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N90-22083DEVELOPMENT OF THE CLAES INSTRUMENT
APERTURE DOOR SYSTEM

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ABSTRACT

This paper describes the design, assembly, and test processes followed in developing a space-qualified aperture door system. A blackbody calibration source is mounted inside the door, requiring the assembly to open and close a minimum of 150 cycles for instrument recalibration. Within the door system are four separate mechanisms, three of which are redundant; a pyro launch latch, a hinge bearing assembly, and a pair of pivot mechanisms. Decoupling devices within the pivot mechanisms allow an active drive unit to automatically overdrive a failed drive unit. The door is also stowable for possible Shuttle retrieval and re-entry.

Throughout the paper, illustrations and photographs of the flight hardware help acquaint the reader with the design. The aim of this paper is to pass on lessons learned in all phases of developing this spaceflight mechanism.

INTRODUCTION

The Lockheed Palo Alto Research Laboratory has designed a space-qualified, Cryogenic Limb-Array Etalon Spectrometer (CLAES). It will be flown on the NASA Upper Atmospheric Research Satellite (UARS) scheduled for launch aboard the Space Shuttle in 1991. The satellite mission is to collect stratospheric sciences data, while the CLAES instrument specifically measures infrared signatures of 13 trace gases 10 to 60 kilometers above the Earth. The instrument is 1.22 meters in diameter, 2.74 meters long, weighs 1200 kg, and has an 18 month operational lifetime.

This paper focuses on the CLAES aperture door and all related structures and mechanisms. The requirements are addressed with discussions relating to safety issues and redundancy definition. Descriptions of the door system's six subassemblies are given with insights into their selection process. Manufacturing, assembly, and testing phases of the door system are also presented.

The aperture door system has passed all tests and is mounted to the CLAES instrument presently undergoing top-level instrument testing.

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DOOR SYSTEM DESIGN REQUIREMENTS

Safety is the primary design requirement of the door system, since the CLAES instrument will be launched aboard the manned Space Shuttle.

The instrument is an assembly of two major components; the instrument package and the cryostat. Refer to Figure 1. The instrument package consists of a vacuum shell, telescope, Fabry-Perot Etalon Spectrometer, focal plane array, and pressure sealing aperture door. The cryostat is a solid cryogen containment system that maintains the instrument package at cryogenic temperatures. The cryostat and instrument package share a common vacuum. This internal vacuum thermally isolates the cryogenics from the outside environment and maintains cleanliness standards within the instrument package. It is critical that the door maintains a vacuum seal at all times. Should there be a sudden loss of vacuum from any source within the CLAES instrument, the cryogenics will sublime causing the pressure within the entire instrument to rise at a rapid rate. Burst disks are designed to release this pressure, venting the gases overboard.

With an operational lifetime of 18 months, reliability is crucial to the success of the mission. The aperture door must open and close at least 150 cycles making its reliability a key element in the instrument design. Even though doors are only one of many critical hardware elements in spaceflight systems, they seem to get more than their fair share of management's attention.

List of Door System Requirements

- 1) Aperture dimensions: 24.4 cm high by 22.7 cm wide oval.
- 2) Door vacuum seal integrity must be maintained throughout launch. Margin of safety: 2.5
- 3) Operating environment: vacuum, 185 K minimum.
- 4) Pivot mechanism drive units: redundant stepper motors.
- 5) Door hinge assembly: redundant bearings.
- 6) Open positions: 135 degrees, 200 degrees.
- 7) Door location feedback: redundant limit switches, 3.0 degree repeatability.
- 8) Expected duty cycle: opened 48 hours, closed 48 hours.
- 9) 150 open/close cycles (minimum) over 18 months.
- 10) Max door closure time from 200 degrees: 60 sec.
- 11) Launch latch: redundant pyro actuated device utilizing a NASA Standard Initiator.
- 12) Relatch mechanism for recovery and re-entry. No redundancy requirement. Added late in the program.
- 13) Door must house a blackbody calibration source - 1.5 Kg.
- 14) A door stop shall provide protection for the vacuum shell.
- 15) Door must fit within the envelope of an external earthshade.
- 16) Maximum door system weight - 10.0 Kg.

DESIGN SELECTION PROCESS

The CLAES door system had many restrictions placed on it prior to the actual design phase. The most definitive restriction was that the door pivots, for lack of a better description, like a toilet seat. Refer to Figure 2. This pivot motion requirement came from the need for the internally mounted blackbody calibration source to view the relatively hot Earth as a heat source when the door was in the fully open position. The pivoting requirement preempted any trade studies of possibly more compact and reliable methods of opening such as translation or swivel motion.

The design requirements also specified the type of actuators and feedback in two of the door system mechanisms negating trade studies in these areas as well. The launch latch required a redundant pyro actuated device. Pyro devices were singled out due to their highly reliable performance record. The pivot drive mechanism requirement mandated redundant stepper motor drive units with redundant limit switch feedback. The CLAES electrical engineering staff chose steppers and limit switches due to the ease in which such devices can be interfaced and controlled with electronics.

An actual design trade study was only performed on the door pivot mechanism. It will be presented in this section.

Reliability

The UARS satellite is to be lifted into orbit by the Space Shuttle. When all satellite bus equipment has been activated to the satisfaction of the launch crew, UARS will be released. No instrument doors will be opened for a period of two weeks due to the anticipated contamination caused by the outgassing of the satellite's predominantly graphite epoxy structure. Without the luxury of an astronaut to aid a failed door opening mechanism, reliability is a major concern.

