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INVESTIGATION OF PACKAGING, DEPLOYMENT, AND LEAK-RATE CHARACTERISTICS OF AN INFLATABLE LUNAR-SHELTER MODEL

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16. Abstract

An investigation was conducted under ambient atmospheric conditions and in an 18.3-m-diameter vacuum chamber at the Langley Research Center to determine the folding, packaging, deployment, and leak-rate characteristics of a large-scale lunar-shelter structures model. A folding and packaging procedure was developed from tests with a 0.10-scale model. It was found from these packaging tests that the packaging factor was 6.5:1 which reduced the inflated volume from 14.58 m^3 to a packaged volume of 2.27 m^3. The internal gas leak rate obtained was less than 0.23 kg per day. The lunar-shelter module was successfully deployed in the vacuum environment at a vacuum pressure of 133.3 N/m^2. An examination of the module after the packaging, pressurization, and deployment tests revealed no appreciable damage to the composite wall structure.

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INVESTIGATION OF PACKAGING, DEPLOYMENT, AND LEAK-RATE CHARACTERISTICS OF AN INFLATABLE LUNAR-SHELTER MODEL

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SUMMARY

An investigation has been conducted at the Langley Research Center to determine the feasibility of folding, packaging, and deployment of an inflatable lunar-shelter structures model and to establish maximum leak-rate characteristics of the structural material. The model was tested under standard ambient atmospheric conditions and at a vacuum pressure of 133.3 N/m^2 in a 18.3-m-diameter vacuum chamber. The packaging factor of the flexible structure was found to be 6.5:1. This packaging factor reduced the inflated volume of 14.58 m^3 to a packaged volume of 2.27 m^3. After 14 folding and packaging tests, there appeared to be no appreciable damage to the bladder, no permanent creasing, and no effect on the permeability of the bladder material. Also, the maximum leak rate in the final test was less than the target rate of 0.23 kg per day of standard air.

Results of the folding, packaging, and deployment tests indicate that the folding and deployment procedures developed can be used for cylindrical-shape configurations. Also, the materials utilized in the construction of the lunar-shelter model were adequate in that they complied with the test-program requirements for a durable inflatable composite that could readily be compactly packaged with minimum damage to the material. Subsequent materials technology development has been accomplished which identified nonflammable materials that would be compatible with the lunar-shelter structures model.

Use of small-scale models for establishing initial folding and packaging procedures for large inflatable cylindrical structures was proved feasible by tests in which a 0.10-scale model was utilized to develop the folding and packaging procedures for a full-scale lunar shelter.

INTRODUCTION

A general research program to explore problems associated with lunar shelters for manned occupancy has been underway at Langley Research Center for several years. An investigation to define problem areas and develop technologies for extending man's stay time capability on the lunar surface has been one of the primary research areas of this program. One of the major guidelines for this investigation has been the requirement for a unitized structure which can be placed on the lunar surface by a single launch vehicle, thus obviating assembly in the lunar environment. Several approaches that have been taken to best satisfy this requirement include utilization of rigid structures and inflatable structures. Inflatable structures have a high ratio of strength to weight and yield a high ratio of deployed volume to launch volume. (See ref. 1.)

An inflatable lunar shelter is basically a pressure vessel and must be designed to carry internal pressure loads. Other factors which enter into its design include division of the shelter into living quarters and an airlock compartment, packageability of the shelter, permeability and outgassing of the bladder material, use of materials that can be repaired in the lunar atmosphere, meteoroid protection, and use of thermal coatings on the outer skin. To develop the technology for extending man's stay time on the lunar surface, such parameters as the lunar environment, crew size, duration of stay time, overall mission objectives, and logistics vehicle integration should be considered with respect to their effect on the design of the shelter configuration and supporting subsystems. (See refs. 2 and 3.)

The expandable lunar shelter or stay time extension module (STEM) concept used in this investigation (fig. 1) is an integral system for operation on the lunar surface at ambient temperatures of approximately +394 K to -422 K. It provides an internal shirt-sleeve environment of about 297 K ± 3 K with a 100-percent-oxygen atmosphere for two persons for periods of time from 8 to 14 (earth) days. The STEM structure comprises an integral shelter-airlock combination having a total volume of 14.58 m^3 with life support, power, and communications subsystems (fig. 2). The packaged configuration of the STEM is contained within a packaging canister having a volume of 2.27 m^3. This packaging canister is designed to be attached to the Apollo lunar module (LM) landing stage. The composite STEM structure consists of a pressure bladder, a structural filament layer, a 5.08-cm-thick open-cell polyurethane-foam micrometeoroid barrier, and an external thermally coated skin fabricated of pliable and expandable material (figs. 3 and 4). The STEM is suitable for erection and assembly by a single astronaut. When the lunar-shelter structures model is fully deployed, the shelter-living-quarters section is a cylinder 2.13 m in diameter and 3.81 m in length with a living volume of 11.61 m^3. (See figs. 2 and 5.) The integral airlock adds an additional 1.52 m in length and has a volume of 2.97 m^3.

The purpose of this report is to outline the procedures developed for the folding, packaging, and deployment of a lunar-shelter structures model and to present the results of the folding, packaging, and deployment tests including the leak-rate characteristics of the model. Recent materials technology advancements (ref. 4) would be incorporated in subsequent fabrication of lunar shelters of this type.

DESCRIPTION OF MATERIALS AND MODELS

Composite Wall Samples

Three different types of composite wall construction were used in the folding tests to determine the resiliency of the open-cell foam micrometeoroid barrier. The three specimens varied in fabrication as follows:

Sample 1 was foamed in place with 0.127-mm-diameter copper wire thermal filaments bonded to the outer skin and to the structural layer; these filaments were spaced approximately four wires per cm^2.

Sample 2 was foamed in place with no thermal wire filaments.

Sample 3 was composed of sheet foam (not foamed in place) and had no thermal wire filaments. The samples averaged approximately 5.1 cm in thickness, 61.2 cm in width, and 81.4 cm in length. (See table I.)

0.10-Scale Model

A 0.10-scale model of the lunar-shelter structure was used to develop the initial folding and packaging procedures. This scale model consisted of an airlock 21.38 cm in diameter and 15.24 cm in length which was attached to the shelter living quarters that were 21.38 cm in diameter and 38.10 cm in length. (See fig. 1.) The airlock and domed ends of the model were constructed of individual gores bonded together, but the cylindrical portion had only one bonded longitudinal seam. The laminate material used for the 0.10-scale model was composed of 0.064-mm-thick polyethylene terephthalate plastic film laminated to a layer of 23.70-g/m^2 nylon fabric. Two layers of laminate material were bonded, nylon to nylon, with neoprene rubber cement as the adhesive. The total thickness of the composite material was approximately 0.191 mm.

Lunar-Shelter Structures Model

The shelter-airlock structure (fig. 2), which is 2.13 m in diameter and 5.33 m in length, was fabricated from pliable material as an integral structure to facilitate logistics packaging, deployment, and erection. The shelter-living-quarters section is a cylinder 2.13 m in diameter and 3.81 m in length and has an internal volume of 11.61 m^3. The primary structural loads are carried by a stainless-steel filament-wound structural layer incorporated into the composite wall structure (fig. 3). Pressure loads are transmitted to the structural layer by a triple-seal laminate pressure-tight bladder (fig. 4). A 5.08-cm thickness of open-cell flexible polyurethane foam provides micrometeoroid protection and thermal insulation. The outer nylon laminate cover material encapsulates the entire structure and has a white thermal coating of zinc-oxide-pigmented silicone paint.

The airlock (fig. 2) is 2.13 m in diameter and 1.52 m in length and has a volume of 2.97 m^3. In structural concept the airlock is an oblate spheroid. It has a circular flange 1.11 m in diameter which mates with a similar flange attached to the living quarters. The flanges are sealed airtight with an O-ring and room-temperature-vulcanizing (RTV) sealant and bolted together into a single structural assembly. The entrance hatch in the airlock is an elliptical door with a minor axis of 0.91 m and a major axis of 1.52 m, operable from either the outside or inside. Entry into the shelter living quarters from the airlock is through a 0.91-m-diameter inner hatch (fig. 5).

The internal operational pressure of the shelter-airlock structure is 34 473.8 N/m^2 with a safety factor of 3. Pressurization of the airlock by using the shelter gas reduces the pressure of the shelter living quarters from 34 473.8 N/m^2 to 27 579.0 N/m^2. Exhausting the airlock to the lunar vacuum incurs an internal gas (pure oxygen) loss of approximately 1.36 kg per cycle. The weight of the shelter-airlock structure is 147.87 kg which does not include any furnishings or subsystems.

A more detailed description of the STEM fabrication process is contained in the appendix.

FOLDING AND PACKAGING REQUIREMENTS

The folding and packaging of the lunar-shelter structures model were greatly complicated by the 5.08-cm-thick micrometeoroid barrier in the composite wall material. Packaging of this type of structure into a compact volume suitable for installation on an existing lunar spacecraft for successful deployment on the lunar surface requires packaging methods and procedures not previously performed. The entrapped residual air in the open-cell polyurethane-foam micrometeoroid barrier in the composite wall must be evacuated as well as the residual air within the bladder. The structure must be placed into the packaging canister with the heaviest and bulky portion folded in first and the end of the structure with the least weight last. This method of packaging allows the structure to unfold without forcing the heavier mass to eject first; this deployment produces less strain on the thin outer and inner skins. Also, within a vacuum environment and reduced-gravity environment such as the lunar environment, the velocity of the deploying structure varies according to the stored energy inherent in the packaged-structure compressed foam wall and in the amount of residual air remaining within the structure. The release of the packaged structure under the lunar surface vacuum and one-sixth gravity conditions should initiate selferection and shaping. Once shaped, the inherent stiffness in the shelter wall should maintain full expanded volume without pressurization; this allows easier and faster assembly of furnishings and required internal subsystems. The folding and packaging requirements that are apparent for successful deployment in a vacuum environment are as follows:

(1) The most efficient folds with no damage to the material must be determined.

(2) The material must not be damaged when subjected to a vacuum environment while still in the packaged state.

(3) Markings or necessary folds must be determined before attempting to package the structure into a container.

(4) The selected folding method must be repeatable for packaging more than once.

(5) Adaptability of folding and packaging aids must be established.

(6) Folds and creases required must be a uniform thickness.

(7) Care must be taken to insure that there are no locking folds when deployed in the vacuum environment.

(8) External and internal surface abrasions occurring during deployment in the vacuum environment must not be excessive.

(9) The external elliptical hatch of the structure must be folded into the packaging container first with the hatch resting upon the bottom surface of the container.

(10) Evacuation of the air from the composite wall foam must be done gradually while folding the structure to allow folds to be adjusted in place smoothly.

(11) During folding, excessive forcing of the material into position within the canister must be avoided.

(12) Folding the bladder material at too sharp a radius must be avoided.

(13) In order to evacuate the air within the bladder, the inner circular hatch and bleed valve must be closed to permit controlling of the internal air pressure through the aft end terminal plate.

TEST PROCEDURES

Folding and Packaging

Composite wall samples.- The objective of these tests was to determine the maximum number of folds and the minimum folded thickness of three different types of composite wall construction. From these parameters, a packaging factor can be established wherewith comparisons can be made between the different types of wall construction in the folded state. Also, the tests would determine whether the air within the wall could be evacuated without leaving a large amount of residual air entrapped in the folds. The folding procedure for the composite wall samples is illustrated in figure 6. The sample shown was folded and inserted into a vacuum bag connected to a vacuum pump and the air was evacuated. The total thickness, width, and length were measured after each folding and evacuation process.

Composite wall samples were also subjected to a severe folding and compression test other than the folding test just described. This test was performed primarily to evaluate the blocking adhesion due to high loads imposed by packaging, launch g loads, and elevated temperatures and, also, to investigate the inherent flexibility of the open-cell polyurethane-foam micrometeoroid barrier and the resistance of the structural layer and bladder to crimping. The samples were 0.093 m square and had a thickness of 47.75 mm before testing. These samples were folded over once and compressed between steel plates at three test temperatures of 294 K, 333 K, and 422 K for a test duration of 24 hr each. The compressed thickness was 3.81 mm with a compression ratio of 12.5:1. All tests were performed under ambient atmospheric conditions.

0.10-scale model.- The 0.10-scale model (fig. 1) was constructed to assist in establishing methods and procedures for folding and packaging a large-scale lunar-shelter structures model for launch as a payload package. This scale model was used to determine the folding method which would be most suitable for this type of structure and which would cause the least damage to the material when all air is evacuated, to determine whether any special markings are required on the large structures model to insure repetition of selected foldings, and to establish whether any special aids are required and the adaptability of these aids to the large-scale-model folding operations. The folding procedure which best suited the 0.10-scale model is as follows:

(1) Most of the air within the bladder was evacuated; a small amount of pressure is necessary to keep the inner surface from adhering together.

