500452	89
0500665	110
0500732	104
0500716	74
0500683	78
0500745	143
Average =	99
Std Dev =	21
Percent of Avg =	21%
NASA Standard Initiator, Lot XPJ, Mfd in 1985	
0384	107
0385	135
0398	143
0393	113
0392	122
0400	121
0414	165
0394	110
Average =	127
Std Dev =	20
Percent of Avg =	16%
NASA Standard Initiator, Lot XDB, Mfd in 1988	
0147	26
0144	19
0150	137
0149	31
0138	54
Average =	53
Std Dev =	49
Percent of Avg =	92%

TABLE II - PERFORMANCE ENHANCEMENT TESTS IN STEEL TEST PIN PULLER ENERGY SENSOR CONFIGURATION.

Ser. No.	Energy in-lb	Test Configuration	
		VSI with epoxy nozzle	
0500695	207		
0500380	271		
0500727	189		
0500755	210		
0500690	202		
Avg	216		
Std Dev	32		
% of Avg	15		
		NSI lot XDB with epoxy nozzle	
0121	111		
0154	257		
0152	128		
0118	192		
0148	144		
Avg	166		
Std Dev	59		
% of Avg	36		
		BKNO3 charge bonded to VSI output closure	
0300009	>270	40.5 milligrams	
0300139	>280	19.3	
0500685	310	20.1	Two honeycomb cubes stacked to double the measuring capability; o-rings still vented due to inadequate length of piston bore.
0500750	370	20.1	
0500389	392	20.0	
0500398	359	20.1	
0500698	320	20.0	
0500693	190	10.0	
		Dual VSI firing	
0500684	>360		Simultaneous initiation with 420 pound-strength honeycomb
0500718			

TABLE III - HALOE PIN PULLER FIRING TEST DATA (NSIs, LOT XPJ)

Test No.	NSI Ser. No.	Crush inch	Energy Delivery inch-pounds
Energy Absorbing Cup Size - 0.154 Inch			
In tests 1 through 9 the cups were fully crushed, producing energies that were greater than 120 inch-pounds.			
Energy Absorbing Cup Size - 0.250 Inch (Non-System Tests)			
10	0448	.124	189
11	0720	.138	210
12	0476	.126	192
13	0489	.123	188
14	0479	.130	198
15	0480	.118	180
		Avg =	193
		Std Dev =	10
		% of Avg =	5
Energy Absorbing Cup Size - 0.250 Inch (Environmentally Exposed Pin Pullers, Non-System Tests)			
16	0454	.102	156
17	0447/symp.*	.167	>254
18	0444/0446	.183	>278
19	0450	.120	183
20	0453	.117	179
21	0449	.128	195
22	0455	.138	210
23	0451	.110	168
24	0448	.107	164
25	0452	.135	206
		**Avg =	183
		Std Dev =	22
		percent of Avg =	12
Energy Absorbing Cup Size - 0.250 Inch (System Tests)			
26	0491	.115	176
27	0456	.096	147
28	0445	.089	136
29	0396	.115	176
30	0390	.124	189
		Avg =	165
		Std Dev =	22
		percent of avg =	13

*Wrong second cartridge installed. **Excluding tests 17, 18.

Viking PYRO OPERATED PIN PULLER — 1/4"

