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INTEGRATION OF PYROTECHNICS INTO AEROSPACE SYSTEMS

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ABSTRACT

The application of pyrotechnics to aerospace systems has been resisted because normal engineering methods cannot be used in design and evaluation. Commonly used approaches for energy sources, such as electrical, hydraulic and pneumatic, do not apply to explosive and pyrotechnic devices. This paper introduces the unique characteristics of pyrotechnic devices, describes how functional evaluations can be conducted, and demonstrates an engineering approach for pyrotechnic integration. Logic is presented that allows evaluation of two basic types of pyrotechnic systems to demonstrate functional margin.

INTRODUCTION

The reluctance to use pyrotechnic devices (explosive and propellant-actuated mechanisms) is based on their unique functional characteristics and limited engineering approaches to pyrotechnic system integration. Although pyrotechnic devices have been successfully applied to a wide variety of mission-critical functions for aerospace systems, failures (references 1, 2 and 3) continue to occur. During the early development of the Space Shuttle, there was substantial resistance to the use of pyrotechnic devices. This resistance was based on one-shot devices being inappropriate for a reusable vehicle. Yet now more than 400 such devices fly on each Orbiter. Pyrotechnic devices: are single-shot, cannot be functioned prior to flight (such as repeatedly cycling an electrical switch), provide short-duration, impulsive outputs (microseconds to milliseconds), and contain explosive materials, requiring special safety considerations. For these reasons, the search for alternate mechanisms is understandable.

Adding to the resistance was the inability to apply approaches for design, test and evaluation that are used on conventional energy sources (electrical, hydraulic and pneumatic). Well-defined test methods and a logic to demonstrate system functional margins were not always available to support new pyrotechnic applications. For example, devices are sometimes qualified with a limited number of "go/no-go" tests. Consequently, systems could be marginal or overpowered. If marginal, unexpected failures could occur with changes in system variables. And if overpowered, other problems could occur, such as inadvertently actuating valves on the Apollo mission, reference 2, and inducing possible damage through structural deformation, fragmentation and pyrotechnic shock (references 4 and 5).

The objectives of this paper are to provide:

1. An introduction to pyrotechnic functional principles and test methods.
2. An engineering approach (with examples) for pyrotechnic integration, including demonstration of functional margin.

PYROTECHNIC FUNCTIONAL PRINCIPLES AND TEST METHODS

Pyrotechnics have been extensively applied, because of high efficiency in terms of long-term storable energy per unit volume and weight.

Some functions accomplished by pyrotechnic systems are:

* initiation	* release	* severance/fracture
* jettison	* valving	* switching
* time delay	* actuation	

The majority of pyrotechnically actuated mechanical functions are accomplished through piston/cylinder devices. Others are accomplished through the use of linear explosives.

<u>Piston/cylinder</u> <u>functional</u> <u>mechanisms</u> - Typical actuators, a thruster and a pin puller, are shown in figure 1 (reference 6). Firing the propellant-loaded, gas-generating cartridges pressurizes the volume behind the pistons to drive each pin from left to right. These actuators can be used to accomplish work by: thrusting or pulling against a force, jettisoning a mass, or working against a mechanism.

To measure the energy delivered in working against a constant force, the energy sensor apparatus, shown in figure 2 and described in references 7, 8 and 9, can be used. The actuator can be simulated by using the piston/cylinder configuration in the initiator firing block, or the actual device could be used. On firing the cartridge, the piston is driven against calibrated aluminum honeycomb cubes, which crush at a constant force. Multiplying the crush distance by the crush strength provides a measurement of energy delivered in inch-pounds. This apparatus, as shown, has been used to measure and compare the outputs of a variety of cartridges.

To measure the energy delivered in jettisoning a mass, the dynamic test device apparatus, shown in figure 3 and described in references 8 and 9, can be used. The piston in this case is a 1-pound, 1-inch diameter mass with an o-ring set to vent after a 1-inch stroke. Energy is obtained by measuring the velocity and calculating the kinetic energy, $1/2\ mv^2$. The pressure vs time history of the cartridge is also obtained in this apparatus for further comparison. Again, this apparatus provides a comparative test method to evaluate a variety of cartridges. Simulating or using the exact mass and piston/cylinder interface is critical for determining the energy deliverable in the actual production item.

<u>Linear explosive functional mechanisms</u> - Figure 4 (reference 6) shows the application of round cross-section explosive cord, called mild detonating cord (MDC), to sever or fracture structure. MDC is composed of a high-explosive core, encased in metal sheaths, such as lead, silver or aluminum. On initiation, the explosive combustion (detonation) proceeds along its length at a rate of about 25,000 feet/second. The detonation pressure (several million psi) is directed against the skin structure, as shown in the sketch on the left, to accomplish severance. Explosive products can be fully contained through the use of a flattened steel tube, as shown in the sketch on the right. Considerable energy is attenuated by the work required to expand the tube, so a notch is machined in the structure to focus the fracture point. Figure 5 (reference 6) shows flexible linear shaped charge (FLSC), which is also used to sever structure. Rather than a round cross section, the metal sheath has been shaped into a chevron. The explosive pressure wave leaves the source perpendicularly from the surface. The two legs of the chevron focus the pressure waves into a high-velocity jet of metal sheathing particles and gases, which penetrate the target structure. This penetration, in conjunction with the pressure wave, can sever structure without FLSC confinement.

