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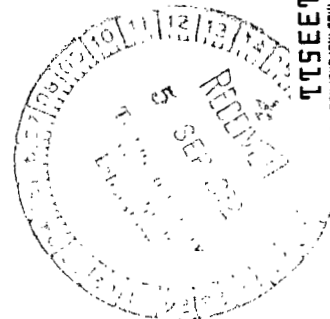
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16. Abstract

The separation concept of the Skylab Payload Shroud is presented, and its behavior in three full-scale jettison tests in vacuum is described. The shroud petal arresting mechanism is explained, as well as the primary and secondary data acquisition systems. The first two tests demonstrated the need for some structural design modifications although the separation process was satisfactory in each test. The third test, incorporating these design modifications, was satisfactory in all aspects of shroud performance.

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SUMMARY

Three full-scale jettison tests of the Skylab Payload Shroud were conducted in vacuum to determine the adequacy of the separation concept. The test chamber is 30.5 meters (100 ft) in diameter by 37.3 meters (122 ft) tall. The test shroud is constructed of aluminum plate with transverse stiffeners. It is 6.6 meters (260 in.) in diameter and 17.1 meters (56 ft) long. The complete assembly has a mass of 11 068 kilograms (24 400 lb). The test shroud used in these tests is essentially identical to the production units.

The jettison tests were performed at altitude, the chamber pressure being 2.4×10^{-4} torr. No aerodynamic heating was simulated, since in the mission, jettison occurs essentially in orbit. The primary data system consisted of 18 high-speed motion picture cameras. The shroud separated into quadrants, each of which was caught in a catch-net arresting system designed to prevent any damage to the quadrants. No difficulty in reassembly of the test shroud occurred after any of the tests.

The test results, that is, center-of gravity velocities, outward rotation, and longitudinal roll, fell well within the performance range established by Marshall Space Flight Center and its contractor. In the first two tests, a number of problems in the separation system and in parts of the structure occurred. These resulted in some design modifications to both the test shroud and the production units. Following incorporation of these modifications, a third test demonstrated completely satisfactory jettison performance. There were no misfirings or malfunctions in any of the firing systems.

INTRODUCTION

The Skylab mission requires the largest, most massive payload shroud ever launched. Mission success, of course, depends on the successful jettisoning of this aerodynamic fairing. Moreover, in contrast to most other missions, this particular payload shroud will not be jettisoned until the spacecraft reaches orbital altitude. Thus,

full-scale tests of the separation concept and jettison process were considered necessary to provide mission analyzers with free-flight separation dynamics data for evaluation of the flight jettison itself. In addition, because of the presence of optical equipment and other experiments inside the shroud, no free-flying particles or objects can be tolerated.

This report presents a description and results of the Skylab Payload Shroud jettison test program carried out at NASA Lewis Research Center's Space Power Facility (SPF) located at the Center's Plum Brook Station near Sandusky, Ohio. The in-chamber time period extended from mid-September 1970 to June 1971. The test program was carried out by SPF personnel at the request of the Skylab Airlock Module Project Office at the NASA Marshall Space Flight Center (MSFC). The Skylab Payload Shroud was built for NASA by the McDonnell Douglas Corporation.

TEST ARTICLE AND SEPARATION CONCEPT

The Skylab Payload Shroud is an aerodynamic fairing protecting the forward portion of the Skylab cluster during launch and ascent to orbit. The shroud mounts on a structure called the Fixed Airlock Shroud (FAS). This structure is mounted on the instrument unit of the S-IVB (Saturn V third stage), which has been converted into an orbital workshop. Inside the Payload Shroud, from the orbital workshop forward, are the airlock module, the multiple docking adapter, the Apollo telescope mount and its deployment assembly, and a number of experiments carried on these modules.

The Payload Shroud thus is the same diameter as the S-IVB stage, 6.6 meters (260 in.). It is approximately 17.1 meters (56 ft) tall, is made of aluminum, and has a mass of 11 068 kilograms (approx. 24 400 lb). It consists of two major parts: a cylindrical section 8.8 meters (29 ft) in length and a conical section 8.2 meters (27 ft) in length. An exploded view of the shroud is shown in figure 1 and the test shroud in the SPF assembly area in figure 2.

The Payload Shroud separates into quadrants. Figure 3 illustrates the separation mode as the shroud is jettisoned from the Skylab cluster. The separation concept is the same as that used in the Air Force Titan IIIC universal payload fairing system (ref. 1), which has completed a number of successful launches. This separation concept uses the gas pressure generated by rapidly burning linear explosive to act on a thrusting joint, shearing rivets which hold the whole assembly together, and imparting the necessary separation velocity to the quadrants to jettison them well clear of the spacecraft. A cross-sectional view of the thrusting joint is shown in figure 4. This thrusting joint extends the full length of the shroud. The linear explosive is contained within the stainless-steel tube indicated on the sketch. Rows of ports in the tube assemblies allow the gas generated to expand into a bellows, which thrusts against the piston on the adja-

cent quadrant, shearing the rivets and separating the shroud. Figure 5 illustrates the action of the joint. The amount of linear explosive is twice that required to shear the rivets. The linear explosive is ignited by electrically actuated detonators at both of its ends. Burn time is roughly 2 to 3 milliseconds, and discernible movement of the separating quadrants occurs within 8 to 16 milliseconds. Details of this separation process, as revealed in these tests, are described herein.

On each edge of each quadrant, then, the separation forces are tangent to the circumference of the shroud. They are thus at a 45° angle to the direction of movement of the quadrant. For each quadrant, the vector sum of these forces produces the net accelerating force on the quadrant in the direction of movement. Moreover, because these forces are compressive, they tend to curl the shroud edges in, and flexing occurs. This can be seen in the films.

The Payload Shroud is held together not only by the shear rivets, but also by dual pin linkages, at both the aft and forward ends of the cylindrical portion of each separation joint. The pins are referred to as "latchpins." Prior to jettison, the pins in these links are retracted by linear explosive and detonators, as in the separation system.

During launch and ascent, the structural load of the Apollo telescope mount (ATM) is carried to the cylindrical portion of the shroud through four linkages, known as the ATM Support Assembly. These linkages are located across the four separation lines at the forward end of the cylindrical half of the Payload Shroud, and are shown in figure 6. Thus, the Payload Shroud must separate not only from itself and its mounting on the Fixed Airlock Shroud, but also from these linkages. Moreover, it must do this without imparting severe shocks or vibration to the Apollo telescope. For the SPF tests, the ATM was simulated by a light structure to which the ATM Support Assembly was attached, allowing flight-like operation of these joints in the ground tests.

Space Power Facility Test Article and Deviations from Flight Article

Three payload shrouds are being manufactured for the Skylab program: One for the mission; one as part of the backup hardware; and one for ground testing both in the tests being described herein and for vibration-acoustic testing at the Manned Spacecraft Center (MSC). All three shrouds are essentially identical; the test shroud as received at SPF differs from the other two in two minor aspects:

(1) The two damper-arm connecting legs near the tip of the cone were removed. These are used to connect damper arms from the tower at the pad, prior to launch. They represent protrusions which could damage the arresting system used to catch and stop the jettisoning quadrants in the ground tests at SPF. Their masses were replaced with equivalent dummy weights.

(2) Separation sensor breakwires, latchpin breakwires, accelerometers, and associated wiring were added to the unit for the SPF test program.

Objectives of the Space Power Facility Tests

Detailed objectives and requirements for the SPF Skylab Payload Shroud jettison tests are given by McDonnell Douglas. This is the baseline document for this program, and its objectives may be summarized as follows:

(1) Demonstrate separation of the shroud quadrants

(2) Demonstrate separation from the Fixed Airlock Shroud and the Apollo telescope mount, and assess separation shock

(3) Verify structural integrity due to separation loads

(4) Verify separation performance characteristics

(5) Verify containment of the gases generated by the linear explosives

Specifically, it was predicted by MSFC and its contractor that the separation characteristics would fall within the performance limits presented in table I. Also, a per-

TABLE I. - PREDICTED DYNAMIC PERFORMANCE

OF SKYLAB PAYLOAD SHROUD JETTISON

	Maximum	Minimum
Center-of-gravity velocity, m/sec (ft/sec)	6.55 (21.5)	4.9 (16.1)
Yaw rate, deg/sec	19	11.0

formance range was evolved from mission studies. This range is illustrated in figure 7, together with the shroud performance from the data of the three tests performed at SPF. Any combination of yaw rates and separation velocities falling to the right of the line labeled "no recontact - orbital mission" represents acceptable performance. The second line, labeled "no recontact - ground test" represents the same performance specification adjusted for gravity effects in ground tests at SPF. Thus, for the SPF tests to be considered successful, the data must indicate performance ranges to the right of the latter line.

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TEST CONFIGURATION AT SPACE POWER FACILITY

The test configuration at SPF consists of the test shroud and the test support equipment. The test support equipment can be divided into three parts: (1) a structural/mechanical system for catching and holding the free-flying quadrants without damage; (2) the electrical/electronic system for controlling the test and collecting certain data; and (3) the prime data system, that is, the high-speed motion picture cameras.

Description of Space Power Facility

The Space Power Facility is essentially a very large vacuum chamber for the testing of spacecraft and/or their subsystems and components in a simulated space environment. In operation, the facility will provide a vacuum of from 10^{-5} to 10^{-8} torr. The test chamber itself is 30.5 meters (100 ft) in diameter and 37.2 meters (122 ft) high, making available a high-vacuum volume of 22 700 cubic meters (800 000 ft^3). Designed to include the capability for ground testing of advanced nuclear-electric space power systems, the test chamber is surrounded by a concrete shell 1.8 to 2.1 meters (6 to 7 ft) in thickness. The facility is shown in figure 8, while a cross-sectional view through the chamber itself is illustrated in figure 9. The view shown in the photograph is from the northwest. To the east of the domed test chamber enclosure is a high bay assembly area; to the west is a second high bay workshop called the dissassembly area. The latter is a concrete structure designed for the handling of radioactive materials and nuclear power systems subsequent to operation in the test chamber.

Test articles are assembled in the assembly area, moved to the test chamber, and after completion of testing, moved to the disassembly area if they are nuclear devices. Facilitating the installation, erection, testing, and removal of test articles of large size and weight are the large chamber doors (providing openings of 15.2 m (50 ft) by 15.2 m (50 ft)) and three sets of standard-gage rails which pass from the apron east of the assembly area, through the test chamber, and into the disassembly area. Overhead cranes and other services are provided in the assembly area, the test chamber, and the nuclear disassembly area. Directly abutting the north side of the concrete test chamber enclosure is a test control center for facility operation, control of tests, and data acquisition.

Structural/Mechanical Test Support Equipment

The stopping and catching of free-flying objects as large as the Skylab Payload

Shroud quadrants without damage requires a sizeable structural/mechanical system.

The test configuration in the SPF test chamber is shown in figure 10. Four free-standing towers tied together at the top supported four large catch-nets made of nylon webbing material. The catch-nets were laced to side frames of aluminum pipe. A typical catch-net assembly is shown in figure 11. Horizontal movement of each catch-net was controlled by three hydraulic cylinders mounted in the four corner towers along each side of the catch-net assembly. Each hydraulic cylinder was connected to a catch-net frame by 2.54-centimeter (1-in.) nylon ropes run through a fairlead and spliced to eye-bolts on the frames. How these ropes were led through the fairleads on the support towers is shown in figure 12. The catch-net frames are outside the picture; the hydraulic cylinders are mounted horizontally behind the plate at the top of the picture. The nets were placed such that free flight of each quadrant in the horizontal direction would be 1.22 meters (4 ft). For a shroud quadrant of 2700-kilogram (5940-lb) mass impinging on an arresting system at velocity of 6.55 meters per second (21.5 ft/sec), the peak stopping force will be between 110 000 newtons (25 000 lb) and 134 000 newtons (30 000 lb), depending on the travel of the arresting system.