(2) The model, excluding the airlock, was then folded-in horizontally on each side along the longitudinal center line parallel with the floor until the two folds met at the center of the model.

(3) The remaining air was then evacuated; this pulled the folds down tightly.

(4) The airlock was creased-in at the sides and folded into the canister with the elliptical hatch down on the floor of the canister.

(5) The living-quarters section was folded at the center, half the distance between the airlock and the end terminal plate.

(6) This section was then doubled over and folded down on top of the airlock.

(7) The aft end terminal plate was doubled back to allow it to face upward.

(8) The packaged model was then strapped in place to maintain its deployment position.

Lunar-shelter structures model.- The lunar-shelter structures model, being a large heavy flexible structure, must have the most massive or heaviest portion deployed from the canister last to avoid damage to the thin skin and to aid in the deployment dynamics. Therefore, in the packaging procedure the lightest and less bulky part of the structure (the terminal end) was folded into the canister last and the heavy airlock was folded in first with the elliptical hatch resting on the floor of the canister.

The procedure for folding and packaging the lunar-shelter structures model was adapted from the procedure used on the 0.10-scale model. Some variation was necessary due to the composite wall construction and the difficulty in handling the large heavy pliable structure. The procedure used is as follows:

(1) Two vacuum lines were connected to the outer skin exhaust ports, one to the airlock and one to the living quarters, to allow evacuation of the air entrapped in the foam of the composite wall. A third vacuum line was attached to the terminal end bulkhead plate connection to allow evacuation of air from the shelter interior.

(2) The inner and outer hatches were closed and locked in place. The air bleed valve on the inner hatch was opened to allow the air to evacuate from the airlock, and the bleed valve in the outer hatch was closed.

(3) While the air in the model was being evacuated, the model was folded-in horizontally from each side along the longitudinal center line until the folds met along the center of the model (fig. 7).

(4) The airlock was folded-in at the sides and inserted into the packaging canister with the elliptical hatch resting on the floor of the canister. (See figs. 8 and 9.)

(5) The living-quarters section was folded at the center, half the distance between the airlock and the aft end terminal plate; it was doubled over and folded down on top of the airlock. (See figs. 10, 11, and 12.)

(6) The terminal end of the model was doubled back to allow it to face upward toward the hinged top of the canister.

(7) The packaged model was then strapped in place to maintain its deployment position (fig. 13).

Leak Rate

Ambient atmosphere.- Internal-gas-pressure leak-rate tests were conducted with the lunar-shelter structures model to determine the gas leakage for a 24-hr period. The maximum design allowable leakage was specified as 226.8 g, or less, per day for the living quarters only. The duration of these tests was from 3 to 8 hr with and without the airlock volume included. Fourteen different pressure tests were conducted under ambient atmospheric conditions. All the test data were compiled on a pressure-time scale. The leak rate was calculated by using the equation of state for an ideal gas, as follows:

$$W = \frac{pV}{RT}$$

where

W	weight of gas
p	gas pressure
V	volume of gas
R	gas constant for air
T	internal gas temperature

In determining the weight differential of the gas for any specific time, the formula

$$\Delta W = \frac{V}{R}\left(\frac{p_1T_2 - p_2T_1}{T_1T_2}\right)$$

was used. (The subscripts 1 and 2 refer, respectively, to the initial value and to the change in value after time lapse.) The leak rate was then obtained by dividing ΔW by the time interval (hr) over which the leakage was measured. The target leak-rate average was set at 9.53 g, or less, per hr. These pressure decay tests conducted under ambient atmospheric conditions were performed by injecting air from the facility pressure line, which is maintained at 689 400.8 N/m^2, into the shelter through the end terminal plate until the internal pressure stabilized at 34 473.8 N/m^2. At this time the internal temperature was recorded by thermocouples mounted on the inner surface of the bladder, and the barometric pressure was recorded. Thus, the three basic parameters needed for measuring the pressure at any given time in order to determine the pressure differential were obtained (internal pressure, external pressure, and temperature). Simultaneously with these readings, the time interval was recorded. This procedure was repeated every 15 min for some tests and every 39 min for other tests for 3- to 8-hr periods, depending upon the test duration specified. The tests performed on the airlock—living-quarters combination were for the shorter period of time.

Vacuum environment.- Internal-gas-pressure leak-rate tests were conducted on the lunar-shelter structures model in an 18.3-m-diameter vacuum sphere at the Langley Research Center. At the beginning of the tests, the specified test pressure of the model was set at 34 473.8 N/m^2 and the chamber pressure at 133.3 N/m^2. Two leak-rate tests were conducted: one test for 8 hr with the living quarters only and one test for 4 hr with the airlock—living-quarters combination. The pressures were measured and the leak rates were calculated by using the same equation of state for an ideal gas, as described in the ambient atmosphere tests. Air was injected through a pressure line connected to the end terminal plate and to an external valve on the vacuum chamber wall, which was metered to allow atmospheric pressure bleed-in. After the desired test pressure was obtained for the model, the three basic parameters needed to determine leak rate (model internal pressure, model internal temperature, and vacuum chamber pressure) were measured along with the time interval.

Deployment in Vacuum

The deployment test utilizing the lunar-shelter structures model was conducted in the 18.3-m-diameter vacuum sphere at the Langley Research Center. In this deployment test the model was folded and packaged in the same sequence as previously described for installation in the canister. However, instead of being installed in the canister, the model was strapped to a steel support frame (figs. 14, 15, and 16) to allow the folded material to deploy outward in a horizontal direction. Two electrical release mechanisms were installed to secure the restraining straps (fig. 14). A pressure line was connected to the end terminal plate (fig. 16) and to an external valve on the vacuum-chamber wall. The vacuum chamber was then pumped down to a pressure of 266.6 N/m^2 in approximately 3.5 hr. However, it took a total of 4.5 hr to reduce the chamber pressure to the specified test pressure of 133.3 N/m^2. Before countdown was started, the folded model appeared as shown in frame 1 of figure 17. A sequence countdown was started at $t - 10$ sec and when $t - 5$ sec was reached, all cameras were started. This countdown was to ascertain whether all cameras were working properly and to allow maximum test coverage with respect to camera speed and film length. At $t - 0$ sec, the model restraining straps were released, as seen in frame 2 of figure 17. Frames 3, 4, and 5 show the expansion due to the internal residual air pressure and the inherent elasticity of the composite wall material; this expansion took approximately 1.8 sec. Frames 6 and 7 show the pressurization to full configuration by opening the external valve in the test chamber and allowing ambient atmospheric pressure to bleed-in and inflate the bladder. Frame 8 shows the full configuration pressurized to 34 473.8 N/m^2; the test chamber pressure recorded at this time was 133.3 N/m^2. Figure 18 shows the locations of the thermocouples and pressure gages for the vacuum tests. Figure 19 shows the test conditions of the lunar-shelter structures model for the vacuum environment tests. Figure 20 shows the final fully pressurized configuration with instrumentation and pressurization attachments.

RESULTS AND DISCUSSION

Folding and Packaging

Composite wall samples.- The three types of composite wall samples utilized were folded a number of times and the size and shape of the samples were measured to determine the number of folds and minimum folded thickness. These results and the packaging factors of each sample are presented in table I.

The folding tests indicate that after exposure to a temperature of 294.3 K, the samples unfolded and regained their original shape with only a slight ridge where the structural layer had been tightly folded. After exposure to a temperature of 333.2 K, the recovery was not complete and the material discolored. After exposure to 422.0 K, the material remained flat and folded and some areas exhibited considerable charring.

0.10-scale model.- The method employed in packaging the 0.10-scale model greatly helped to establish the procedures necessary for folding and packaging the large-scale lunar-shelter structures model. Experimentation with the small-scale model enabled various folding and packaging procedures and techniques to be easily evaluated. In the folding procedures, it was determined that evacuation of the air within the bladder must be done gradually to allow positioning of the folds as the folding progresses. The folded model deployed from the container without damaging the material, and restraint of the packaged material in the container was necessary even though not in a vacuum environment.

Lunar-shelter structures model.- The lunar-shelter structures model was folded by utilizing the procedures developed with the 0.10-scale model and was packaged to one-sixth of its fully inflated volume. The model was folded and packaged 14 times and contained in the packaging canister for 60 days for one of these tests. Close inspection revealed that there was no apparent damage to the bladder material, no major leakage, no permanent creasing, and no effect on the permeability of the bladder due to the folding and packaging. The structural layer, bladder, foam micrometeoroid barrier, and outer skin remained tightly bonded together. The results of these tests indicate that the procedures used would be applicable for any inflatable cylindrical configuration utilizing the same type of construction and exposed to the same type of environment.

Leak Rate

Ambient atmosphere.- The specified leak rate of 226.8 g, or less, per 24 hr under an operational internal pressure of 34 473.8 N/m^2 was obtained in 5 of the 14 pressure tests conducted under ambient atmospheric conditions. In the rest of these tests, the leak rate varied and was greater than the acceptable limit. In the second test conducted, there was some structural damage in which the airlock outer elliptical hatch frame ruptured. However, this problem was corrected by installing horizontal fiber-glass ribs on the hatch frame. A leak-rate summary is presented in table II; the test number, test conditions, section of the shelter being tested, test duration, gas leak rate obtained, and location of excessive leakage are given.

Most of the leakage occurred at rigid joints and this type of leakage problem would be eliminated in a thorough ground-based test program. Breaks in the bladder could be repaired by astronauts using a repair kit. This type of patching was actually performed during one of the tests under ambient atmospheric conditions with an internal pressure of 34 473.8 N/m^2.

With the exception of the second test, in which the airlock outer elliptical hatch frame ruptured during the first pressurization of the airlock, none of the breaks in the pressure bladder resulted in leak rates greater than 381.0 g of air per hr. Leak rates of this magnitude should not be considered as instantly catastrophic since the crew would have adequate time to take corrective action.

Vacuum environment.- There were two leak-rate tests conducted in a vacuum environment under the model internal operating pressure of 34 473.8 N/m^2. The specified leak rate was not obtained in either test. In the first test, the leak rates far exceeded the limit specified due to a cut in the bladder in the living quarters directly behind the inner hatch. In the second test, a leak was detected in the terminal end bulkhead. The two tests are listed in the leak-rate summary shown in table II.

Deployment in Vacuum

The lunar-shelter structures model was successfully deployed in a vacuum environment without binding or snagging the inflatable wall material. The stored elastic energy in the packaged-structure compressed foam wall assisted in the initial phase of deployment. Entrapped residual air in the foam and bladder also helped to deploy the structure under the vacuum conditions. Once the structure assumed its shape, the inherent stiffness in the shelter wall maintained the fully expanded volume and configuration without pressurization of the model under reduced external pressure conditions.

CONCLUDING REMARKS

A large-scale inflatable lunar-shelter model suitable for manned occupancy was constructed and tested. The model was folded into a compact package in the ratio of 6.5:1 without damaging the composite wall material. The model obtained leak rates of less than 2 percent of the internal volume of gas (0.23 kg) per day when initially pressurized at 34 473.8 N/m^2 with standard air. The model was successfully deployed and inflated to a pressure of 34 473.8 N/m^2 while in a vacuum environment at a pressure of 133.3 N/m^2. The basic shelter and airlock, without subsystems and furnishings, were successfully packaged and reinflated 14 times without any major damage to the bladder material, structural layer, or composite wall construction.

Satisfactory folding and packaging methods and procedures for large heavy inflatable structures can be developed by using small-scale models.

Fabrication of a large expandable structure utilizing a stainless-steel filament winding process and construction of a composite wall that can be greatly reduced in thickness by evacuation of air are considered new approaches to construction of large or full-size inflatable structures suitable for manned occupancy.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., September 10, 1971.

APPENDIX

CONSTRUCTION OF FULL-SCALE LUNAR STAY TIME EXTENSION MODULE

The construction methods utilized in the fabrication of the stay time extension module (STEM) are unique, especially for a module of this size. Briefly, the module lay-up consists of a hard-core mandrel, constructed of foam, on which a pressure bladder, filament-wound structural layer, open-cell foam meteoroid barrier, and outer skin (figs. 3 and 4) are formed. For this application, where flexibility and packageability are of prime importance, a high-strength stainless-steel wire (0.0914 mm diam) filament was selected. The construction phase that is unique is the filament precision winding process and equipment developed for this job (ref. 2). The winding machines are capable of producing closed-end polar and multiport pressure vessels with exacting filament placement under controlled fiber tension and proper resin impregnation. The winding method used in the fabrication of the filament-wound structure is known as the Polar-Circumferential winding concept illustrated in figure 21. The longitudinal filaments are applied in a plane 0.183 rad from the horizontal which skirts both the polar openings, and the circumferential windings are applied to the cylinder. The last circumferential end filament is rigidly bonded to the adjacent wires with epoxy resin, while the longitudinal filaments at the hatches and the terminal ring are bonded with epoxy adhesive to its respective end fitting. The filaments are wound with a constant tension in an evenly spaced pattern of 30 hoop filaments and 16 longitudinal filaments per cm. The adhesive and elastomer components used in the lay-up construction are cured at room temperature. The complete STEM structure is then placed on a rotating fixture in a hot-air oven at a prescribed time-temperature cycle to completely dry off all volatiles. The mandrel is then extracted from the completed structure shell after applying the thermal control coating to the outer skin. Actual weighing was conducted on all components of the composite structure including all hatches and parts necessary for constructing the complete model. The weight breakdown is given in table III.