The apparatus, shown in figure 6 (reference 8), was developed to measure the capability of linear explosives to accomplish severance as well as detonation and energy-delivery characteristics. The linear explosive is placed in a machined groove, which represents the backup structure shown in figure 4. A tapered plate of the same material to be severed for a particular application is placed on the linear explosive and is followed by the external backup structure (hold-down plate), which further enhances it's severance ability. The energy sensor, described in figure 2, is placed over a length of the explosive to measure the energy delivered. Timing circuit wires are placed across the explosive to measure the velocity of detonation propagation (typically 40 microseconds/foot) through supporting electronic timing circuits. The tapered plate provides a method of obtaining the maximum severance capability of the linear explosive in each firing. The thickest dimension of the plate is selected to assure that full severance is not achievable. Again, emphasis must be placed on simulating or using the flight structure to relate test results with expected system performance.

APPROACHES FOR PYROTECHNIC SYSTEM INTEGRATION

Following are two examples of the engineering evaluation of pyrotechnic devices. These efforts were prompted by failures (fortunately in non-flight evaluations) of two devices that had been fully qualified 20 years earlier.

The approach for these investigations was either: 1) measure and compare the energy required to accomplish the desired mechanical function with the energy deliverable from the pyrotechnic or explosive source; or 2) quantify functional performance. To obtain a reliable functional margin: 1) the energy deliverable must substantially exceed the energy required; or 2) the performance of key functional parameters must substantially exceed conditions allowed in flight hardware. In the following examples, functional margin based on an energy comparison was applied to the Viking pin puller; margin based on functional performance was applied to the Super*Zip separation joint.

Viking Pin Puller

The Viking pin puller released an antenna on the mission's Mars Lander. It's design and system variables are shown in figure 7, and the investigation is described in reference 3. Firing either cartridge first failed the shear pin and drove the piston from left to right to withdraw the pin. The shock absorber, a thin-walled steel crush cup, expanded on impact to lock the piston, remove the excess energy from the piston and reduce the pyrotechnic shock impulse.

Following failures in subsequent attempts to apply this same device to current spacecraft, an investigation was initiated.

<u>Energy required</u> - The energy required to stroke the piston/pin was determined by dropping small weights on the vertically oriented pin. The drop height, multiplied by the weight, produced a direct measurement of energy in inch-pounds. Furthermore, dropping these weights at heights of several feet, simulated the dynamics of an actual firing (3 ms for the drop tests versus 0.5 ms for the actual pyrotechnic function). Increasing the energy in subsequent drop tests provided a calibration of the shock absorbing crush cup.

The largest energy consumer was friction, particularly without lubrication of the o-rings. Without lubrication, the o-ring rolled on its axis and had material torn from its body, yielding an energy required to stroke of over 100 inch-pounds. For the properly lubricated flight hardware, the energy required to stroke was less than 20 inch-pounds. The total energy required to fail the shear pin, stroke the piston/pin and lock the energy absorbing cup was 25 inch-pounds.

Energy deliverable - The energy deliverable (measured by the crush of the steel shock absorber cup) by the cartridge was influenced by the housing material, the coatings on the pin and the interior housing and the o-ring seals.

Early firings at Langley Research Center of residual Viking hardware in three system-level tests indicated no excess energy. That is, the piston had not traveled its total possible stroke, or the shock absorber cup had just contacted the pin puller cap with no indication of crush.

Three different cartridge lots, manufactured to similar specifications in 1972 (the original Viking unit), 1985 and 1988, were functionally evaluated, using the honeycomb energy sensor placed against the stroking piston in a steel-bodied pin puller. Five to ten units tested in each group produced 99 inch-pounds with a standard deviation of 21; 127 with a standard deviation of 20; and 53 with a standard deviation of 49; respectively. These variations were caused by combustion inefficiencies, possibly by different particle sizes of the cartridge propellant materials. The 1985 lot was selected for flight.

As examples of design and manufacturing variables influencing energy deliveries, the first laboratory firing at Langley Research Center produced considerable melting and deformation of the bottom of the cartridge port. Also, blowby occurred around each set of o-rings. The blowby problem was caused by the coatings. Some of the molybdenum disulfide coating on the pin wiped off and was deposited on the pressurized side of the o-ring, preventing contact with the pin. This was corrected by using an electrodeposited nickel/Teflon coating. The soft chemical chromate coating on the piston bore wiped off on the o-rings, again preventing a seal. This was corrected by using a steel housing for the flight units. This problem was also corrected in later tests, using hard anodized aluminum housings.