Reliability is determined by the quantity and type of moving parts in any mechanism. The design thrust was to create elegantly simple mechanisms with redundant elements that allowed for uncomplicated solutions.

Pivot Mechanism

The requirements placed on the pivot mechanism were that it be driven by redundant stepper motors with redundant limit switch feedback. NASA added the constraint that two separate mechanisms drive the door. Single point failures were unacceptable. It was clear that two highly reliable clutching mechanisms were necessary; one to disengage the failed stepper drive while another engaged the healthy drive.

Of the ten clutching mechanisms investigated, all had one common disadvantage; they required an actuator. These actuators were deemed single point failures and could not be tolerated. A mechanism was sought which automatically performed the needed clutching action.

After searching through mechanisms literature for many weeks, the solution presented itself during an inspirational moment at a weekly design meeting. By placing a simple torsion spring device between the door shaft and each drive unit, a soft-coupling will exist that can effectively perform the needed automatic function. The required spring rate and applied loads dictated a helical torsion spring design. A complete description of this device can be found in the following section.

DOOR SYSTEM DESCRIPTION

The door system is located on the outer radial surface of the instrument package vacuum shell. The door boss is integrally machined to the 1.22 meter diameter shell. Analysis showed that bonding or welding the boss to the shell would not have given a sufficient load carrying safety margin.

The door seals to the door boss by way of a Viton O-ring. The O-ring seal has a 2.62 mm cross-sectional diameter and is retained to the shell boss by a dovetail gland.

The door system contains six subassemblies; the door/blackbody calibration source assembly, hinge bearing assembly, pivot mechanism, launch latch mechanism, door stop assembly, and relatch mechanism. Refer to Figure 3. Descriptions of each subassembly will be given in this section.

Door/Blackbody Calibration Source Assembly

The door is machined out of a solid block of 6061-T651 aluminum. External ribs stiffen the door to pressure loads. A special coating, Magnaplate HCR, is applied to the sealing surface of the door flange to prevent stiction of the O-ring seal. The surface treatment hardens and lubricates aluminum surfaces. General Magnaplate performs this proprietary process on many different materials at its plant in Ventura, California.

The blackbody calibration source is an aluminum plate mounted to the door by four insulating, fiberglass posts. Radial grooves machined into the top surface of the clear anodized plate help create a high emissivity blackbody source. The back surface of the plate is instrumented with platinum resistance thermometers (PRTs) and flat element heaters for fine temperature control. Multi-layered insulation and an outer aluminum shield surround all but the front surface of the plate. The blackbody electrical harness ends at a hermetically sealed connector affixed to the top, inner surface of the door.

There was concern that the external mating harness would fail under bending loads after many door cycles in the cold space environment. It was decided to have the harness twist during the door cycles since the kinematics of twisting are less stressful to wires than bending. The Kapton wrapped electrical harness is routed from the door through a cable mount and retainer. The mount supports the harness to the door while the retainer guides the bundle through its twisting motion. An 11.0 cm diameter loop was

used to distribute the twisting over a reasonable length and to lower the spring rate of the cable. With this cabling arrangement the door is free to pivot with negligible resistance.

Hinge Bearing Assembly

A bearing assembly is mounted on either side of the door hinge shaft. Coaxially mounted, deep-groove ball bearings are attached through a "Z" arrangement within each assembly. Refer to Figure 4. A stainless steel mount links the outer race of one bearing to the inner race of the other. If one bearing seizes, the linking element allows the good bearing to spin the entire subassembly. Deep groove ball bearings were chosen for this assembly due to their low friction, small size, and ample load rating. Barden Bartemp bearings were singled out from other manufacturers due to their low temperature operating capability. Two wave washers preload each assembly 178 newtons to ensure all of the balls in the bearings are immobilized during the launch environment. Otherwise, the balls would be free topeen the races.

The "Z" mount configuration was chosen due to its compact size and high reliability. A disadvantage of this arrangement is that a moment can be applied to the bearings when under a radial load. This was minimized by mounting the bearings as close together as possible.

Pivot Mechanism

The heart of the door system design is the redundant pivot mechanism. It consists of duplicate drive trains connected to opposing ends of the door hinge shaft. Both drive trains are composed of a drive unit (integral two degree stepper/100:1 harmonic drive) and a helical spring decoupler. Each drive unit generates 6.78 N-m energized torque and 2.26 N-m detent torque at the splined output shaft. The drive units are manufactured by Schaeffer Magnetics in Chatsworth, California; a professional outfit that delivered excellent flight hardware on schedule.

Each decoupler consists of a helical torsion spring, rod center, sleeve bearing, bearing mount, and a pair of cam plates. Refer to Figure 4. Both decouplers are identical except for oppositely wound springs. Each spring is wound in the direction that increases coils when opening the door since applied stresses are lowest in this arrangement. Each decoupler is capable of 1.56 N-m torque at their 370 degree yield deflection.

The sleeve bearing is manufactured out of DuPont Vespel SP-3; a 15% molybdenum-filled polyimide resin composition with low outgassing and friction coefficient properties. Both the stainless steel rod center and bearing mount have splined ends for attachment to the door hinge shaft and drive unit. Each decoupler is secured to the door hinge shaft with a cotter pin. The cam plates trigger the limit switches at the 0, 135, and 200 degree door locations.

As a redundant feature of the mechanism, it is planned to have both drive units wind the decouplers 251 degrees in the open direction before

launch. If a total failure of the redundant door drive electronics occurs prior to the initial door open command, firing the pyro launch latch will allow the spring decouplers to automatically open the door.

