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APOLLO COUCH ENERGY ABSORBERS

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ABSTRACT

Load attenuators for the Apollo spacecraft crew couch and the potential applications thereof are described in this report. Energy absorption is achieved through friction and cyclic deformation of material. In one concept, energy absorption is accomplished by rolling a compressed ring of metal between two surfaces. In another concept, energy is absorbed by forcing a plastically deformed washer along a rod. Among the design problems that had to be solved were material selection, fatigue life, ring slippage, lubrication, and friction loading.

INTRODUCTION

Landing conditions and allowable stroking distances within the Apollo spacecraft necessitated that the crew couch struts (1) be designed to a close tolerance on the stroking force, (2) be designed to absorb energy in both directions, and (3) be designed to control the deceleration-onset rate to reduce the secondary impact of the crewman striking the couch.

The struts designed to meet these requirements incorporated two concepts of energy absorption: cyclic deformation of metal (ref. 1) and metal-to-metal friction (ref. 2). Impact protection of the Apollo crewman during land landing was accomplished by supporting the crew couch on load-attenuating struts (fig. 1). Cyclic deformation of metal (cyclic strut) is the principle energy absorber for the X-X and Z-Z struts. To overcome the overshoot problem inherent in constant-load absorbers, the low-onset device was added to the cyclic strut (fig. 2). The load/time characteristics of the two types of struts are shown in figures 3 and 4. Although the initial onset rate of loading up to "breakout" was approximately the same for both struts, the primary difference between the two was the breakout. As shown in figure 4, this point is lower than the nominal stroke load, and the rate of loading is controllable between breakout and nominal. With this application, the maximum load was never higher than nominal.

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PRINCIPLE OF OPERATION

Cyclic Strut

The concept of continuous material deformation in the plastic range for energy absorption is used in the cyclic strut. Material is deformed by rolling a ring of metal (reaction ring) between an inner and an outer tube (fig. 5). When the space between the tubes is less than the diameter of the ring, the ring is forced "out-of-round," thus absorbing energy as it rolls. Because the ring is free to roll in either direction, load attenuation occurs for compression or tension and at any position of the strut. The reaction load was controlled by varying the number of reaction rings installed. Heat-treated, high-strength bearing rings are located at each end of the gang of reaction rings to maintain concentricity of the tubes and to control the deflection of the reaction rings.

Low-Onset Device

The low-onset device consists of a slender, hard rod of very uniform diameter onto which has been pressed a series of washers. The washers are forced onto the straight portion of the rod, thus causing the washer to be deformed plastically and elastically and thereby maintaining a "squeeze" on the rod. When the washer is forced to slide along the rod, drag occurs from metal-to-metal friction and energy is absorbed.

The total load (or total energy consumed) is the cumulative effect of all the washers stroking along the rod. If spaces are left between the washers, the load is increased each time a washer is picked up and pushed along the rod. This incremental loading produces an approximate ramp function of the applied force, which, for a given mass, reduces the deceleration-onset rate as shown in figure 4. Thus, the deceleration-onset rate of a mass can be controlled by selecting the appropriate washer spacing, and the magnitude of the deceleration can be controlled by selecting the proper number of washers. The energy-absorption capacity of this device is very great. Conventional brakes, for example, absorb approximately 58 W/cm^2 of contact area, while this device absorbs 1250 W/cm^2.

DESIGN AND DEVELOPMENT

In the initial design of the struts, the stroking-load levels were calculated for attenuating a rigid single mass; final values were determined by full-scale impact testing of the Apollo command module and the couch/strut system. Strut loads were verified by impact tests and on a controllable stroking machine to determine the precise load levels during development.

Cyclic Strut

Parameters for the reaction-ring elements necessary for the design of the strut, which are deformed into the plastic-deformation range of the material, are defined in reference 3. The parameters evolved from a consideration of the mechanics of the cyclic plastic deformation of a thin-walled ring or of tube elements; a first-order correction was applied to account for the effect of wall thickness. The parameters were substantiated by predevelopment tests.

The selection of a material for cyclic-strut reaction rings was based on the amount of energy per unit volume of steel that could be absorbed for a given stroke distance. A series of screening tests was conducted on different materials, and the most efficient material in terms of energy absorption was found to be 18 nickel maraging steel.

During design-verification testing of the struts, several failures were noted with regard to ring slippage, and a program was undertaken to identify the failure mode. The conclusion from testing was to grit-blast both the inner and outer tubes of the strut and the ring tractive surface for an optimal friction surface. Also, the ratio of squeeze force to roll force should be selected so that the sliding-friction force is always greater than the roll force.

