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EXPERIMENTAL INVESTIGATION OF PACKAGING AND DEPLOYMENT CHARACTERISTICS OF AN INFLATABLE TOROIDAL-SPACE-STATION CONFIGURATION

by Clarence O. Keffer

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1965

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EXPERIMENTAL INVESTIGATION OF PACKAGING AND DEPLOYMENT CHARACTERISTICS OF AN INFLATABLE TOROIDAL-SPACE-STATION CONFIGURATION

By Clarence O. Keffer
Langley Research Center

SUMMARY

[An investigation has been conducted at the Langley Research Center to determine the feasibility of a method for folding, packaging, and deployment of an inflatable 24-foot-diameter toroidal-space-station model. The model was tested under atmospheric conditions and in a 60-foot-diameter vacuum sphere at a vacuum pressure of 1 mm Hg.

It was found during these tests that the packaging factor of the torus component of the 24-foot-diameter space-station model torus was 4.1. This packaging factor was determined by dividing the folded volume of the material by the calculated material volume based on 0.084-inch material thickness. The torus was folded and packaged to 1.38 percent of the fully inflated volume.] This procedure reduced the volume from 2311 cubic feet to 32 cubic feet; it caused no apparent damage to the torus bladder and no permanent creasing, nor did it have any effect on the material permeability in the tests performed. Cords of the filament cage remained tightly bonded to the bladder and did not appear to be damaged. The internal collapsible compartments did not hinder the folding process of the torus and there was no apparent damage to these compartments due to the packaging.

Results of the folding and packaging tests indicate that the folding procedures developed can be used for inflatable toroidal-shape configurations. Also, the materials utilized in the construction of the torus were adequate in that they complied with the test-program requirements of a durable inflatable material that could readily be packaged into a tight compact unit with minimum damage to the material. Use of small-scale models for establishing folding and packaging procedures for large inflatable toroidal structures was proved feasible by tests in which a 1/8-scale model was utilized to develop the folding and packaging procedures for a 24-foot-diameter toroidal space station.

INTRODUCTION

The Langley Research Center has conducted an investigation to define problem areas and develop technologies applicable to long-duration manned space flights such as the earth-orbiting space station. One of the major guidelines for this experiment has been the requirement for a unitized structure which can be placed in an earth orbit by a single launch vehicle, thus obviating assembly in the space environment. (See ref. 1.) Several approaches that have been taken to satisfy best this requirement include utilization of rigid self-erecting modular structures and inflatable structures. Inflatable structures having a high strength-weight ratio are a particularly good combination of small-volume launch configuration and large-volume deployed configuration. A toroidal flight configuration was selected for this study because it maintains its geometric shape over a fairly large range of inflation pressures, has both natural stability and low gravitational gradient when rotated about the axis of generation for producing artificial gravity, and is compatible with existing booster configurations when packaged.

In a toroidal-space-station living quarters the most important stresses are those due to the internal pressure; therefore, the minimization of the torus weight should be based upon the inflation stress pattern. However, in constructing an expandable space station other influencing factors must be considered, such as dividing the space station into compartments, packageability of the space station, permeability of the bladder material, and use of material that can be repaired in space.

The purpose of this report is to demonstrate procedures developed for folding, packaging, and deployment of a 24-foot-diameter toroidal-space-station model.

DESCRIPTION OF APPARATUS

1/8-Scale Model

A 1/8-scale model was used to develop the folding and packaging procedures for a 24-foot-diameter inflatable toroidal space station. This scale model consisted of a torus having a maximum diameter of 36 inches and a minimum diameter of 12 inches with a cross section of 12 inches, mounted to a hub 12 inches in diameter and 6 inches in length. (See fig. 1.) The hub was a cylindrical structure fabricated of approximately 3/16-inch-thick polyester resin and fiberglass cloth. The torus was constructed from 52 individual gores bonded together with an overlap joint of 1/2 inch per gore. The ends of the gores were bonded to the cylindrical hub and a conventional tire stem was inserted in the hub to evacuate or inflate the torus.