The catch-net frame assemblies were supported vertically by breakwires whose breaking strength was slightly greater than the weight of each catch-net and frame. When the shroud quadrants impinged on the nets, these wires broke, allowing the catch-net frame and the quadrant to move outward and downward. Arresting of vertical movement was provided by polyurethane closed-cell foam blocks arranged in stacks 3.66 meters (12 ft) by 4.9 meters (16 ft) by 1.37 meters ($4\frac{1}{2}$ ft) high underneath each catch-net assembly. Each stack was secured in place with rope and covered with cotton cloth. The Fixed Airlock Shroud Simulator on which the test shroud was mounted was itself mounted on a structural steel base such that the aft (lower) edge of the shroud was approximately 2.75 meters (9 ft) above the chamber floor. Thus, each net-quadrant combination could free fall 1.37 meters ($4\frac{1}{2}$ ft).

Inside the shroud was an internal work tower extended up to the cone-cylinder interface level. This tower supported four cameras and served to arrest the fall of the ATM Simulator as the ATM Support Assembly joints separated during the jettison process.

To prevent the shroud quadrants from bouncing back out of the nets toward the centerline of the test assembly, a restraint mechanism was devised. Inboard and above each catch-net, a rope was suspended so that the separating shroud quadrant would pass under it. This rope was tied to one tower, passed through a fairlead on the adjacent tower, over a No. 35 Barient ratcheting sailboat winch, and connected to shock cord pre-tensioned to about 2670-newton (600-lb) load. First movement of the catch-net frame pulled a pin, allowing the shock cord to relax and thus pull the rope down. The winch prevented any slackening of the rope due to shroud quadrant impingement. These bounce-back restraint ropes acted in about 0.2 second after the pin was pulled, moving

down some 4.6 meters (15 ft). A typical bounce-back restraint rope after triggering is shown in figure 13. Thus, after jettison, each quadrant was securely held by the catch-net outboard of it and the restraint rope inboard of it.

The principal elements for adequately minimizing the peak stopping forces on the free-flying shroud quadrants were the hydraulic cylinder assemblies. As noted previously, each catch-net had six of these connected to it by means of nylon ropes. A schematic of the circuitry used is shown in figure 14. The cylinders had a bore of 0.063 meter ($2\frac{1}{2}$ in.) and a maximum stroke of 1.22 meters (48 in.).

The continuing outward motion of the shroud segments after net impact extends the hydraulic cylinder shaft. The piston thus displaces the incompressible hydraulic fluid into the accumulator, where the trapped nitrogen gas is compressed. The kinetic energy required to compress the gas is the energy supplied by the moving shroud segment as it decelerates. The compression characteristics of the nitrogen gas closely approached adiabatic conditions.

Use of the accumulator to dissipate the shroud segment energy has the following advantages:

(1) When the shroud impacts the net, the cylinder reaction force is a minimum. This tends to decrease the initial decelerating force on the shroud.

(2) The accumulator precharge pressure is not critical when a range of jettison velocities is expected. If the shroud velocity were higher than predicted, the cylinder would simply stroke longer and thus compress the gas to a greater degree.

(3) No pretensioned springs, and so forth, were required. Prior to a test, the accumulators were charged to the desired pressure and sealed.

The total travel involved in stopping a free-flying shroud quadrant is the sum of the movement of the hydraulic pistons plus the stretch in the connecting rope plus the outward component of the stretch in the catch-net. The latter two are, of course, elastic, and will return some of their potential energy to the quadrant, which will bounce back with an equal kinetic energy. The characteristics of each of these components as determined by pretesting are shown in figure 15. For less than 689×10^3 newton-per-square-meter (100-psi) precharge, the hydraulic cylinder characteristic moves to the left on figure 15.

To estimate an expected bounce-back velocity, shroud quadrant bounce-back energy is equated to elastic energy stored in the ropes plus the catch-net. The result indicated that quadrant bounce-back velocities between 3.05 and 3.97 meters per second (10 and 13 ft/sec) can be expected, depending on the precise shape of the nylon stress-strain characteristic.

Primary Data System

The primary data system used in the Payload Shroud jettison tests consisted of high-speed motion picture cameras. A total of 18 high-speed 16-millimeter motion picture cameras were used in recording the separation and flight of the shroud quadrants. The objectives of the photo-optical data system were to be able to measure or calculate (1) center-of-gravity velocity of each quadrant, (2) yaw rate, (3) roll rate, (4) flexing of the quadrants during separation, and (5) general observation of the test shroud during separation.

To accomplish these objectives, cameras were placed internally and externally to the shroud at each separation joint. The camera locations are shown in figure 16. Externally, a 500-frame-per-second camera was placed at the tip of each quadrant separation joint and also at the base, all looking perpendicular to the vertical axis of the test configuration. Also, one 1000-frame-per-second camera was placed beneath each separation joint of the shroud such that its field of view was vertical to and in line with each separation line. Another group of four 1000-frame-per-second cameras was placed inside the shroud at the level at which the cone section of the shroud attaches to the cylinder section, observing each of the four ATM Support Assembly separation joints. Each of these data cameras observed the separation of two shroud quadrants simultaneously. Another 500-frame-per-second camera was placed directly over the shroud in a downward vertical viewing position such that it could observe the symmetry of separation. This was the only camera that could view all four quadrants simultaneously. A 120-frame-per-second general observation camera was placed in the test chamber such that its field of view encompassed the full length of the shroud. The camera make, speed, lens focal length, power requirements, and other associated information are summarized in table II.

Every data camera was furnished with two neon timing lights internal to the camera. One recorded a coded timing pulse along one edge of the film. The Inter-Range Instrumentation Group-A (IRIG A) time code system was used in this test. This system utilized a 1000-pulse-per-second time code generator. Real time may be read to 1 millisecond accuracy, and is updated every 0.1 second. On the opposite edge of the film, the separation fire command time was recorded. This appeared as a pulse break in the 10-kilohertz carrier frequency. Both the IRIG A time code and the separation fire command signal were generated by a common time signal generator and were recorded on the film in every camera simultaneously regardless of camera type or speed.

Cameras and film may be vulnerable to malfunction problems when operated in a vacuum atmosphere; that is, 110-volt-ac cameras may experience arc-over problems causing power failure to the camera and the film emulsion may dry out and become brittle, with the possibility of breaking during operation. Therefore, each camera was

TABLE II. – DATA CAMERA SUMMARY

Camera group	Number of cameras	Location and direction of view	Camera make, type, lens, and power
I	2	One camera directly over nose cap, looking down	Mitchell, 500 frames/sec, 5.7-millimeter lens, 110 volts ac
		One camera approximately 15.25 meters (50 ft) away with full-length view of shroud	Mitchell, 120 frames/sec, 9.2-millimeter lens, 110 volts ac
II	4	One camera at each split line, viewing nose cap perpendicular to longitudinal axis of shroud	Mitchell, 500 frames/sec, 10-millimeter lens, 110 volts ac
III	4	One camera at each split line, viewing base of shroud perpendicular to longitudinal axis of shroud	Mitchell, 500 frames/sec, 10-millimeter lens, 110 volts ac
IV	4	One camera viewing each internal separation joint (ATM Support Assembly) at cone-cylinder junction level	Fairchild, 1000 frames/sec, 13-millimeter lens, 28 volts dc
V	4	One camera at each split line, viewing separation from below shroud base and parallel with longitudinal shroud axis	Fairchild, 1000 frames/sec, 13-millimeter lens, 28 volts dc

mounted inside an airtight aluminum container which had a glass viewing port. This can be seen in figure 12.

The container was closed and sealed in atmosphere after loading the film such that the camera would be able to operate at 1-atmosphere pressure inside the container while the test chamber was at vacuum during testing. All power leads and timing light leads were fed into the containers to the cameras by means of hermetically sealed bulkhead feedthrough connectors. Although all camera containers were individually leak-checked at 1-atmosphere pressure differential, a 0.327-centimeter (1/8-in.) supply line was connected to each container after installation in the vacuum chamber and run to atmosphere. Thus, if a small leak should occur from the container to the test chamber, the container would remain at atmospheric pressure.

There was at least a 12-hour period after film was loaded during which detonators were installed on the test article and the chamber was closed and pumped down. Thus, the possibility of the film taking a "set" around the drive spools, causing breaking upon

startup of the camera, existed especially in the Mitchell register-pin cameras. Therefore, a slow-start device was used with the Mitchell cameras. This device utilized a time-delay relay and voltage splitter circuit, allowing the camera to start slowly at about 60 frames per second for a period of 2 seconds, after which the camera automatically was switched to full speed of 500 frames per second. The slow-start device was placed in line with the power leads and was located inside each container housing a Mitchell camera. With this approach, no data were lost due to film breakage.

The camera fields of view were illuminated by 1000-watt photographic flood lamps. Two to four such lamps were required for each camera, depending upon their location and distance from the targets. The lights were manually turned on approximately 1 minute before jettison and manually turned off approximately 2 to 3 minutes after jettison.

Since the run times of the Mitchell and Fairchild cameras are 8 and 4 seconds, respectively, they were started automatically by the Discrete Events Programmer such that there would be no danger of missing the 1/2-second-duration shroud separation. All 500-frame-per-second cameras turned themselves off upon running out of film. The 1000-frame-per-second cameras were switched off by the Discrete Events Programmer. Because of high power requirements during startup, the cameras were sequentially started in four groups of four cameras each and one group of two cameras. The ratio of starting current to run current was approximately 3 to 1.

A calibration run for each camera was made prior to the first test. An aluminum rod graduated in 5.08-centimeter (2-in.) increments was suspended in each camera's field of view along a line which the target portion of the shroud would follow during jettison. A reel of film was then exposed and processed. This reel of film was retained and used as the distance calibration in analyzing velocity data from the films.

Test Control System

The test control system is the equipment required to conduct an integrated separation test and data collection operation. The major elements of the system include (1) the Discrete Events Programmer, (2) the detonator circuits, (3) the camera and lighting circuits, (4) the instrumentation system, and (5) the FM and computer recording equipment. The system design used minimized the chance of inadvertent operation by providing electrical arm-safe switch features. In addition, the design provided for panel display of the state of critical components to aid in analysis of possible system malfunction. This latter feature is important because these components are located in the vacuum chamber and are not accessible for checking while the chamber is evacuated.

Discrete Events Programmer. - The Discrete Events Programmer, designed and built at SPF, generated up to 12 discrete signals in a preset sequence to command events

to occur. The time base was derived from the 100-hertz output of a crystal-controlled clock synchronized to WWV. There were a total of 12 set and 12 reset thumbnail switches to provide the 12 sequenced events. The elapsed time (from programmer start command) for a given event to begin was selected by dialing its channel set thumbnail switch, which was calibrated in 0.01-second units. The reset time was selected in a like manner. A programmer abort feature was provided which stopped the timed event sequence and reset the counter to zero in the event a "go" condition was not present when the fire command came on. This abort signal was derived from the separation firing unit charge monitors so that the test would be aborted if any one of the units failed to charge properly within 2.5 seconds after charge command was given. The programmer thumbnail selector switches were positioned prior to beginning the test, and a clear plastic cover was installed to prevent accidental change of setting. The sequence of events used during the tests is given in table III.

TABLE III. - DISCRETE EVENTS PROGRAMMER

SEQUENCING

Event	Time, sec
Programmer start	0
Camera groups 1 and 2 start	5.00
Camera group 3 start	5.50
Separation firing unit charge command	8.00
Camera groups 4 and 5 start	9.00
Test abort scan	10.50
Separation firing unit fire command	11.00
System safe commands:	20.00
Latch firing unit panel safe	
Separation firing unit panel safe	
117 volt and 28 volt safe	
Camera groups 1 to 5 and camera 19 stop	
Computer stop	30.00

Detonator circuits. - As noted previously, the Skylab Payload Shroud separation concept involves two different systems activated by linear explosive energy. Thus, there are two separate sets of detonators: one to activate the separation system itself, and one to retract the latchpins prior to separation. Thus, there was flight cabling run from each detonator in both sets to connectors at the base of the shroud. SPF circuitry connected at these interfaces; on jettison these connectors were pulled apart by lanyards. With this arrangement, SPF provided two sets of detonator circuits: one to arm and

fire the latchpin retractors prior to separation, and one to arm and fire the separation units. These control circuits provided separate relays to arm the latchpin firing units bus and the separation firing unit bus.