A strong tendency was observed for highly deflected reaction rings assembled on bracelets to deflect in a preferential manner (to not load share) that caused the tubes to become eccentric. The reaction-ring material tended to "neck down" and deform locally on the rings at first flexure, while reaction rings on opposite sides of the bracelet were not deflected evenly. The solution for this problem was as follows.

1. Hold the tubes centered with additional bearing bracelets.

2. Limit the energy absorption of reaction rings so that the slope of the load-deflection curve gives a reliable centering force, as determined by test.

3. Size the tube-wall thickness by testing so that the reaction rings that had been cycled would hold the tubes concentric.

The final design of the cyclic strut was held to a breakout load of 10 percent over nominal and a stroking load of ±5 percent of nominal. The total stroking life of the cyclic struts was proved to be a minimum of 254 centimeters of stroke, which allowed preinstallation testing to determine the actual stroking-load value.

Low-Onset Device

The low-onset device used for the Apollo spacecraft is shown in figure 6. This device consisted of a slender, straight, smooth, and relatively hard rod 46.45 centimeters long and 9.5 millimeters in diameter, with 76 washers on 0.304-centimeter centers for tension stroking and 26 washers on 0.174-centimeter centers for compression stroking.

To maintain consistent loading as the washers slid along the rod, the diameter of the rod was held to ±0.012 millimeter, with the variations in diameter from end to end not to exceed 0.0025 millimeter. The material selected for this design was Inconel 718, which is a relatively new nickel-chromium base alloy having excellent mechanical, thermal, and friction properties. The rod was also heat-treated to a 40 Rockwell C hardness and surface-ground and polished to a fine finish.

The proper amount of "squeeze" by the washer on the rod was obtained by machining the inside diameter of the washer 2-1/2 percent smaller than the rod diameter. The washer was sized to an inside diameter of 9.30 millimeters, an outside diameter of 15.9 millimeters, and a thickness of 1.0 millimeter. The overall tolerances of the washers were maintained at ±0.025 millimeter.

For the washers, several materials were considered, but only 304 and 416 stainless steel were tested. The 416 stainless steel was determined to be satisfactory. After machining from process-annealed stock, the washers were fully annealed and then cooled at an appropriate rate for 416 stainless steel. Annealing and cooling must be done in an inert-gas atmosphere.

The selection and application of the correct lubricant was also necessary for this energy absorber to function properly, because it is a friction device. Several oils and greases were tried but discarded because of high-stick-slip tendencies. A spray-type dry-film lubricant worked successfully with high repeatability.

Before assembly, the rod and washers had to be completely degreased with Freon and then handled only with gloves to avoid contamination. Lubricant had to be sprayed thoroughly onto the rod before each washer was installed, and the assembly had to be sprayed thoroughly again before it was installed in the strut.

An approximate solution for the stroking load of the washer can be found by considering the deformation of a thick-walled cylinder for a perfectly plastic material. The internal pressure p necessary to deform the entire cylinder plastically is given (ref. 4) in terms of the yield stress σ_y and the natural logarithm of the ratio of the outside and inside radii b/a as

$$p = \sigma_y \ln b/a \tag{1}$$

This solution can be applied without much loss of accuracy to the washer. As shown in figure 7, the force F required to stroke the washer along the rod of diameter d and thickness h is then

$$F = \mu p d h \tag{2}$$

where μ is the coefficient of friction. For the values $a = 4.65$ millimeters, $b = 7.93$ millimeters, $d = 9.53$ millimeters, and $h = 1$ millimeter, $\sigma_y = 276\ \mathrm{N/mm^2}$.

The pressure and stroking load are 148 N/mm^2 and 4500 μN, respectively. For boundary lubrication under carefully controlled conditions, the coefficient of friction generally ranges from 0.05 to 0.15, in which case the stroking load is between 225 and 675 newtons.

Preliminary testing of the low-onset device was conducted on a simple, single-mass system to determine the feasibility, best design features (materials and lubricants), and preliminary-design data. More advanced testing was conducted by using a two-mass system that closely simulated spacecraft landing impacts.

A typical load-stroke curve resulting from a full complement of 76 washers is shown in figure 8. As shown, the load is initially higher than desired; in midstroke, it is lower than desired. The load then rises at the end of the stroke. This performance is indicative of the velocity effects on the coefficient of friction but does not degrade the basic ability to absorb energy.