The laminate material used for the 1/8-scale-model torus was composed of aluminum-vapor-coated 1/4-mil-thick polyethylene terephthalate plastic film laminated to 1 oz/sq yd 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 0.0075 inch.

24-Foot-Diameter Model

A 24-foot-diameter toroidal inflatable space station with a C-annulus cross section (fig. 2) was constructed to serve as a mock-up for ground packaging and deployment tests and as a structural prototype. This model consisted of a filament cage of 76-mil-thick dacron cords arranged meridionally around the torus to take primary loads due to internal pressure. A bladder of 7-mil-thick butyl-impregnated square weave nylon fabric sealed with a 1-mil-thick polyurethane sealing liner was employed to retain the air pressure (7 psi) and transfer the pressure loads to the filament cage; the total thickness was 0.084 inch. At each terminus of the C-annulus cross section the filament-cage cords were fastened to steel cables mounted on opposite ends of an 8-foot-diameter, 4-foot-long cylindrical-shaped hub of conventional sheet-metal construction. The cables reacted to the radial components of the load in the filament-cage cords and delivered the axial components to the rigid hub structure (ref. 2).

The internal volume of 2311 cubic feet was divided into eight equal compartments (fig. 3). The floor of the torus had a scuff resisting material compatible with use of the station as a demonstration device. A 5-foot-long zipper was installed to allow access to the inside of the torus to facilitate its use as a research test device. The total weight of the station, including hub, was approximately 1780 pounds, with the torus component weighing 280 pounds.

The major components of the inflatable space station C-annulus torus are the bladder and filament cage. The bladder provides for structural integrity without being required for support of the primary loads. As such, it is not part of the primary structure. The bladder is also capable of supporting loads due to internal attachments up to 90 pounds per inch ultimate at normal operating pressure (7 psi). (See appendix A for bladder construction.) The filament cage is an isotensoid structure designed to provide complete structural support of the living module component. This filament-cage construction consists of two major components: the dacron filaments and the hoop rings. (See fig. 2 and appendix B.)

Equipment Module

The equipment module, or central hub, was 8 feet in diameter and 4 feet long. It was constructed of aluminum with the two outer rims supported by a corrugated type of structure. (See fig. 4(a).) The surface that comes in contact with the torus bladder was formed with smooth aluminum sheets (fig. 4(b)) and riveted to the flange of the corrugations as shown in figure 4(a). Eight ports equally spaced around the periphery of the equipment module allowed installation of inflation inlets, internal lighting, and test instrumentation such as internal pressure and vacuum gages, thermocouples, air-conditioning-unit monitor, and air-circulation flow meters.

The equipment module also supported the inflation-system equipment, which consisted of eight spherical pressure bottles containing the inflation gases, manifold, pressure regulator, torus shaping valve block, and all necessary hardware as shown in figure 5.

Supporting Structure

The handling rig (fig. 6) that supports the torus and equipment module consisted of a tower approximately 13 feet from the base to the horizontal axis of rotation of the torus, when in a vertical position. This tower pivoted at a point of 10 feet down from the center line and allowed the torus to assume any angular position from vertical to horizontal. The tower was operated by a hydraulic cylinder, capable of functioning with a maximum load of 3000 pounds and cantilevered approximately 8 feet out from the tower. The center hub that supported the equipment module was designed to allow the torus to rotate about its central axis at any position of the tower.

TEST PROCEDURES

Folding and Packaging Techniques

The 1/8-scale model (fig. 1) of the 24-foot-diameter mock-up space station was constructed to establish methods for folding the 24-foot mock-up into a configuration suitable for launch as a payload package. This scale model was used to determine the most efficient fold with minimum damage to the material when evacuated, to determine markings required on the 24-foot mock-up inflatable structure to insure repetition of selected folding methods, and to establish folding aids required and adaptability of aids to the 24-foot-model folding operations.

The folding method was developed with the following requirements:

(1) The folds and creases required to provide a uniform thickness in the folded configuration must not be excessive.