The latchpin firing units were charged by applying 28 volts dc to the charge input. This charged a capacitor in the firing unit to 2300 volts. A 500/1 voltage divider fed a 4.6-volt signal back to the control room, where electronic circuits evaluated the signal and turned on a light when the signal rose above 4.0 volts. On the fire command, another electronic circuit noted the sharp decrease in capacitor voltage and turned on a fire light. There was one charge light and one fire light for each firing unit. Provision was also made for monitoring the state of pulse sensors (simulated detonator-electrical load) during checkout prior to the actual test. For the latchpin system, charging and firing was done manually; if any malfunction was indicated, a hold could be initiated until a decision was made.

Similar circuitry and operation applied to the separation firing units, except that these operations were done automatically in the Discrete Events Programmer. This system included circuitry for verification that all firing units were charged: if this condition was not met, the automatic sequencing stopped and an abort existed. As with the latchpin control system, provision was included for monitoring the state of pulse sensors during checkout.

Camera and lighting circuits. - Camera lights were turned on manually prior to the test by panel controls. The cameras were operated in five different groups (three ac and two dc voltage drives). Relays were provided to separately energize the ac and dc supply buses. The camera run circuits also provided for a 1-second timed pseudo-run for use during checkout and testing. The IRIG A neon lamp current was monitored for each camera to provide an indication back to the control center that the time code information was being supplied to the camera.

Instrumentation system. - The instrumentation system consisted of nine triaxial accelerometers mounted on the Payload Shroud and ATM Support Assembly, latchpin and separation breakwires, and miscellaneous parameter measurements of the detonator system.

Endevco 2261M piezoresistive accelerometers were used on triaxial mounting blocks to provide shock data at nine locations on the separation points, pin-puller brackets, and ATM support mounts. Seven of the accelerometers were on two of the shroud quadrants. Cabling to these sensors, as well as to the breakwires, was by means of an umbilical cable strung from the internal work tower to the center of gravity of the shroud. Excitation and conditioning for the accelerometer channels were supplied from bridge conditioning equipment in the data room outside the test chamber.

Sixteen pin-puller breakwires were installed on the latchpin pullers to obtain verification that the pins were retracted. From these continuity loops, signals were derived

which turned on 16 lights on the panel when the pins were retracted. On the first test, eight breakwires were installed to monitor separation. Four additional breakwires were installed for the second and third jettison tests.

FM and computer recording equipment. - Three 14-channel FM tape recorders were used to record test data. Two of these were used for 24 accelerometer channels. The third recorded three accelerometer channels along with 60 channels of multiplexed back-up data. All recorders were operated at 60 IPS (1.53 m/sec). Each magnetic tape had one channel of IRIG A recorded for time correlation, along with a 200-kilohertz reference signal for data processing uses. The multiplexed data recorded 10 channels per tape channel with 1-kilohertz bandwidth. The data include firing unit charge currents, fire currents, capacitor voltage, bus voltage, and breakwire data.

SHIPPING, ASSEMBLY, AND INSTALLATION OF TEST SHROUD

The Payload Shroud for the SPF tests was completely assembled in the contractor's plant. The final assembly mode used was essentially the same as that to be used at SPF, and the same as that to be used with the flight shroud at Kennedy Space Center. Following the initial fitup, during which no problems were encountered, the test shroud was disassembled into four cylindrical quadrants and four conical quadrants. These eight pieces were shipped by truck to SPF. As each truck arrived, the shroud segment was off-loaded onto a railroad car.

In the SPF high bay asembly area, a stacking plate was mounted on an additional flatcar, and leveled with jacks so that all the points on which the bottom edge of the shroud rested were within ±0.079 centimeter (±1/32 in.) of a true flat plane. Figure 17 illustrates the stacking plate in place on the railroad car. Suitable lateral support for the shroud segments and internal work scaffolds was provided. Figure 2 shows the conical half of the shroud resting in place on this stacking plate.

In the reassembly sequence, the cylindrical portion of the test shroud was reassembled first, then removed from the stacking ring and placed on wood blocks on the floor of the assembly area. The stacking plate was then used to reassemble the conical portion of the test shroud, and the conical portion was then mated to the cylinder in the assembly area to assure good alinement of the surfaces before final mating inside the chamber. After this check, the conical half was set aside, and the cylindrical half was repositioned on the stacking plate and moved into the chamber. It was then lifted over the internal work scaffold and mated to the FAS Simulator. The laminated shims and tension cleats were then bolted in place. These flight components are illustrated in figure 18. The ATM Simulator was installed next. At the same time, the conical half of the test shroud was returned to the stacking plate, and the separation system linear ex-

plosives were installed in it, while those for the retracting pins were installed in the cylindrical half. The conical half of the test shroud was moved into the chamber and lifted into place on top of the cylindrical half. The two halves were then bolted together and the linear explosive fed through the separation system tubing on the cylindrical half. Pulse sensors were installed in place of detonators, and the test shroud was then ready for a dry run checkout.

Refurbishment of the test shroud for the second and third tests was carried out in the SPF assembly area. The separated quadrants were removed from the catch-nets and returned to the assembly area. They were reworked and reassembled into the two halves. Mounting on the test stand and final reassembly for the second and third tests then proceeded the same as for the first test.

TEST PROCEDURE

When all installations and checkouts were complete, a pretest review was held. Following the review, execution of the test procedure was initiated. Although the jettison test itself took less than a second, about 5 days "in test" were involved in running each of the three tests performed. A complete dry run at vacuum was performed. The vacuum chamber was returned to ambient pressure, and film from all cameras removed and developed. Following camera reloading, the dry run pulse sensors were replaced by the linear explosive detonators. The chamber was sealed, and pumpdown for the test itself was initiated. All operations from initial closing of the chamber for the dry run through returning the chamber to ambient pressure following the actual test were governed by a detailed checksheet test procedure. All events were manually controlled up through the retraction of the 16 latchpins. Following an arbitrary hold after latchpin retraction, events through jettison were triggered automatically upon starting the Discrete Events Programmer.

After each test, upon opening the chamber, a safety inspection was made. All detonators were moved. Then a detailed inspection of the shroud quadrants, the test support equipment, and the surrounding area was performed. Detailed measurements of the location of each quadrant in the polyurethane foam blocks were made, as well as the amount of extension of each hydraulic piston in the arresting system. Any anomalies were noted. Preparations for removing the shroud quadrants from the catch-nets were initiated. The shroud quadrants after jettison, in the catch-net system, are shown in figure 19.

TEST RESULTS

The results presented here are those measured from the data by SPF personnel. Except for observing that the major results of the jettison tests, that is, the separation dynamics, fell within the acceptable performance range provided by MSFC, SPF did not attempt to interpret any of the test results as far as flight implications were concerned. This includes a number of events which occurred in the first two tests, resulting in a number of design modifications to the test shroud and the production units. Those interested in such aspects of this test program should contact cognizant MSFC personnel. Chamber pressure for all three tests was approximately 2×10^{-4} torr.

Separation Velocities and Yaw Rates

Table IV lists the center-of-gravity separation velocities, yaw rates, and roll rates for all three tests performed at SPF. From figure 7, it can be seen that while the measured yaw-rate range was lower than that predicted, the center-of-gravity velocity range fell within the lower half of the range predicted. Moreover, the measured ranges fell well within the acceptable performance limits established by the MSFC Payload Shroud

TABLE IV. - SUMMARY OF SKYLAB PAYLOAD SHROUD JETTISON

TEST RESULTS

Test	East Quadrant I[a]	North Quadrant II	West Quadrant III	South Quadrant IV
Center-of-gravity separation velocities, m/sec (ft/sec)				
1	5.32 (17.42)	5.30 (17.37)	5.25 (17.18)	5.28 (17.28)
2	5.41 (17.72)	5.18 (16.95)	5.22 (17.10)	5.44 (17.80)
3	5.05 (16.51)	4.75 (15.53)	5.05 (16.53)	5.00 (16.38)
Yaw rates, rad/sec (deg/sec)				
1	0.0925 (5.3)	0.1135 (6.5)	0.124 (7.4)	0.117 (6.7)
2	.228 (13.1)	.215 (12.3)	.227 (13.0)	.187 (10.7)
3	.133 (7.6)	.0750 (4.3)	.147 (8.4)	.138 (7.9)
Roll rates, rad/sec (deg/sec)				
1	0.232 (13.3)	0.263 (15.1)	0.326 (18.7)	0.241 (13.8)
2	0 (0)	.0977 (5.6)	.195 (11.2)	.248 (14.2)
3	.138 (7.9)	.0977 (5.6)	.037 (1.9)	.105 (6.0)

[a]Contains spherical nose cap.

contractor from mission considerations. Thus, from this standpoint, all three tests successfully met MSFC requirements.

Roll Rates

No limiting specifications on allowable quadrant roll rates were established for this program. Instead, MSFC and its contractor analyzed measured roll rates from the standpoint of possible recontact of a quadrant aft corner with some part of the spacecraft. Quadrant roll rates measured in the jettison tests are shown in table IV. The maximum SPF roll rate measured was 18.7 degrees per second and the minimum, zero. MSFC-contractor analyses of these data indicated that the range measured in the SPF tests is acceptable.

Accuracy of Photo-optic Measurements

Calibration. - The major source of error in calibrating the data cameras was due to resolution limitations on the film of the marked increments on the calibration bars. The increments when measured on a Vanguard film data analyzer were found to have a maximum dispersion of ±2.4 percent of the value, over a calibration range of 1.22 meters (4 ft).

Velocity calculations. - The quadrants did not separate at precisely right angles to each other, that is, at 45° to the data cameras. In addition, quadrant flexing occurred. These observations are discussed later, in the section Trajectories and Flexing of Quadrants. Because of the flexing, it was not possible to measure precisely the deviation of the quadrant "flightpath" from a true 45° angle to the data cameras. For the four cameras photographing separation near the nose cap, this error was estimated to be a maximum of 6 percent; for the four cameras photographing separation at the shroud base, the error was estimated to be 1 percent. The difference is due to the fact that trajectories and flexing could be measured more accurately at the base, with the up-looking cameras, than at the nose cone region.

Camera film velocities. - The actual speeds (frames/sec) of the films in all cameras used in the tests were measured by using the IRIG A time code along the edge of the film. These speeds were used in calculating the test results; however, since the film velocities could be determined very accurately, the error involved in measuring them was negligible compared to other sources.

Frame uncertainty. - In determining the number of frames of film for a target image to travel a known distance, there was a maximum of ±1/2 frame uncertainty be-

tween data analyzers; this amounted to a maximum of ±2 percent for 0.305 meter (1 ft) of travel.

Total effect. - The total effect of these uncertainties on the separation characteristics of table IV are given in table V.