Pyro Launch Latch Mechanism

The launch latch is a slight modification of a mechanism previously designed by the Lockheed Missiles and Space Company (LMSC). Refer to Figure 5. An aluminum bracket mounts two LMSC developed pyrotechnic pinpullers to the vacuum shell boss. Each pinpuller contains one NASA Standard Initiator and can actuate under a 3380 newton double shear load at 185 K. An aluminum threaded rod with spherical end fits between the pinpuller shafts and up through the door into a spring tensioning device. The tensioning device consists of a compression spring, housing, spherical washer, thirty spring washers and a castellated nut. This device performs two functions. If only one pinpuller actuates, the threaded rod will be free to pivot around the failed pinpuller shaft while being pulled up into the door by the compression spring. The thirty spring washers allow for an accurate application of 667 newtons tensile preload to the load carrying rod.

Door Stop Assembly

If a complete failure of the door drive electronics occurs prior to the initial door open command, the pyro launch latch will be fired allowing the prewound spring decouplers to open the door. A pair of door stop assemblies decelerate the door ten degrees past the 200 degree position.

These simple devices mount to the vacuum shell. Each stop device consists of a compression spring, stud, and plunger. The springs are sized to compress to half of their stroke capability. The door will impact the stop assemblies near its center of gravity.

Relatch Mechanism

The requirement that the door be stowable for Shuttle retrieval and re-entry came from the customer after most of the door system drawings had been completed. Waiving a redundancy requirement on this device allowed for an inexpensive solution.

A TRW Globe D.C. motor/gearhead/brake assembly was chosen as the drive unit. This stock catalog item was originally designed for operation in a one atmosphere environment. The supplier made minor material modifications in the unit for vacuum compatibility. A load carrying cam with a 19 mm moment arm slides onto the splined output shaft of the drive and is secured with a cotter pin. The entire assembly mounts to a bracket on the vacuum shell boss. A 6.3 mm diameter dowel pin is pressed into the door side wall to carry the 14 g Shuttle landing loads. A limit switch assembly is placed at the cam open location for position feedback. When the door is closed, the drive unit cam pivots over the pin and presses the door to the vacuum shell boss. The drive electronics automatically de-activate the D.C. motor through a current limiting circuit. When the unit is de-energized, the brake clamps down on the motor shaft allowing the cam to secure the door in the closed position with a preload of 593 newtons.

The relatch drive actually has a dual role. The drive cam will be positioned under the door relatch pin at launch. Should the vacuum O-ring seal stick to the door, the relatch drive will push up on the pin with 1779 newtons to overcome the seal stiction.

A simple backup to the cam relatch design was added due to the negligible cost of implementation. A 1.0 cm diameter hole is located in the door flange near the pivot hinge shaft with a threaded hole in the vacuum shell boss. An astronaut EVA will be required to thread a bolt through the door and into the vacuum shell boss.

TEST PERFORMANCE

Six separate qualification tests were performed on the door system. An aluminum mounting plate was used in the tests for accurate duplication of all vacuum shell interfaces. The mounting plate also provided a void behind the door for pressure testing. All tests were performed in an ambient environment unless otherwise stated. The tests were performed in the order in which they are listed in this section.

Manufacturing, assembly, and testing difficulties will be addressed in the following section.

Relatch Drive Unit Torque Test

The relatch drive unit was mounted with a pulley, cable, and weight bucket attached to the output shaft. To determine the stall torque, successive weights were added to the weight bucket until the drive stalled. The brake torque was acquire by adding weights to the weight bucket until backdriving of the deactivated unit commenced. The drive unit torque measurements were; 34.0 N-m (stall), 11.3 N-m (brake).

Door Pressure Test - Figure 6.

A vacuum was pulled on the door and a helium leak detector found no leaks. Nitrogen gas was then used to backfill and positively pressurize the door. The door was found to vent at 10.34 kPa. This was 27 percent below the pressure requirement. After replacing the O-ring seal with one of a lower durometer, the test was repeated with more favorable results. The door vent pressure was determined to be 13.10 kPa.

Blackbody Electrical Harness Life Test - Figure 7.

A representative harness and test fixture simulating the harness interfaces were placed in a styrofoam container with dry ice to achieve the 185 K space environment. An insulated shaft passing through the container wall allowed personnel to cycle the harness assembly through a 200 degree arc. The harness was cycled 600 times (four times the anticipated lifetime cycles) while an ongoing continuity check confirmed a successful test.

Door System Functional Test

The entire door system was assembled to the test mounting plate. This assembly was in turn mounted to a holding fixture that oriented the door pivot axis along the gravity vector to simulate a zero gravity environment. A comprehensive functional test was then performed on all subsystems including; the door pivot mechanism, pyro launch latch, and relatch mechanism. Anomalies were found and corrected during the pivot drive microswitch actuation. The microswitch and pivot mechanism problems will be addressed in the next section.

Door System Vibration Test

The complete door system test assembly was mounted to a three axis vibration fixture. Random vibration exposures were performed on all three axes per the NASA Shuttle launch specification. The door maintained a vacuum throughout the test with no measurable leakage. After the test, an abbreviated functional test of the pivot drive units was performed while the pyro launch latch remained engaged. No anomalies were found.

Pyro Launch Latch Actuation/Cold Functional Test - Figure 8.

The door test assembly was mounted to the holding fixture and placed in a cryogenically cooled vacuum chamber. While in a vacuum at 185 K, one of the two pyro pinpullers was fired. This single pinpuller actuation successfully tested the redundant feature of the launch latch mechanism. The pivot drives and relatch mechanisms were then fully function tested with no abnormalities.