The energy deliverable by the flight cartridges in system-level tests (functioned in a spacecraft interface with a maximum side load on the pin), as determined by the amount of shock absorber cup crush, averaged 165 inch-pounds.

Functional margin - The functional margin for the redesigned pin puller was determined as follows:

$$\text{Functional Margin} = \frac{\text{energy deliverable} - \text{energy required}}{\text{energy required}}$$

$$= \frac{165 - 25}{25} = 5.6$$

Lockheed Super*Zip Separation Joint

The Super*Zip separation joint has been used on a wide variety of rocket staging systems, including the release of the Inertial Upper Stage (IUS) from the Shuttle cargo bay. It's design and functional variables are shown in figure 8, and the investigation is described in reference 10. Initiating either explosive cord produces an explosive pressure wave that is transferred through the silicone rubber extrusion and steel tube to the 7075 aluminum doublers. Expansion of the steel tube fractures the doubler ligaments.

Functional Parameters - Since this design did not permit an energy comparison, functional parameters were quantified and compared. The key parameters were explosive load and doubler severability. A standard tapered witness plate, was used to quantify severance (reference 10).

Explosive load - The influence of the explosive on joint severance was established by determining the functional limits of the system. The minimum explosive load that could fracture the worst-case joint conditions (maximum thickness) was determined to be 7.5 grains/foot. Since the tube ruptured at 11 grains/foot, the maximum allowable explosive load was set at 10 grains/foot. The flight load was controlled at a maximum of 10 grains/foot and a minimum of 9.5 grains/foot.

Doubler severability - Of the total of 18 variables evaluated, the primary functional parameters proved to be the mechanical properties of the doublers, the web thickness (thickness of the doubler at the edge of the fasteners), and the ligament thickness. The aluminum doubler was heat treated (annealed) from 7075-T6, a fracture-sensitive condition to 7075-T73, a fracture-resistant condition to avoid stress-corrosion. The web thickness was critical, because the plates had to bend to induce the tensile failure at the ligament. Failures occurred in ground tests of a complete separation joint at doubler thicknesses of 0.083 to 0.086 inch. Tapered plate tests, using a nominal explosive load for the redesigned joint, demonstrated that the maximum thickness of the doubler to allow ligament fracture was 0.098 inch; the maximum allowable thickness of the doubler for flight was 0.082 inch.

Functional margin - The functional margin for this system was analyzed based both on explosive load and on web thickness.

For explosive load, functional margin is:

$$\frac{\text{minimum flight load} - \text{min. load to break thickest doubler}}{\text{min. load to break thickest doubler}}$$

$$= \frac{9.5 - 7.5}{7.5} = 0.27$$

For web thickness, recognizing that the bending moment to deflect beams is proportional to the thickness of the beam, cubed, and assuming that the web behaves in that manner through failure, Functional Margin is:

$$\frac{(\text{minimum thickness severed})^3 - (\text{max. allowable thickness})^3}{(\text{Maximum allowable thickness})^3}$$

$$= \frac{(0.098)^3 - (0.082)^3}{(0.082)^3} = 0.71$$

These margin equations indicate: 1) the minimum flight explosive load is 27% greater than that required to sever the thickest flight doubler, and 2) the severing capability of the doublers in this joint is 71% greater than the flight doublers.

CONCLUSIONS AND RECOMMENDATIONS

Engineering test methods and logic have been demonstrated to integrate pyrotechnics into aerospace systems by providing quantitative assessments of performance and functional margin. The unique characteristics of pyrotechnics (single shot, inability to evaluate flight units functionally, and short-duration, dynamic delivery of output) require a quantitative approach for evaluation and analysis. Principles of pyrotechnic performance, test methods and functional analysis have been explained and justified in this paper by providing examples of investigations of two pyrotechnic designs that had failed to function 20 years after their initial qualification. The cause of these failures was demonstrated to be that adequate functional margins had not been achieved in the original designs. In the case of the pin puller, the initial design could not accommodate lot-to-lot variations in cartridges, combined with improper o-ring seals. In the case of the separation joint, the design had inadequate functional margin to accommodate changes in the properties and thicknesses of the material to be fractured.

To avoid such failures, it is recommended that variables of a pyrotechnic system be evaluated and functional margins established. Tests should be conducted with flight-representative hardware and functional dynamics to either: 1) measure and compare the energy delivery capability of the explosive or pyrotechnic power source to the energy required by the mechanical function, or 2) quantify and compare key functional performance parameters.

REFERENCES

1. Bement, Laurence J.: "Pyrotechnic System Failures: Causes and Prevention." NASA TM 100633, June 1988.

2. "Flight Separation Mechanisms." NASA Space Vehicle Design Criteria. NASA SP-8056, October 1970.

3. Bement, Laurence J. and Schimmel, Morry L.: "Determination of Pyrotechnic Functional Margin." Presented at the 1991 SAFE Symposium, Las Vegas, NV November 11-14, 1991.