TABLE V. - PHOTO-OPTIC MEASUREMENT

ACCURACY SUMMARY

	Error, percent
Error due to calibration bar:	
Nose cone area cameras	±2.4
Base cameras	±2.0
Error due to variance in angle of flight:	
Nose cone area cameras	±6.1
Base cameras	±1.0
Error due to uncertainty in determining number of frames per distance traveled – nose cone area cameras and base cameras	±2.0
Maximum error in calculating tip velocities	±10.5
Maximum error in calculating base velocities	±5.0
Maximum error in calculating center-of-gravity velocities	±7.2

Initiation of Separation Process

The longitudinal separation system is fired at the aft end of each separation joint. At a nominal burn velocity of roughly 6100 meters per second (20 000 ft/sec) for the linear explosive, between 2.5 and 3.0 milliseconds are required for the explosive to burn the entire length of the separation joint. Some time is then required for the gas generated to build up sufficient pressure in the joint bellows to initiate shearing of the rivets holding two adjacent quadrants together. At this time, outward movement of the payload shroud quadrants begins. This process is illustrated by the data of table VI, which correlates data from accelerometers, breakwires placed across the separation joints, and the high-speed cameras. The data shown are from jettison test 3. The sketch indicates the approximate locations of the instrumentation along the separation joints. The accelerometer traces showed an initial vibration or shock, followed by a time delay, followed by a larger shock. The data shown are times measured to the lead-

TABLE VI. - SKYLAB PAYLOAD SHROUD JETTISON

TESTS - ANALYSIS OF INITIATION OF

SEPARATION PROCESS, TEST 3

Position along separation joint	Accelerometer data		Breakwires	Cameras
	First vibration	First shock		
	Time[a], msec			
Aft end	4.8	17.6	7.0	18.2
Mid cylinder	5.0	15.0	---	----
Top cylinder	5.7	14.7	7.7	12.3
Bottom conic	6.2	10.9	---	----
Biconic interface	6.3	11.1	---	----
Forward end	7.1	9.9	7.8	13.0
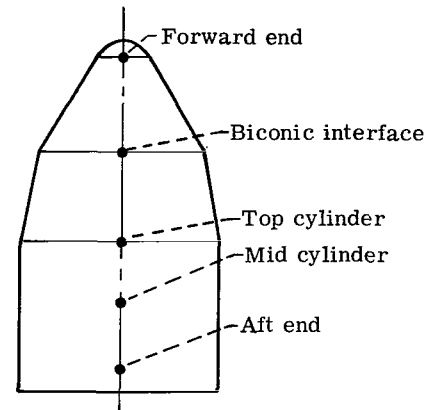
[a]Times are averaged elapsed times after fire command for all
four separation joints.

ing edge of each of these indications. The column labeled "first vibration" is taken to be an indication of the progress of the explosive detonation from the aft end of the shroud (bottom in these tests) to the forward end. Note that the time taken is, on the average, 2.3 milliseconds, about what would be expected. The column labeled "first shock" indicates the initiation of separation as rivets are sheared, with the forward (top) end of the separating quadrants moving out first. This agrees with the yaw rates given in table IV. The camera data in the last column also indicate the same thing. A slight time lag between the times as indicated by the accelerometers and first discernible movement as indicated by the cameras is to be expected, since the latter were determined visually.

The breakwire times noted in table IV indicate that the wires broke upon detonation of the linear explosive, and not on the initiation of separation. These wires were rather fine, somewhat brittle material furnished and epoxied in place by the MSFC contractor.

Trajectories and Flexing of Quadrants

Ideally, the shroud quadrants separate and follow trajectories at right angles to each other. With the test shroud orientation used in the SPF chamber, this would be north, east, south, and west. For the data camera locations specified, this would be exactly 45° to the optic axis of the cameras looking at targets on the sides of the shroud. This did not quite happen. None of the quadrants in any of the tests separated exactly along

its ideal trajectory. Figure 20 is illustrative of plots that were made of the motion of the lower corner of each quadrant made from the 1000-frame-per-second uplooking cameras. It shows the horizontal movement of the corners of quadrant I (east) and quadrant IV (south) in test 1. Measurement of a straight line drawn through these points for the edge of quadrant IV indicates a deviation of about 5.5° from the ideal path. Figure 21 is a map of where each quadrant came to rest in the polyurethane blocks. It indicates that quadrant IV in test 1 came to rest between 5° and 6° away from the ideal path. This is the maximum deviation which occurred.

Figure 20 also is illustrative of the flexing of each separating quadrant. It can be seen that this flexing tended to damp out after about 0.305 meter (1 ft) of travel. Thus, the SPF-measured shroud velocities quoted in table IV were taken from the film which covered the second 0.305 meter (1 ft) of travel. The maximum displacement of this flexing observed (at the lower corners) was approximately 2.54 centimeter (1 in.). It is not known whether the displacements along the separation joints toward the forward end of the shroud were any greater than this. Flexing along the joint could be observed in the film, but it was not possible to measure it. This flexing of the shroud quadrants was entirely elastic in all three tests; there was no difficulty reassembling the test article after any of the tests.

Latchpin Performance

It was mentioned that, in addition to the riveted separation joints, the shroud quadrants are held together prior to jettison by eight linkages, essentially steel plates with a hole near each end, one on either side of a separation joint. Through each hole passes a pin which is retracted prior to jettison. Thus, there are 16 latchpins. If at least one in each of the eight plates retracts, separation is possible. These pins are retracted by a linear explosive system the same as that used for actual jettison. In the SPF tests, the pullers for these pins were fired manually prior to initiating the automatic test sequencing. The MSFC requirement was that all 16 must retract before proceeding with a jettison test. This requirement was met in all three tests; that is, no latchpin failed to retract in any of the three tests.

Lanyard Disconnects

Electrical power to both the latchpin retraction system and the separation firing systems is supplied from the spacecraft to the Payload Shroud by cables which are joined by connectors across the FAS - Payload Shroud interface. Lanyards are fixed

to the Payload Shroud side of these connectors, to pull them from their respective
mating halves on the FAS side. In addition to supplying power, each connector has a
continuity loop which provides a signal upon separation of these connectors. There are
four such sets of cabling, one to each quadrant. In all three tests, all four of these
disconnects performed as expected.

Accelerometer Data

As noted previously, accelerometers were mounted at various locations along the
separation line between the north quadrant and the west quadrant. The peak accel-
erometer readings and the times at which they occurred are summarized in table VII

TABLE VII. - MAXIMUM SHOCK TRANSMITTED TO

APOLLO TELESCOPE MOUNT SIMULATOR

[Weight of ATM Simulator, 354 kg (672 lb); data
from test 3.]

	Accelerometer A		Accelerometer B	
	Maximum g's	Time, msec	Maximum g's	Time, msec
Vertical	300		300	18.0
Northeast	300	13.8	-300	13.6
Northwest	240		300	14.0

for the two accelerometers mounted on the northwest ATM Simulator attachment to the
Payload Shroud. Comparison with table VI indicates that these shocks occurred as the
quadrants began to separate. After separation, the ATM Simulator was supported on
polyurethane blocks suitably located on the internal work platform. Detailed analysis
and interpretation of all accelerometer data and meanings in terms of Skylab mission
effects will be carried out by MSFC and its contractor.

Design Modifications

In the first two jettison tests, a number of events occurred which required design
modifications in both the test shroud and the production units. Detailed discussions of

these events, analyses of them, and the resultant design changes are beyond the scope of this report. The following problems were observed:

(1) Oscillation of the forward nose cap caused recontact with the other three quadrants, resulting in metal chips falling through the shroud interior.

(2) The transverse member fastening the conical half of the shroud to the cylindrical half failed structurally.

(3) A large number of sheared rivets on the separation rail flew free.

(4) On the second test the tubing containing the linear explosive burst at all four elbows leading into the rail assembly at the aft end of the shroud.

No problems in the test shroud occurred in the third test.

PERFORMANCE OF TEST SUPPORT EQUIPMENT

The separating shroud quadrants moved out of the field of view of the data cameras almost at impingement in the catch-nets, and the camera showing the overall view was not calibrated for making measurements involving performance of the mechanical test support equipment. Thus, only qualitative information can be provided concerning this equipment.

Post-test measurements and visual examination of the films from the overall view camera led to the observations discussed in the following paragraphs.

Peak Stopping Force

The total movement of all the hydraulic pistons was measured following each test. The overall range was from 0.48 to 0.94 meter ($18\frac{3}{4}$ to 37 in.), depending upon the cylinder position (the lower ones moved least) and the test. The overall average was about 0.76 meter (2.5 ft). From these measurements and from simple impulse theory, it was estimated that peak stopping forces averaged about 116 000 newtons (26 000 lbf).

Performance of Polyurethane Blocks

As discussed previously, bounce-back velocities in the range 3.0 to 4.0 meters per second (10 to 13 ft/sec) were expected. Visual study of the films support the notion that the actual bounce-back velocities in these tests were much lower. The aft (bottom) edges of the shroud quadrants have a rather wide flange attached to them, for mounting

on the FAS Simulator, as indicated in figure 18. This flange penetrated the polyurethane blocks between 0.067 and 0.153 meter ($2\frac{5}{8}$ and 6 in.), with the average estimated to be 0.089 meter (3.5 in.). Thus, apparently, the poor elasticity of the foam blocks reduced the bounce-back to about half that expected. Considering the inexpensiveness of the foam blocks, their ready availability, the fact that little engineering was required, and the beneficial results obtained, the use of these blocks was one of the more interesting aspects of this test program. The aft end of a quadrant resting in the cloth-covered foam block assembly is shown in figure 22. The energy absorption in the foam, of course, was beneficial to the operation of the bounce-back restraint rope shown in figure 13.

Catch-Nets and Towers

Visual study of the films indicated that once a jettisoned quadrant impinged in its catch-net, the two moved outward and downward as a unit: that is, little or no sliding of the quadrant relative to the net could be observed. Of course, after the breakwires supporting the catch-nets vertically broke, they were unrestrained in vertical motion. Impact of the quadrants in the nets was sufficient to produce noticeable flexing of the side frames. No damage to the test shroud occurred, although a frame and a quadrant edge did touch in at least one case. No problems with the tower assemblies were encountered in any of the tests.

Bounce-Back Restraint System

In the first test, the rope shown in figure 13 struck the spherical nose cap attached to that quadrant. It slid off outboard of the quadrant, and the particular quadrant came to rest leaning against the central structure. No damage could be detected to the test shroud. In subsequent tests, the tension in the shock cord was increased somewhat, and all four mechanisms performed satisfactorily. It should be noted that the winches were obviously not designed for vacuum operation. To condition them for vacuum operation, they were dismantled, cleaned, and relubricated with vacuum oil. This did not appear to affect their operation.

Primary Data System

As previously noted, 18 cameras were installed as the primary data system for

TABLE VIII. - CAMERA PERFORMANCE

AND MEASURED FILM SPEEDS

Camera	Test 1	Test 2	Test 3
	Film speed, frames/sec		
Upper target data cameras	495.0	492.5	493
	496.0	495.0	486
	494.0	492.0	493
	499.0	498.0	500
Lower target data cameras	495.0	495.5	509
	489.0	488.0	490
	497.0	478.5	433
	(a)	495.0	496
Camera inside shroud	943.5	836.0	872
	855.3	778.0	905
	956.5	863.0	911
	936.0	855.0	886
Upward-looking cameras	[b]870.6	893.0	822
	1021.8	982.0	1010
	1132.0	1037.0	1085
	821.3	780.0	918
Overhead camera	(a)	497.0	501

[a]Camera malfunction.
[b]Estimated.

these tests. Thus, for the three tests, a total of 54 camera runs were made, excluding calibration and dry runs. In the first test, two cameras failed to operate: the overhead camera and the one target camera. There were no camera malfunctions in either the second or third tests. A summary of camera performances is given in table VIII.
The film speeds shown were used in calculating the shroud separation velocities. There were approximately 80 floodlights used in conjunction with the primary data camera system. The lamp envelopes were exposed to the vacuum. In the third test, one of these burned out. This was the only lamp failure which occurred; it did not affect the obtaining of photographic data.

CONCLUSIONS

Three full-scale jettison tests of the Skylab Payload Shroud were conducted at the

Lewis Research Center's Plum Brook Space Power Facility. The following conclusions were reached:

1. Skylab Payload Shroud quadrant separation velocities and yaw and roll rates, as measured through the use of high-speed motion picture cameras, fell well within the performance envelopes established by MSFC and its contractor.

2. All detonators, redundant or not, in both the latchpin retraction systems and the separation systems fired in all three tests.

3. Various problems occurring in the first two tests resulted in design modifications to both the test shroud and the production units. No problems occurred in the third test.

4. The structural/mechanical test support equipment, designed to catch and arrest the free-flying shroud quadrants, functioned as designed. No difficulty in refurbishment and reassembly of the shroud after the tests was experienced.

5. Out of 54 runs, two camera malfunctions occurred. There was no significant loss of data, however.

6. No problems of any significance occurred with the electrical/electronic control/data systems.

Lewis Research Center,
  National Aeronautics and Space Administration,
    Cleveland, Ohio, May 8, 1972,
      491-01.

REFERENCE

1. Burch, B. A.: Titan III-C Payload Fairing System Full-Scale Separation Test. Rep. AEDC-TR-68-247, ARO, Inc. (AD-846062L), Jan. 1969.