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TABLE I.- FOLDING TEST RESULTS OF COMPOSITE WALL SAMPLES

(a) Pertinent sample data before tests

Sample	Width, cm	Length, cm	Thickness, cm	Weight, kg	Unit weight, g/cm^2	Type of foam wall
1	61.28	81.60	4.83	1.71	0.342	Foamed in place (with copper wires)
2	61.12	81.44	4.64	1.52	.305	Foamed in place
3	61.12	81.28	5.36	1.25	.252	Not foamed in place

(b) Folding test data

Fold	Layers	Thickness, mm	Vacuum pressure, N/m^2	Weight, kg	Remarks
Sample 1					
0	1	6.10	98 205.28	1.71	
1	2	13.97	98 205.28	1.71	
2	4	35.56 to 58.42	98 205.28	1.71	Difficult to fold
3	8	------------	98 205.28	---	Would not fold
Sample 2					
0	1	6.99	98 205.28	1.52	
1	2	16.26	98 205.28	1.52	
2	4	33.06 to 40.64	98 205.28	1.52	Difficult to fold
3	8	------------	98 205.28	---	Would not fold
Sample 3					
0	1	5.08	98 205.28	1.26	
1	2	10.54	98 205.28	1.26	
2	4	20.70	98 205.28	1.26	Easy to fold
3	8	58.42 to 63.50	98 205.28	1.26	Folds without any difficulty

(c) Packaging factors

$$\left[\text{P.F.} = \frac{\text{Original volume}}{\text{Folded volume}}\right]$$

Sample 1:

Fold 1 . . . . $\frac{24\ 130.64}{3\ 446.88} = 7.00$

Fold 2 . . . . $\frac{24\ 130.64}{4\ 958.28} = 4.87$

Sample 2:

Fold 1 . . . . $\frac{23\ 111.85}{3\ 984.55} = 5.80$

Fold 2 . . . . $\frac{23\ 111.85}{4\ 384.56} = 5.27$

Sample 3:

Fold 1 . . . . $\frac{26\ 612.16}{2\ 592.29} = 10.27$

Fold 2 . . . . $\frac{26\ 612.16}{2\ 508.23} = 10.61$

Fold 3 . . . . $\frac{26\ 612.16}{3\ 912.77} = 6.80$

TABLE II. - LEAK RATE SUMMARY OF LUNAR-SHELTER STRUCTURES MODEL

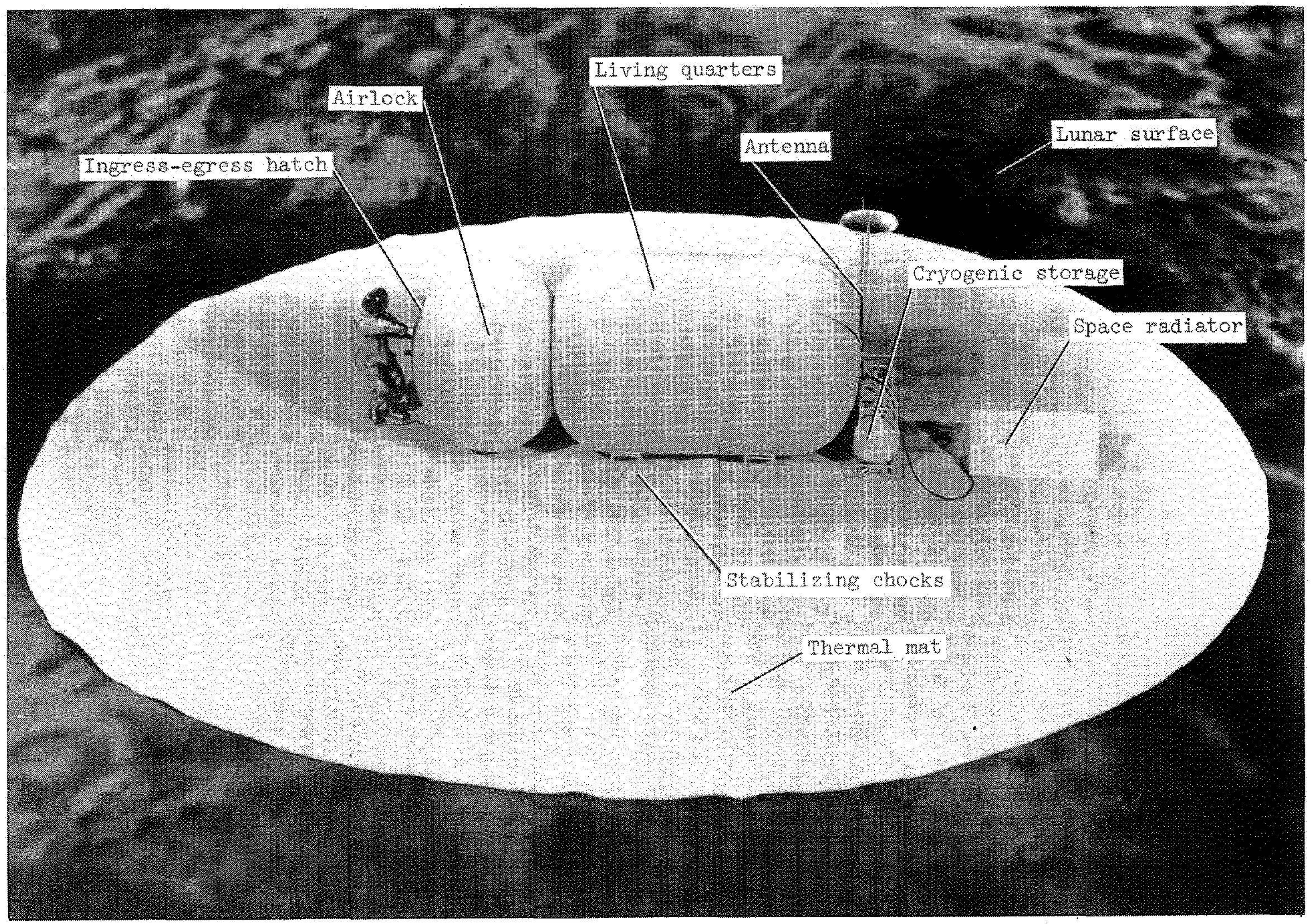
[Model internal test pressure, 34 473.8 N/m^2]

Test	Ambient air environment	Vacuum environment (133.3 N/m^2)	Shelter (living quarters)	Shelter and airlock	Test duration, hr	Leak rate, g/hr (a)	Remarks
1	X		X		8	13.6	Above specified allowable leak rate
2	X			X			Rupture of airlock outer elliptical hatch frame
3	X			X	5	18.1	Deflection of inner circular hatch frame
4	X		X		8	13.6	Above specified allowable leak rate
5	X		X		8	9.1	Acceptance test conducted by contractor
6	X			X	4	9.1	Acceptance test conducted by contractor
7		X	X		8	367.4	Tear in bladder near inner hatch during packaging
8		X		X	4	381.0	Leak in shelter aft bulkhead terminal plate
9	X		X		6	72.6	Leak in inner circular hatch bleed valve
10	X			X	7	199.6	Leak in airlock outer elliptical hatch bleed valve
11	X		X		6	49.9	Leak at mating surfaces of shelter and airlock circular hatch frame
12	X			X	4	290.3	Bladder seam separation in airlock
13	X		X		6	9.1	Acceptable leak rate
14	X			X	4	281.2	Capran seal leak in airlock
15	X			X	6	9.1	Acceptable leak rate
16	X		X		6	9.1	Acceptable leak rate

[a] Specified allowable leak rate, 9.07 g/hr or 217.68 g/day of standard air.

TABLE III.- WEIGHT SUMMARY OF LUNAR-SHELTER STRUCTURES MODEL

Shelter (living quarters) weight:	
Composite wall, kg	85.28
Entry hatch, kg	4.08
Hatch ring, kg	3.18
Terminal bulkhead, kg	1.81
Bulkhead ring, kg	0.91
Total weight, kg	95.26
Airlock weight:	
Composite wall, kg	29.48
Airlock door, kg	14.97
Door frame, kg	5.44
Shelter attach ring, kg	2.72
Total weight, kg	52.61
Total weight of lunar-shelter structures model, kg	147.87



L-65-7689.1
Figure 1.- Illustration of STEM assembly on lunar surface using 0.10-scale inflatable model.