POTENTIAL APPLICATION

These energy absorbers could be applied specifically to the automobile industry. As automobile bumpers, two 40 295-newton struts would attenuate a 2055-kilogram vehicle within 15.24 centimeters at a velocity of 10.9 m/sec and maintain the acceleration on the passengers at the level acceptable for spacecraft landing. With the application of a low-onset device to automobile struts, the deceleration-onset rate could be controlled, which would decrease the difference in velocity between the passenger and the vehicle, thereby reducing the secondary impact. By installing a low-onset device on the passenger seat, the secondary impact could be reduced further.

Other potential applications for the energy absorber are telescoping steering columns, vehicle seats, packaging of delicate instruments, and air dropping of cargo.

CONCLUDING REMARKS

The cyclic concepts described herein allow energy absorbers to be fabricated with precise stroking loads and with the added advantages of pretesting and absorption in both tension and compression.

The low-onset device is a simple device that is readily assembled for any desired load level and rate of onset. The combination of a cyclic strut and a low-onset device results in a strut that will start stroking at a level lower than the nominal stroke level and will build up to maximum stroke value at a desired rate. This combination allows impact loading to be applied without initial overshoot.

DISCUSSION

G. W. H. Stevens:

With reference to the problem of slippage of the central rod over the rings, one would expect that, at some level of acceleration, the inertia of the rings would have an influence on the slippage. Is there any information on this point?

Drexel:

The inertia does have an influence on ring slippage; however, because the inertia could not be changed, grit blasting the rings and properly selecting the squeeze force eliminated slippage up to an onset rate of loading 1.5 times our expected rate. The inertia does have an effect on the overshoot of initial load. Our tests resulted in 10-percent overshoot at a 2.5×10^{6} lb/sec onset rate and in 20-percent overshoot at a 4.8×10^{6} lb/sec onset rate.

G. W. H. Stevens:

Can you give any information on the efficiency, specific energy absorption, of both ring and low-onset shock-absorber units (that is, work done per full stroke against the weight of units)?

Drexel:

Cyclic attenuators have been tested successfully up to a force value of 16 000 pounds with a weight of 14.5 pounds. The cyclic attenuator has a total cumulative stroking life of 100 inches (tension and compression) while maintaining the force value within 5 percent of the nominal stroke value. Attenuators have been tested to 200 inches of stroking before the force value fell below the 5-percent margin. Based on the 100-inch stroke life, the efficiency of the largest unit we have tested is 9195 ft-lb/lb. The low-onset device used in our application absorbed 26 000 inch-pounds and weighed 1.5 pounds. This, of course, does not include the weight of a mechanism to actuate the device because this weight is included in the cyclic attenuator. For our applications, the device has an efficiency of 1450 ft-lb/lb for a single tension stroke.

M. M. Creel:

Have tests been conducted to determine the effect of long-term aging or corrosion (that is, metal to metal fusion) on the low-onset device?

Drexel:

No specific tests have been conducted on unprotected attenuators. The spacecraft attenuators are assembled in an inert atmosphere and are sealed. Tests have been conducted on a sealed unit after 2.5 years of storage, and the resulting stroking force was within the allowable limits, indicating no effect from aging.

REFERENCES

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4. Timoshenko, S.: Strength of Materials. Part II, Advanced Theory and Problems. Third ed., D. Van Nostrand Co., Inc., 1956, pp. 386-392.