Individual cleats

Cylinder
frame
assembly

Access door

ATM
support
fitting

Forward
frame assembly

Cone
separation rail

Cylinder
separation
rail

Door

Cylinder
assembly

ATM support link

Cone
assembly

CD-11276-22
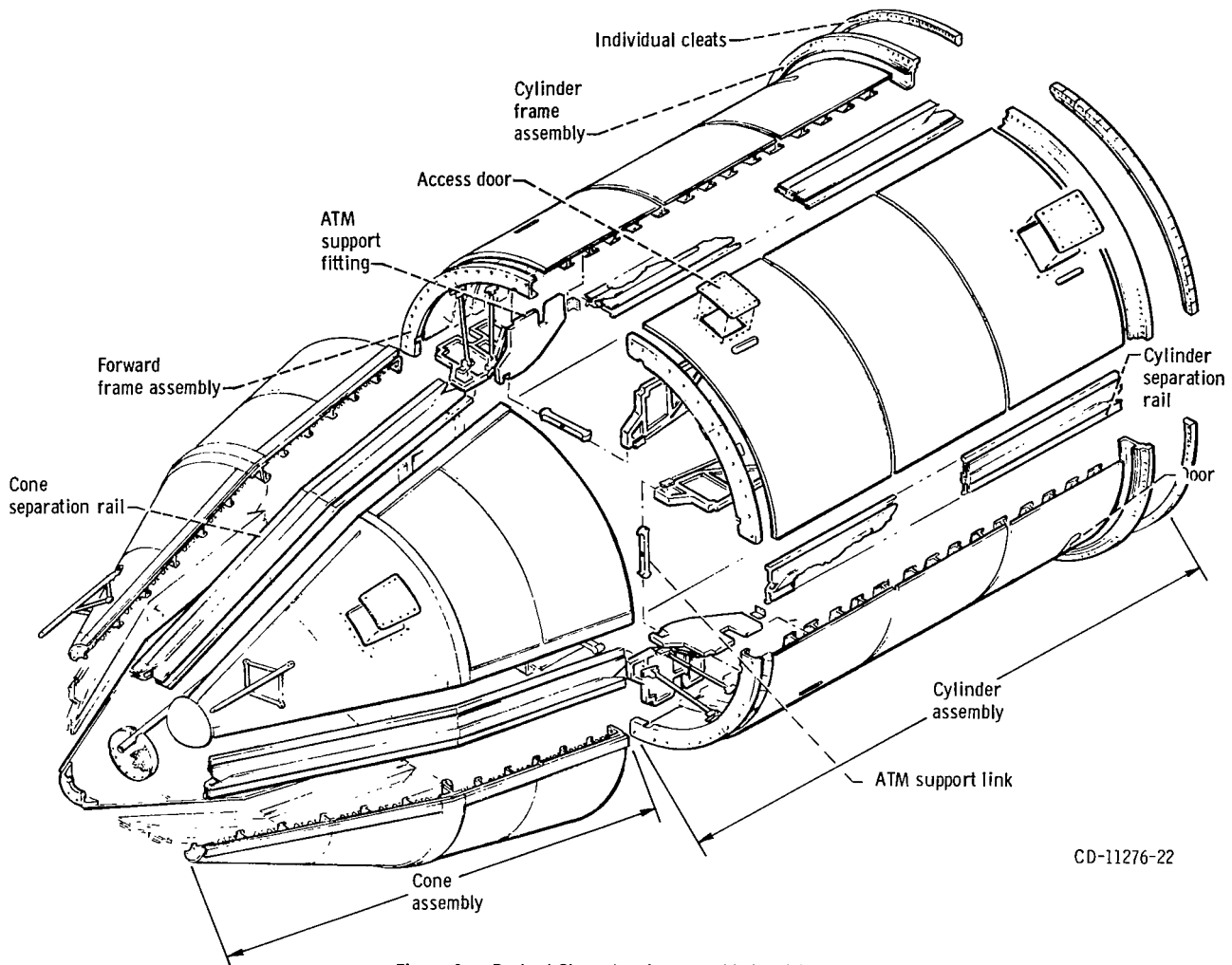
Figure 1. - Payload Shroud major assembly breakdown.
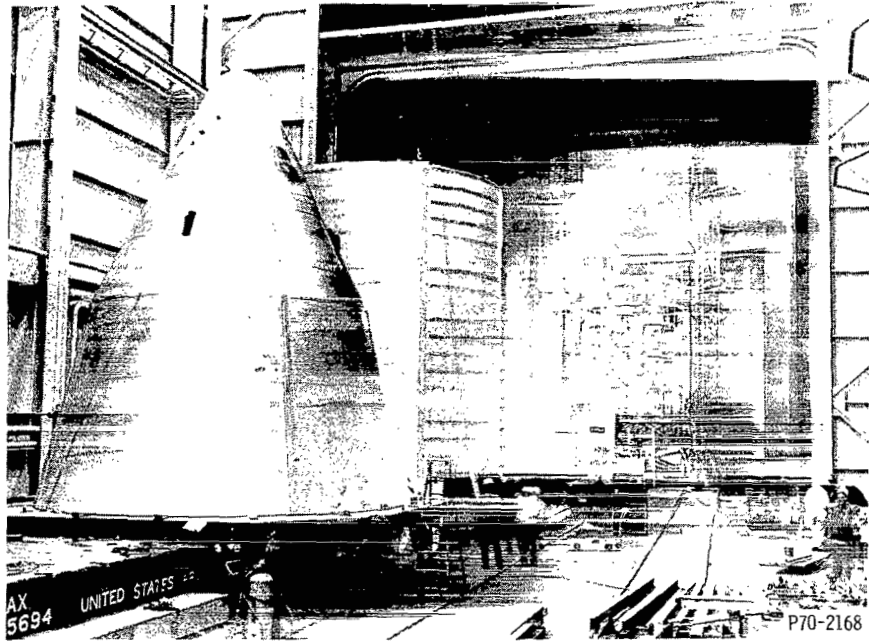
Figure 2. - Payload Shroud conical and cylindrical halves in Space Power Facility assembly area.
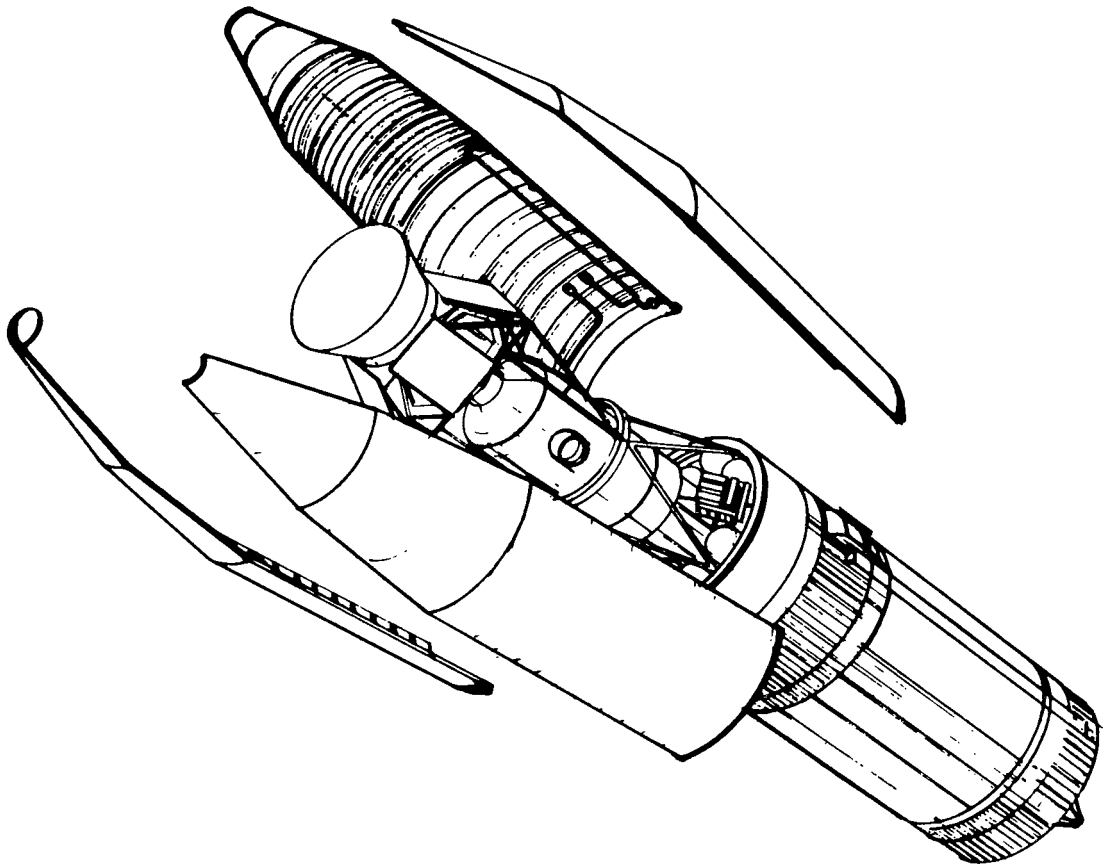
Figure 3. - Payload Shroud orbital jettison.

CD-11277-22

304-Stainless-
steel tube

Cylinder

Piston

Frame

Frame

CD-11278-22

Bellows installation, butyl-
rubber-coated woven fabric

0.318-cm (0.125-in.) diam
aluminum wire
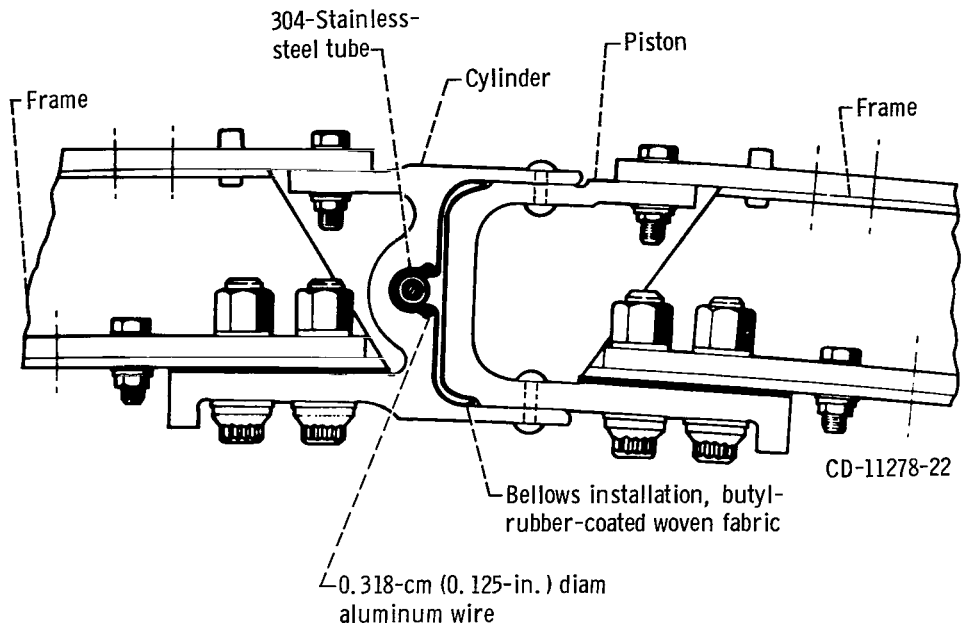
Figure 4. – Payload Shroud typical separation thrusting joint.