4. Bement, Laurence J. and Neubert, Dr. Vernon H. (Pennsylvania State University): "Development of Low-Shock Pyrotechnic Separation Nuts." Presented at the Eighth Aerospace Mechanisms Symposium, NASA LaRC, Hampton, VA; October 18 and 19, 1973.

5. Evans, Maria J.; Neubert, Vernon H.; Bement, Laurence J.: "Measurement, Data Analysis, and Prediction of Pyrotechnic Shock from Pin Pullers and Separation Joints." Presented at the 57th Shock and Vibration Symposium, New Orleans, LA, October 14-16, 1986.

6. Lake, E. R, Thompson, S. J., and Drexelius, V. W.: "A Study of the Role of Pyrotechnic Systems on the Space Shuttle Program." NASA CR-2292.

7. Schimmel, M. L. and Drexelius, V. W.: "Measurement of Explosive Output." Proceedings of the Fifth Symposium on Explosive Devices, June, 1967.

8. Bement, Laurence J.: "Monitoring of Explosive/Pyrotechnic Performance." Presented at the Seventh Symposium on Explosive and Pyrotechnics, Philadelphia, PA, September 8-9, 1971.

9. Bement, Laurence J. and Schimmel, Morry L.: "Cartridge Output Testing: Methods to Overcome Closed-Bomb Shortcomings." Presented at the 1990 SAFE Symposium, San Antonio, TX, December 11-13, 1990.

10. Bement, Laurence J. and Schimmel, Morry L.: "Investigation of Super*Zip Separation Joint." NASA TM 4031, May, 1988.

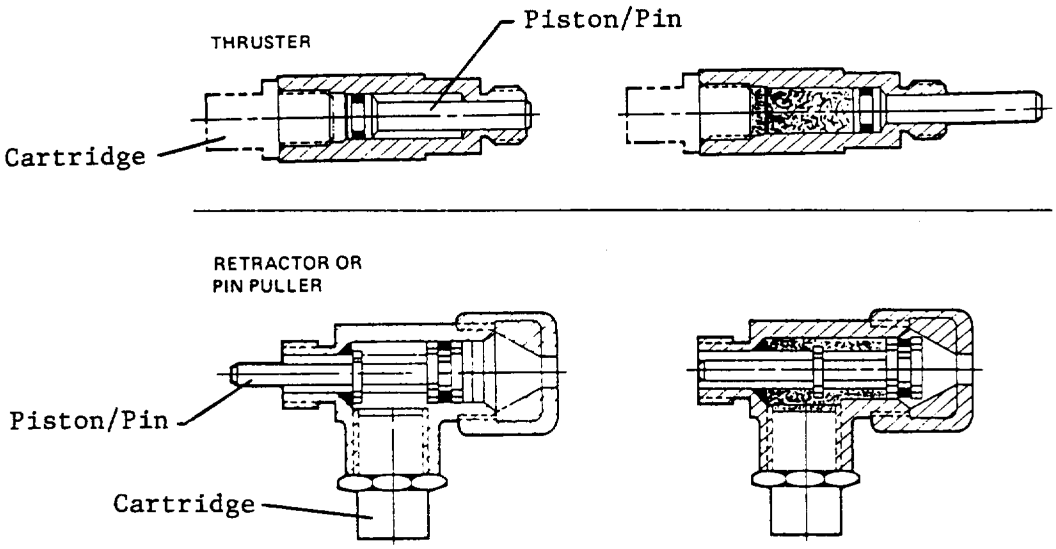

Figure 1.- Typical propellant-powered actuators.