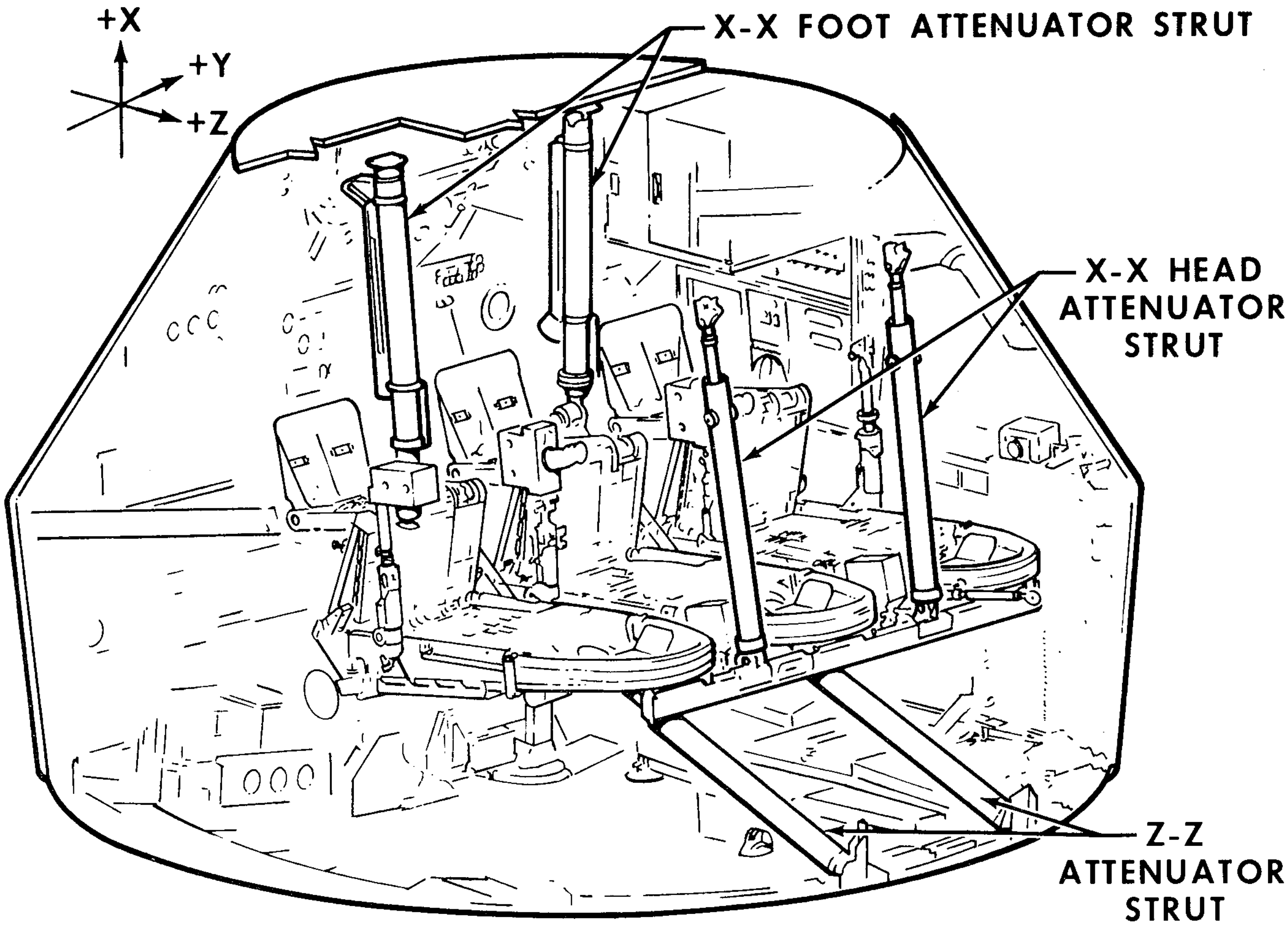

Figure 1. - Apollo load-attenuation-strut configuration.

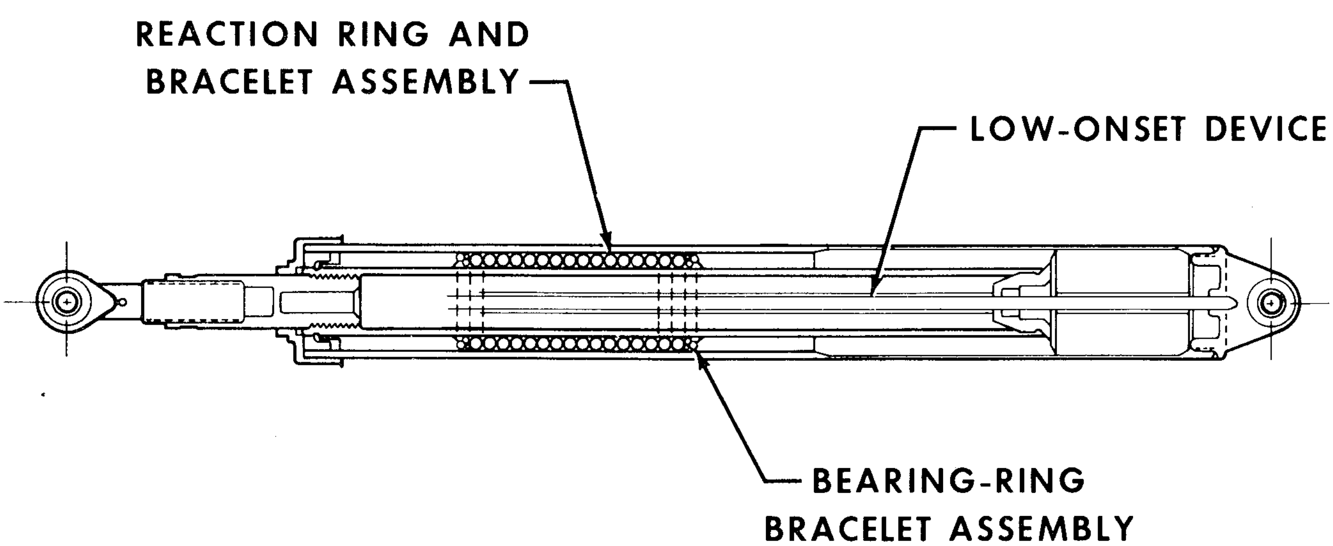

Figure 2. - Configuration of Z-Z axis cyclic-deformation-strut assembly combined with low-onset device.