Bellows

Cylinder

Separated position

Piston

Typical
tangent
line

Bellows

Cylinder

Piston

CD-11279-22

Position at end
of power stroke
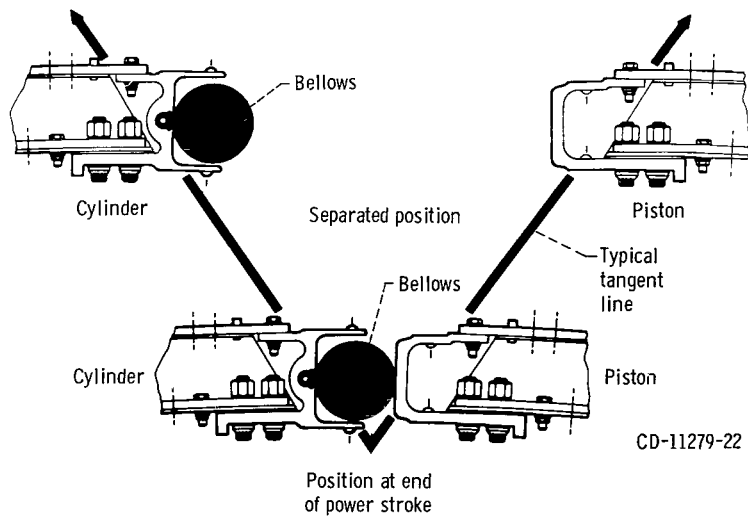
Figure 5. – Payload Shroud – action of separation system.
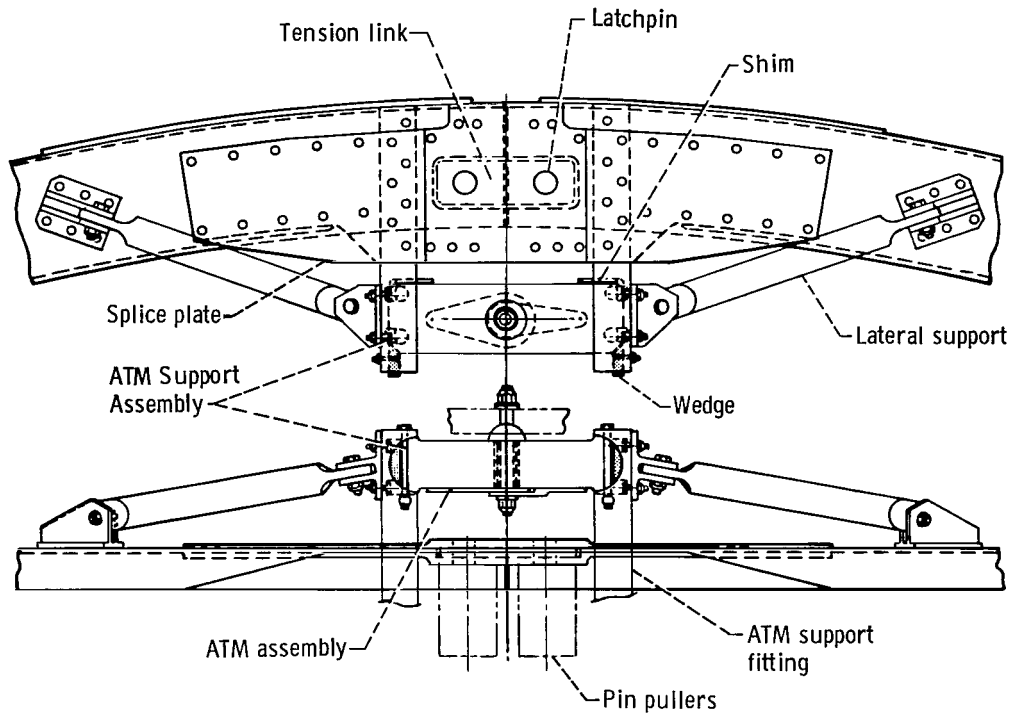
CD-11280-22

Figure 6. – Payload Shroud ATM Support Assembly.
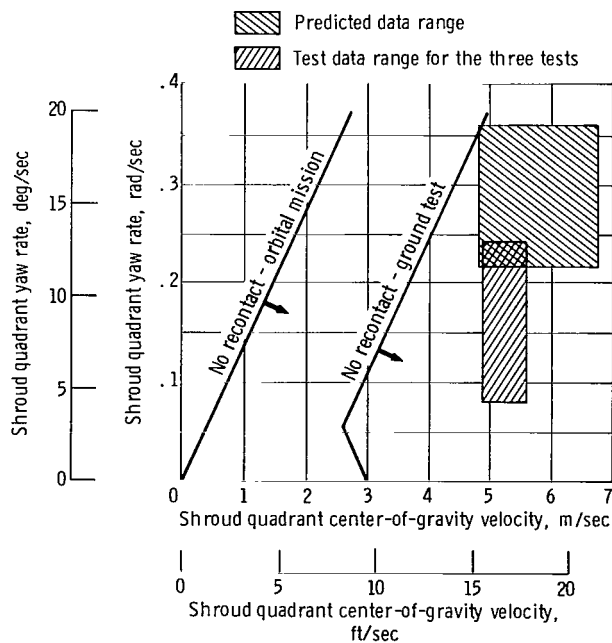
Figure 7. – Performance envelopes and test data range for Skylab Payload Shroud ground jettison tests.
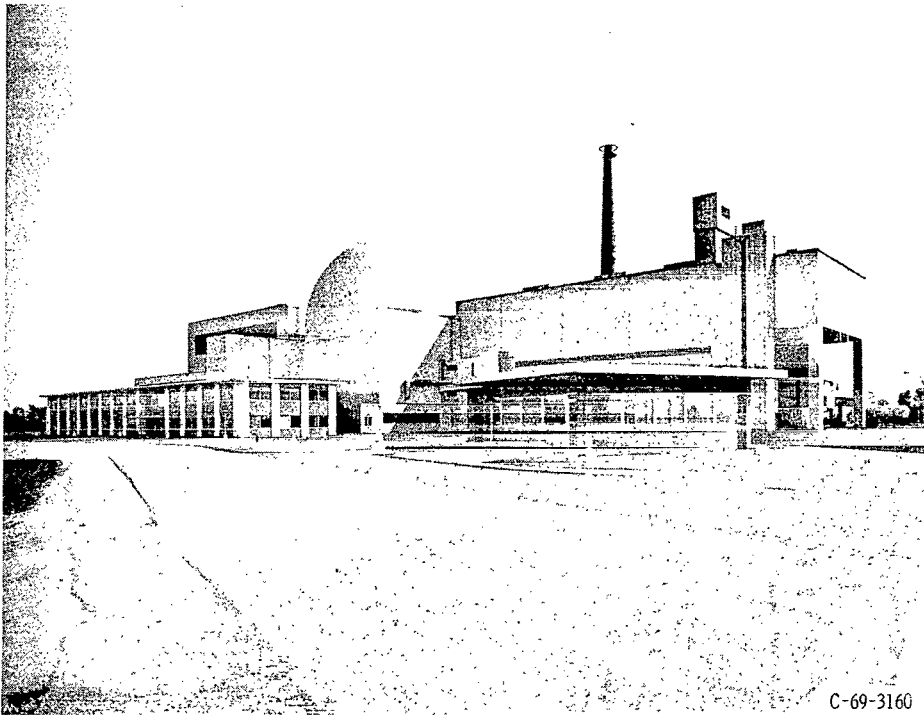
Figure 8. - Space Power Facility.

C-69-3160
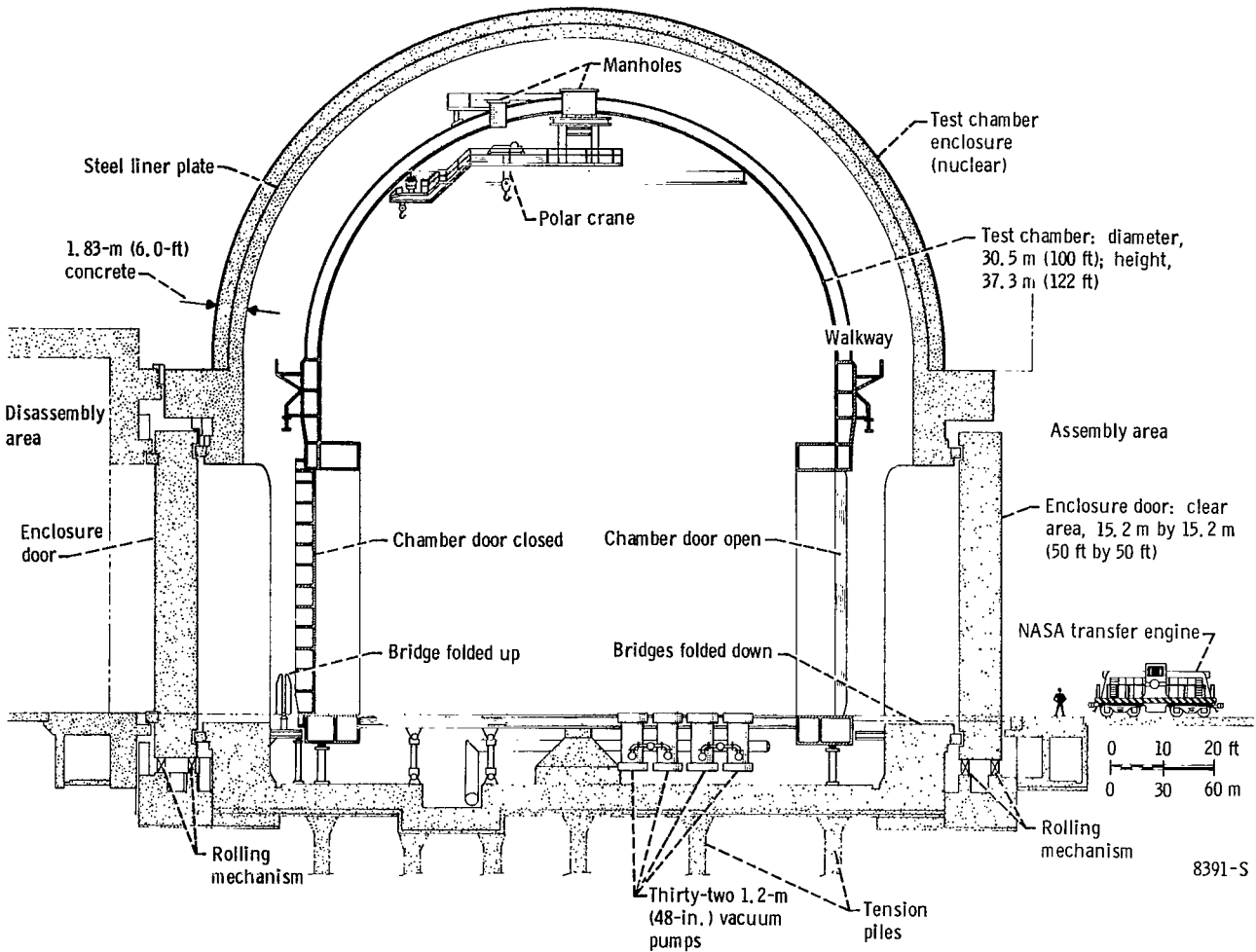
Figure 9. – Cross section through test chamber of Space Power Facility.

Manholes

Test chamber enclosure (nuclear)

Steel liner plate

Polar crane

Test chamber: diameter, 30.5 m (100 ft); height, 37.3 m (122 ft)

1.83-m (6.0-ft) concrete

Walkway

Disassembly area

Assembly area

Enclosure door

Chamber door closed

Chamber door open

Enclosure door: clear area, 15.2 m by 15.2 m (50 ft by 50 ft)

NASA transfer engine

Bridge folded up

Bridges folded down

0   10   20 ft

0   30   60 m

Rolling mechanism

Rolling mechanism

Thirty-two 1.2-m (48-in.) vacuum pumps

Tension piles

8391-S

31

C-70-3692

Figure 10. - Test shroud mounted in Space Power Facility chamber prior to start of test program.