MANUFACTURING, ASSEMBLY AND OPERATIONAL DIFFICULTIES

The CLAES instrument is a protoflight design; no funding was allocated for a development test unit. With this requirement, the tested door system hardware was also to be flown.

There are always countless annoying little problems to overcome when building new hardware. The major difficulties in developing the aperture door system will be addressed in this section. Problems arose in three areas; decoupler spring creep, limit switch actuation, and door stiffness.

Decoupler Spring Creep

The most compliant members in the door pivot mechanisms are the two decoupler torsion springs. Under normal operating conditions the decoupler springs must only overcome the spring forces in the door location feedback microswitches. The decoupler spring rate is designed as high as practical to insure repeatable angular displacements at the decoupler ends. Otherwise, the orientation of the door with respect to the pivot drive steppers will change continually over the life of the mechanism. This can create major problems for the control electronics.

Each spring is heat treated and shot peened to reduce undesirable residual stresses in the 304L stainless steel material. Under a stepper drive unit failure, the worst case deflection of either decoupler will be 251 degrees; 200 degrees to rotate the door and 51 degrees to actuate the microswitches. The springs yield after a deflection of 370 degrees.

During the pivot mechanism functional testing, orientation of the decoupler ends shifted up to 15 degrees for any combination of loading conditions. Angular displacement commands sent to the stepper motors did not correlate consistently with the displacement of the door.

During a spring design literature search it was discovered that a crucial step was left out of the spring manufacturing process. Helical torsion springs tend to creep at stress values less than those in the plastic region unless they are "stress set". Displacing a spring to its highest working stress level will place a memory into the material. The spring will then deflect consistently at stresses less than the "set" level. Each decoupler spring was set at the plastic yield stress level. The springs now register consistently throughout the door pivot operations.

Limit Switch Actuation

Four limit switch assemblies provide orientation feedback for the door pivot mechanism. Two switch assemblies are mounted on either side of the door hinge for redundancy while the remaining two are located at the stepper drive units. A complete switch assembly consists of three microswitches, three actuators, and a mounting bracket. In this design, the actuator is a cantilevered strip of stainless steel that transfers the actuation force from the decoupler cam to the delicate switch. Each assembly has switches oriented at 0, 135, and 200 degrees.

During functional testing, the switches did not operate in a repeatable manner to the three degree location tolerance. The switch actuator's cantilever slope angle was found to be too shallow for close tolerance feedback. The solution was simple. By locally bending the switch actuator into a sharp "V", the cam displaces it over a much smaller deflection angle. Refer to Figure 9. With this feature, the switch feedback tolerance is easily met.

Door Stiffness

As the Shuttle passes through the max Q launch condition, the door external pressure is one-tenth of an atmosphere while the random vibrations are at their peak. To ground test the door sealing capability for this worst case condition, a relationship between g-level and internal pressure was created; equivalent inertial load pressure. This internal pressure was determined to be 4.83 kPa. The door seal margin of safety requirement dictated a minimum pressure of 12.07 kPa. During pressure testing, the door vented at a differential pressure of 10.34 kPa.

The door is machined out of a solid piece of 6061-T651 aluminum. The cost of redesigning the door structure would be high. It could be machined out of a stronger material such as a 300 series stainless steel but the increased weight would have been prohibitive. Alternate solutions were sought.

The solution was found in the door O-ring seal. The seal material, cross-sectional diameter, and contact length determine the door sealing force. Lowering this force would allow the door to seal with less deflection, raising the venting pressure. The contact length and cross-sectional diameter could not be changed since the dovetail gland was already machined in the vacuum shell. A search to replace the original 70 durometer Viton material was enacted. We located a moldable, 60 durometer Viton material manufactured by Parker Seal Company in Lexington, Kentucky. With this new seal material, the door vents at 13.10 kPa.

SUMMARY

This paper has described the design, assembly, and test processes followed in developing the CLAES aperture door system. All operational tests have been successfully completed, demonstrating the door system meets all of the original performance requirements. The CLAES instrument will be flown on NASA's Upper Atmospheric Research Satellite (UARS) scheduled for launch aboard the Space Shuttle in 1991.

ACKNOWLEDGEMENTS

The development of the CLAES instrument was performed by the Lockheed Palo Alto Research Laboratory under contract to NASA Goddard Space Flight Center. The author wishes to express his gratitude to the CLAES Program office for the opportunity to work on this challenging assignment. Special thanks goes to Bruce Steakley, the CLAES opto-mechanical group leader, for his ideas, patience, and continued support.