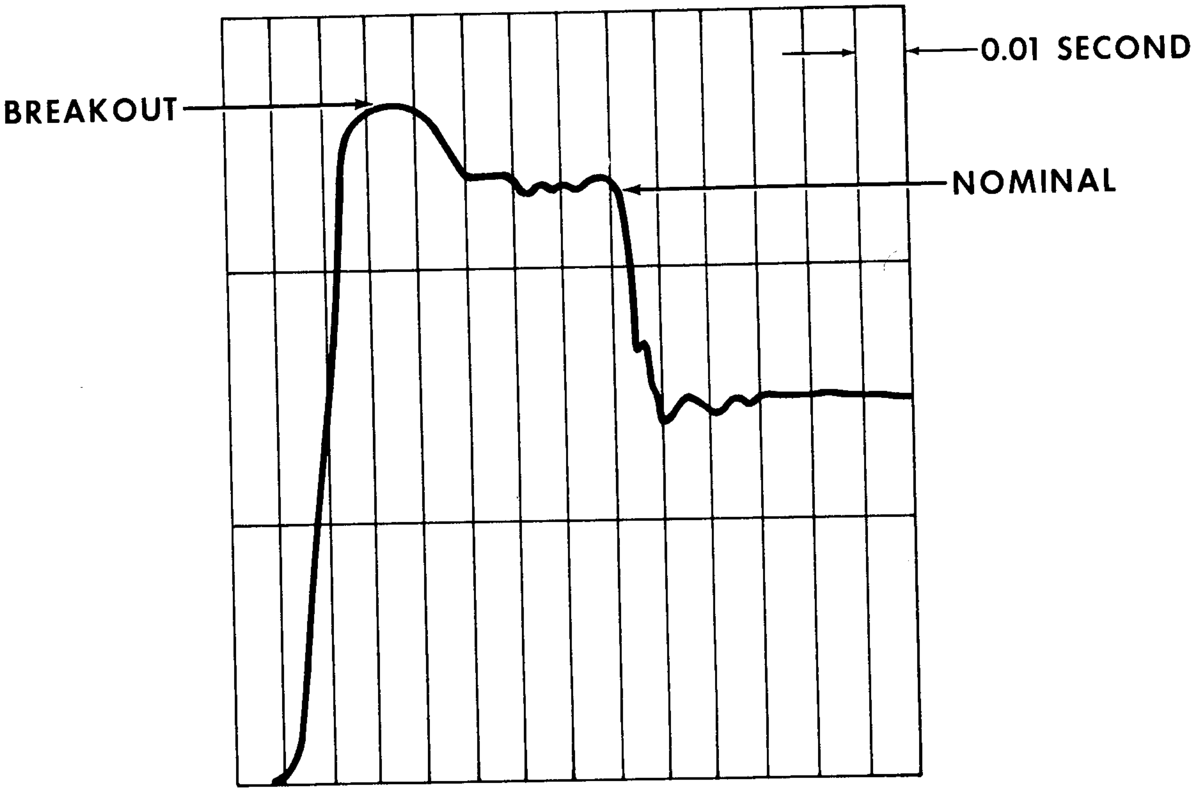

Figure 3. - Cyclic-strut load/time characteristic.