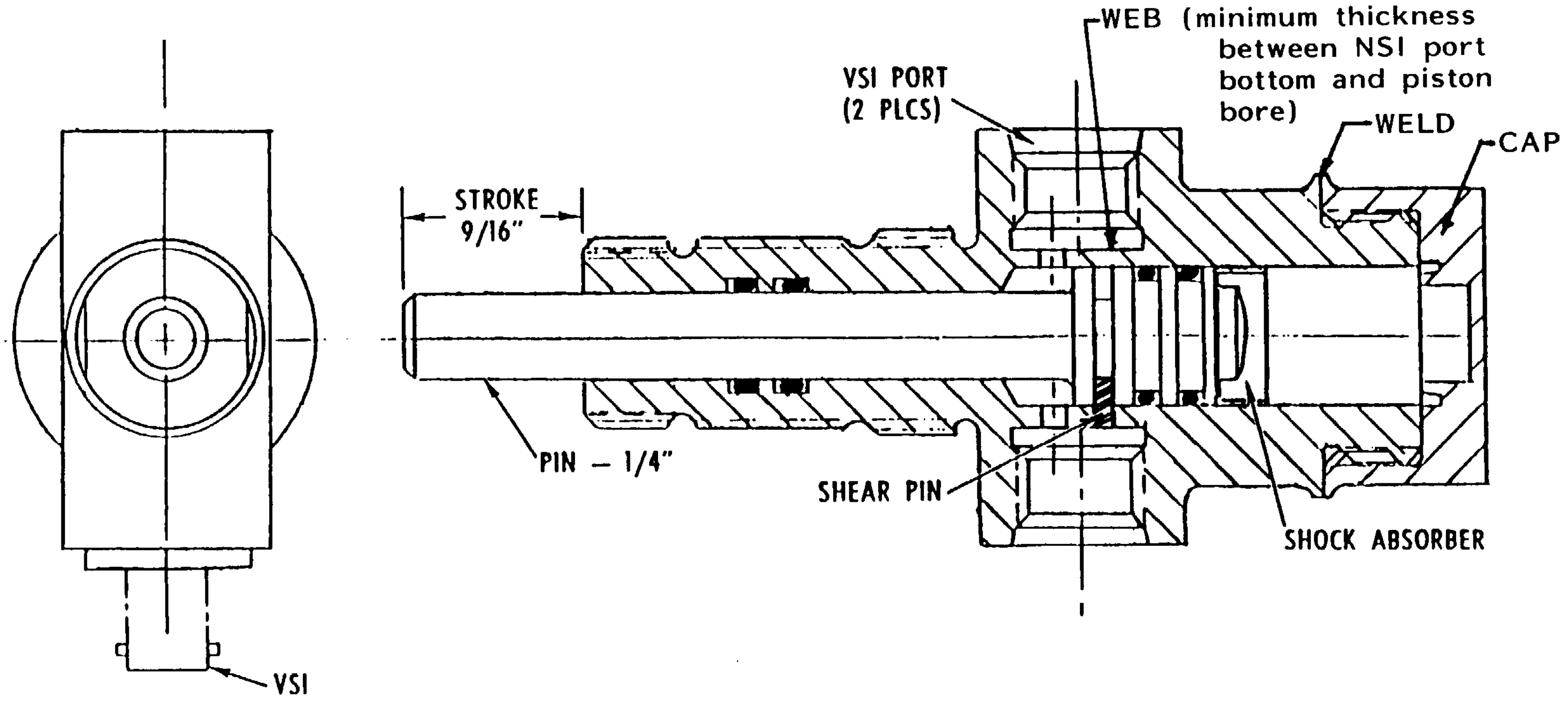

Figure 1.- Cross sectional view of aluminum-bodied Viking pin puller.

