23. HOLDDOWN ARM RELEASE MECHANISM

USED ON SATURN VEHICLES

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SUMMARY

With the development of the Saturn launch vehicle, it became mandatory to develop a system for restraining the vehicle until after all checks and engine thrust buildup were completed. The basic Saturn I holddown arm constrains the vehicle by clamping it between a fixed support and a movable jaw. The jaw is on a link pinned to rotate sufficiently to release the vehicle. There are three links in the jaw (restraining) system arranged so that with a small force provided by a pneumatic separator mechanism, the large loads of the vehicle can be restrained. Design details discussed are the link system, the separator, adjustments, and the energy absorber. The function of preloading is discussed. The secondary release system is described. Finally, the design differences between the Saturn I and the Saturn V arm are described.

INTRODUCTION

The first large-scale rocket propelled vertical-fired missiles developed in the 1940's and 1950's were freestanding. Upon ignition of the engines and thrust buildup, launch was achieved when thrust exceeded missile weight. Overturning moments due to winds were countered by wind locks or clamps around the base of the missile. The clamps required removal prior to flight. Any increase in winds approaching redline values (loads where vehicle would not freestand) required personnel to return to the pad to reinstall these wind locks. Obviously, propulsion system faults that resulted in decayed thrust were catastrophic.

For the extremely large and expensive Saturn, it was mandatory that a system be developed that would safely support and restrain the vehicle on the pad until all checks, including engine start and thrust buildup, were completed. The holddown arm system was designed to fulfill this function, and is described in this paper.

NOTE: In general, this paper describes the Saturn I holddown system. The Saturn V holddown system is quite similar - differences will be pointed out at the end of the paper.

BASIC ARM

The basic Saturn I arm, as shown in Figure 1, is essentially in the shape of a pyramid and weighs approximately 3,765 kilograms (8300 pounds). Attached to the front (directly under the vehicle) is a plunger that supports the vehicle. The plunger is supported on a wedge that is moved up or down an inclined plane machined into the housing. See Figure 2. This provides the plunger with approximately 5.08 centimeters (2 inches) of vertical adjustment to level and align the vehicle. The screw that moves the wedge is turned by use of a 3-to-1 multiplying gear box that is bolted to the housing.

The main pin, which is approximately 6.98 centimeters (2.75 inches) in diameter, is aft of and slightly above the plunger. The main pin attaches the upper link to the holddown base at a point approximately one-fourth back from the front of the upper link. The center link is attached to the aft end of the upper link and to the forward end of the lower link by pins approximately 6.35 centimeters (2.5 inches) in diameter. The lower end of the lower link is fastened to the base with a pin also 6.35 centimeters (2.5 inches) in diameter. This arrangement of three links pinned to each other and to the base at two points allows the aft end of the upper link to rotate through approximately 90 degrees.

Looking at Figure 1, it can be seen that if the lower and center links are held in a vertical position such that a straight line would pass through the three pins, any load applied in the up direction at the plunger end of the upper link would be reacted through the center and lower link and would have a magnitude equal to the ratio of the moment arms about the upper link main pin. This condition, however, is unstable, because the center/lower link pin could move in either direction (fore or aft).

Stability can be gained for the linkage by moving the center/lower pin point a small distance fore or aft. By keeping the distance that the pin is moved forward small, a large load through the links can be restrained with a small horizontal load. Figure 3 is a representation of the three-link system. If the angle α that the lower/center link pin subtends is set at 3 degrees, and the length b is set at 3 times the length a, the relationship of force F to force F'' is defined as follows:

M about pin = 0

$$FA = F'b$$

$$F' = \frac{Fa}{b} \qquad (1)$$

$$\frac{F''}{F'} = \text{Tan}\,\alpha$$

$$F' = \frac{F''}{\text{Tan}\,\alpha}$$

Substituting into (1) above

$$\frac{F''}{\text{Tan}\,\alpha} = \frac{Fa}{b}$$

$$F'' = \frac{Fa}{b} \tan\alpha$$

Substituting $\alpha = 3^o$; $b = 3a$

$$F = 57.2F'' \qquad (2)$$

To restrain the vehicle until after thrust buildup requires that the holddown arms restrain a vertical up-load equal to the vehicle thrust minus weight of the vehicle, plus the overturning moment due to wind. This value of up-load is then preloaded into the linkage to assure no separation of the vehicle from the holddown arm plunger during engine start. For the Saturn I, the value of this load is 444,822 newtons (100,000 pounds) per holddown arm.

NOTE: Additional allowances must be made for thrust overshoot, hardover engines, and unknowns, i.e., wind gust, misaligned engines, etc.

For a load on a holddown arm of 444,822 newtons (100,000 pounds), the separator is required to provide a restraining force of approximately 7,784 newtons (1750 pounds) in tension (using equation 2 above).

SEPARATOR

The separator (Figure 4) is essentially a cylinder with a piston that includes a rod having a groove or ball race machined near its end. Ball bearings that are seated in the cylinder protrude through the cylinder wall; and in the holddown position rest on the outer end of the piston rod and in a machined race in the separation link of the separator, which is essentially a continuation of the cylinder. In the holddown position, the piston is held aft in the cylinder by spring action so that the balls protrude outside the cylinder wall into the machined race on the separation link. Tention loads can then be carried from the separation link (which is bolted to the lower link of the holddown arm) through the balls and through the cylinder to the holddown arm base.

To operate the separator, pneumatic pressure pushes the piston forward, allowing the balls to be pressed into the piston groove by the load being transmitted through the separation link. When the balls are forced into the piston groove, the separation link is no longer attached to the separator cylinder and is free to move with the lower link.

PRELOADING

To assure a tight connection between the vehicle and the holddown arm, the arm is clamped with a preload large enough to assure no separation between the vehicle and the arm plunger until release. This preload takes care of bending in the upper link and any tolerance in the linkage system. To preload the arm, the vehicle is placed on the plunger blocks and leveled. Then the holddown arm linkage is erected, using a demountable winch. The separation link is connected to the separator, and the separator rear swivel nut (Figure 1) is tightened to develop the necessary preload. Curves of torque of the swivel nut versus preload or clamping force on the vehicle have been developed. The preload value selected must be attained with the linkage in a particular geometry. For the Saturn I arm, the center/lower link pin must be located forward of a straight line between pins by approximately 3 degrees. This is measured by an alignment gage on the arm base. If either the proper preload torque value (74.7 joules) (55 ft-lbs) is not attained or the pin geometry is not obtained, the linkage is lowered and shims are added to or removed from the upper arm section pad and the torqueing procedure is repeated. The arm is now preloaded and ready for firing. The 3 degrees mentioned was selected to keep separator tension load small and assure the center/lower link pin would always be forward of the unstable point (straight line between pins).

ENERGY ABSORBER

When released under load, the linkage has kinetic energy equal to gravity plus the preload reaction. Obviously, because of the large preload, the linkage travels with great speed and must be arrested without damage to the linkage. For the Saturn I arm, a shear module (Figure 5) is used to absorb this energy. The module is essentially a housing with four shear rods staggered such that as the lower link falls, a striking plate mounted on the bottom of the lower link breaks each rod in succession, absorbing the energy.

ZERO MOMENT

Because machining of a perfectly flat plane on the base of a vehicle such as the Saturn is impossible, means must be provided to assure that moments about the plane of the linkage are not introduced. This would not only be detrimental to the linkage, but would add unnecessary loads to the vehicle as well. To assure that moments are not introduced, the attach point on the vehicle contains a spherical surface. Likewise, the forward end of the upper link also contains a spherical surface (Figure 6). The separator is designed for a straight tension pull. Bending would apply unsymmetrical loads to the separator balls. To prevent bending in the separator mechanism, spherical washers are incorporated between the separator rear swivel nut and the hold-down base (Figure 1).

SYNCHRONIZATION/RELIABILITY

To assure synchronization of the release of all eight arms, a pneumatic circuit (Figure 7) was designed that provided the same length pneumatic line to each separator from the pressure source. This concept of equal lengths of line removed the problem of orifice design that would be required because of the location of the source. For reliability, two circuits were provided to each separator, as shown in Figure 7.