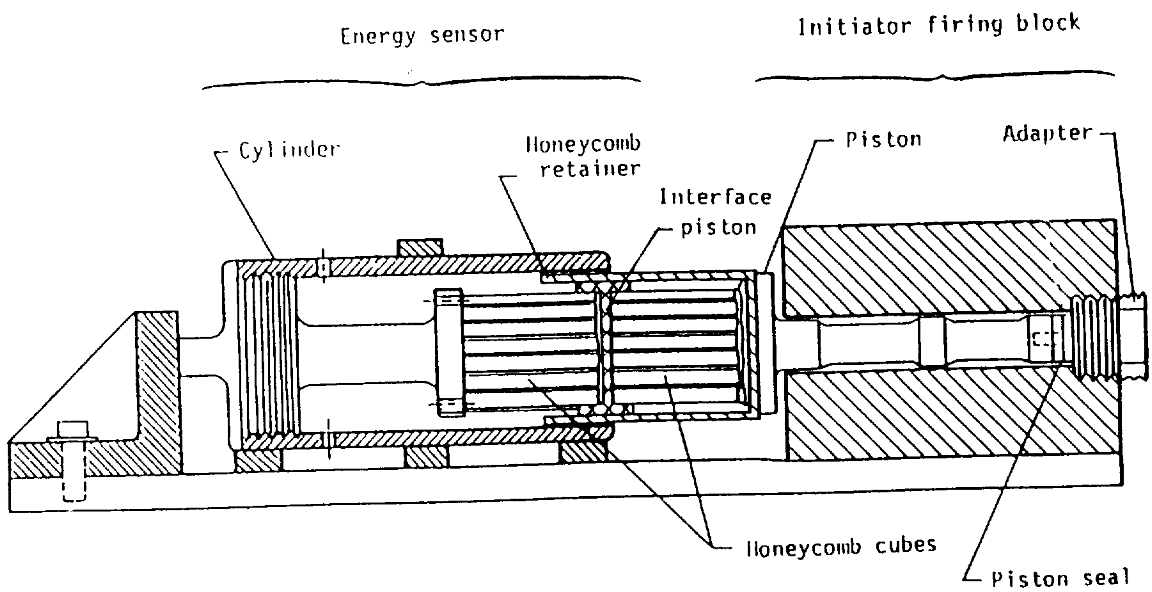

Figure 2.- McDonnell energy output test fixture.

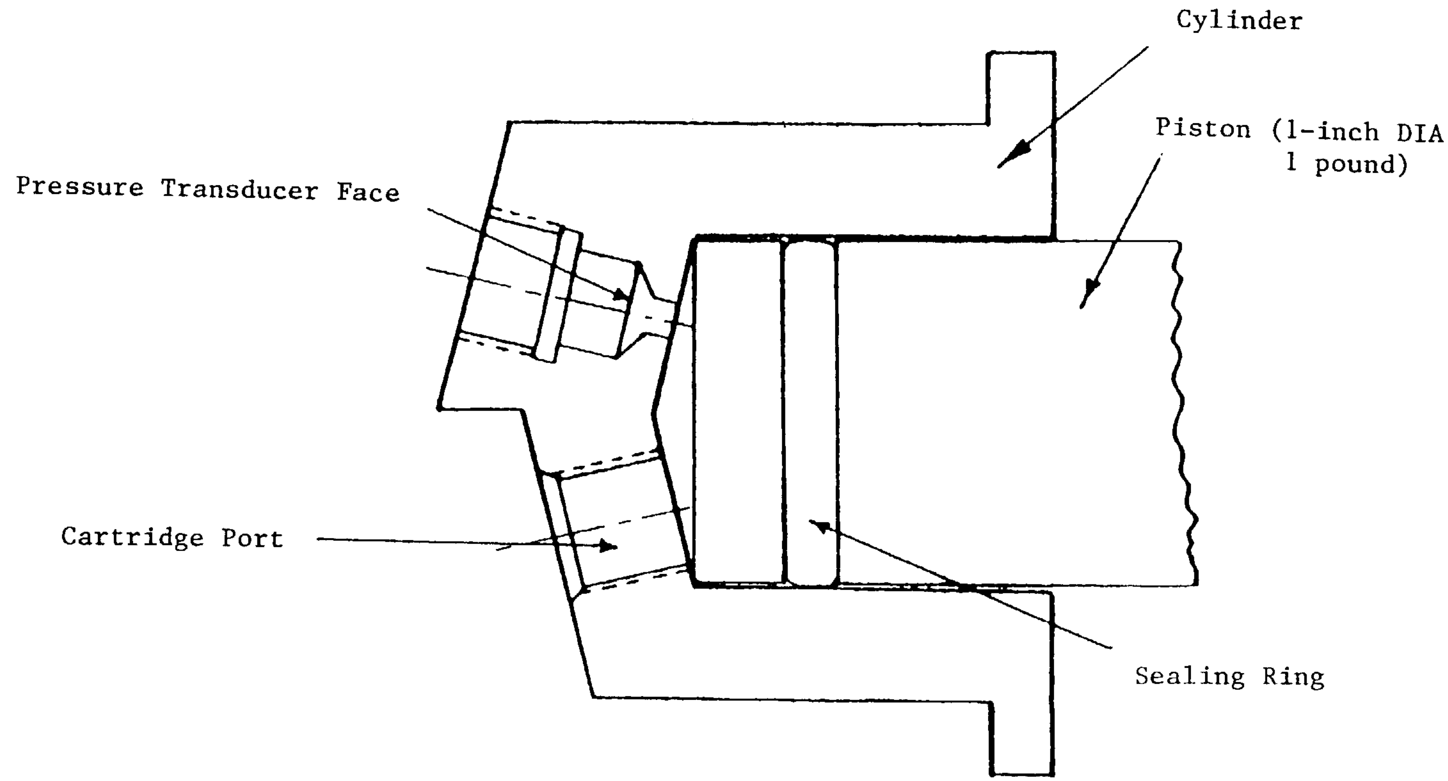

Figure 3.- NASA LaRC dynamic test device.