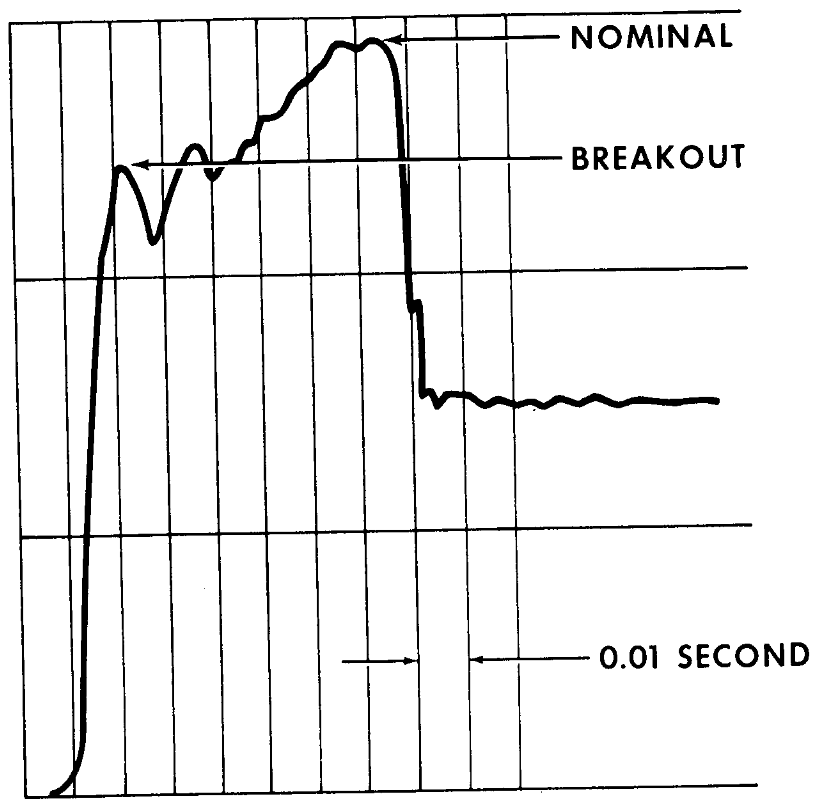

Figure 4. - Combined cyclic-strut and low-onset-device load/time characteristic.

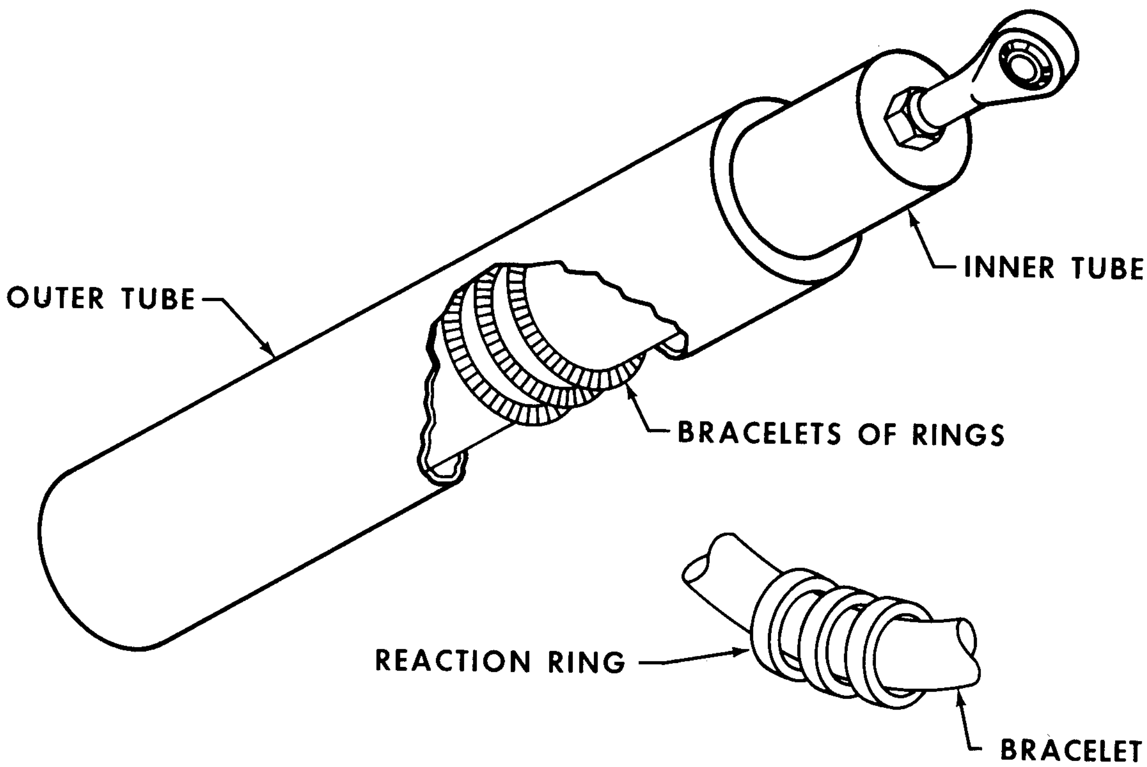

Figure 5. - Cyclic-deformation crew attenuator strut.