(2) No locking folds should be apparent when the selected folding is deployed by inflation in the atmosphere.

(3) The external and internal surface rubbing occurring during deployment in the atmosphere must not be excessive.

To assist in developing symmetrical folds around the torus hub, markings in the circumferential and meridional directions were found to be necessary. Color coding of the meridional and circumferential lines greatly assisted in clarifying the folding operations. The meridional lines were identified by numbers 1 to 16 and the circumferential lines were identified by letters A to F. The identification of the markings used to fold the torus and to describe the folding procedures is shown in figure 7.

The steps in the description of the folding procedure are for one side; however, since the 1/8-scale model and the 24-foot model are symmetrical about the section center line, the description is applicable to both sides. When it is necessary in the folding description to indicate an intersection point or line on opposite sides simultaneously, they will be identified by right side or left side. The folding procedure included the following steps:

Step 1:

Meridional and circumferential markings (fig. 7) were applied while the inflatable torus was pressurized to approximately 3 psig. The internal pressure was reduced by a vacuum pump attached to the stem in the hub to assist in folding. After a partial vacuum was obtained, the material could be more readily positioned and held in place.

Step 2:

The points of intersections of the meridional lines 1 to 16 and the circumferential line C were brought in contact with the intersections of the same meridional lines and circumferential line A. The internal pressure was gradually reduced as required during this phase. Circumferential line B was positioned to crease on the center line of the hub and resulted in eight tapered equally spaced meridional pleats, originating on line B and terminating on line A. The excess material along line C was positioned in a "semi-V" shape but was not pleated. The intersection points of the even meridional lines and circumferential line E of both the left and right sides of the torus were brought together and fastened. The odd meridional lines were creased, from line E on the left to line E on the right, to form a peak. Figure 8 shows step 2 completed and the material positioned in place by fasteners.

Step 3:

The intersection points of the even meridional lines and circumferential line E were brought in contact with the same meridional lines and intersections of circumferential lines A and C and creased and pleated as required on circumferential line D for an even distribution of material. The configuration at the completion of step 3 is shown in figure 9.

Step 4:

The material of the eight points in figure 9(a) were creased and distributed to fold in a clockwise direction. The internal pressure was reduced as required. Figure 10 shows step 4 completed with the material partially folded into the final position.

Final Folded Configuration

The configuration in the folded and packaged condition is shown in figure 11. The folded material thickness was a nominal 3/16 inch (with a leeway of ±1/32 inch) when measured at the two plastic tie tapes seen in figure 11(b). The largest discrepancy in thickness (1/16 inch) occurred where the V-shaped ridges appear in figure 11(b). Discrepancies also occurred when the folds were made in step 4 (fig. 10(a)) while the internal pressure was being reduced. It was difficult to increase the internal pressure sufficiently to allow movement of the folds at these points without losing the folds near the inflation stem.

Residual Air Test

A nitrogen inflation test was conducted to ascertain the volume of residual air within the folded 24-foot-diameter torus. This test was important for determining the deployment rates and internal pressure of the torus within a vacuum or space environment. A relatively small amount of residual air trapped in the folds could cause a too rapid deployment rate and create a failure in the bladder, resulting in either small leaks or a catastrophic failure.

The equipment required for this test consisted of 12 nitrogen cylinders with a volume of 250 cubic feet per cylinder, a high-pressure manifold, connecting pressure line from manifold to torus hub, 3 nitrogen sample bottles with attached vacuum valves at either end, and a vacuum pump. The following procedure was used in securing these samples.