Redundancy was also provided in the firing panel by installing an accumulator with sufficient gas to fire the complete circuit. The firing panel itself is made up of two solenoid-operated 3-way valves installed in a parallel circuit. With a history of several hundred firings during tests and launch, the firing panel has never fired prematurely or failed to fire on command, and a separator has never failed to release. Looking at the pure numbers of reliability, however, a single failure point exists in the separator. Reliability numbers obtained by testing cannot match the confidence provided by a second or redundant system. Therefore, a second system for holddown release was developed.

SECONDARY RELEASE SYSTEM

The secondary release system consists of an explosive nut attaching one end of the pneumatic separator to the link. Figure 8 shows an exploded view of the separator, explosive nut, and the separation link. An eyebolt connects the separation link to the lower link. The nut that holds this eyebolt to the separation link is slotted and is sufficiently long to allow attachment of an explosive charge that has enough power to split the nut.

Figure 9 is a schematic of the circuit that fires the explosives. The circuit contains three relays such that prior to start of countdown the power supply is shorted. Upon receiving the signal to release, which for both the pneumatic and the explosive system is the same signal and is furnished by vehicle ground equipment, relay contacts PK 1 close and relay contacts PK 2B open. This arms the circuit. This same signal starts a timer that closes relay contacts PK 2 after an appropriate time - 130 milliseconds in the case of the Saturn I. If the separator has operated pneumatically, the movement of the separation link forward will break the lead wires to the explosive nut, and therefore the redundant explosive system will not operate. If the pneumatic separator has not operated, the nut will blow it free and allow operation of the arm.

TIMING

It has been found during testing that helium under a pressure of 5.17 X 10^6 newtons per square meter (750 psi) will operate the separator in 20 milliseconds with a length of tubing containing approximately 819 cubic centimeters (50 cubic inches) volume (Saturn I). Gaseous nitrogen, on the other hand, requires approximately 69 milliseconds. Other gases possibly would be satisfactory, but have not been investigated, because helium is the lightest gas available, and therefore should be the fastest.

A normal time for release shows first arm release is approximately 130 milliseconds after signal, and the last of the eight must release in a maximum of 180 milliseconds after signal. The time for the secondary release system explosion is set such that all separators have a full chance to operate pneumatically. If the system were being designed today, it is possible that the explosive release method would be considered primary, but because of such a long history of satisfactory use (over 13 years), the pneumatic separator is considered primary. There is one important advantage to the pneumatic separator: The unit can be tested in configuration as late in the countdown as desired, while the explosive system cannot be tested.

TEST PROGRAM

Because of such high loads and the absolute necessity of sure operations, each arm is loaded in a test fixture to the design load. For the Saturn I, the down-load applied is 1.8 X 10^6 newtons (400,000 pounds) and the up-load applied is 1.1 X 10^6 newtons (250,000 pounds). In addition, once installed, all arms are fired as a system to check linkage release timing. Timing is critical, because the time span between first arm release and last arm release must not exceed 50 milliseconds.

LAUNCH ENVIRONMENT PROTECTION

The launch environment subjects the arm and system to not only the loads mentioned above but engine exhaust gases having a temperature of approximately 1649°C (3000°F) and a velocity of approximately Mach 3. Fortunately, this condition exists for only a few seconds at the most. For protection, the mass of materials must be large to serve as a heat sink, and sharp points must be eliminated or provided with protection. Water is also sprayed on the arms a short time after liftoff to absorb the heat and prevent heat-soaking deterioration. In addition, the rocket engines generate a sound level of approximately 170 decibels and generate a vibration level of 24g maximum at all frequencies up to 1500 Hz. All moving parts, such as the separator piston, must be designed with a natural frequency that is not in resonance with these vibrations.

DESIGN POINTS OF INTEREST

In a paper it is difficult to tie all points of interest into a narrative discussion, but there are a few points of interest in the design and operating experience of these arms that should be shared. It is not intended to explain the reason or theory behind each, but simply to provide the information in hope that it may be of use.

1. It has been our experience that an odd number of balls in the separator, such as 3 or 5, will give unsatisfactory results, while an even number will result in satisfactory operation.

2. The point loading of the balls on the separation link groove has always resulted in brinelling no matter how hard the material. Cutting a groove at the edge of the groove provides a place for material to flow. Then the only detrimental effect due to brinelling is the necessity of remachining the face of the groove after several operations.

3. Precipitation hardening steels, such as 17-4 PH, have been used very satisfactorily when a close-tolerance part, such as the main pins, was required. This allows machining to close tolerances after final heat treatment.

4. Stress risers in the form of sharp corners are to be avoided under all conditions. They will invariably result in a crack.

5. Sand castings for the base structures have proven very satisfactory, provided care is taken in inspecting for cracks, voids, and inclusions in the areas of stress - primarily around the main pins. Be prepared, however, to explain the surface cracks that are visible everywhere under magnetic particle or zyeglow inspection to the operating engineer.

6. If a heavily loaded structural component must be thicker than 5.08 or 7.62 centimeters (2 or 3 inches), forgings offer advantages in grain growth and eliminate the heat-treating difficulties of castings.

SATURN V HOLDDOWN ARMS

In the preliminary engineering stages of the Saturn V vehicle, it was apparent that to save flight weight, the number of supports should be four, rather than eight as used on the Saturn I. This, and the fact that the Saturn V would have a thrust and weight of five times the Saturn I, led the ground equipment engineers to re-examine the holddown scheme in detail. This examination reiterated the basic simplicity and load-carrying properties of the Saturn I arms. The decision was made to maintain the same basic designs for the Saturn V, as shown in Figure 10. Obviously, all components are larger, but the basic design has been followed very closely.

DETAIL DIFFERENCES

With such a large vertical down load (13.34 X 10^6 newtons) (3000 kips), it was decided to abandon the inclined plane and sliding wedge to achieve vertical adjustment and use shims instead. Figure 11, detail A, shows the shims between the adjustable head and the base. For the Saturn V, the spherical surface to assure zero moment transfer is incorporated into the adjustable head of the holddown rather than into the vehicle, as with the Saturn I. This saves flight weight with no real hardship on the ground design.

The shock absorber was also changed to a block of wood in the Saturn V program. During the test program, a piece of oak wood 20.32 by 14.61 by 63.50 centimeters (8 by 5.75 by 25 inches) was substituted for the bolt shock absorber to save costs, and this wood worked so well it was decided to adopt it for all operations.

The remaining paragraphs describe added systems for Saturn V.

CONTROLLED RELEASE SYSTEM

The holddown arm upper link system will restrain the Saturn V vehicle until launch commit and programmed release of holddown linkage. At launch, the upper link is pivoted rapidly away, releasing the restraining force at a rate which, without design refinement, could create unallowable stresses in the vehicle structures. To provide a smooth, controlled release of the vehicle, control release devices were designed.

The controlled release mechanism consists basically of a bracket, which is bolted to the holddown arm base, and a draw pin, which is connected to the bracket and to the vehicle through a die. The die is fastened to the vehicle, and at launch the pin is drawn through the die for the first 15.2 centimeters (six inches) of vehicle travel. See Figure 12.

As the pin is drawn through the die at launch, the force decreases from 3.3×10^5 newtons (75,000 pounds) to zero after 15.2 centimeters (six inches) of travel.

PROTECTIVE HOOD

Due to increased exhaust plume characteristics for the Saturn V, a protective hood was designed to protect the holddown arm linkage and components inside the arm. The hood is actuated with a lanyard as the vehicle rises. See Figure 13.

Listed below are a few statistics and facts of the Saturn I and Saturn V holddown arms and their components.