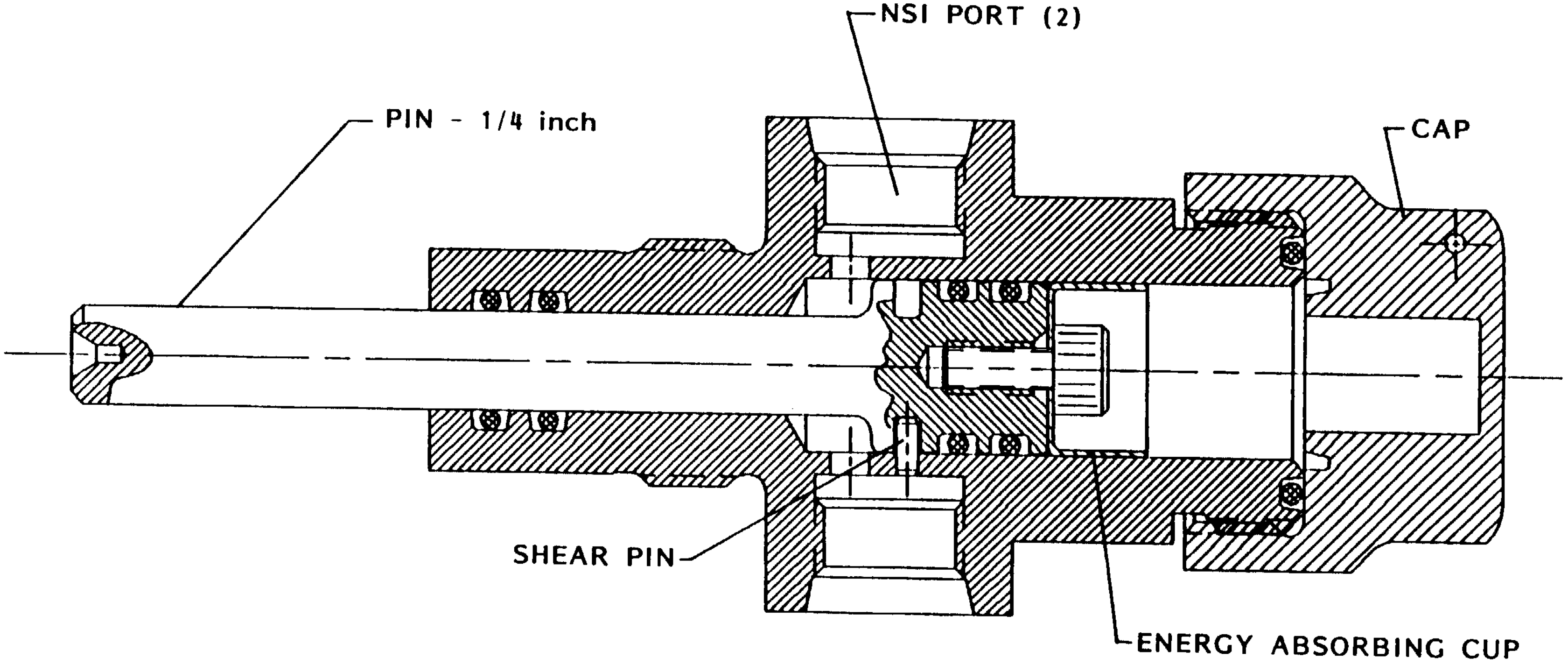

Figure 2.- Cross sectional view of steel-bodied HALOE pin puller.