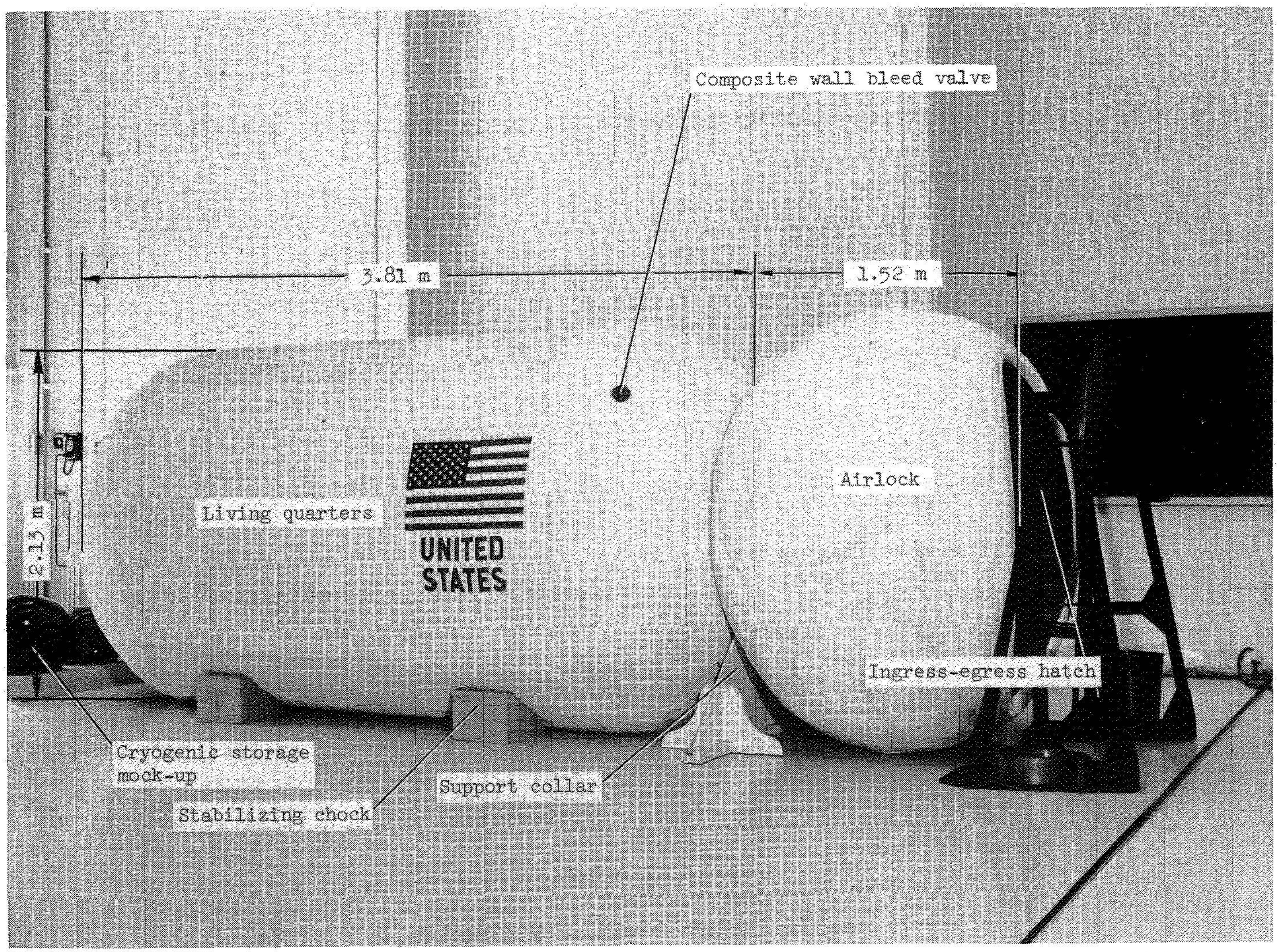


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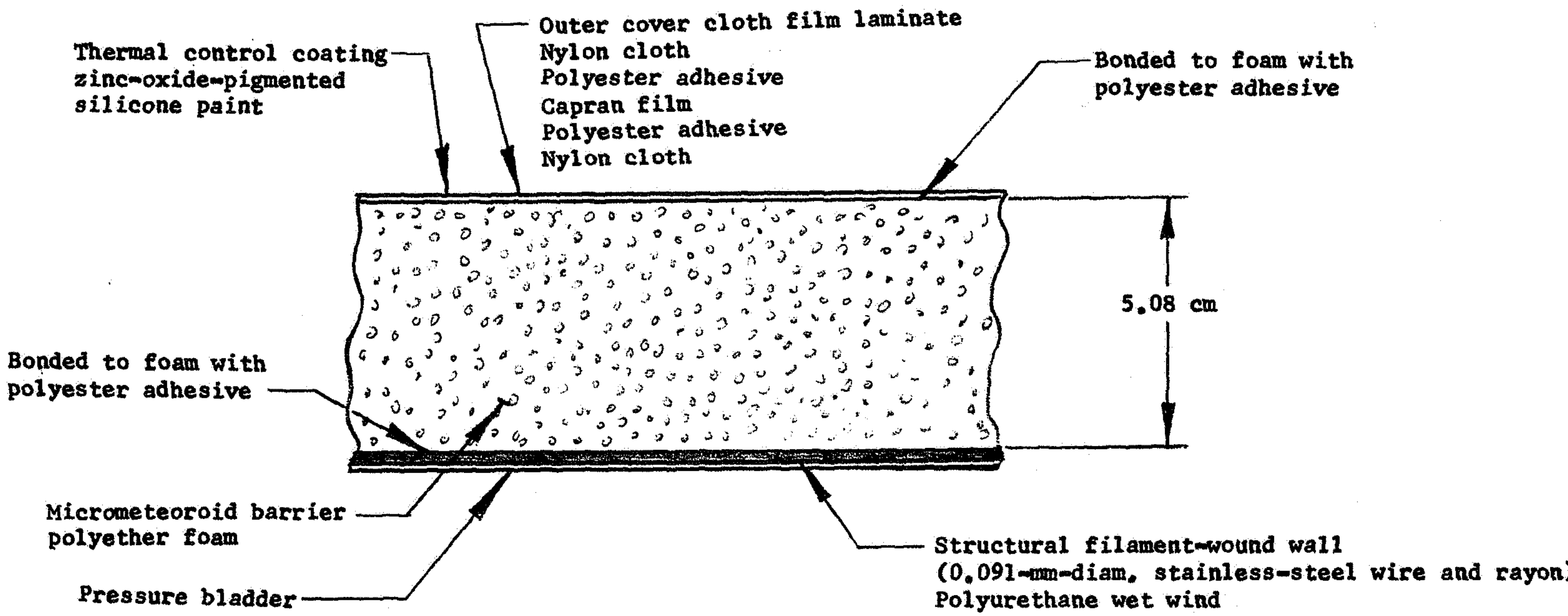
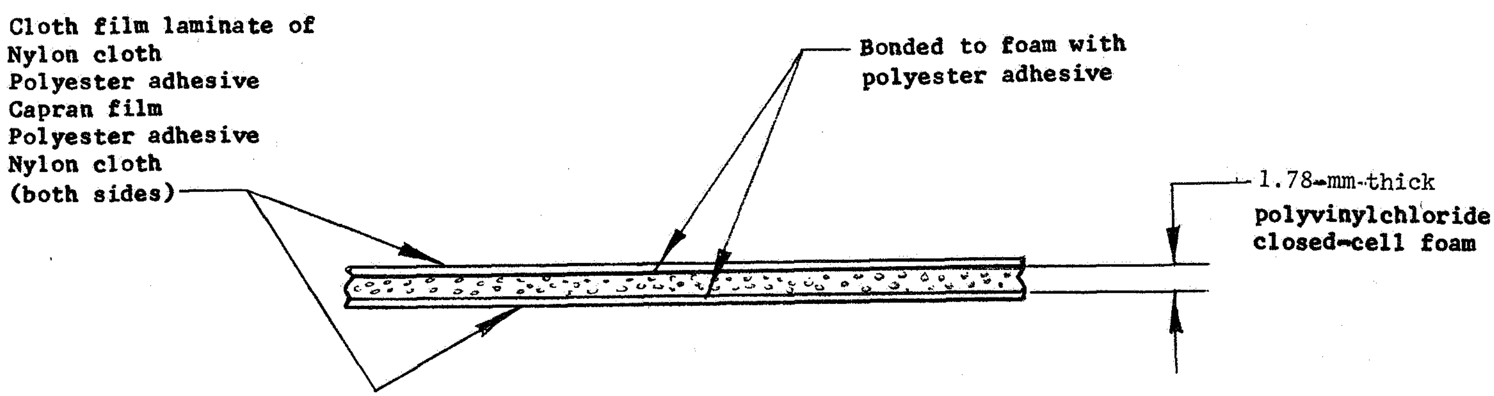
Figure 2.- Lunar-shelter structures model. Airlock volume, 2.97 m^3; living-quarters volume, 11.61 m^3; total internal volume, 14.58 m^3.



Weight:

Pressure bladder	0.062 g/cm^2
Structural layer	0.098 g/cm^2
Micrometeoroid barrier	0.098 g/cm^2
Polyester adhesive	0.013 g/cm^2
Outer cover	0.029 g/cm^2
Total unit weight;	0.300 g/cm^2

Figure 3.- Lunar-shelter-structures-model composite wall construction.



Weight:	
Inner nylon laminate	0.0073 g/cm^2
Polyester adhesive	0.0132 g/cm^2
Closed-cell foam	0.0205 g/cm^2
Polyester adhesive	0.0132 g/cm^2
Outer nylon cloth	0.0073 g/cm^2
Total unit weight;	0.0615 g/cm^2

Figure 4.- Lunar-shelter-structures-model pressure bladder construction.

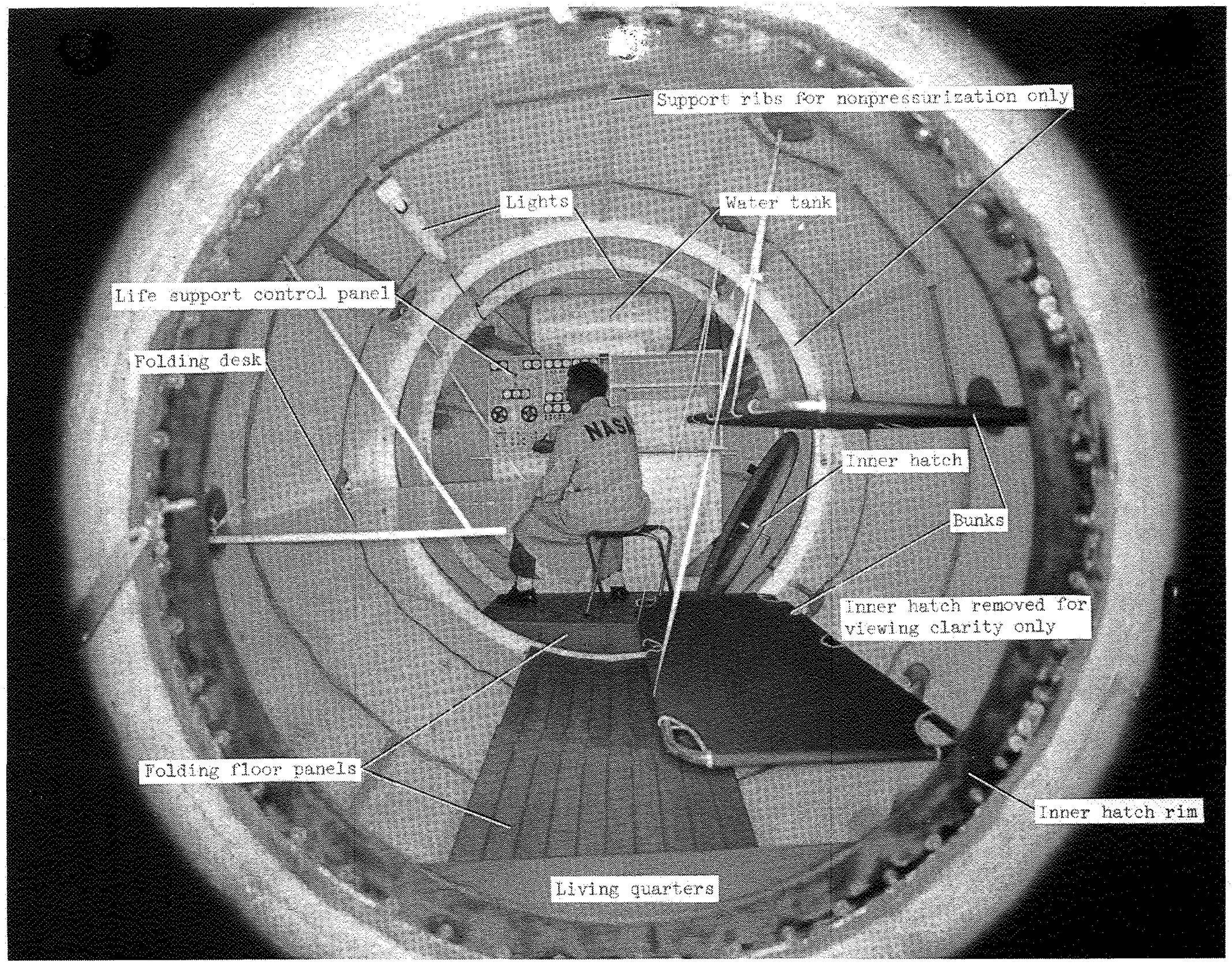


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Figure 5.- Interior of living quarters of lunar-shelter structures model.