ITEM	S-I	S-V
Load Carrying Capability	1.1×10^6 N	6.7×10^6 N
UP	(250,000 lb)	(1,500,000 lb)
DOWN	1.8×10^6 N	13.34×10^6 N
	(400,000 lb)	(3,000,000 lb)
Weight Complete Arm	3765 kg	20,412 kg
	8300 lb	45,000 lb
Base Material (Cast)	ASTM A27	ASTM A27
Upper Link Material	ASTM A487	4340 Electric
	Grade 70	Furnace Steel
	Casting	Forging

ITEM	S-I	S-V
Main Pin Material	17-4 PH	17-4 PH
Link Pin Material	Type 431 Cres	ASTM A36
Pneumatic Separator Tension Load Capability	22,240 N (5000 lb)	222,411 N (50,000 lb)
Pin Lubricant	25:1 Halocarbon and Molykote (Used because of LOX compatibility requirement.)	
Separator Lubricant	Dow-Corning Silicone DC-510-500-C-S	

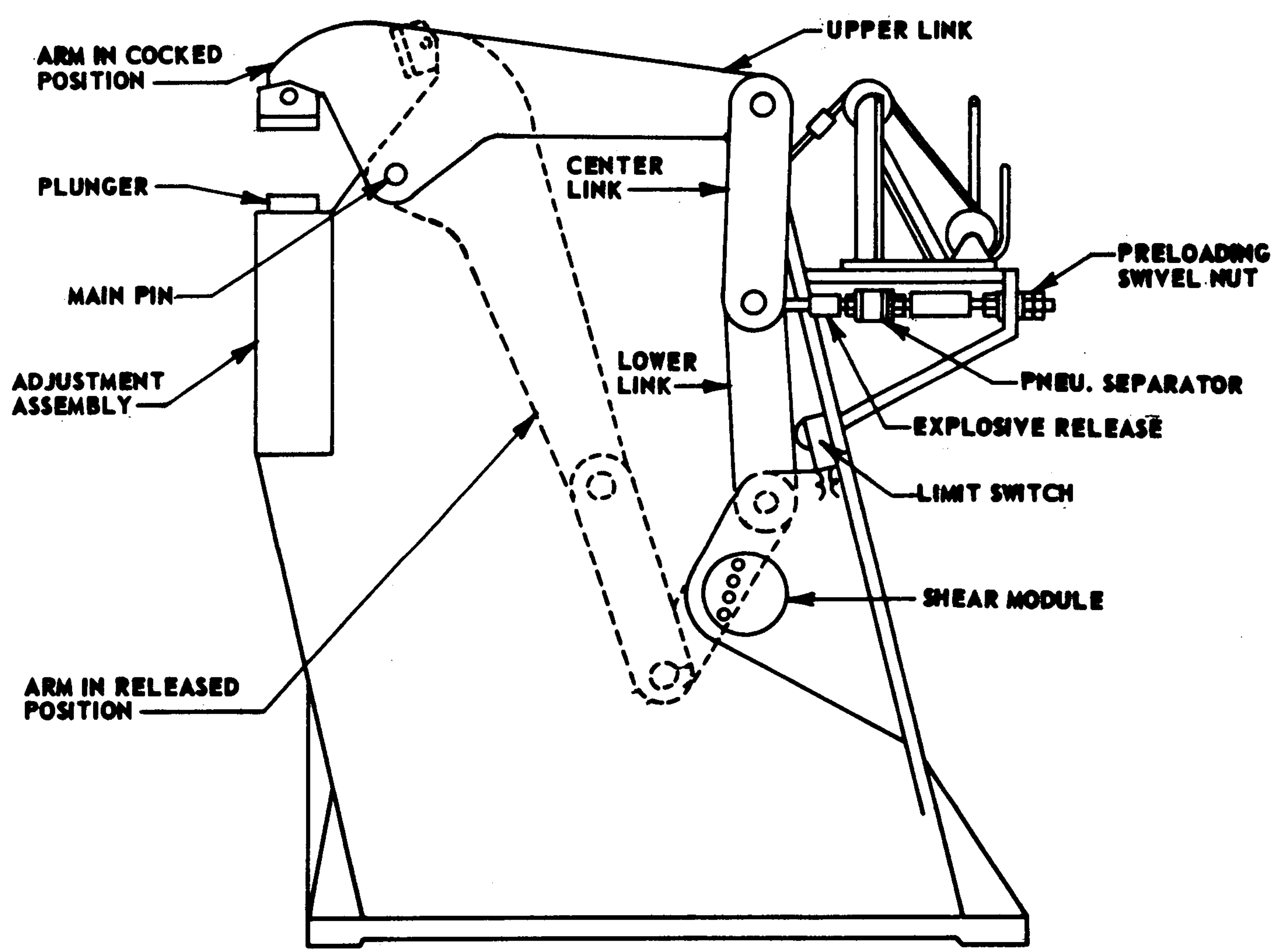


Figure 1. Holddown Arm Assembly

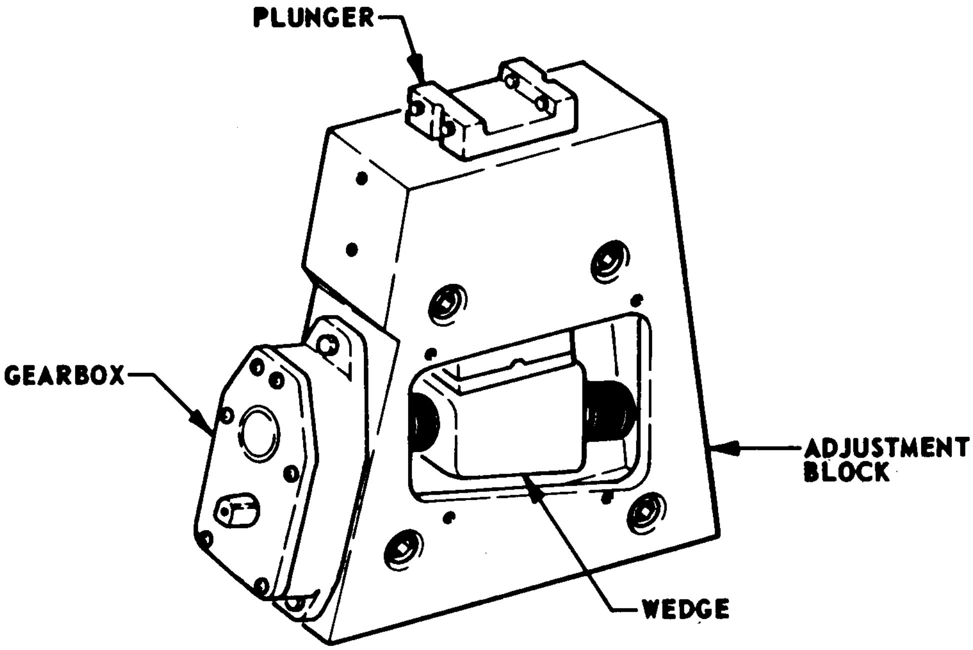