P70-2162
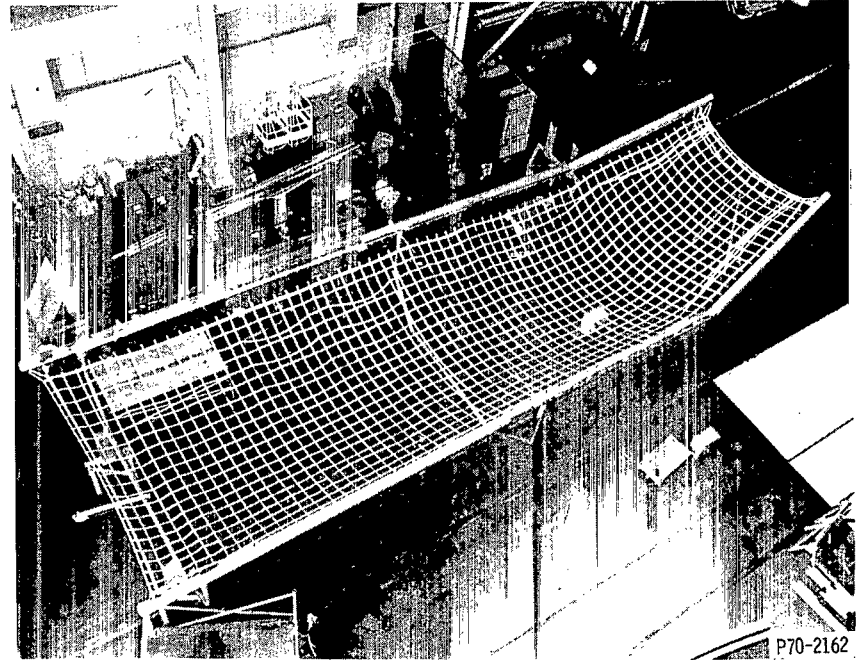
Figure 11. - Typical catch-net assembly.
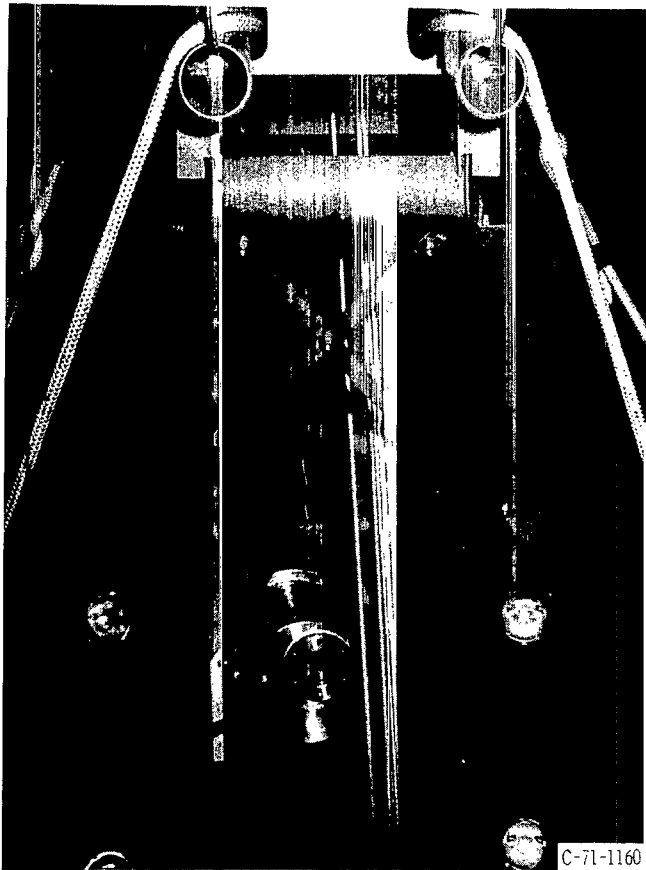
Figure 12. – Fairlead and camera mounting on support tower.
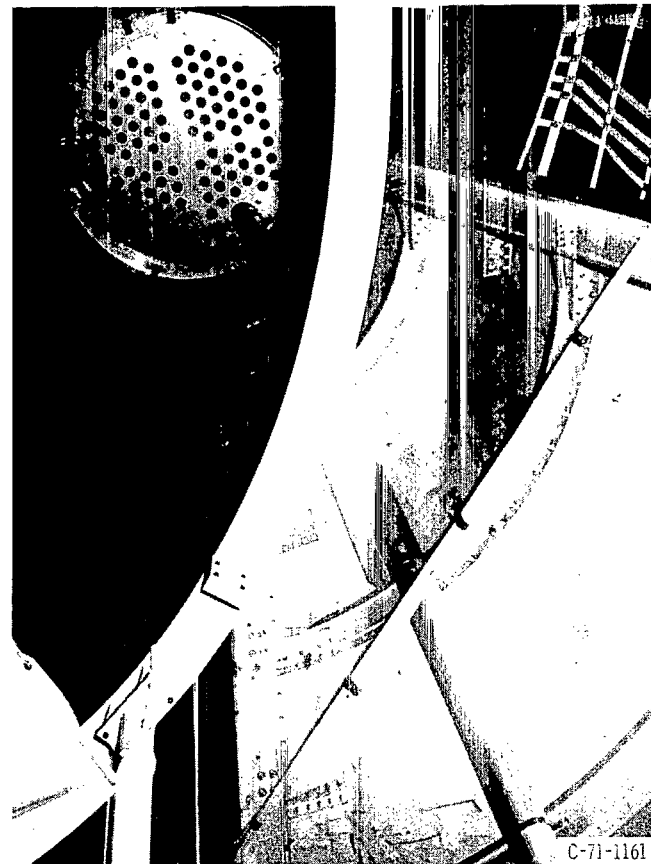
Figure 13. – Typical bounce-back restraint rope – after triggering.
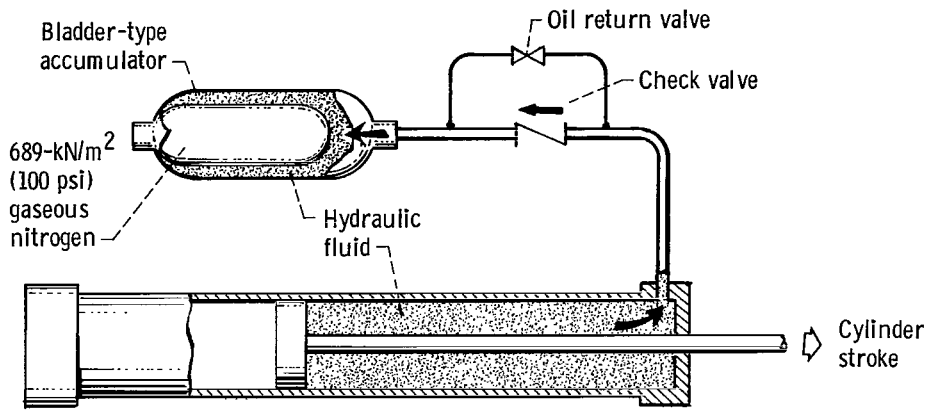
Figure 14. – Hydraulic cylinder schematic.

CD-11281-22
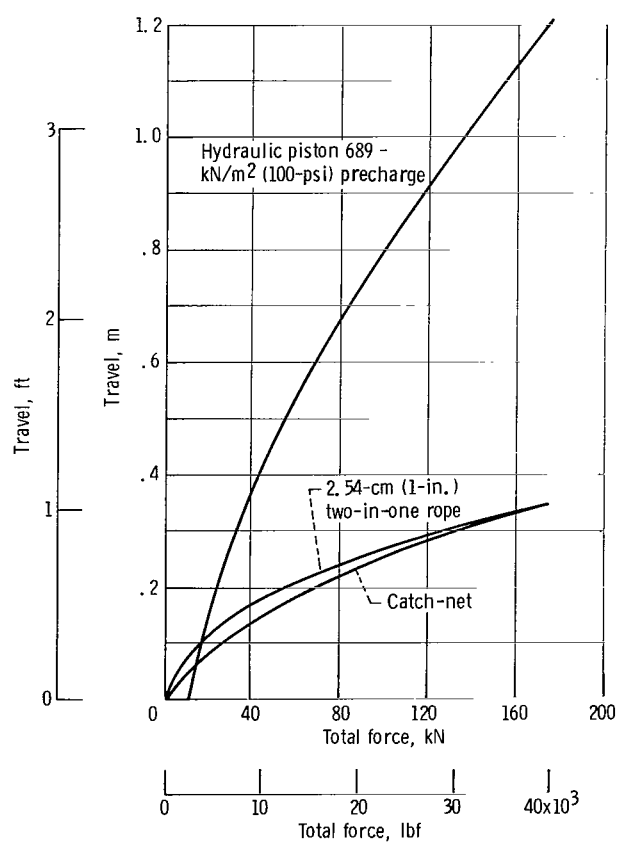
Figure 15. – Characteristics of arresting mechanism components.
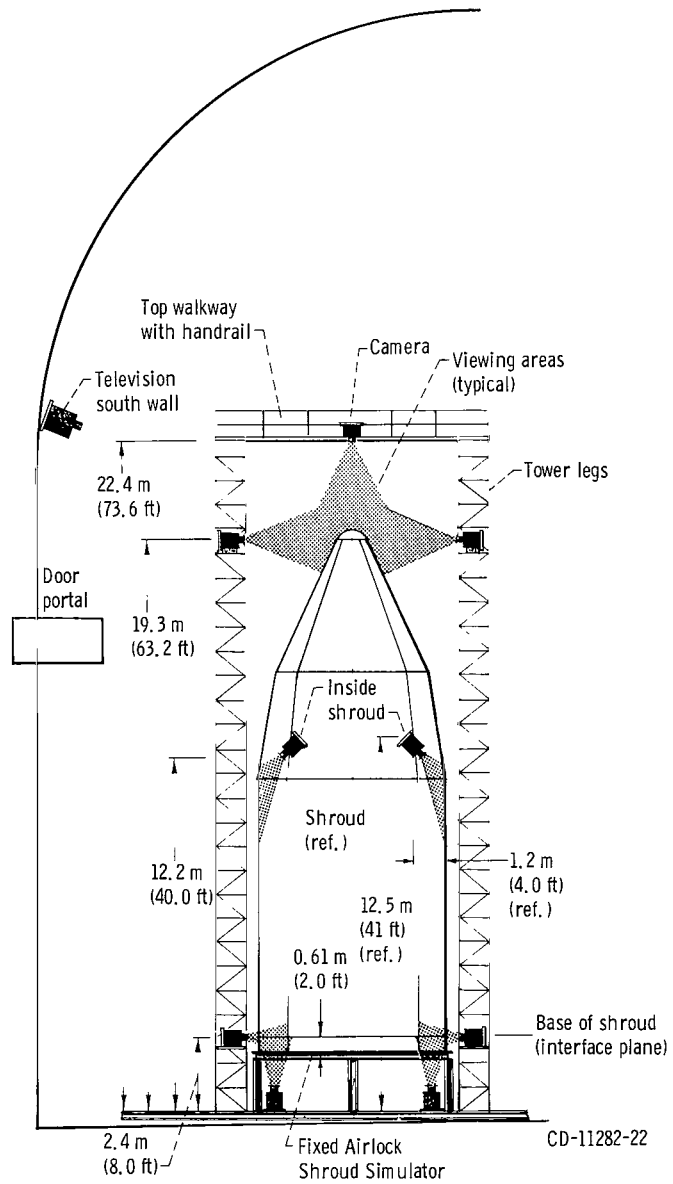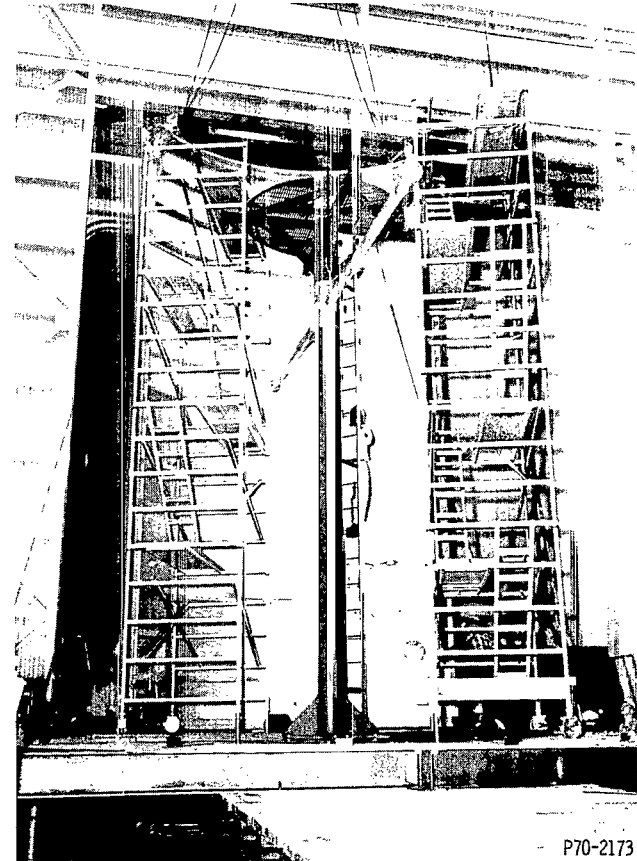
Figure 16. – Data camera locations for Skylab Payload Shroud jettison tests.