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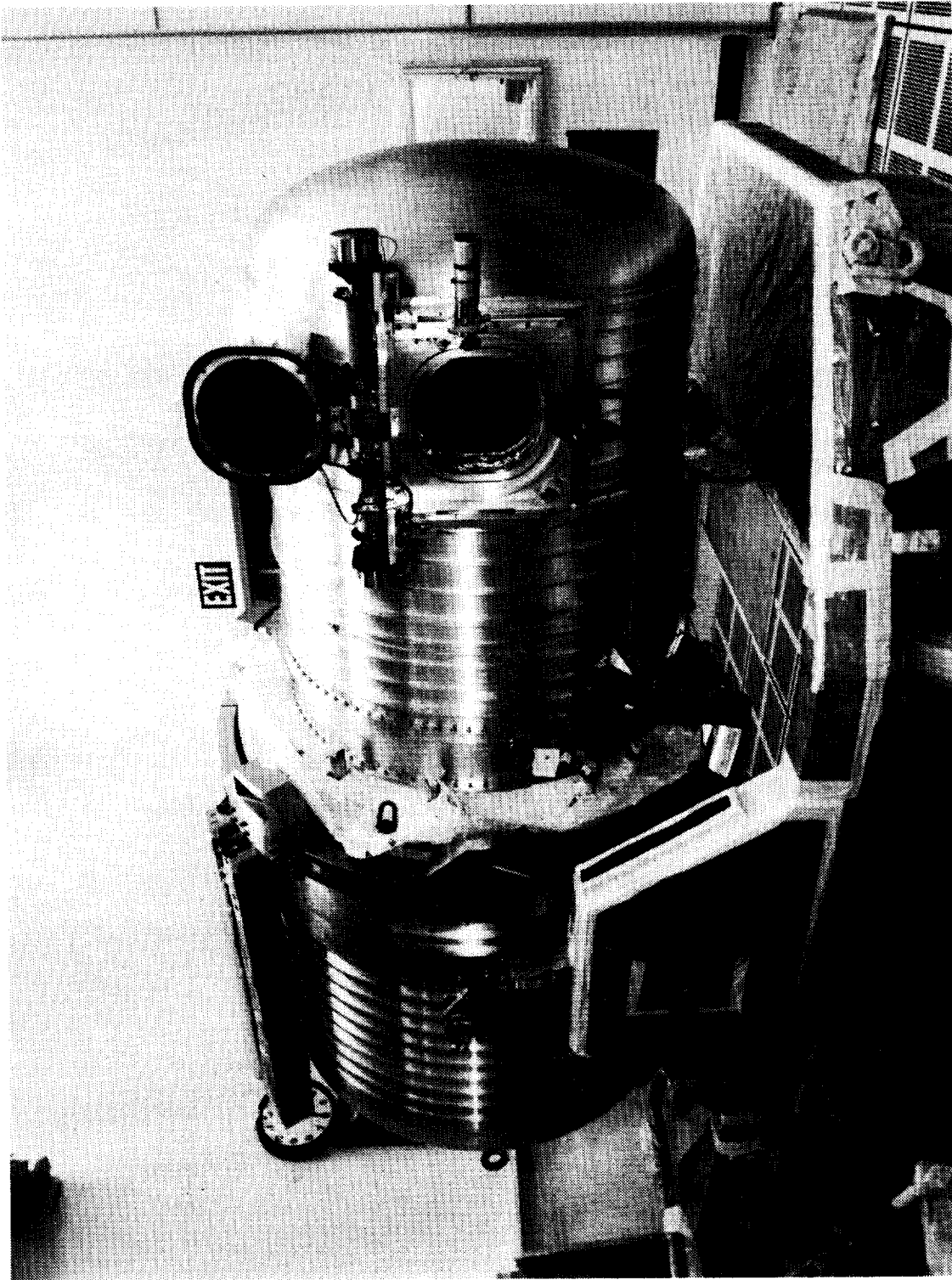


Fig. 1 CLAES Instrument Mounted to Ground Handling Dolly

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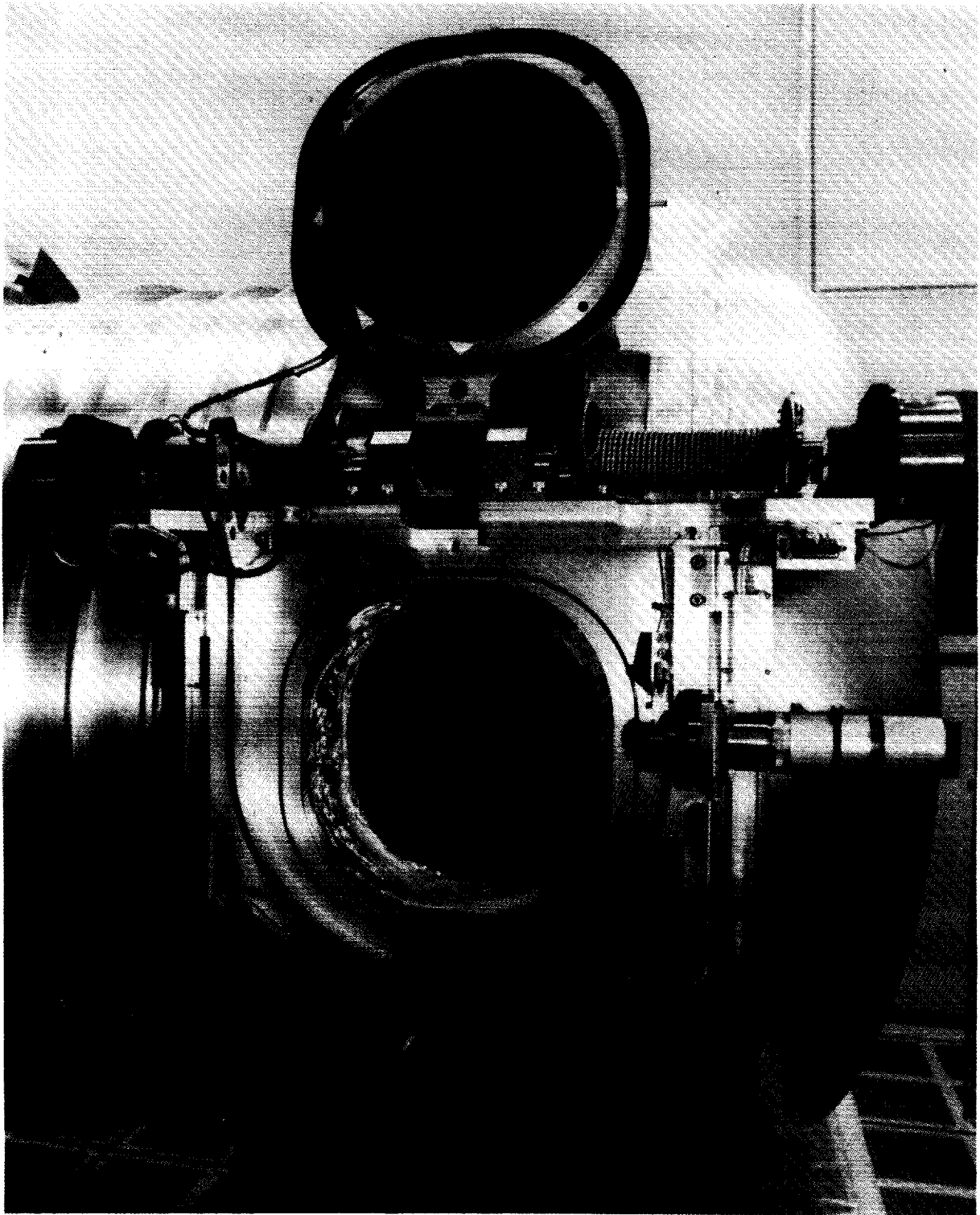