Figure 2. Adjustment Assembly

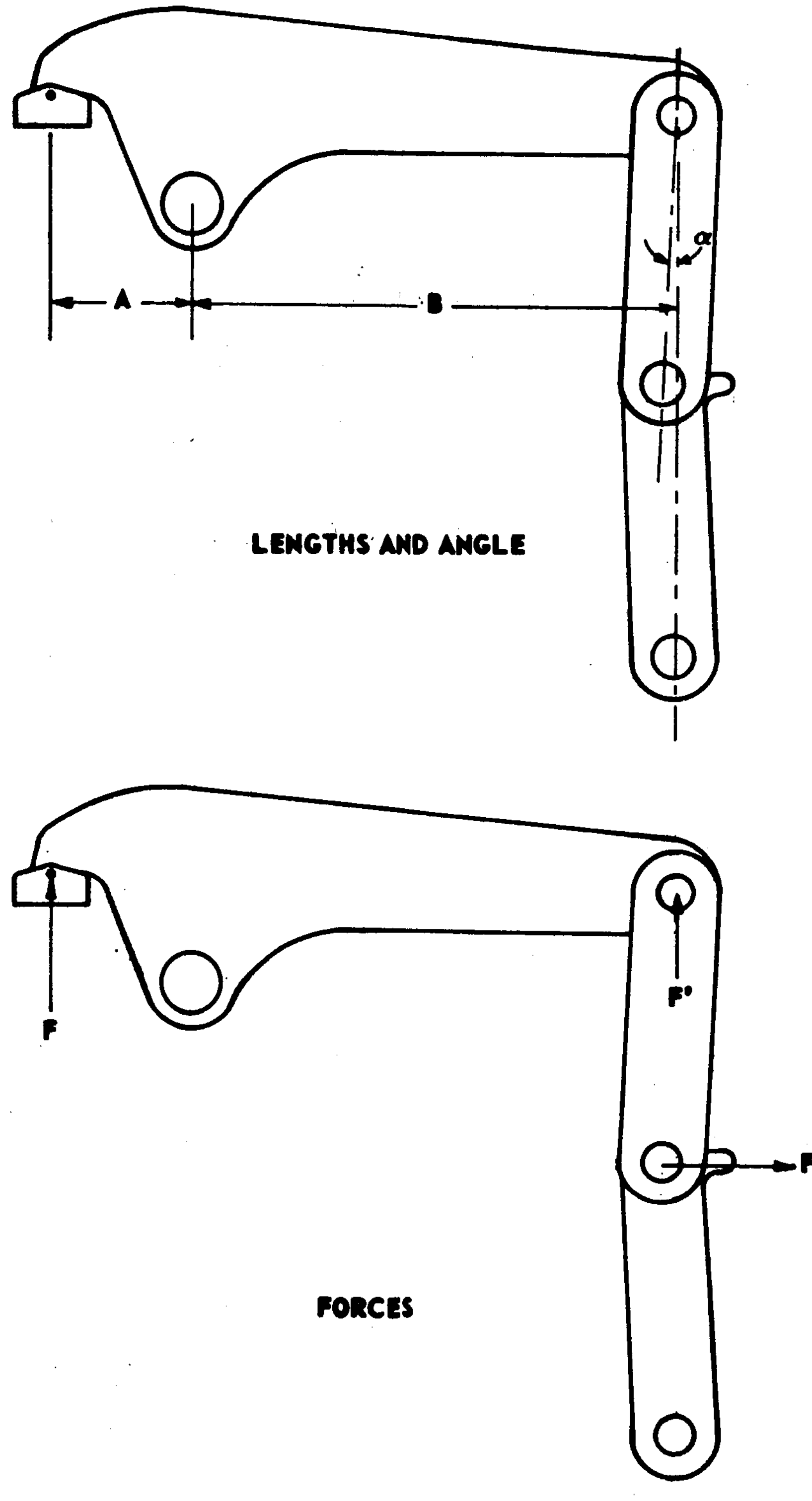


Figure 3. Load Diagram

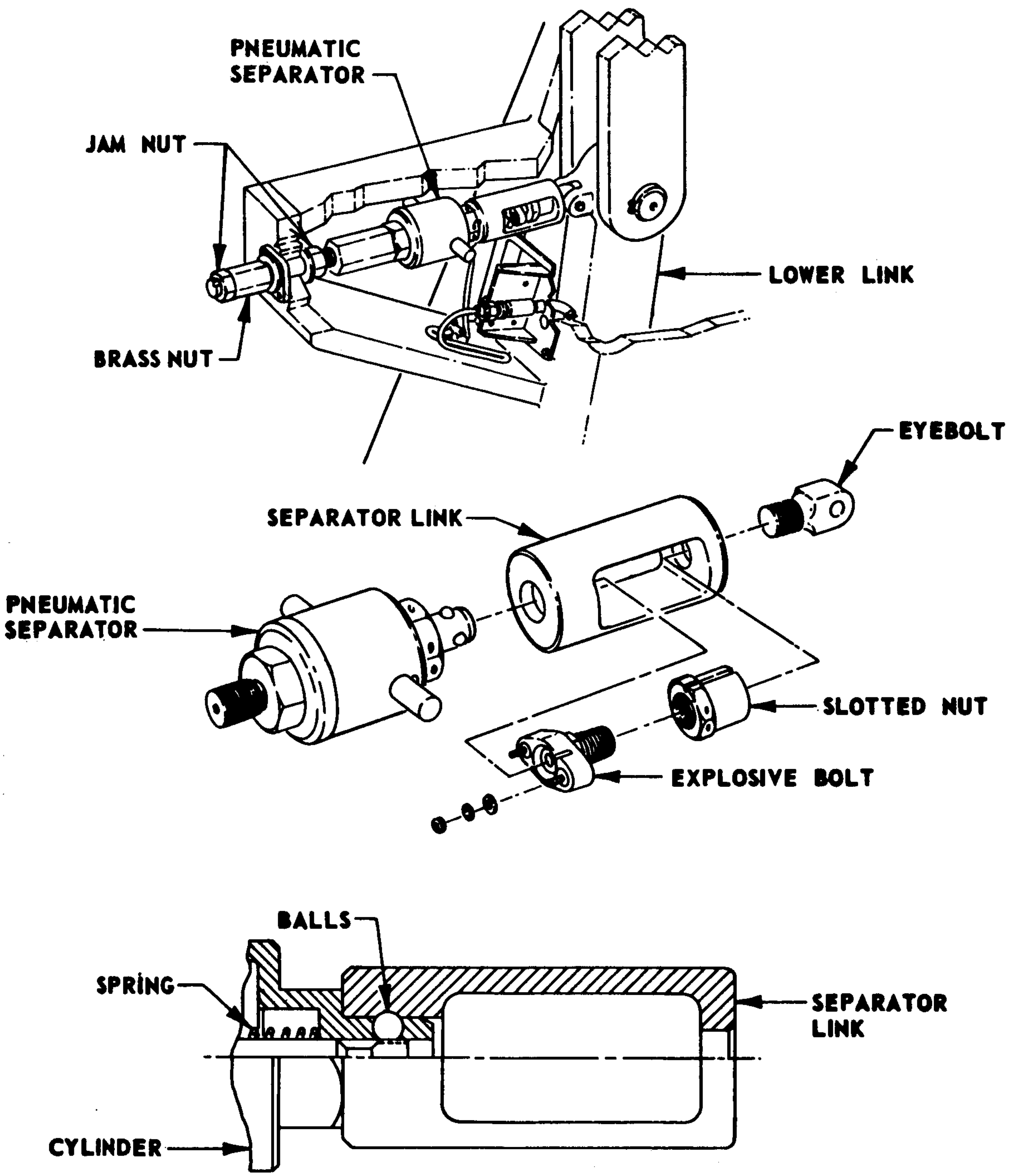


Figure 4. Pneumatic Separator Assembly

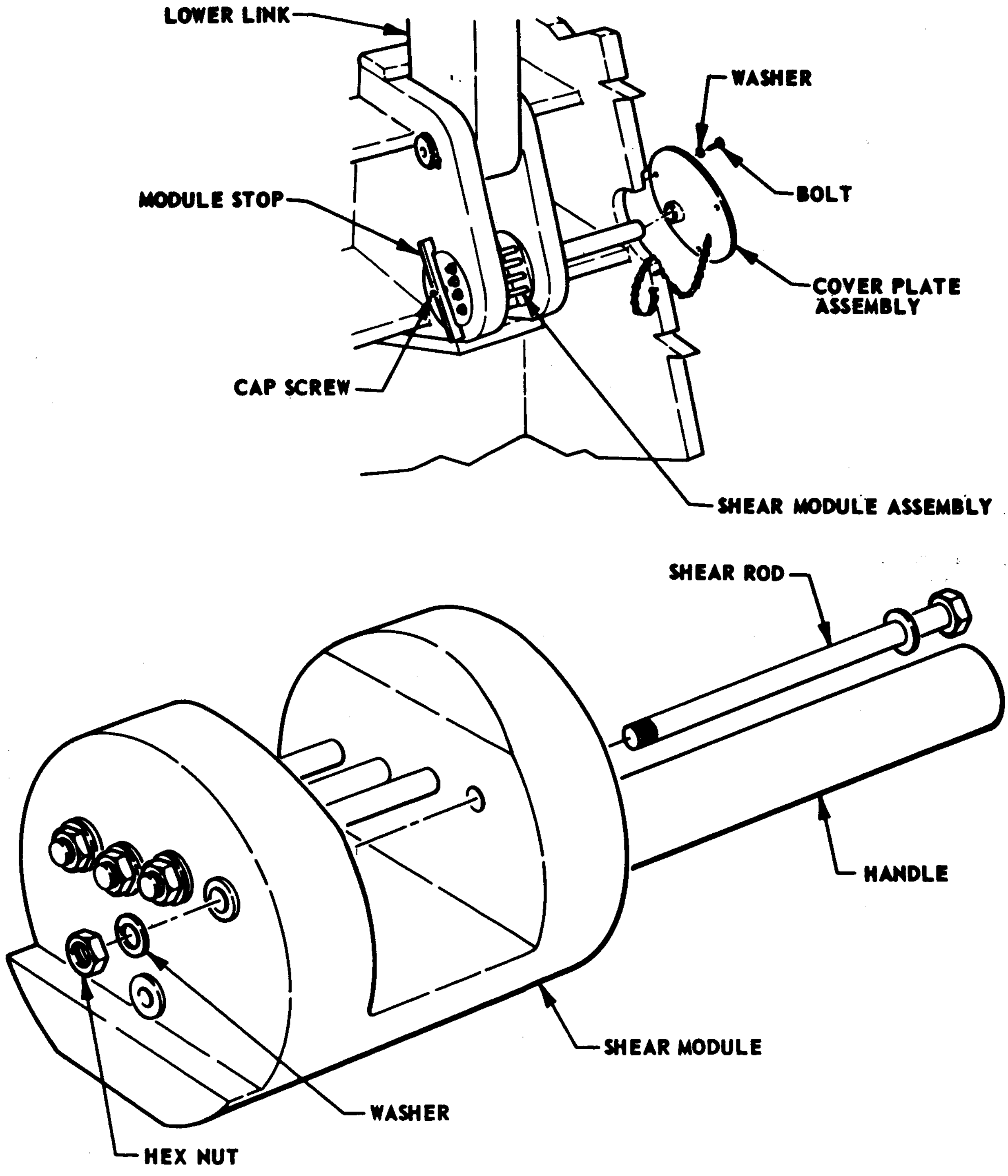


Figure 5. Shear Module Assembly

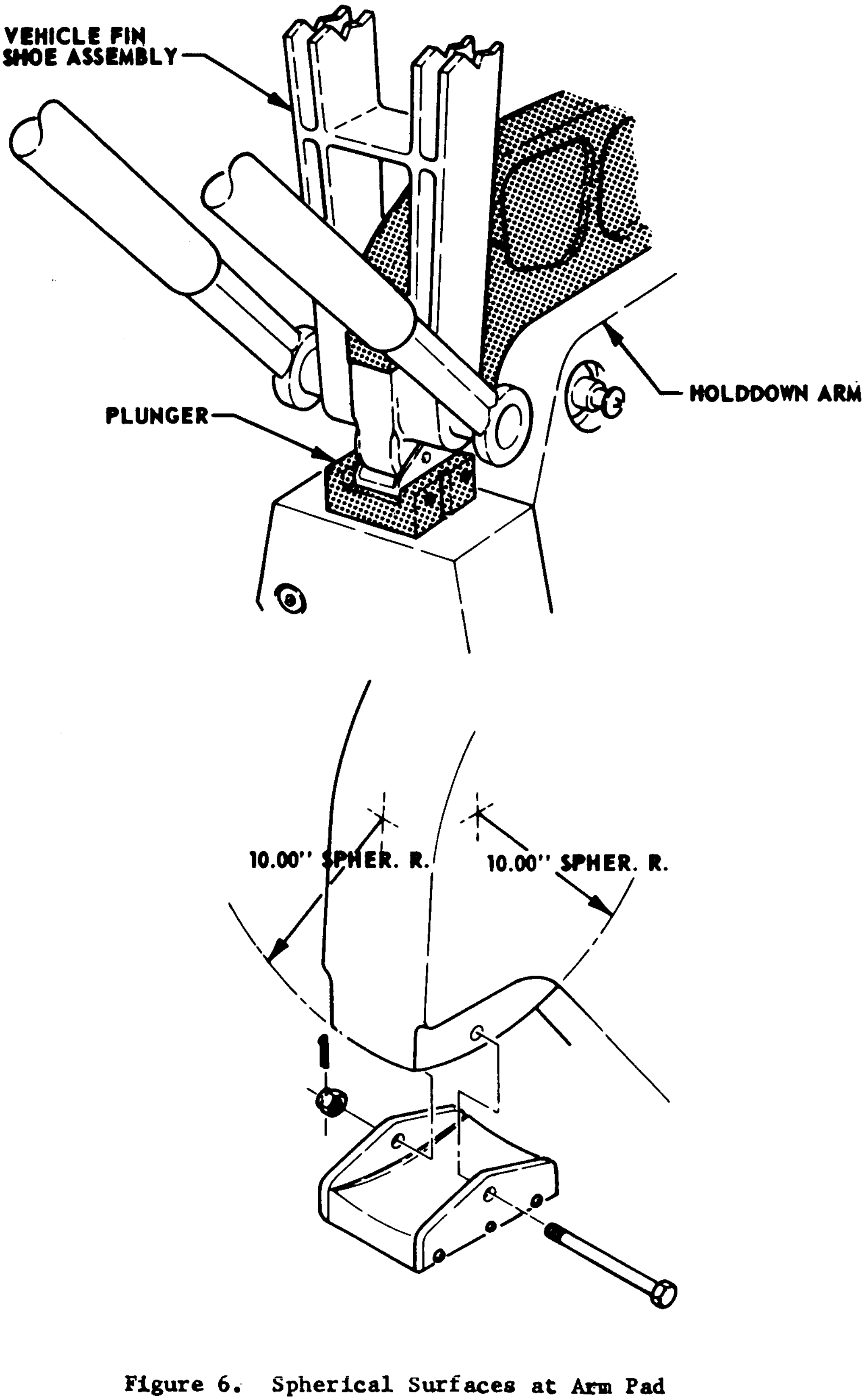


Figure 6. Spherical Surfaces at Arm Pad

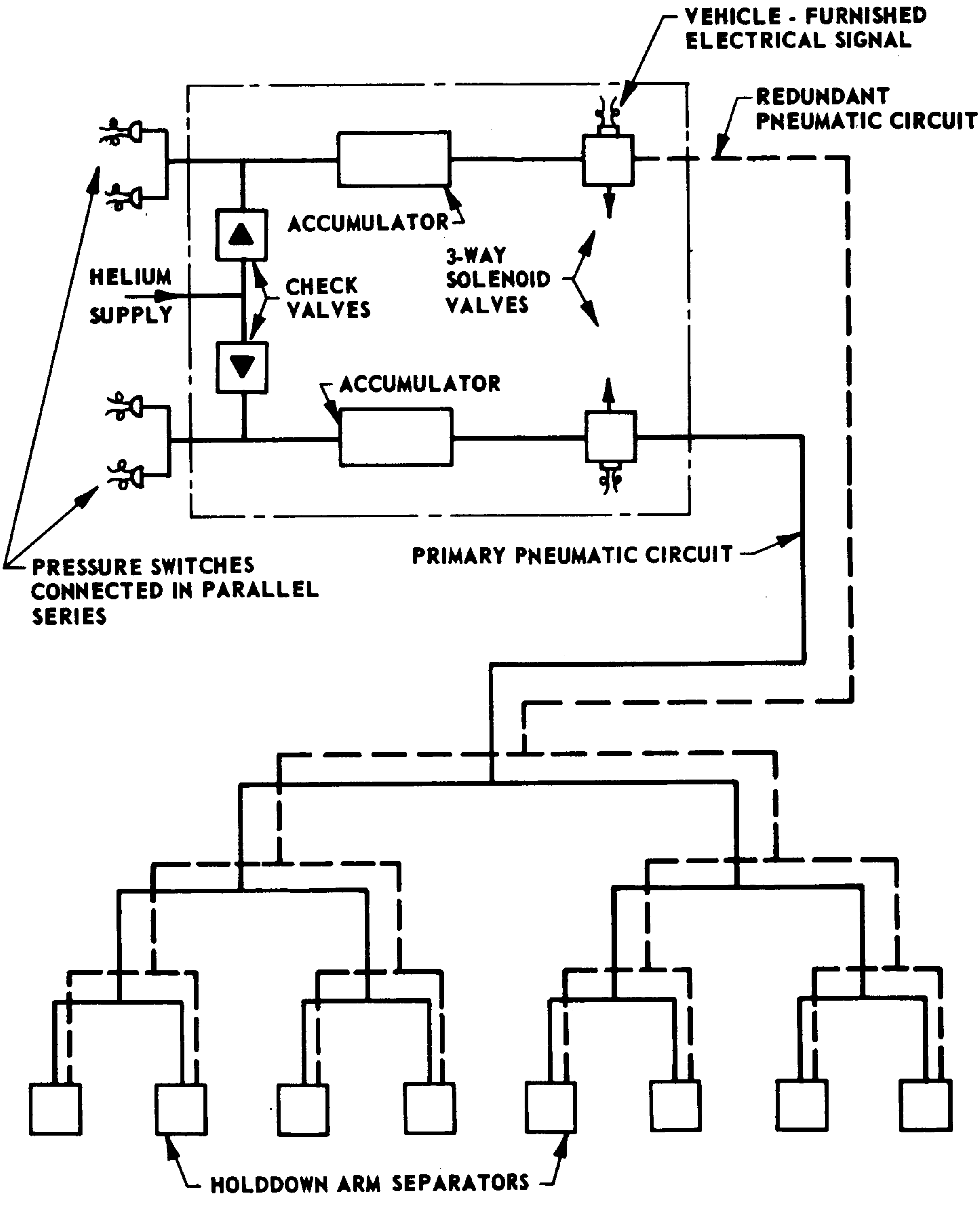