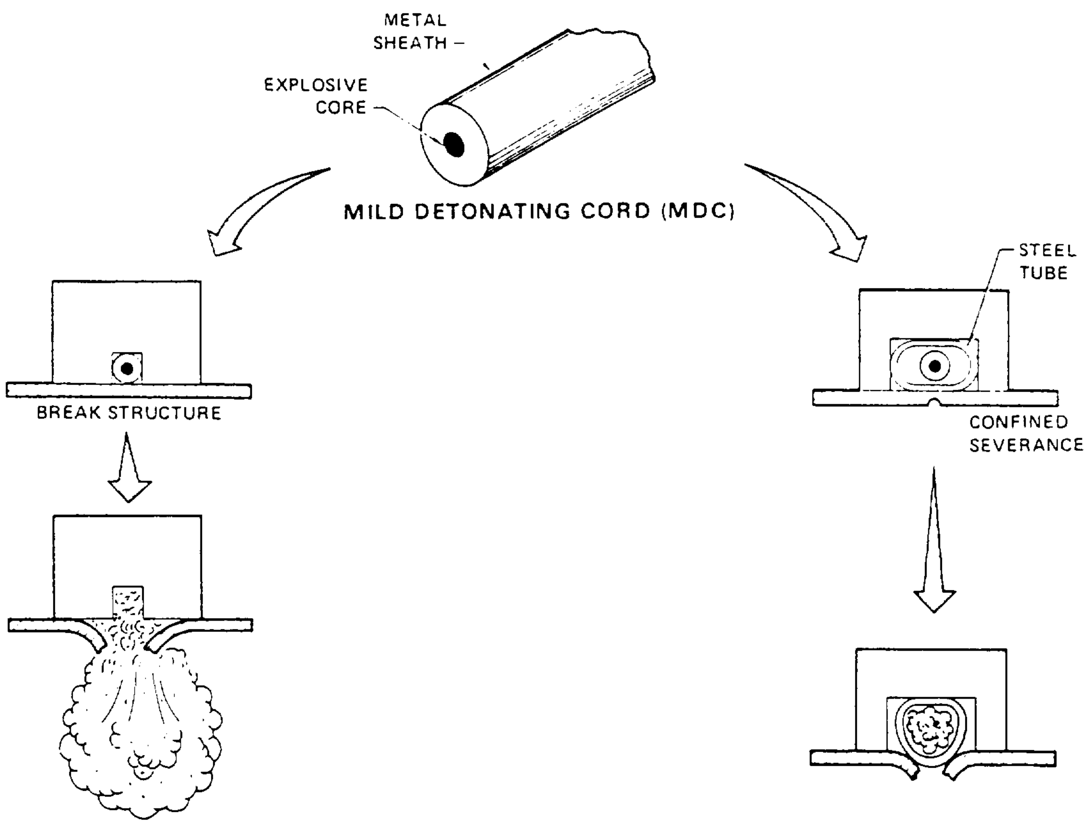

Figure 4.- Linear explosive (MDC) applications.

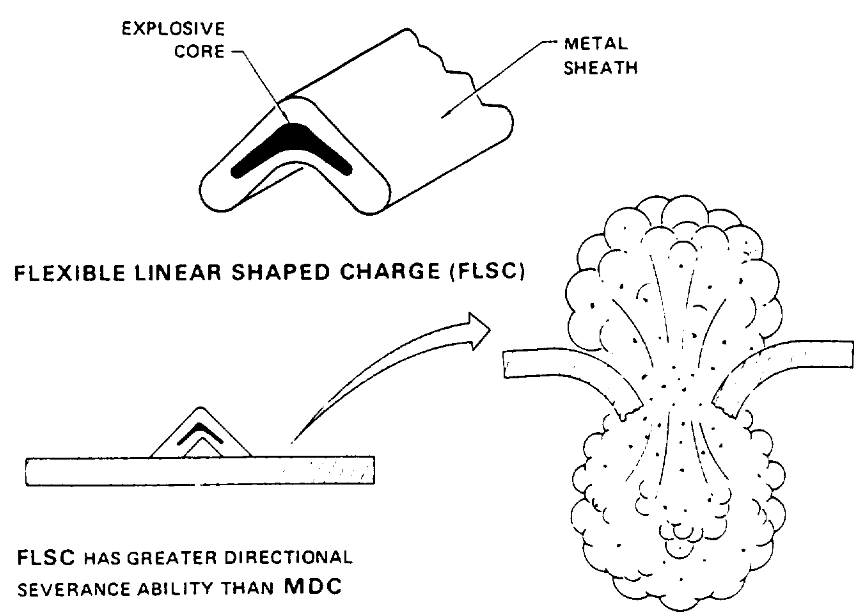

Figure 5.- Linear explosive (FLSC) application.