Fig. 2 Door System Assembled to CLAES Instrument

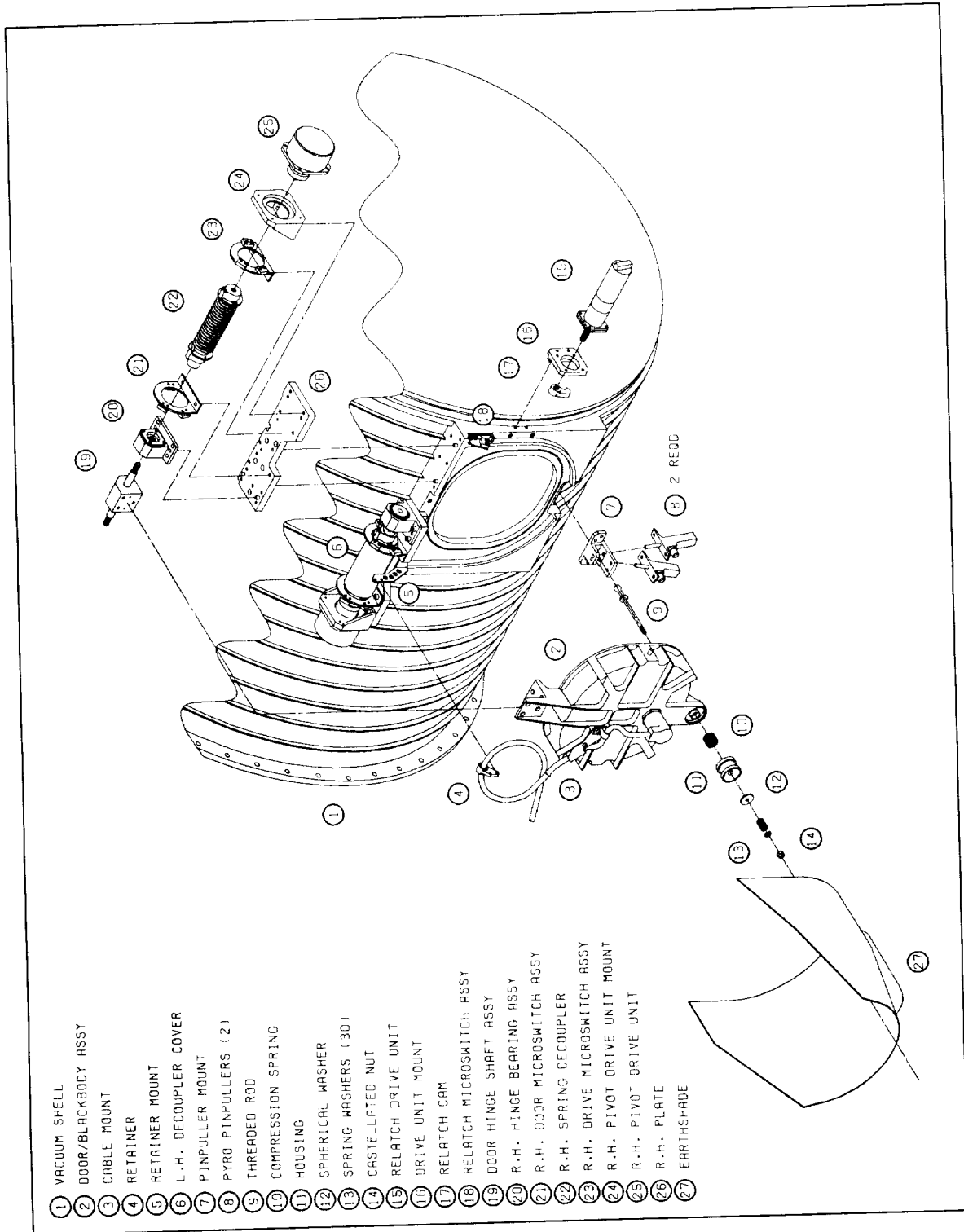


Fig. 3 Isometric Exploded View of Door System

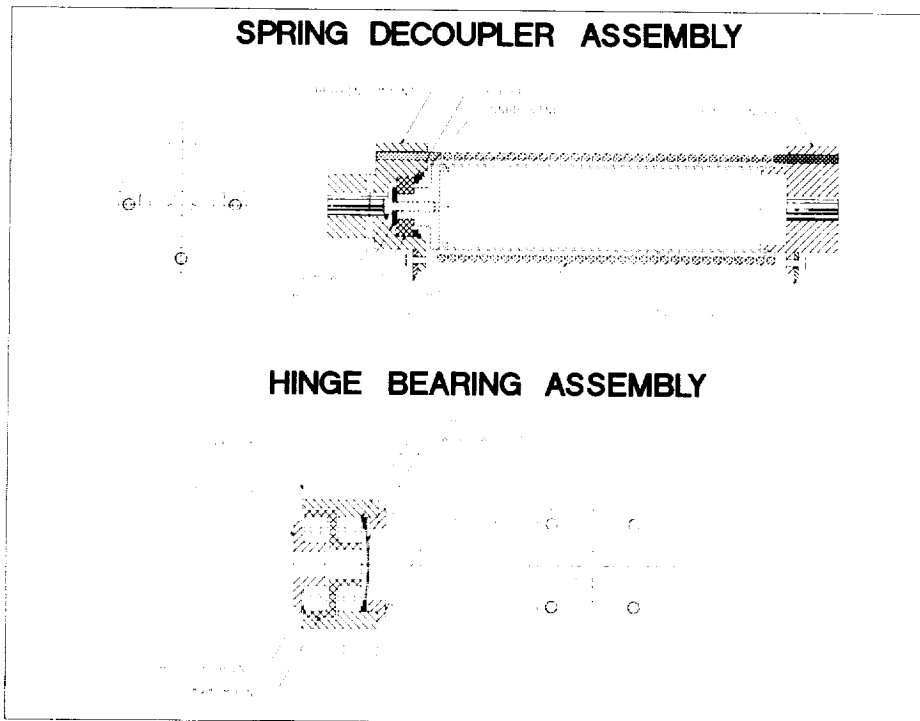


Fig. 4 Cutaway Views of Decoupler and Hinge Bearing Assemblies