Figure 7. Pneumatic System Schematic

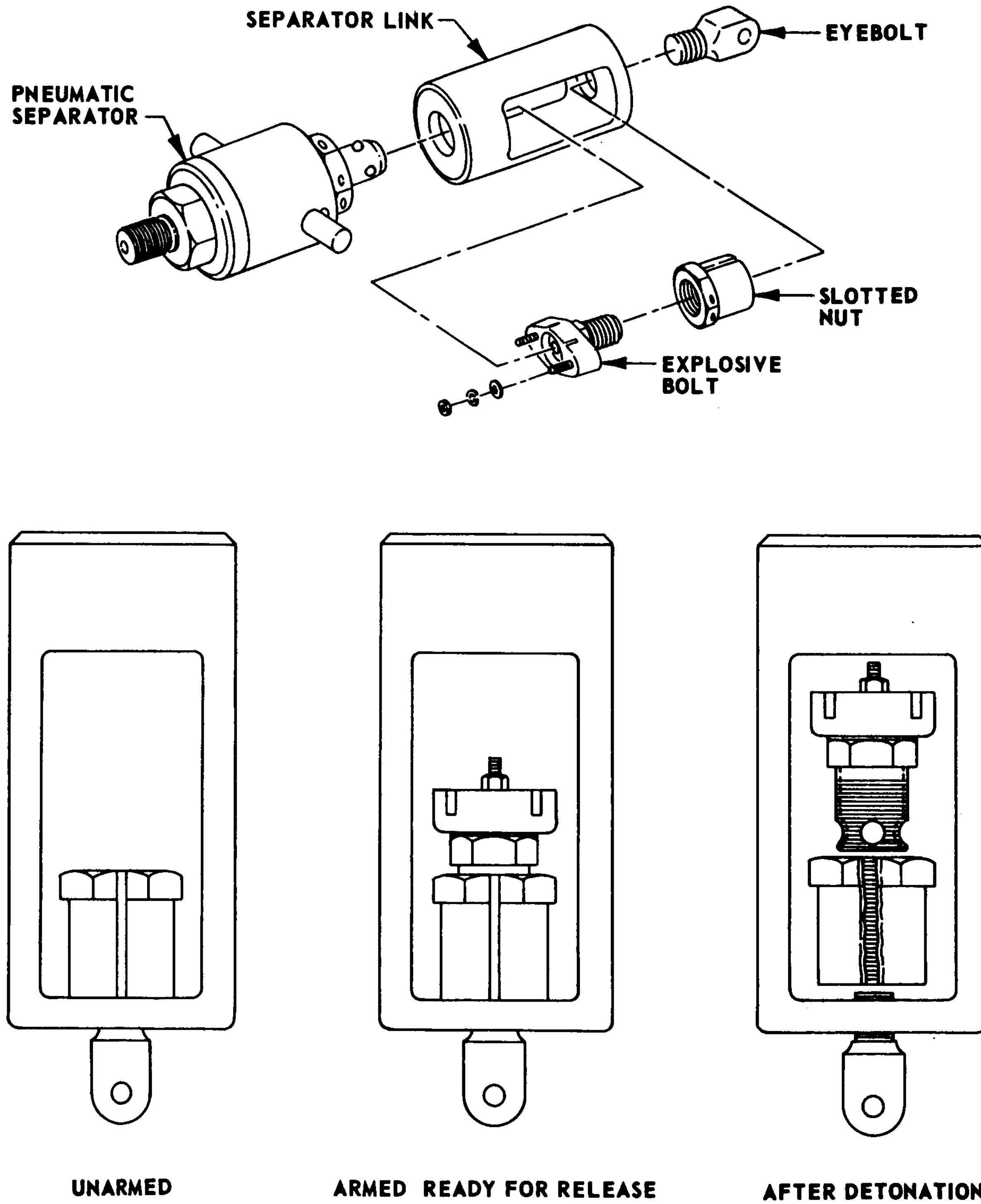
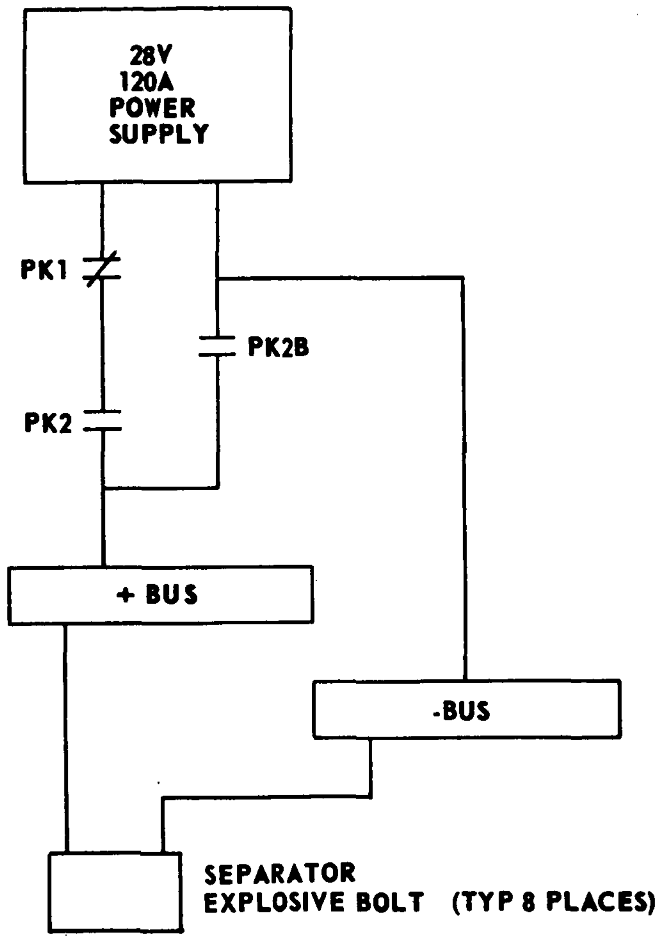


Figure 8. Pneumatic Separator Explosive Release



1. CONTACTS SHOWN JUST AFTER VEHICLE RELEASE SIGNAL. VEHICLE - FURNISHED RELEASE SIGNAL CLOSES PK1 AND OPENS PK2B.
2. TIMER FURNISHES SIGNAL 130 MS AFTER PNEUMATIC RELEASE SIGNAL TO CLOSE PK2.