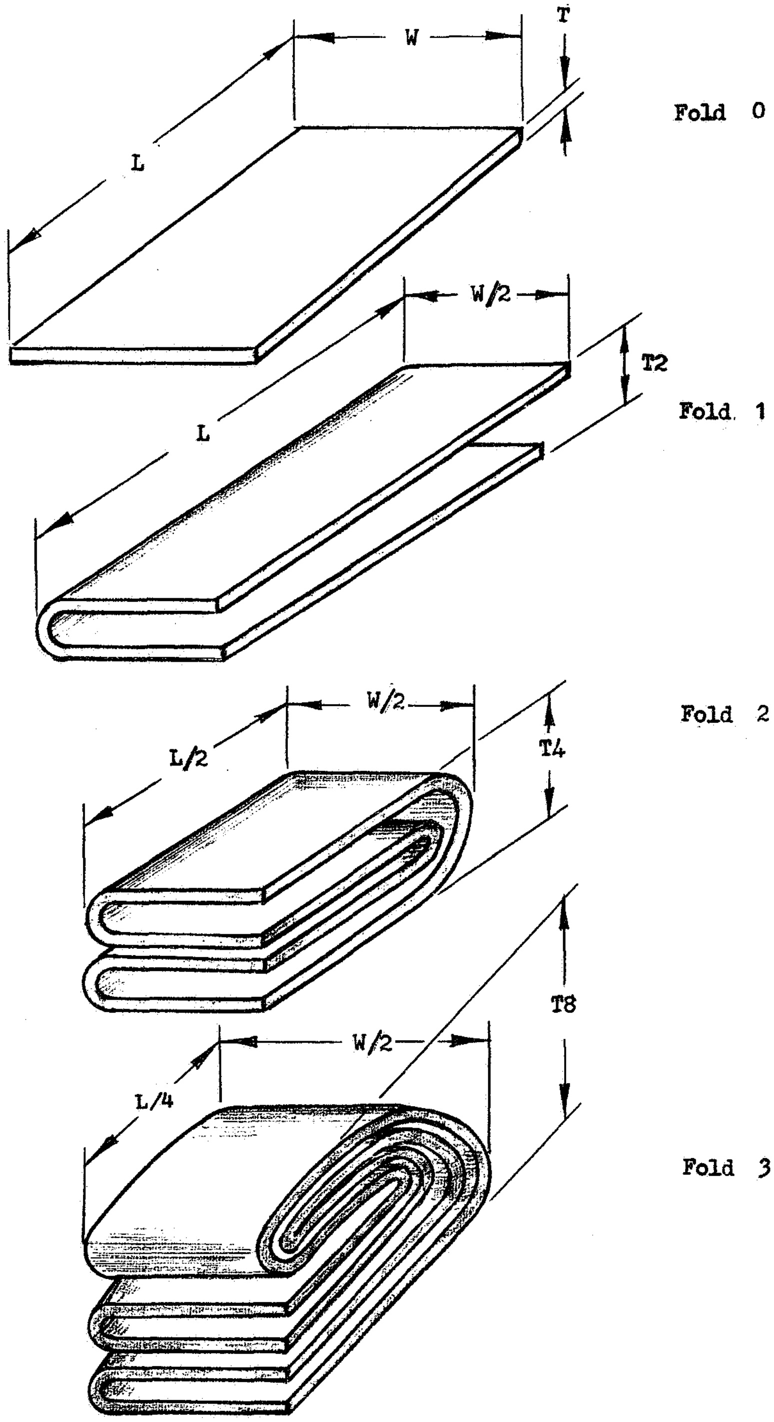
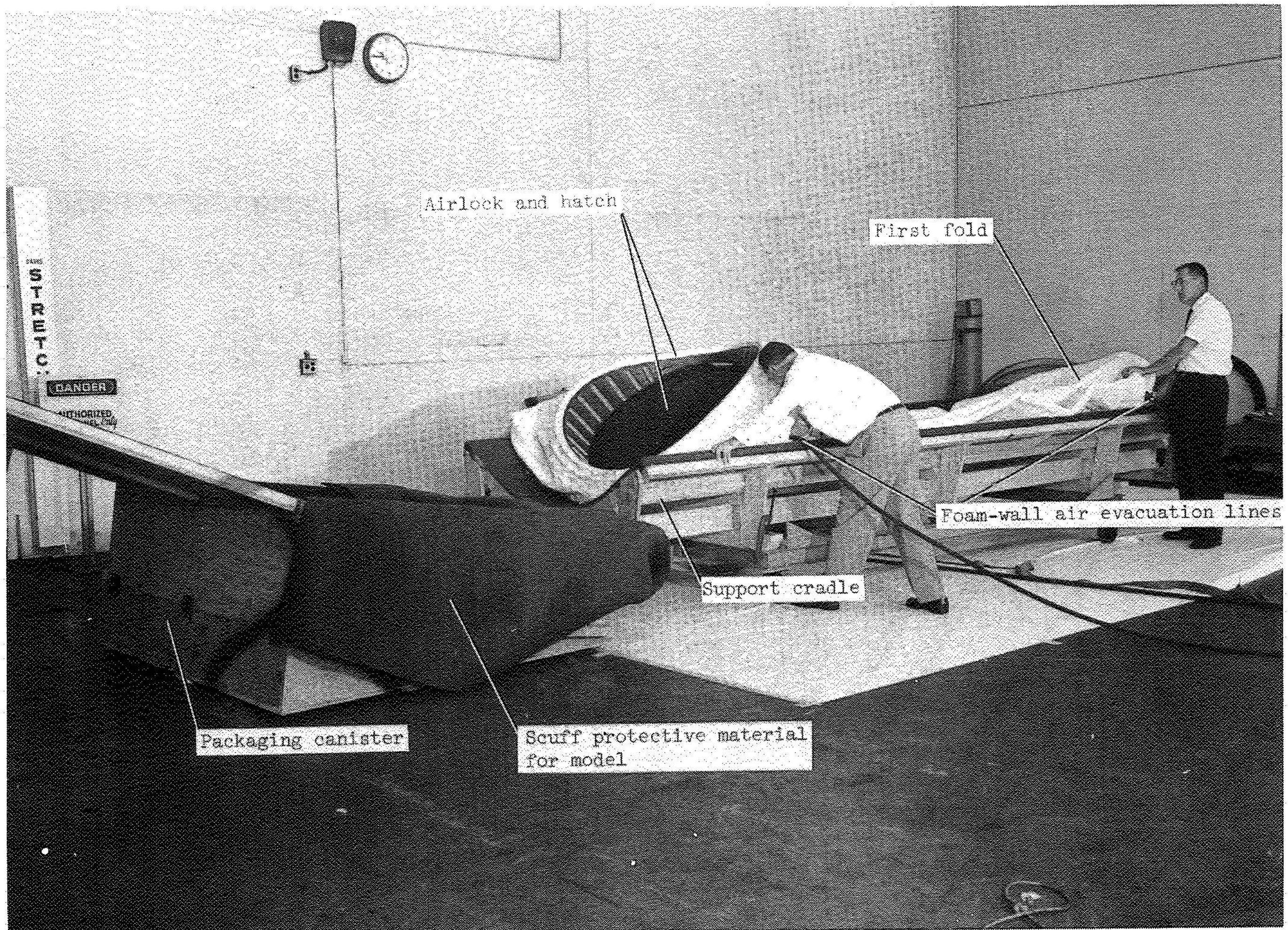


Figure 6.- Folding procedure for composite wall sample.

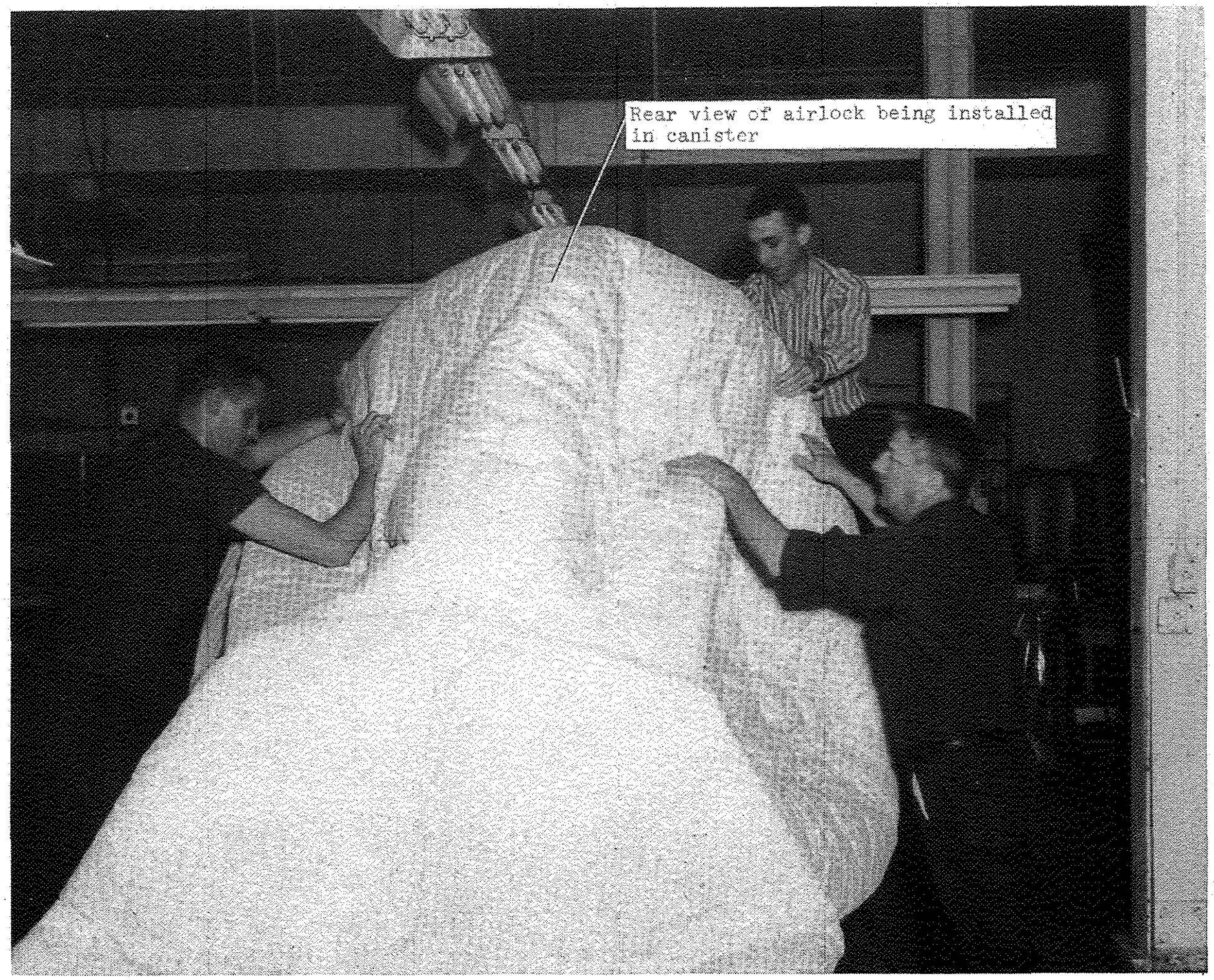


L-71-7101

Figure 7.- Position 1 in folding and packaging of the lunar-shelter structures model.

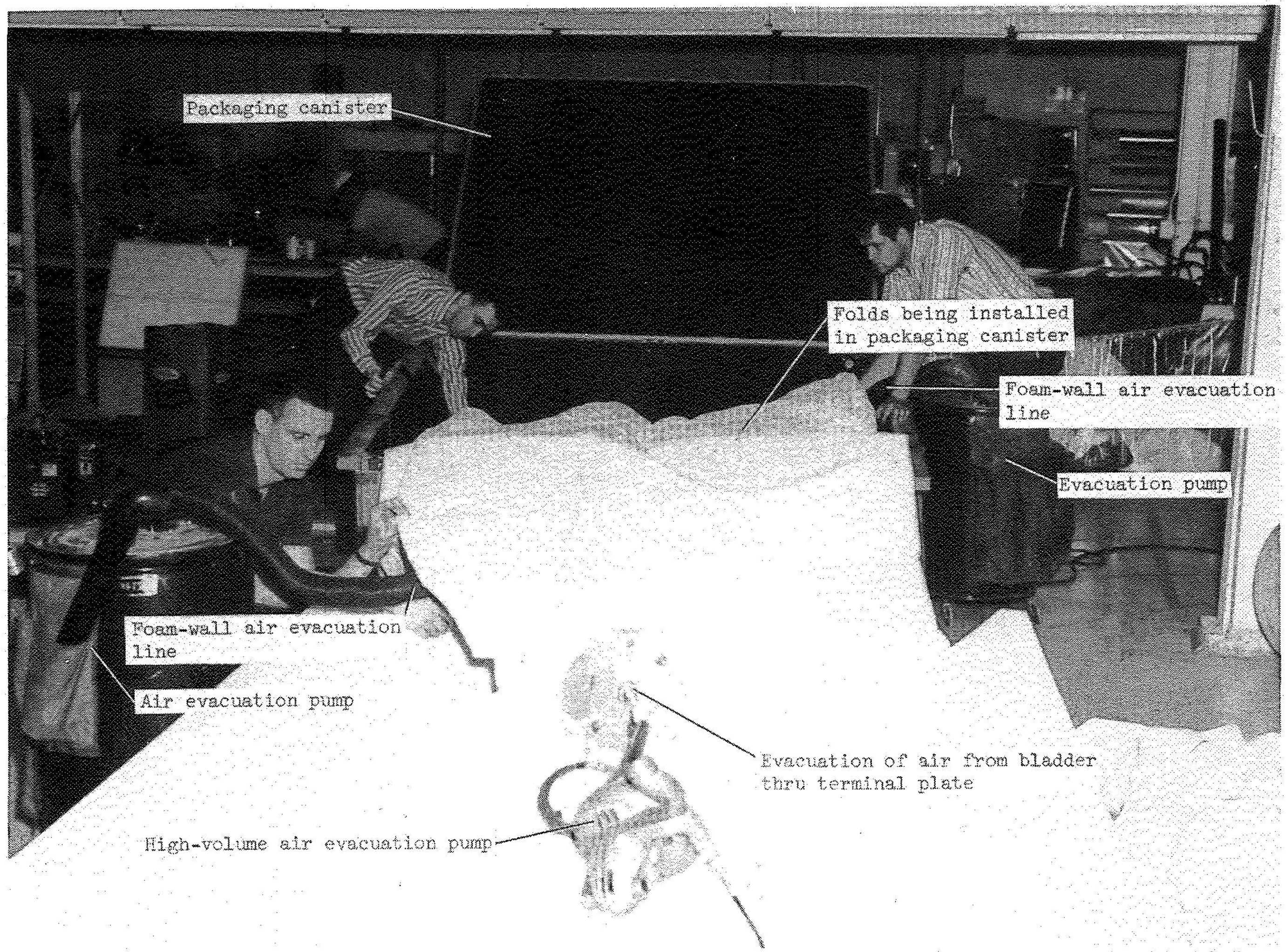
L-66-3121.1

Figure 8.- Position 2 in folding and packaging of the lunar-shelter structures model.