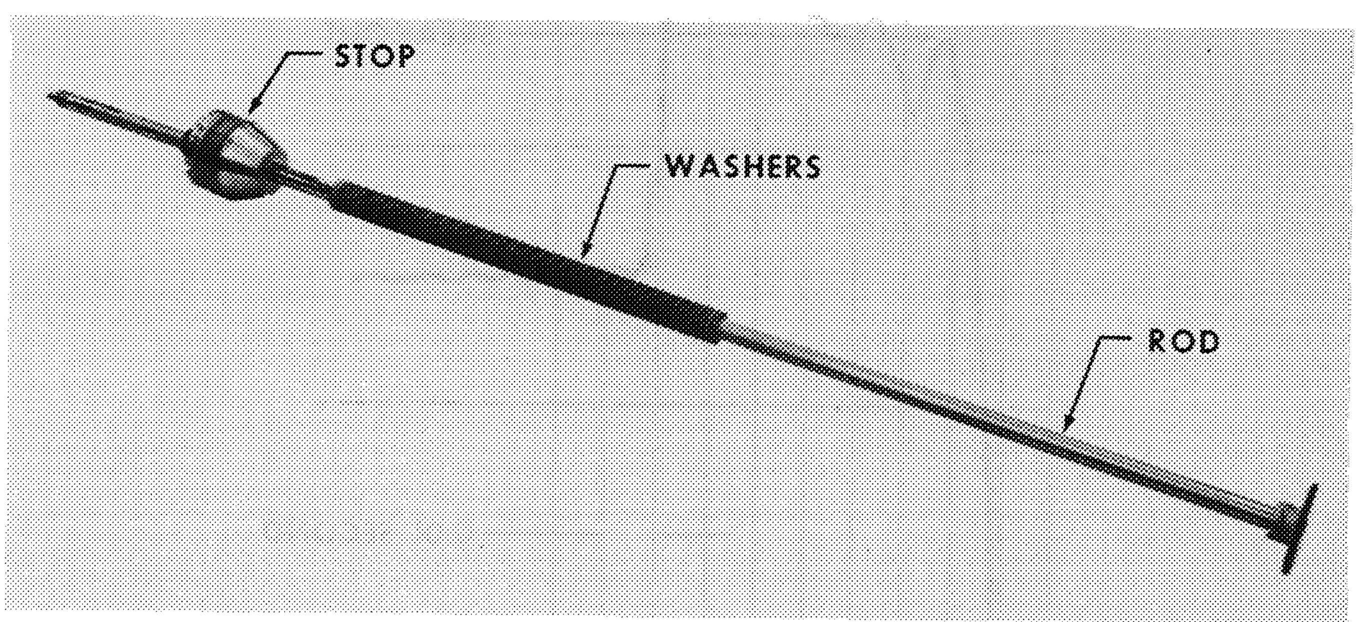

Figure 6. - Apollo low-onset device.