From a folded and packaged condition at atmospheric pressure the 24-foot torus was inflated to a pressure of 0.50 psig with dry, 99 percent nitrogen. Three evacuated sampling bottles equipped with two-way stopcocks at each end were connected with vacuum tubing to ports spaced at 120° intervals around the hub. The connecting tubing between the bottles and the sampling points was then evacuated. Gas from the torus was then allowed to flow through the sampling bottles for 2 minutes. The stopcocks of the sampling bottles were then closed, trapping the gas samples to be analyzed. A mass spectrometer was used to sample the inflation gas in order to attempt to determine the quantity of oxygen that was inside the nitrogen inflated torus. If the quantity of oxygen could be detected, then the volume of residual air inside the torus in the folded condition at atmospheric pressure could be determined as follows: Let p_a be the atmospheric pressure inside folded torus, V_a be the volume of atmospheric air inside folded torus, p_o be the oxygen pressure inside nitrogen inflated torus (detected by mass spectrometer to 0.01 percent of total torus inflation pressure), and V_t be the volume of inflated torus; then considering both Boyle's and Dalton's laws and with a constant temperature assumed

$$5p_aV_a = p_oV_t \tag{1}$$

with p_aV_a multiplied by 5 because the oxygen content in the inflated torus would be only one-fifth of the air inside the folded torus which would be composed of approximately 80 percent nitrogen and 20 percent oxygen.

Vacuum-Sphere Deployment Test

A deployment test of the 24-foot-diameter torus, from its folded and packaged configuration, was conducted within a 60-foot-diameter vacuum sphere at the Langley Research Center. The 24-foot torus material packaged around the central hub was strapped in place (fig. 12) to prevent premature deployment. The station was then mounted horizontally in the vacuum sphere and supported by the inflation-system support frame. Burnout wires were installed on the two straps restraining the packaged torus and attached to the control panel. A vacuum line was then connected to an external plug on the vacuum sphere and to a connection inside the folded torus; this line was connected to a small vacuum pump outside the chamber. This vacuum pump was used during the vacuum-sphere pump down to reduce the residual air contained within the folded torus. Cameras were mounted at various points around the test chamber to cover the entire inflation process. The inflation bottles were then connected to a portable air compressor and filled to a pressure of 400 psig. The pyrotechnics, which included three explosive-type metered air valves to operate the torus inflation system, and the burnout wires holding the restraining straps on the folded torus were wired and connected to an automatic programer.

When the vacuum pumps on the 60-foot vacuum sphere were started, the small portable vacuum pump outside the sphere, which was connected to the inside of the folded 24-foot torus, was also started to evacuate the residual air trapped inside the torus. When this residual air was evacuated, the portable vacuum pump was switched off. The 60-foot-vacuum-sphere pump down to 2 mm Hg was accomplished in approximately $3\frac{1}{2}$ hours; however, it took approximately 45 minutes more to reduce the chamber pressure to 1 mm Hg. When the vacuum-sphere pressure reading indicated 1 mm Hg, the folded-torus internal pressure reading was 2.9 mm Hg, indicating a torus residual air pressure of 1.9 mm Hg.

Before countdown was started, the folded torus appeared as shown in figure 13(a). A sequence countdown was started at T-10 seconds and when the count reached T-5 seconds, all cameras were started. This countdown was used to make certain that all cameras were working and to allow maximum test coverage due to camera speed and film length. At T-3 seconds the torus restraining straps were released (fig. 13(b)) and at T-2 seconds the torus was unfolding (fig. 13(c)). At T-0 the explosive valves were energized to permit the torus to fill with the inflation shaping gas (fig. 13(d)). An orifice metering valve between the explosive valve and the torus allowed 1/10 pound of inflation gas to enter the torus during a 30-second time period. Figures 13(e) and 13(f) show the torus beginning to fill with the inflation shaping gas and figure 13(g) shows the torus approaching its deployed configuration. This shaping procedure was to alleviate some of the initial shock of the full charge of the inflation gas. At T+62 seconds the main deployment valve opened and inflated the torus to its full configuration at T+95 seconds (fig. 13(h)). The vacuum-sphere pressure reading at this time was 1.118 mm Hg. The elasped time from start of inflation (fig. 13(d)) to full inflation (fig. 13(h)) was 1 minute and 35 seconds. At T+95 seconds the full internal pressure of 2 psig was obtained.