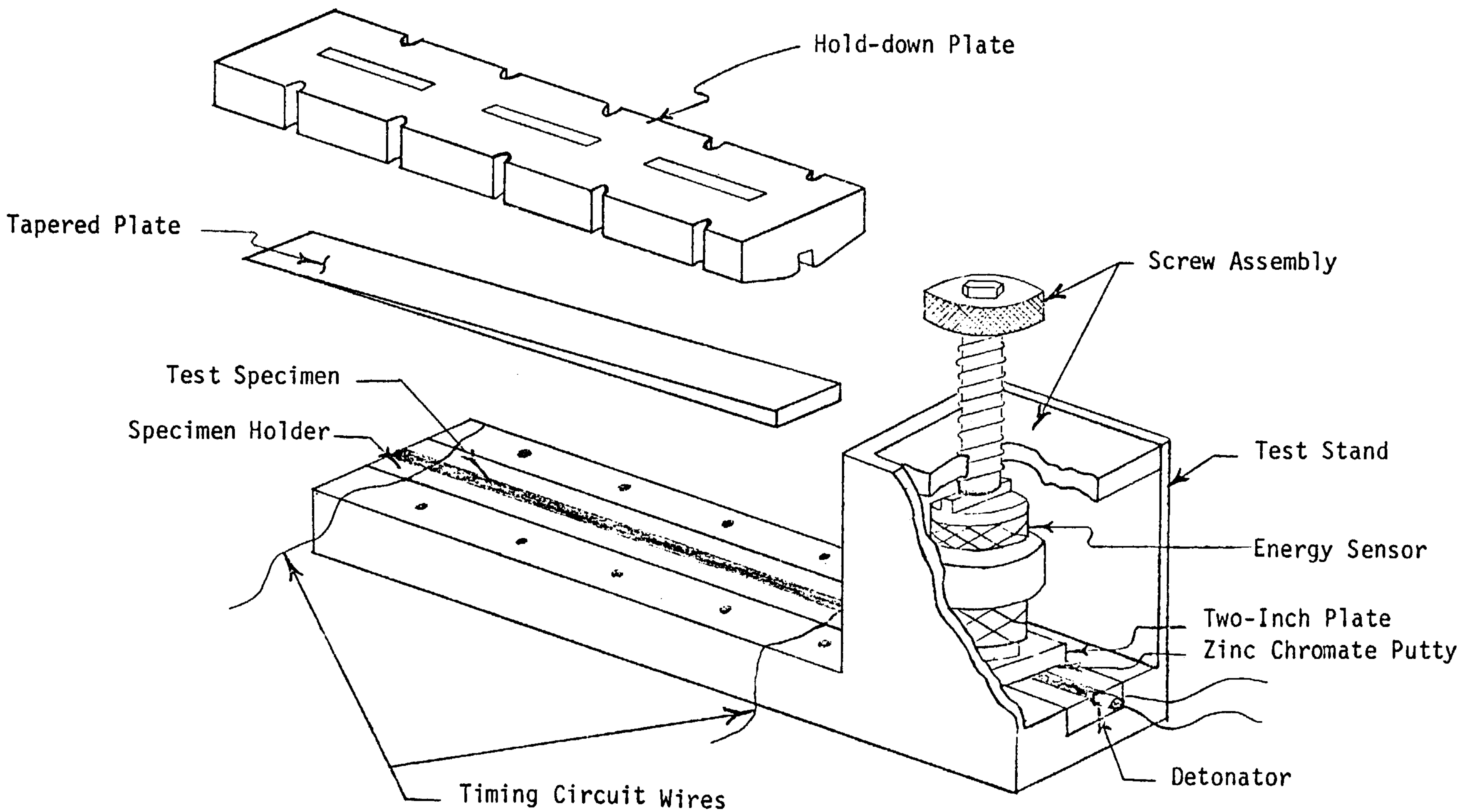

Figure 6.- Linear explosive test fixture.