Figure 17. – Stacking plate.
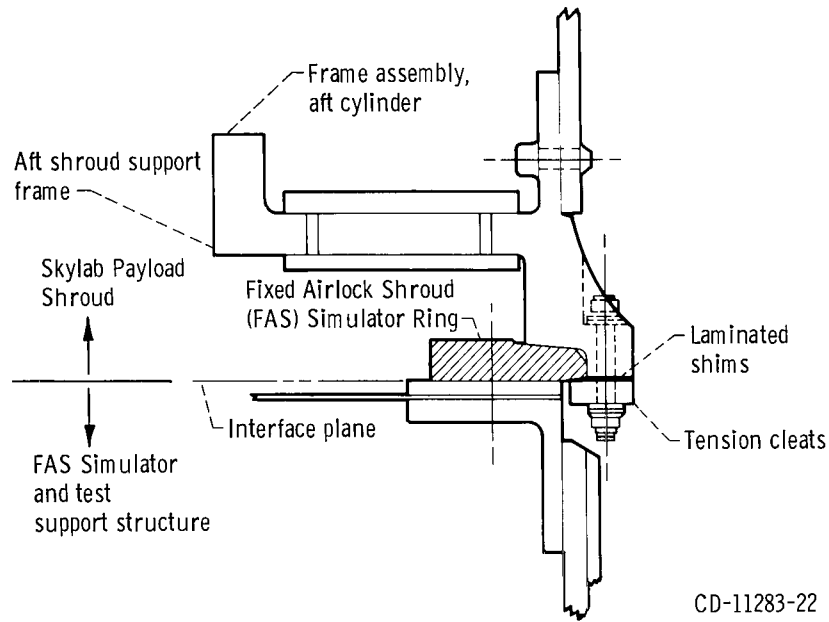
Figure 18. - Payload Shroud mounting on test support structure.
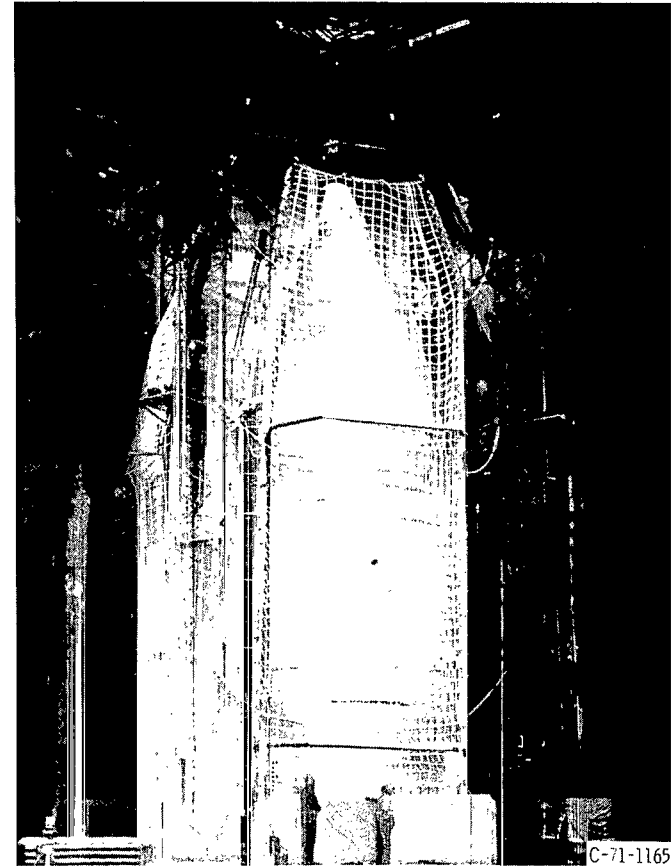
CD-11283-22

Frame assembly, aft cylinder

Aft shroud support frame

Skylab Payload Shroud

Fixed Airlock Shroud (FAS) Simulator Ring

Laminated shims

Interface plane

Tension cleats

FAS Simulator and test support structure

Figure 19. - Shroud quadrants after a test.
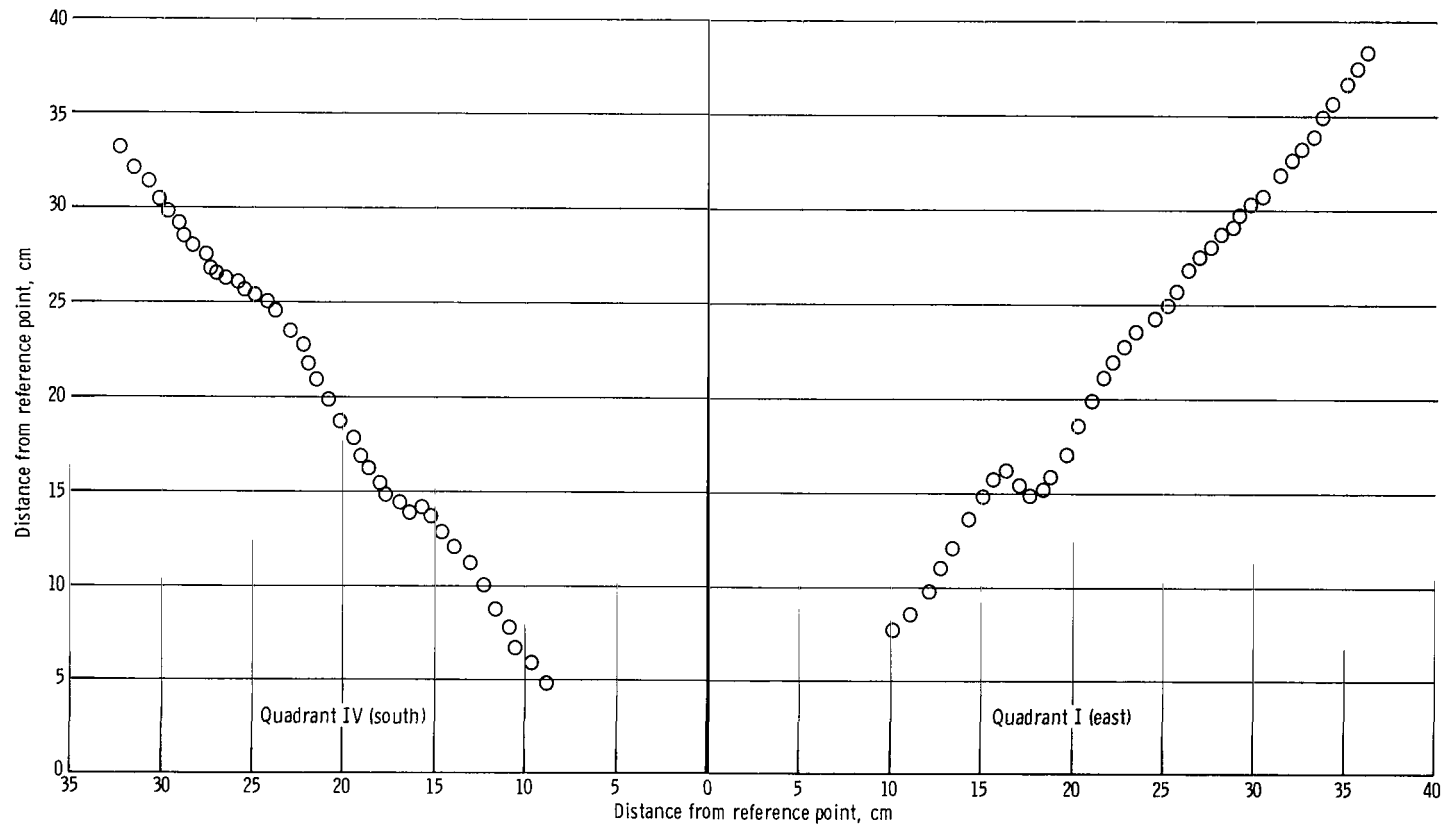
Figure 20. - Movement of aft corners of two adjacent quadrants after jettison - viewing upward. Camera speed, 870.6 frames per second; data points at two-frame intervals.
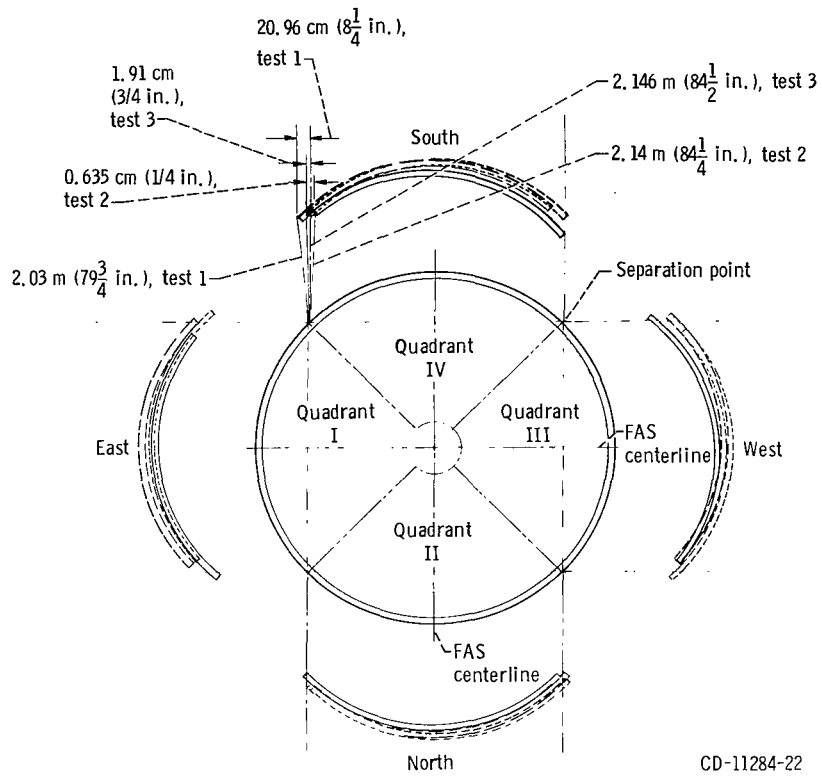
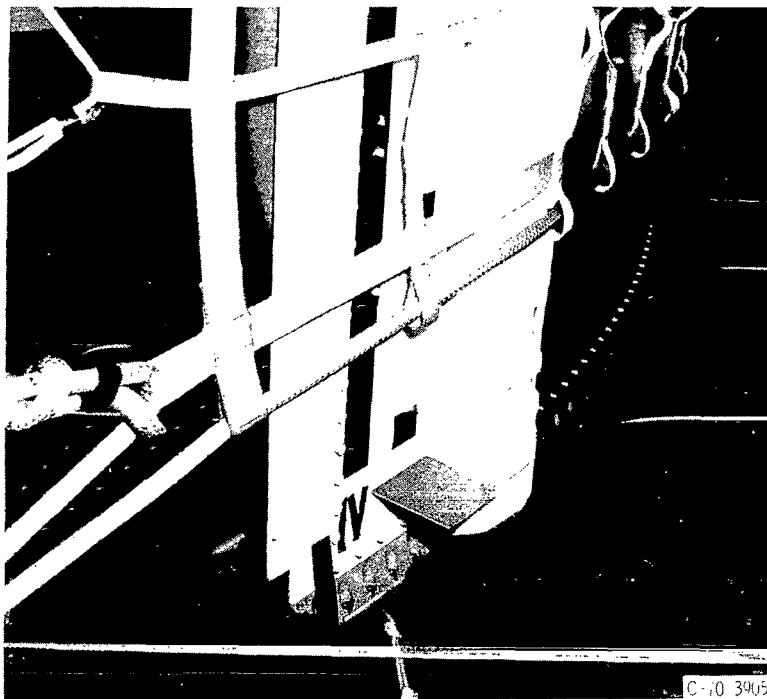Figure 21. - Position of shroud quadrant lower edges after tests.

Figure 22. - Aft (lower) edge of shroud quadrant imbedded in polyurethane block.

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