L-66-3120.1

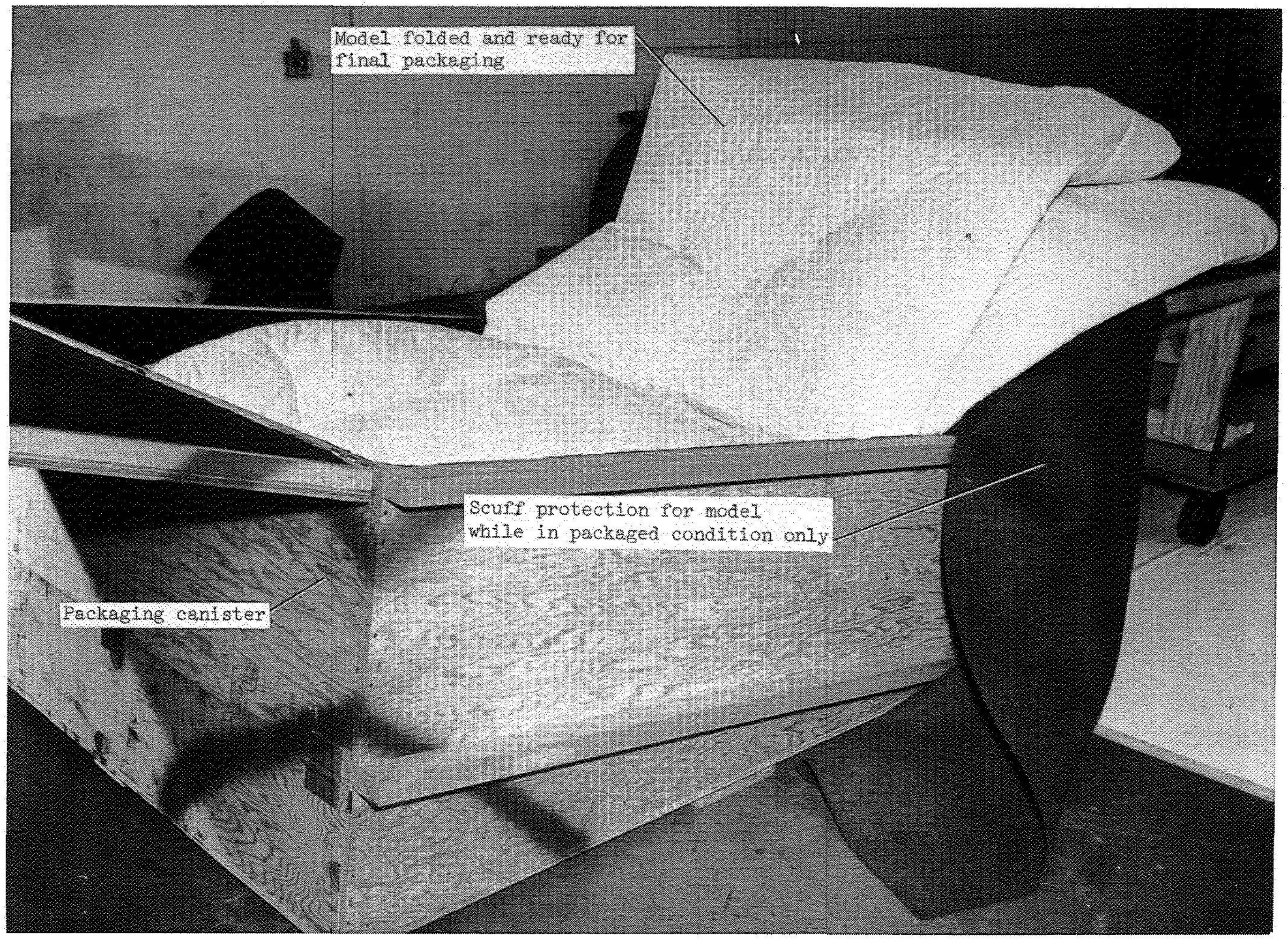
Figure 9.- Position 3 in folding and packaging of the lunar-shelter structures model.



L-66-3119.1

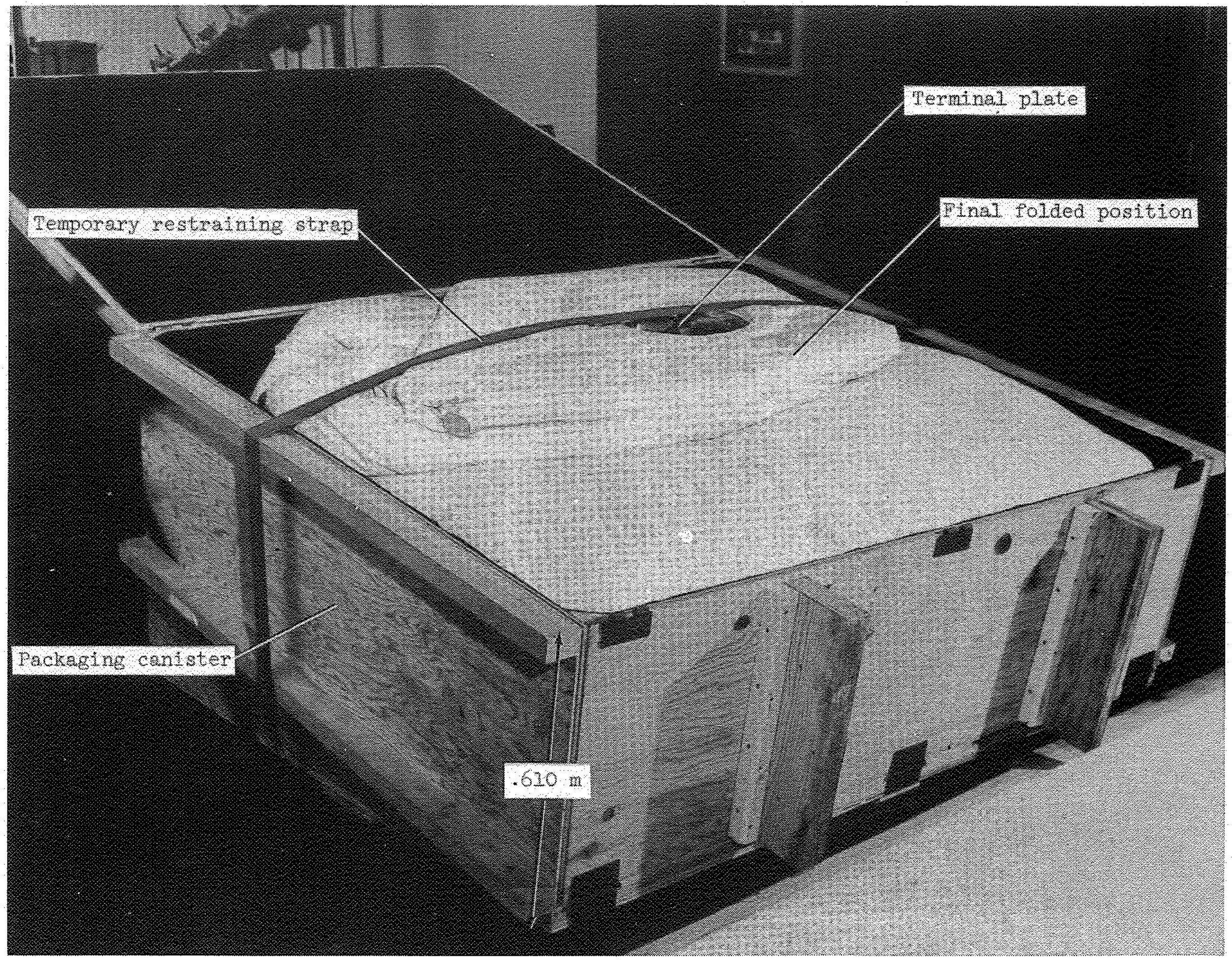
Figure 10.- Position 4 in folding and packaging of the lunar-shelter structures model.

L-66-3118.1
Figure 11.- Position 5 in folding and packaging of the lunar-shelter structures model.



L-71-7102

Figure 12.- Position 6 in folding and packaging of the lunar-shelter structures model.



L-71-7103

Figure 13.- Lunar-shelter structures model in packaged condition (position 7). Packaging factor, 6.5:1; packaged volume, 2.27 m^3.

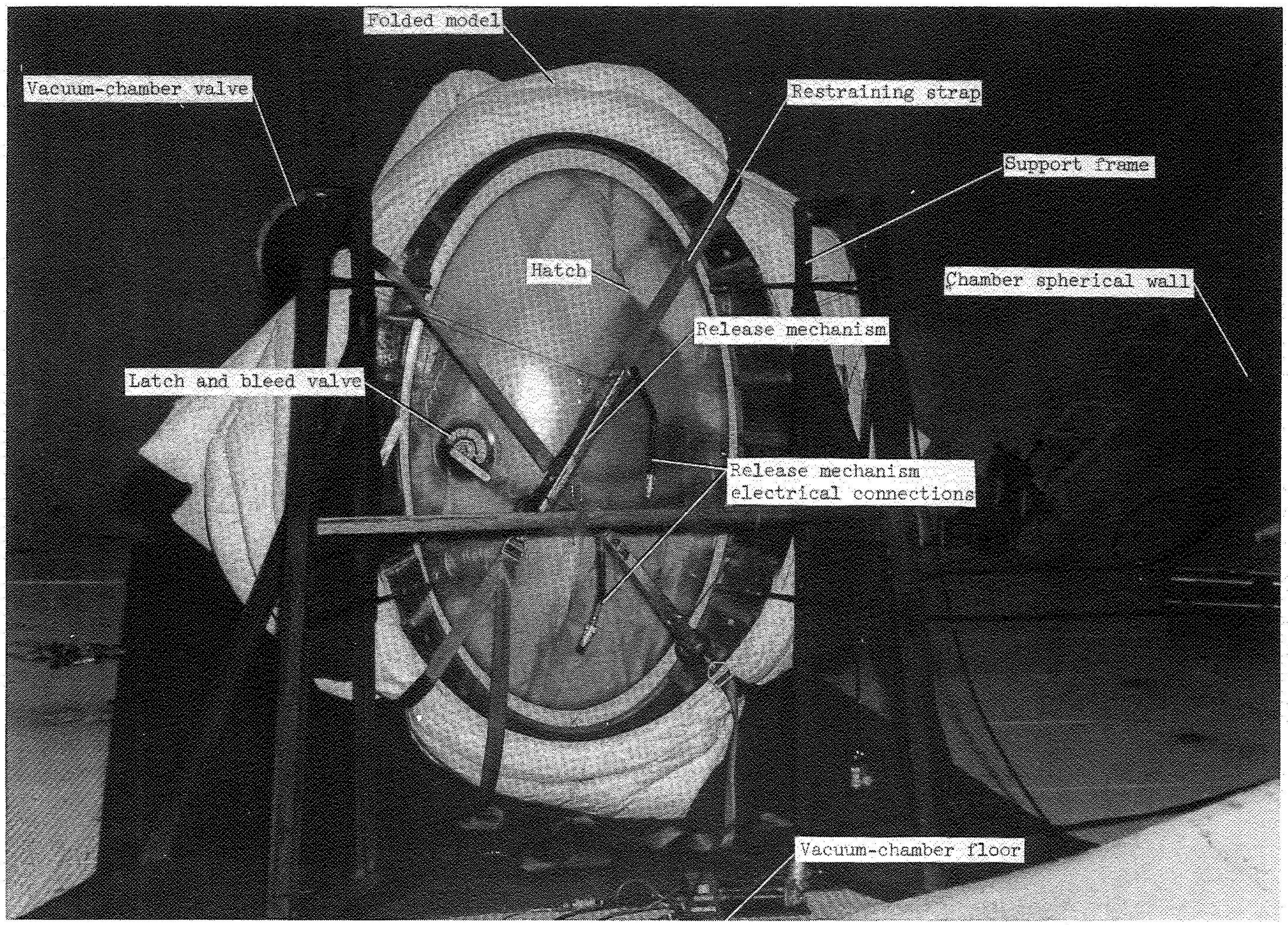


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Figure 14.- Front view of lunar-shelter structures model in packaged position installed in 18.3-m-diameter vacuum chamber.