RESULTS AND DISCUSSION

Folding and Packaging Techniques

The 24-foot-diameter torus was folded by the procedures developed with the 1/8-scale model. The effects of the initial folding and packaging on the material of the 24-foot torus were determined after it had been reinflated to full toroidal configuration, as shown in figure 14(a). Upon close inspection there was no apparent damage to the bladder material, no leak or permanent creasing or effect on the permeability of the bladder detected due to the test conducted. The dacron cords used in the filament cage remained tightly bonded to the bladder and did not appear to be physically damaged. The results of the folding and packaging tests conducted with the 24-foot torus indicate that the folding procedures initially developed on the 1/8-scale model can be used for the inflatable toroidal-shape configuration.

Several problems that developed while folding the 24-foot-diameter torus were due to its large configuration and material thickness and were alleviated by the following minor modifications to the folding method developed with the 1/8-scale model:

(1) In step 2 of the folding procedure it was found that folding from the top of the 24-foot torus from platforms (fig. 14(b)) was advantageous in that the folds could be adjusted in place much easier and more accurately.

(2) In connecting the points of intersection of circumferential line C and meridional lines 1 to 16 at circumferential line A, it was found that the 24-foot torus had to be rotated 90° between each clamping point - that is, if meridional line 1 was clamped at circumferential line A the torus would be rotated 90° to meridional line 5 and clamped at circumferential line A, then from meridional line 5 to meridional line 9, and so forth. This rotation allowed the torus excess material to be much more evenly distributed.

(3) Wooden bars slotted at each end to receive bar clamps were needed to hold the 24-foot torus material in place (as shown in fig. 14(b)) while the next section of material was pulled into a fold. These bar clamps, 16 on each side, were fastened to the inner surface of the rim.

(4) To prevent the torus zipper from becoming damaged because of the sharp radius of the 24-foot torus material in folding, a wooden insert with a 1-inch radius was attached to the inner fold to prevent the breaking or pulling loose of the zipper teeth.

(5) Evacuation of air from the torus at too fast a rate while folding tended to cause the inner surfaces of the material to adhere together. During some phases of folding it was necessary to slightly inflate the torus to allow the folds to move into their proper positions. After these folds were completed, it was then necessary to evacuate the air to permit the folds to be pulled down as flat as possible.

After the 24-foot-diameter model was folded, there were two restraining straps placed around the circumference of the folded torus to hold the folds in place. These straps had quick disconnect buckles to allow the torus to be deployed quickly. The average height of the folded torus material (fig. 14(c)), measured from the outside edge of the rim of the equipment module, was approximately 3.7 inches. The packaging factor of the 24-foot-diameter torus was 4.1; it was determined by dividing the folded volume by the calculated material volume. The 24-foot model's fully inflated volume of 2311 cubic feet was folded into a volume of 32 cubic feet or 1.38 percent of its fully inflated volume.

Residual Air Test

The analysis of the gas from the nitrogen inflated torus showed that the residual air volume in the torus folded condition was less than the detection range of the mass spectrometer which is 0.01 percent of the total entrance pressure. Therefore, the residual air volume inside the torus must be less than 0.05 cubic foot and was determined as follows: From equation (1),

$$V_a = \frac{p_o V_t}{5p_a}$$

and $p_o = 0.0001p_t$ $\left(p_t\right.$ is fully inflated pressure of torus$\left.\right)$ where

$V_t = 2311$ cubic feet

$p_t = 15.2$ psi

$p_a = 14.7$ psi

Since the calculated material volume is 7.78 cubic feet and the total folded volume is 32 cubic feet, then the total residual air volume can be considered to be 24.22 cubic feet with less than 0.05 cubic foot within the torus envelope and the remainder outside the torus envelope between the folds.

Vacuum-Sphere Deployment Test

The packaged torus in the 60-foot-diameter vacuum sphere at a vacuum pressure of 1 mm Hg is shown in figure 13(a). There was no apparent excessive strain on the torus restraining straps from the pressure differential of 1.9 mm Hg.