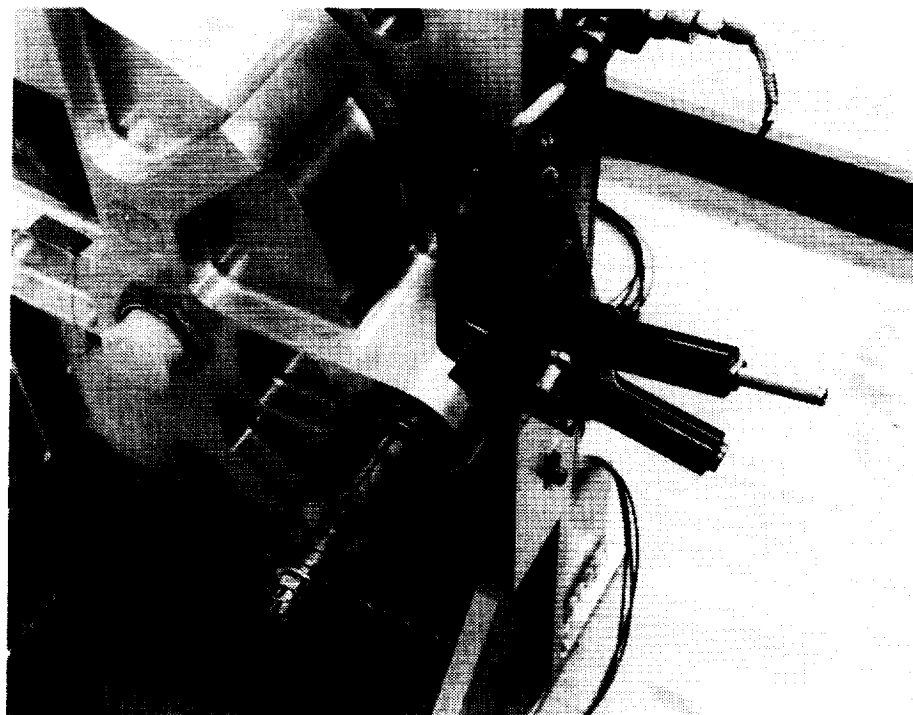


Fig. 5 Launch Latch With One Fired Pinpuller

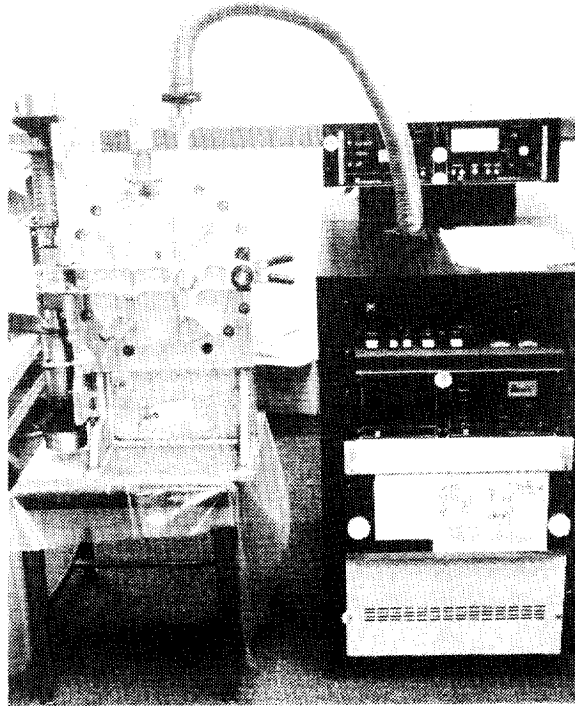


Fig. 6 Door Pressure Test Setup

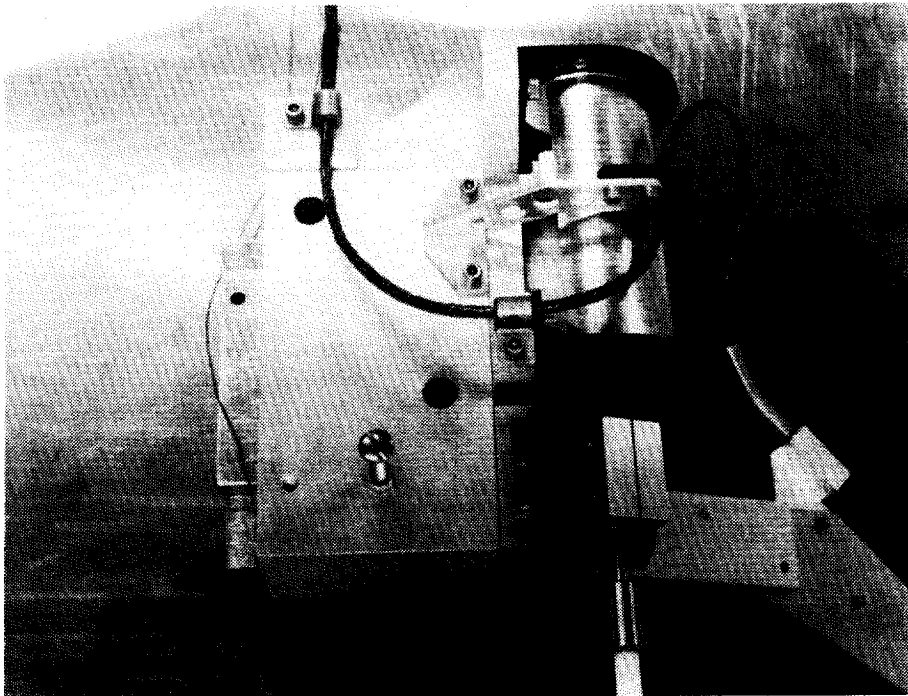


Fig. 7 Blackbody Electrical Harness Test Fixture