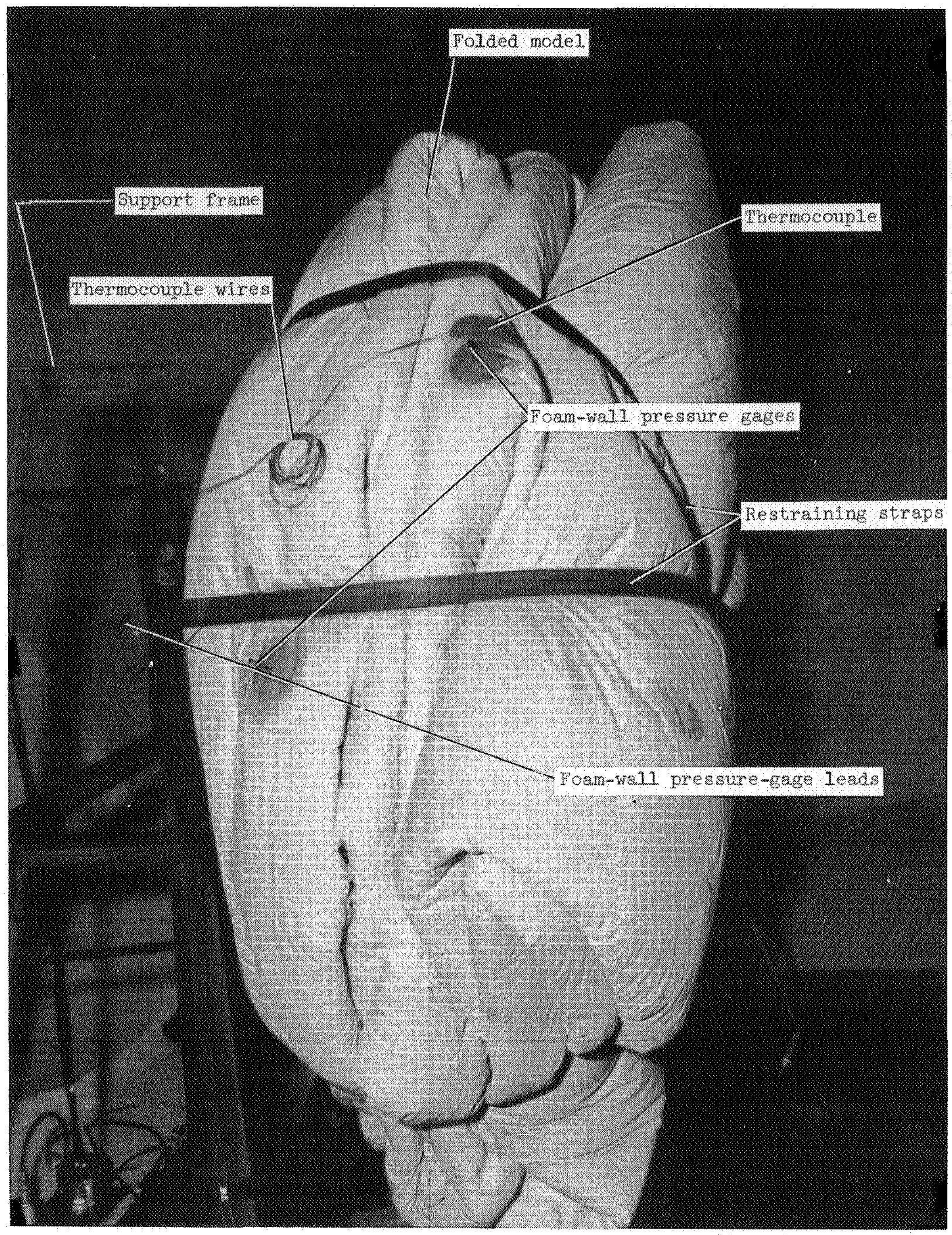

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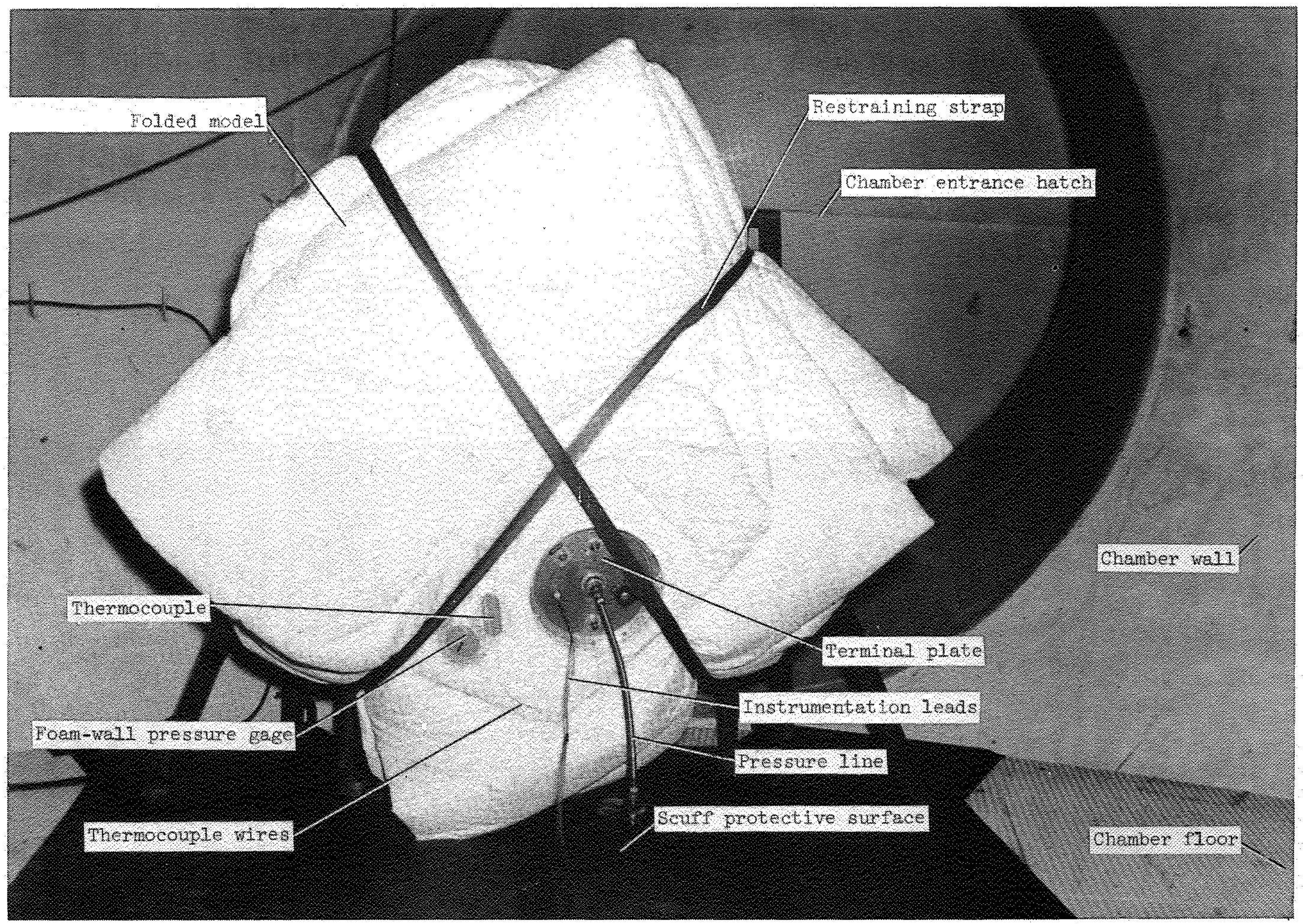
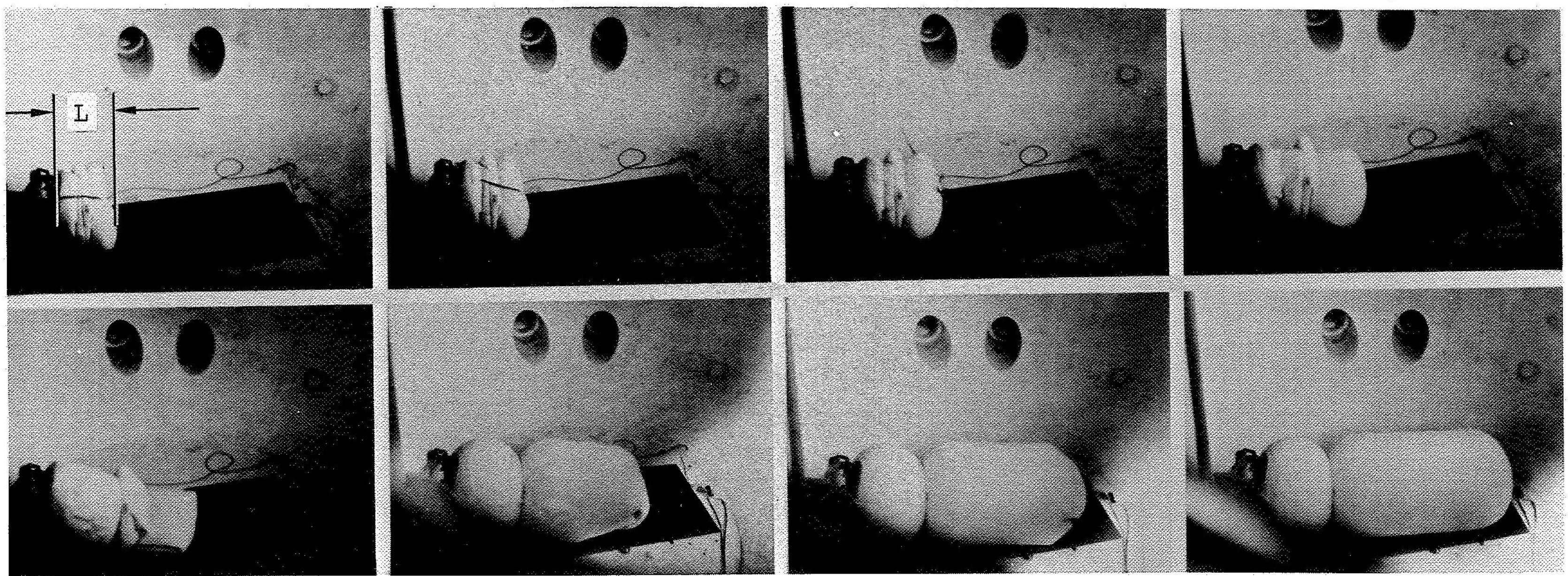
Figure 15.- Side view of lunar-shelter structures model in packaged position installed in 18.3-m-diameter vacuum chamber.



L-66-3408.1

Figure 16.- Rear view of lunar-shelter structures model in packaged position installed in 18.3-m-diameter vacuum chamber.

Frame 1 L = 133.40 cm | Frame 2 L = 155.63 cm | Frame 3 L = 177.88 cm | Frame 4 L = 244.58 cm

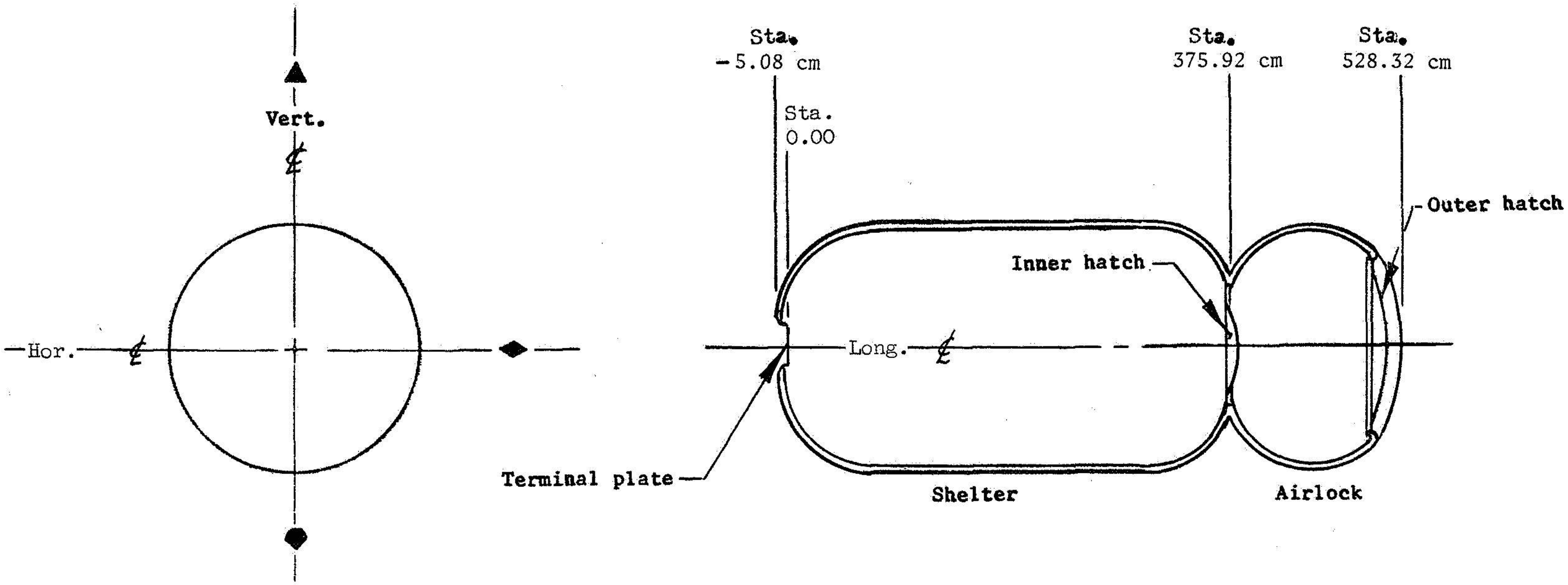


Frame 5 L = 322.12 cm | Frame 6 L = 422.45 cm | Frame 7 L = 489.15 cm | Frame 8 L = 533.60 cm

Frame	
1	Before release of restraining straps
2	At instant of release
3,4,5	Expansion due to stored energy; time, 1.8 sec
6,7	Internal pressurization to full configuration
8	Full model pressure, 34 473.8 N/m^2; test-chamber pressure, 133.3 N/m^2

L-66-5351.1

Figure 17.- Deployment of lunar-shelter structures model in 18.3-m-diameter vacuum chamber. (L, length of model.)