Figure 9. Explosive Release Systems Schematic

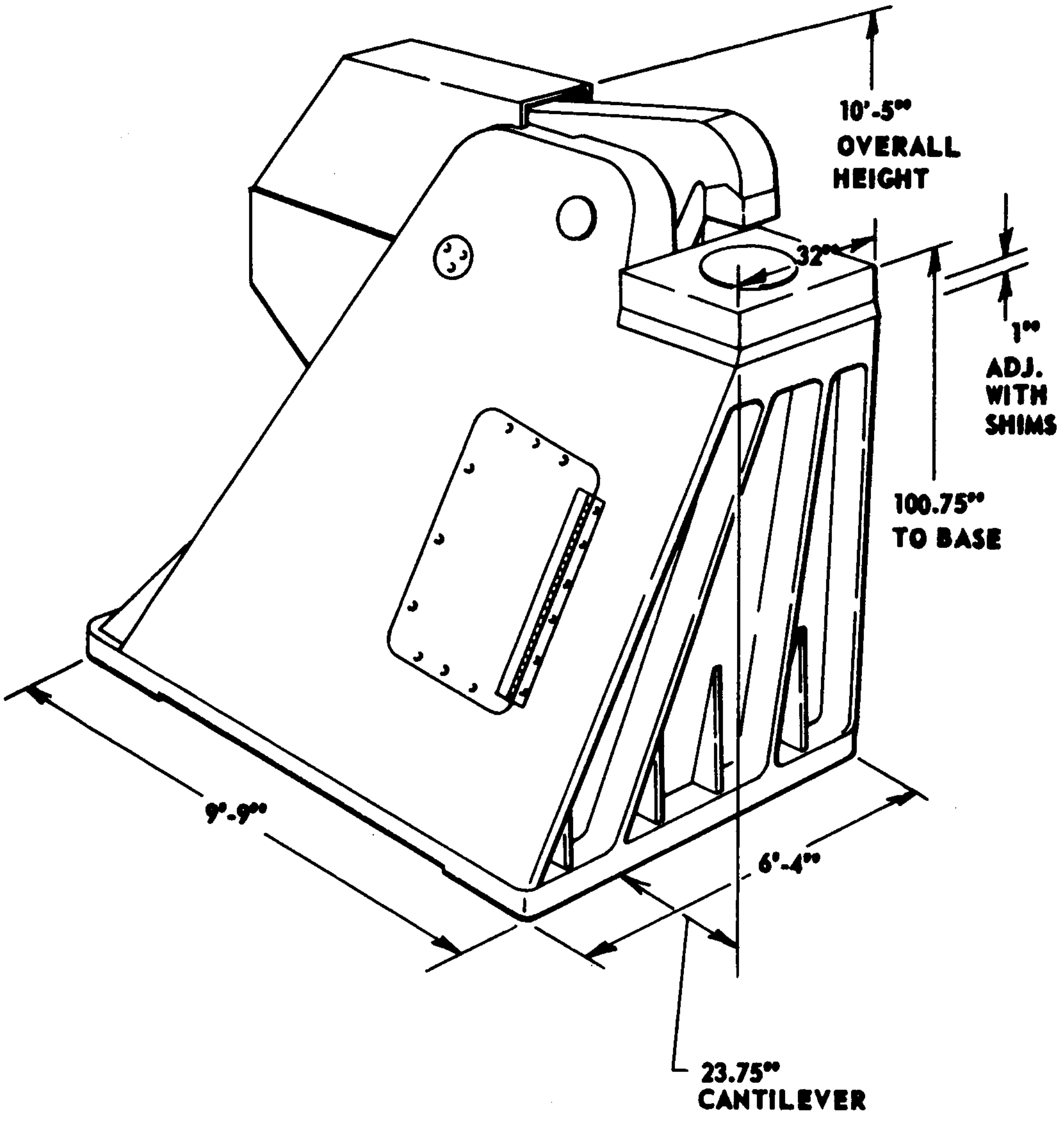


Figure 10. Saturn V Holddown Arm

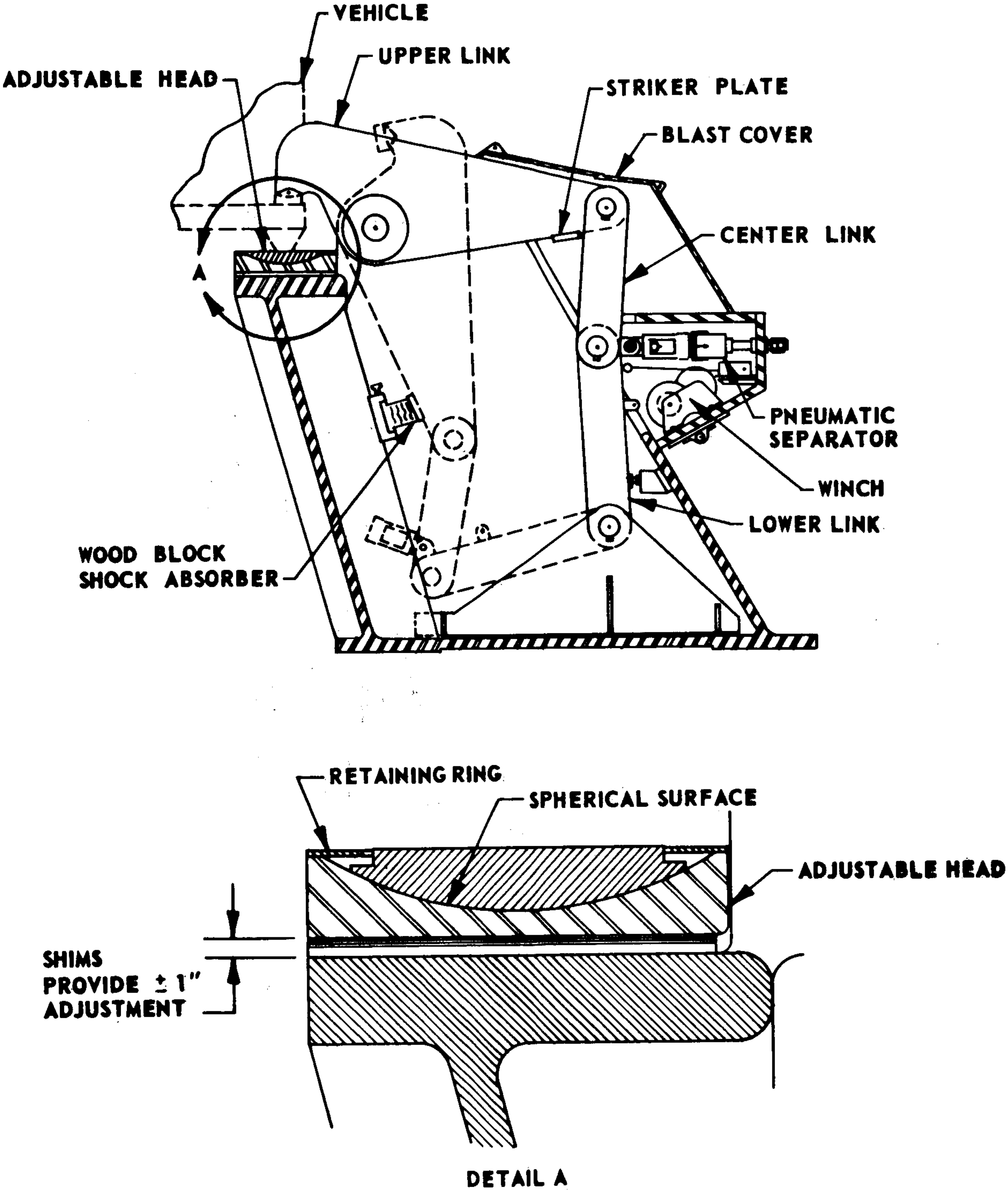