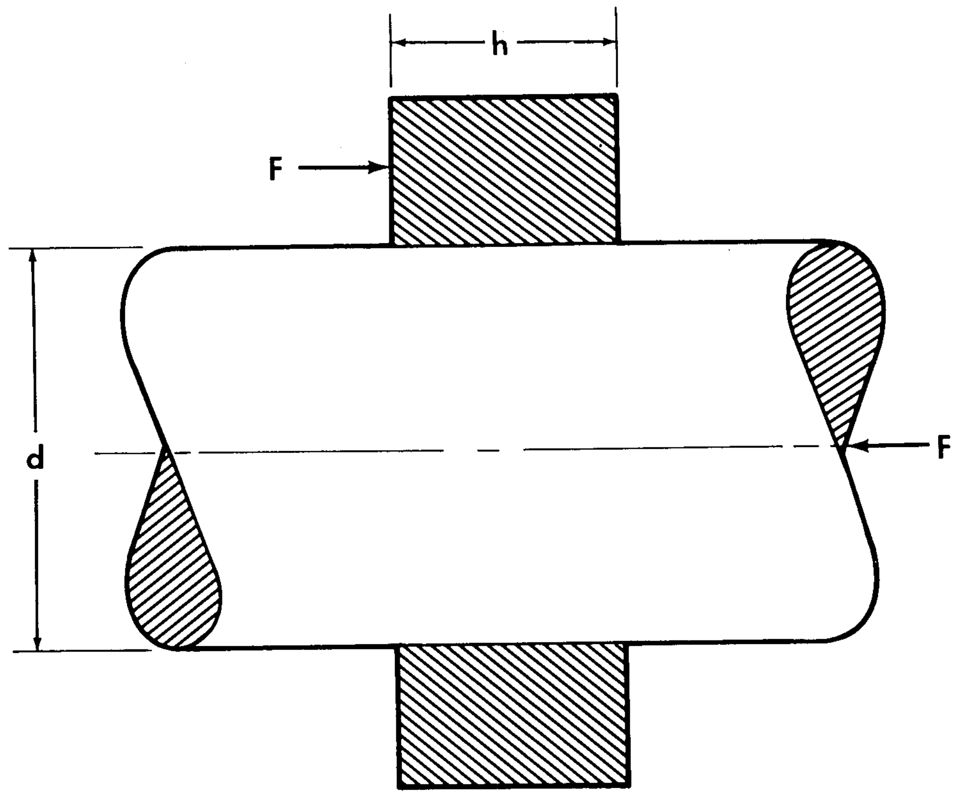

Figure 7. - Rod and washer geometry.

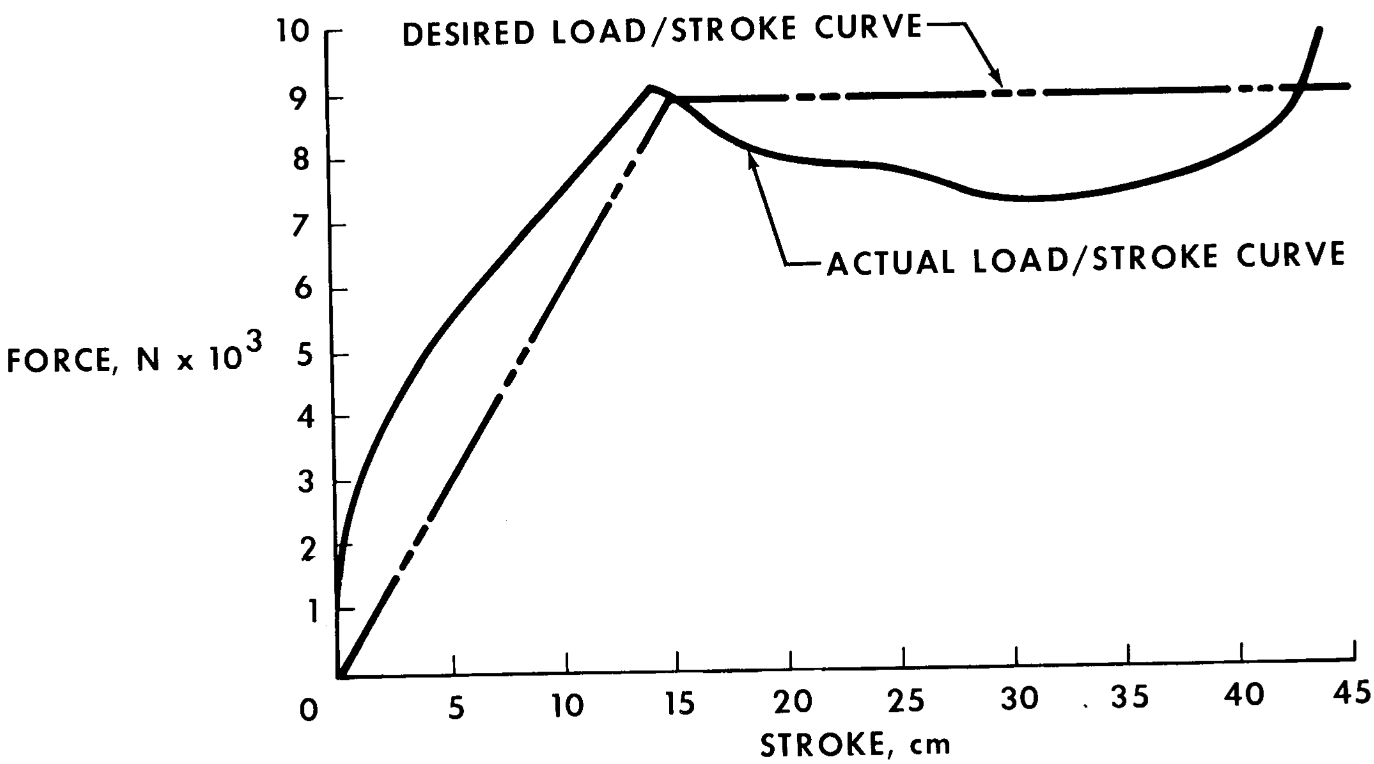

Figure 8. - Load as a function of stroke.