Test	Instrumentation	Station & Instrumentation number						
1 and 3	Thermocouple, internal	60.96	147.73	233.68	320.04	381.00	416.56	cm
		10 ▲	11 ▲	12 ▲	13 ▲	14 ▲	15 ◆	
	Thermocouple, external	60.96	147.73	233.68	cm			
		16 ▲	17 ▲	18 ▲				
	Pressure gage, internal	127.10	253.90	416.56	cm			
		2 ●	3 ●	1 ●				
	Pressure gage, external	127.10	253.90	416.56	cm			
		16 ●	17 ●	18 ●				
2	Thermocouple, internal	60.96	147.73	233.68	320.04	cm		
		10 ▲	11 ▲	12 ▲	13 ▲			
	Thermocouple, external	60.96	147.73	cm				
		16 ▲	17 ▲					
	Pressure gage, internal	60.96	253.90	cm				
		2 ●	3 ●					
	Pressure gage, external	60.96	253.90	cm				
		16 ●	17 ●					

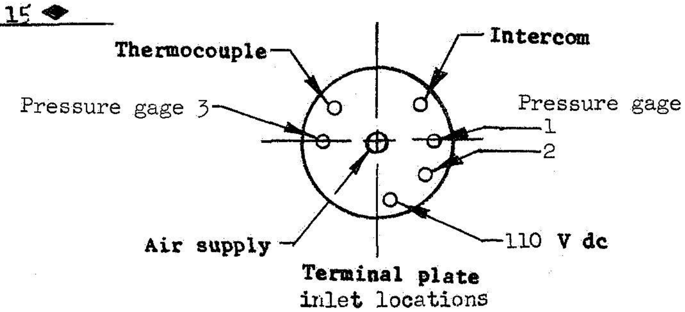
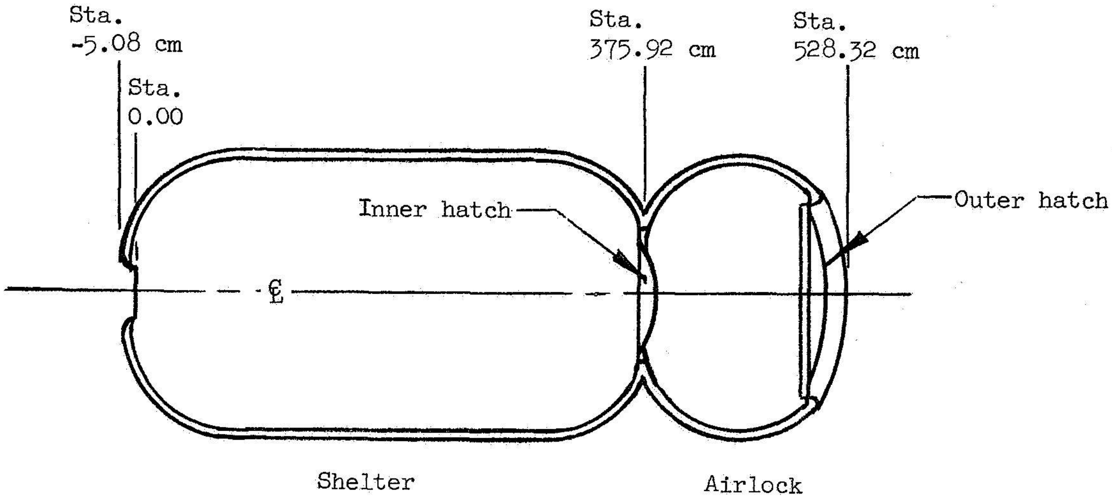


Figure 18.- Instrumentation location for tests in 18.3-m-diameter vacuum chamber.

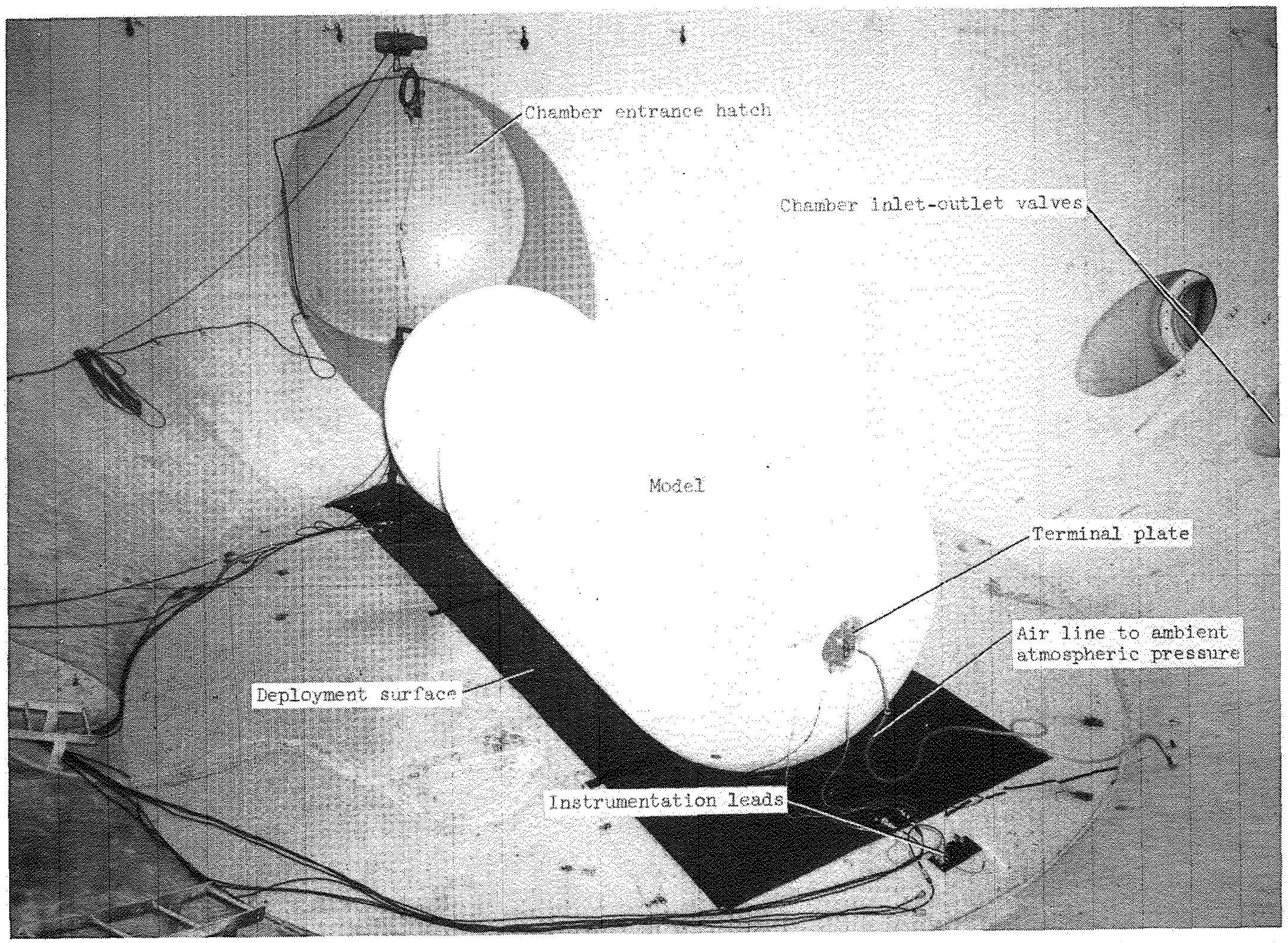


Test	Section	Hatch (inner)	Hatch (outer)	Test duration
1	Shelter-airlock	Bleed thru	Closed	4 hours
2	Shelter	Closed	Open	8 hours
3	Shelter-airlock	Open	Closed	4 hours

Test 1: Outer hatch closed before packaging; gas leak rate measured directly after deployment.

Tests 2 and 3: Hatch closed; model pressurized to 3386.4 N/m^2; bleed valve and hatch O-ring checked for leakage; vacuum chamber pumped down to 133.3 N/m^2; model pressurized to 34 473.8 N/m^2; gas leakage with time recorded.

Figure 19.- Sequence of tests in 18.3-m-diameter vacuum chamber.



L-66-3488.1

Figure 20.- Lunar-shelter structures model fully deployed in 18.3-m-diameter vacuum chamber. Vacuum chamber pressure, 133.3 N/m^2; model pressure, 34 473.8 N/m^2.

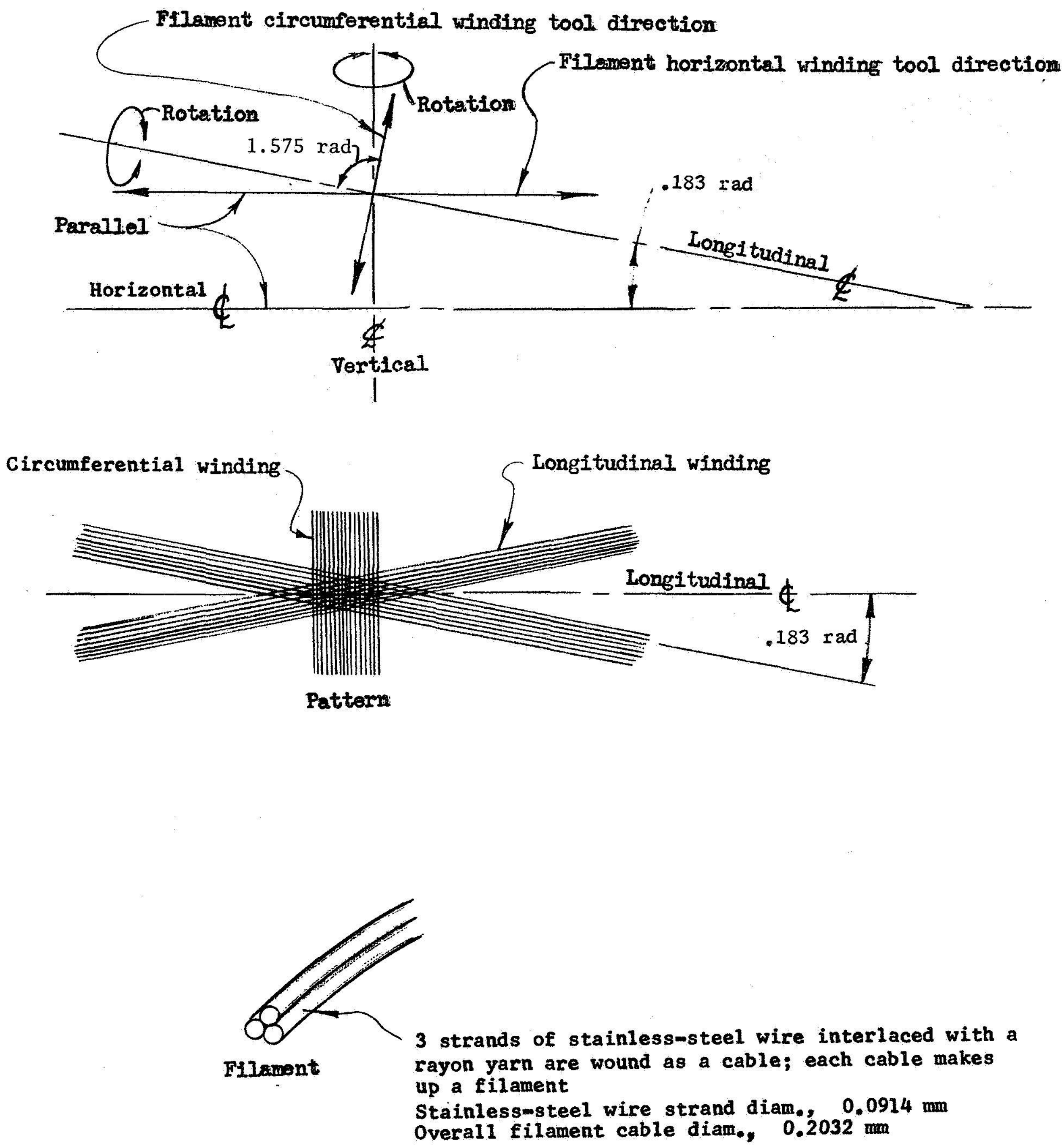


Figure 21.- Structural-layer filament winding pattern.

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