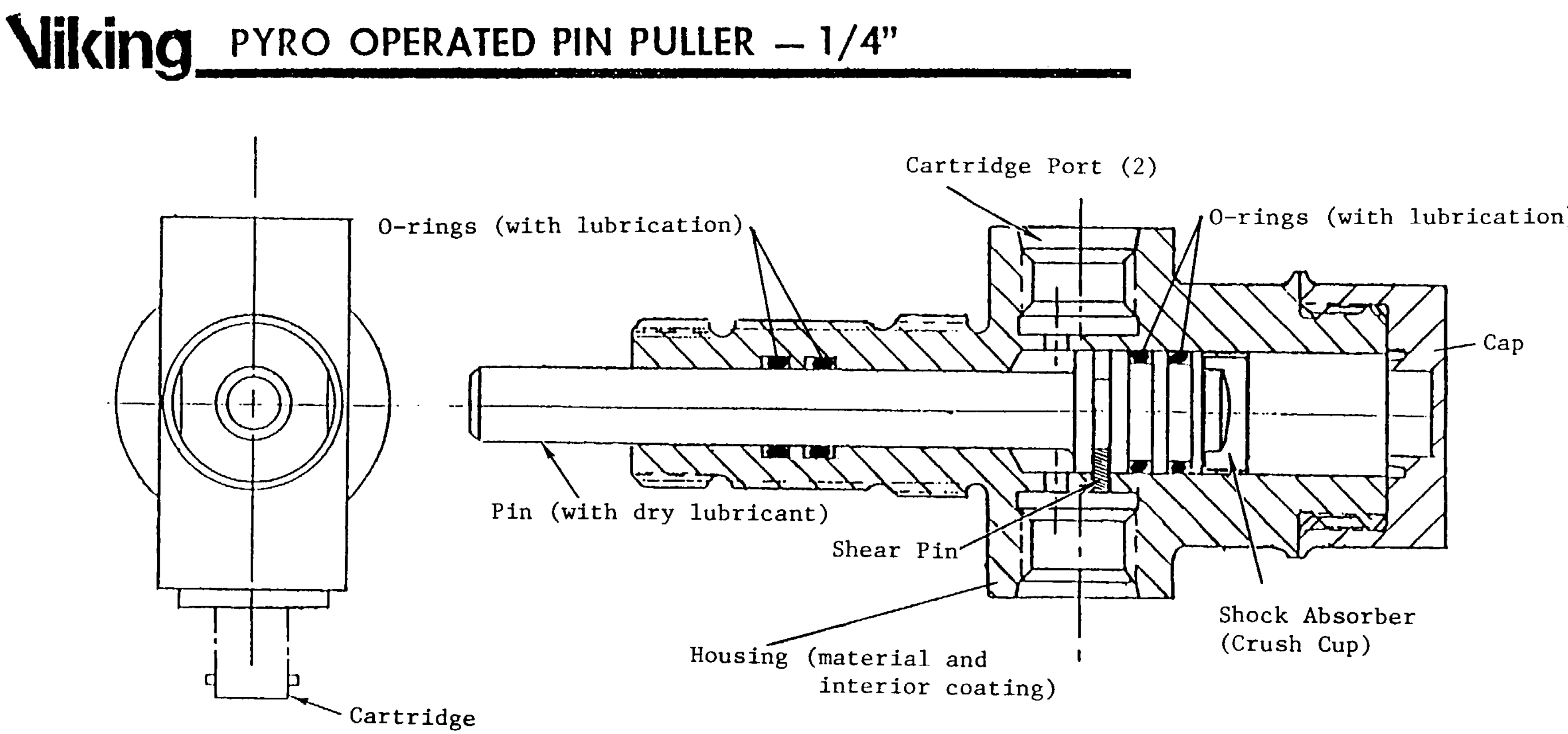

Figure 7.- Viking pin puller design and functional variables.

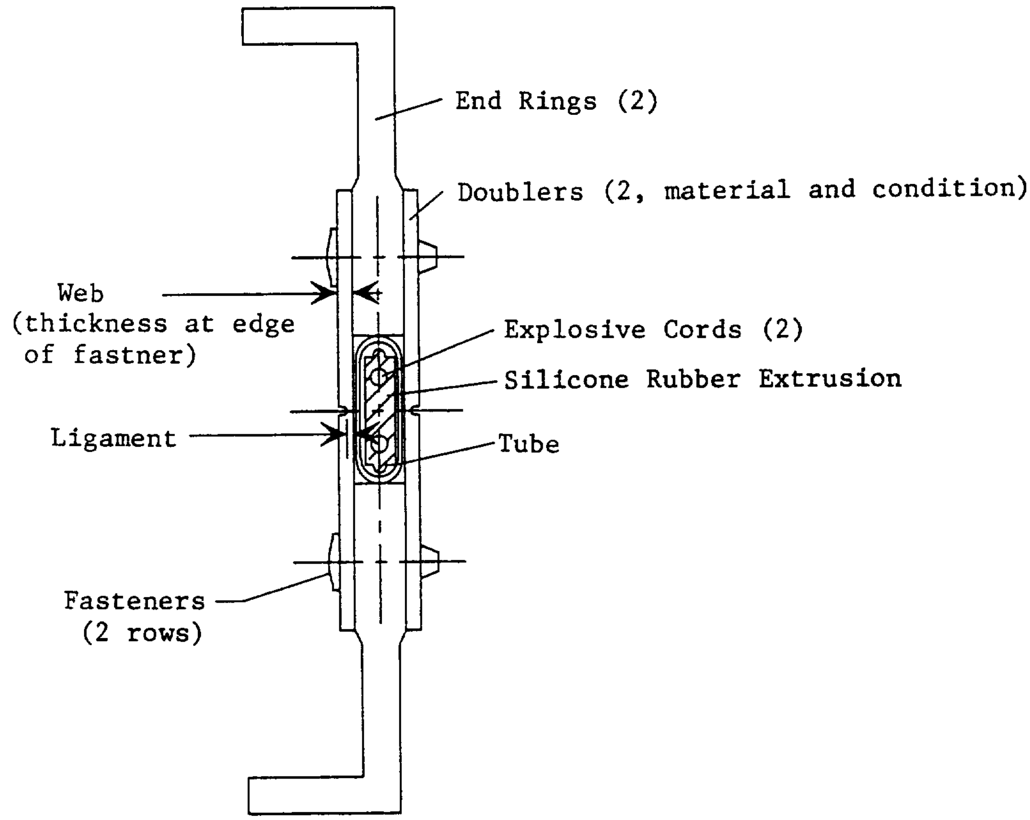

Figure 8.- Super*Zip separation joint design and functional variables.