Figure 11. Holddown Arm Features

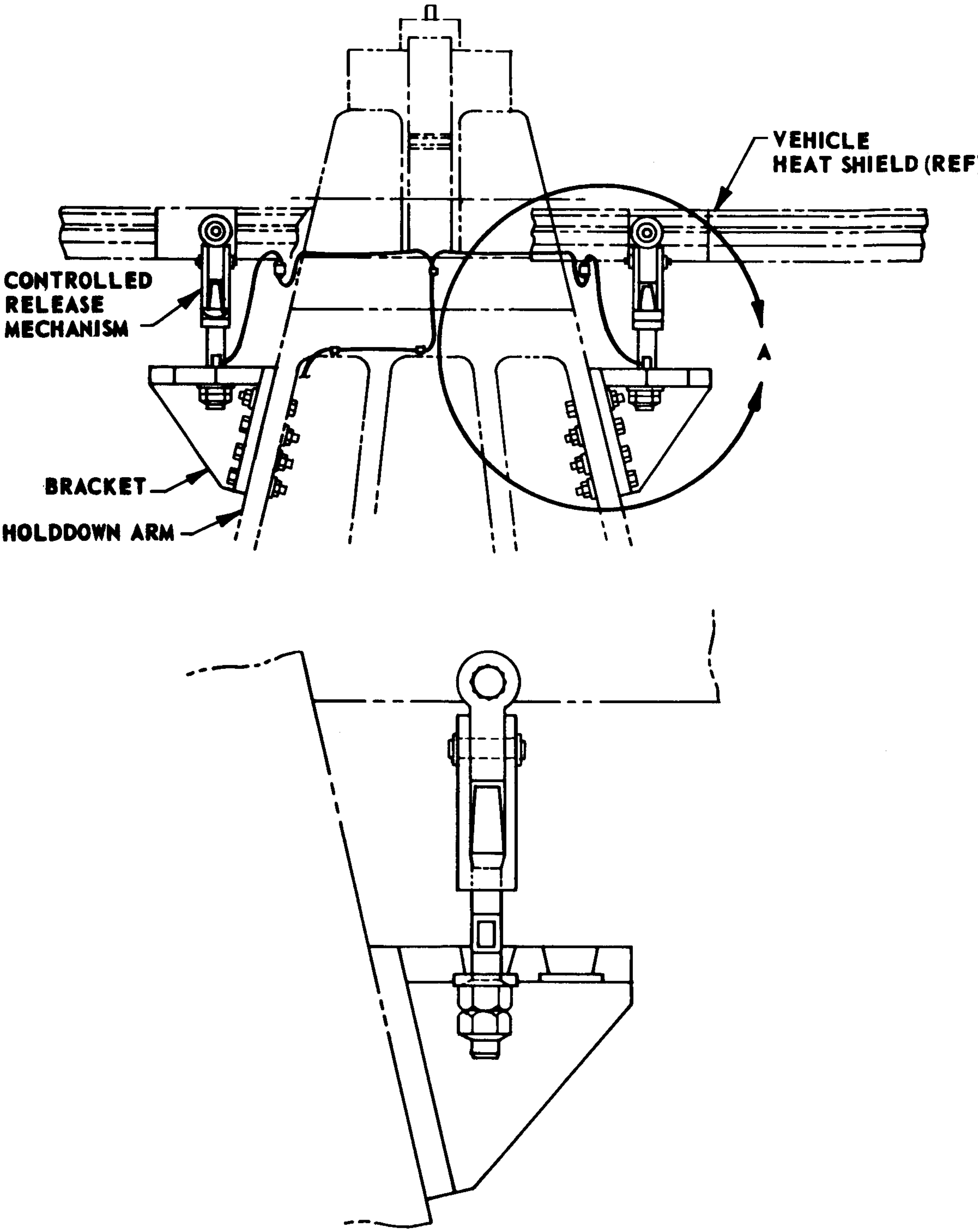


Figure 12. Controlled Release Mechanism.

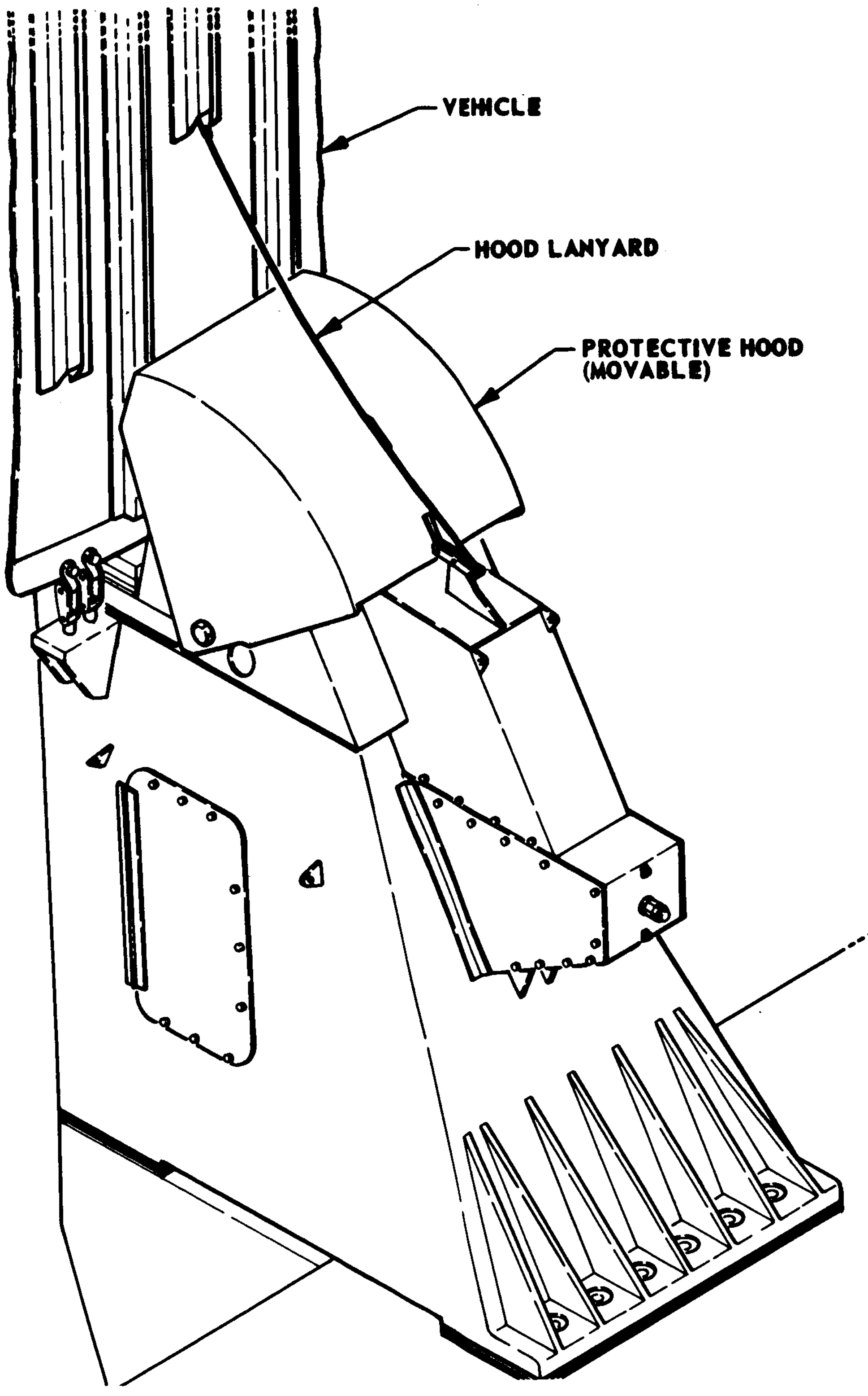


Figure 13. Protective Hood