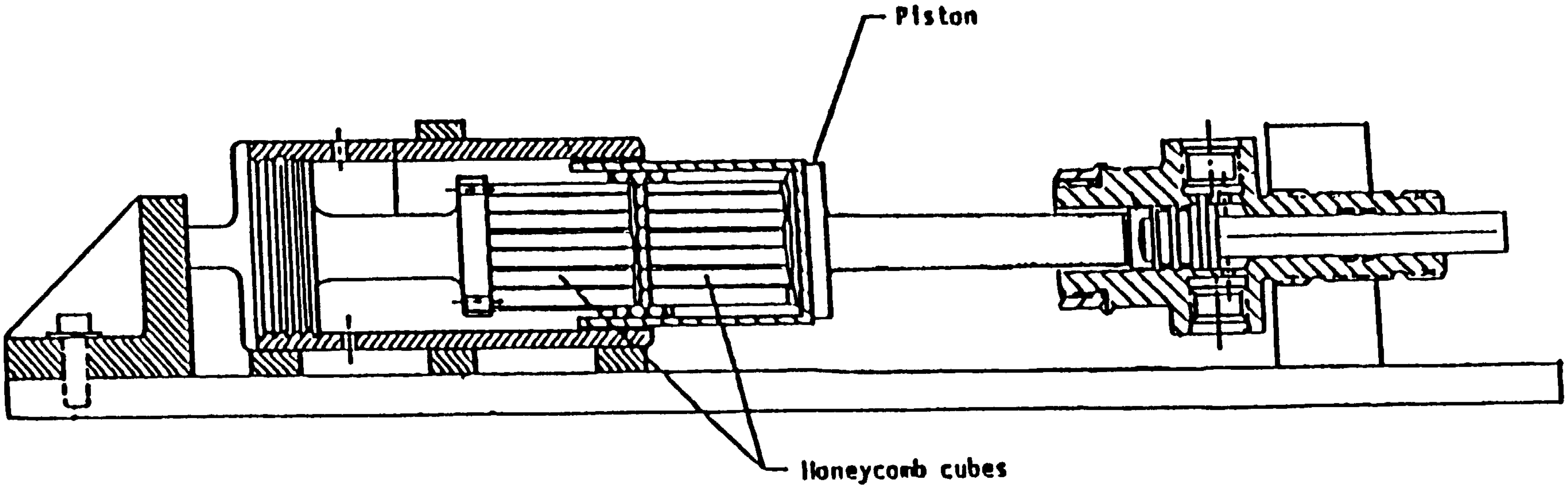

Figure 3.- Cross sectional view of energy sensor adapted to pin puller.

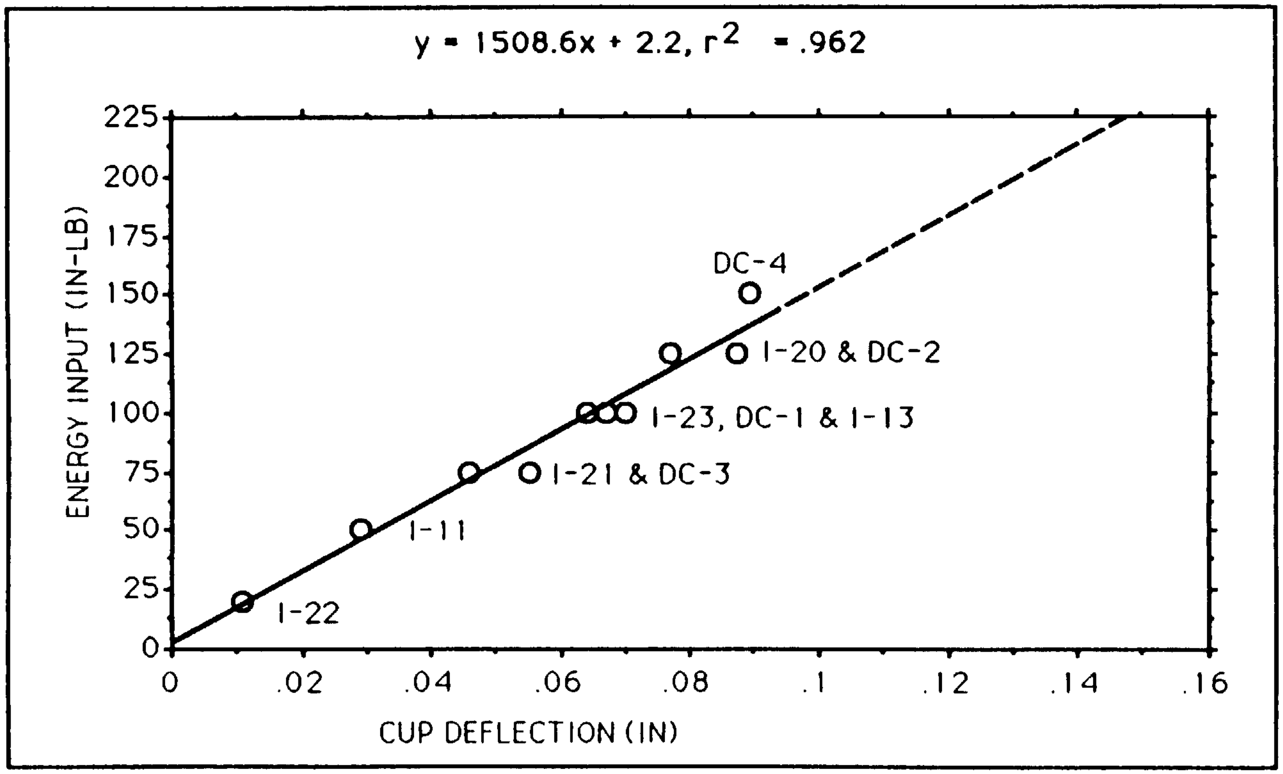

Figure 4.- Crush characteristics of the energy absorbing cups obtained by drop tests.