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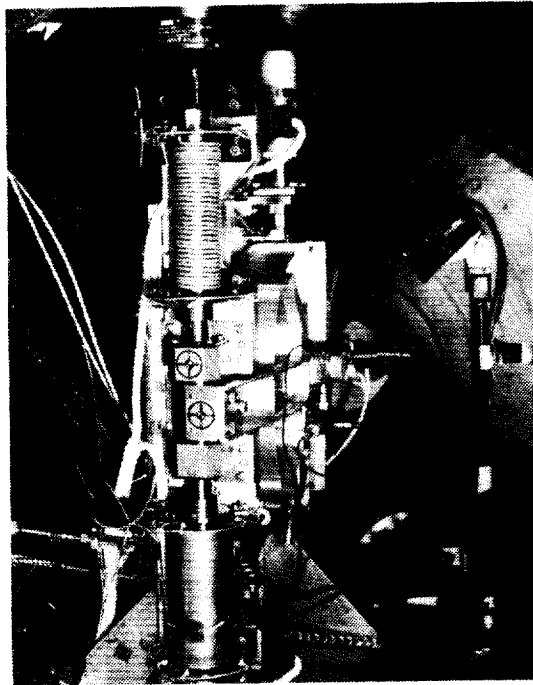


Fig. 8 Cold Functional Test

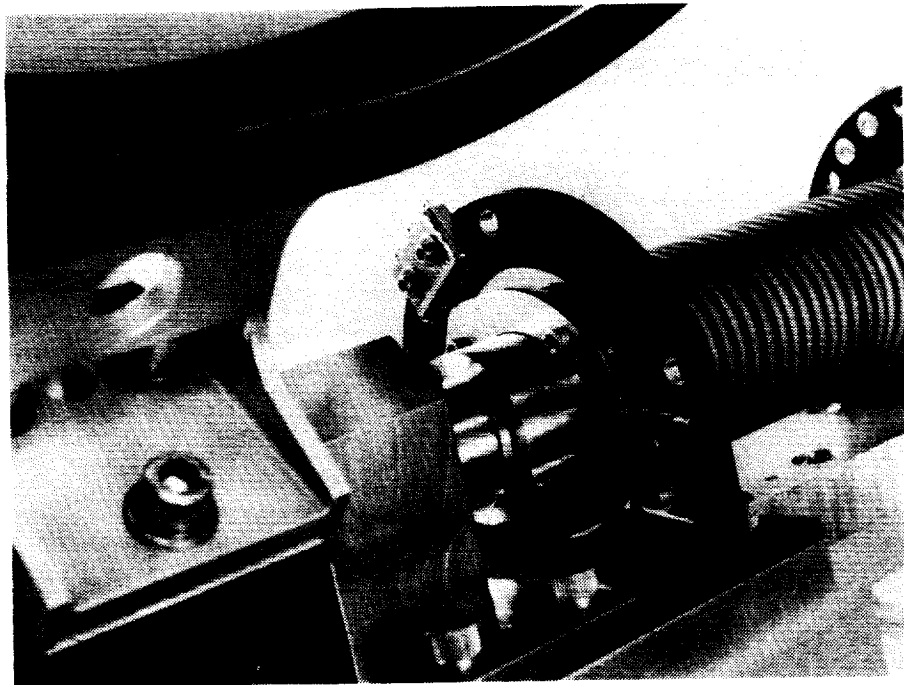


Fig. 9 Microswitch Assembly With Door at 135° Position