The deployment of the torus folds was conducted without any binding or snagging of the bladder material, as shown in figures 13(b) and 13(c). The torus assumed the position shown in figure 13(d), partially because of the internal pressure of the residual air.

Examination of the torus bladder material and filament cage after the vacuum-sphere tests revealed no apparent damage to the bladder material - no leak or permanent creasing or effect on the permeability - even though the 24-foot-diameter torus model had been folded and reinflated eight times. The dacron cords used in the filament-cage construction remained tightly bonded to the bladder and there was no apparent damage to these cords.

Presented in figure 15 are the pressure time histories for the 60-foot-diameter vacuum sphere and the torus.

These vacuum-sphere tests indicate that the folding procedures and deployment techniques as initially developed on the 1/8-scale model will be satisfactory for the deployment of an inflatable toroidal-shape configuration within a space environment.

CONCLUDING REMARKS

Results of an investigation to determine the feasibility of a method for folding, packaging, and deployment of an inflatable toroidal-space-station model indicate that the following statements should be emphasized:

A 24-foot-diameter inflatable space-station model can be constructed by using current state-of-the-art technology, folded into a compact package, and successfully deployed and inflated in a vacuum of 1 mm Hg.

The torus component of the 24-foot-diameter inflatable space-station model weighed 280 pounds and was folded into a 32-cubic-foot volume and reinflated to a volume of 2311 cubic feet eight times without damaging the bladder material or affecting its permeability.

Satisfactory folding and packaging procedures for a large toroidal inflatable space station can be developed by using scale models.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 15, 1964.

APPENDIX A

24-FOOT-TORUS BLADDER CONSTRUCTION

The bladder material was a single-ply nylon-butyl fabric. This fabric was 4-mil-thick nylon cloth weighing 2.25 ounces per square yard. When impregnated with butyl rubber, the thickness of the fabric was increased to 7 mils with a resulting weight of 5.00 ounces per square yard. The sealing liner mixed with TDI (tolylene diisocyanate) in the ratio of 100 cc TDI per gallon of solution was applied to the inside surface of the fabric. The sealing liner used for the pressure bladder was a solution of a high-molecular-weight cross-linked polymer of the polyurethane class. This sealing liner was sprayed or brushed on the inside of the pressure bladder. Upon total evaporation of the solvent a unique completely cured elastomeric film remained. Pigments were added to the sealing liner to give the walls of the pressure bladder a light green color and the floor a tan color.

APPENDIX B

24-FOOT-TORUS FILAMENT-CAGE CONSTRUCTION

The filament cage consisted of dacron cords 0.076 inch thick with a breaking strength of 358 pounds tensile per cord. These cords were spliced together to form a continuous filament.

Two hoop rings each 96 inches in diameter were required for the filament cage. (See fig. 16(a).) The hoop-ring cable had a nominal cross-section diameter of 1 inch and consisted of seven strands of stainless-steel wire. The cables were wrapped with a dacron film, and a "square wire spring" was threaded with the dacron filaments as shown in figure 16(b). The hoop-ring cable had a composite cross-section nominal diameter of 1.18 inches. The hoop rings were spaced 21 feet apart in a special jig for winding the filaments around the cables. (See fig. 16(a).) This jig allowed the filament cage to be constructed as a cylinder with the filaments parallel to the longitudinal axis. During the process of winding the dacron filaments over the hoop rings, elastic pick threads were simultaneously woven between the dacron filaments in a transverse direction (fig. 16(b)). These pick threads were spaced approximately 6 inches apart and prevented the dacron filaments from becoming tangled after removal from the jig and during assembly with the bladder and hub. The outer surface of the bladder was then painted with three coats of clear polyurethane cement thinned with 1 quart of DMF (dimethyl formamide) to 1 gallon of cement and treated with 100 cc per gallon of TDI (tolylene diisocyanate).

After the torus (bladder and filament cage) was fabricated (fig. 16(c)) and assembled, it was then inflated to a pressure of 7 psig.

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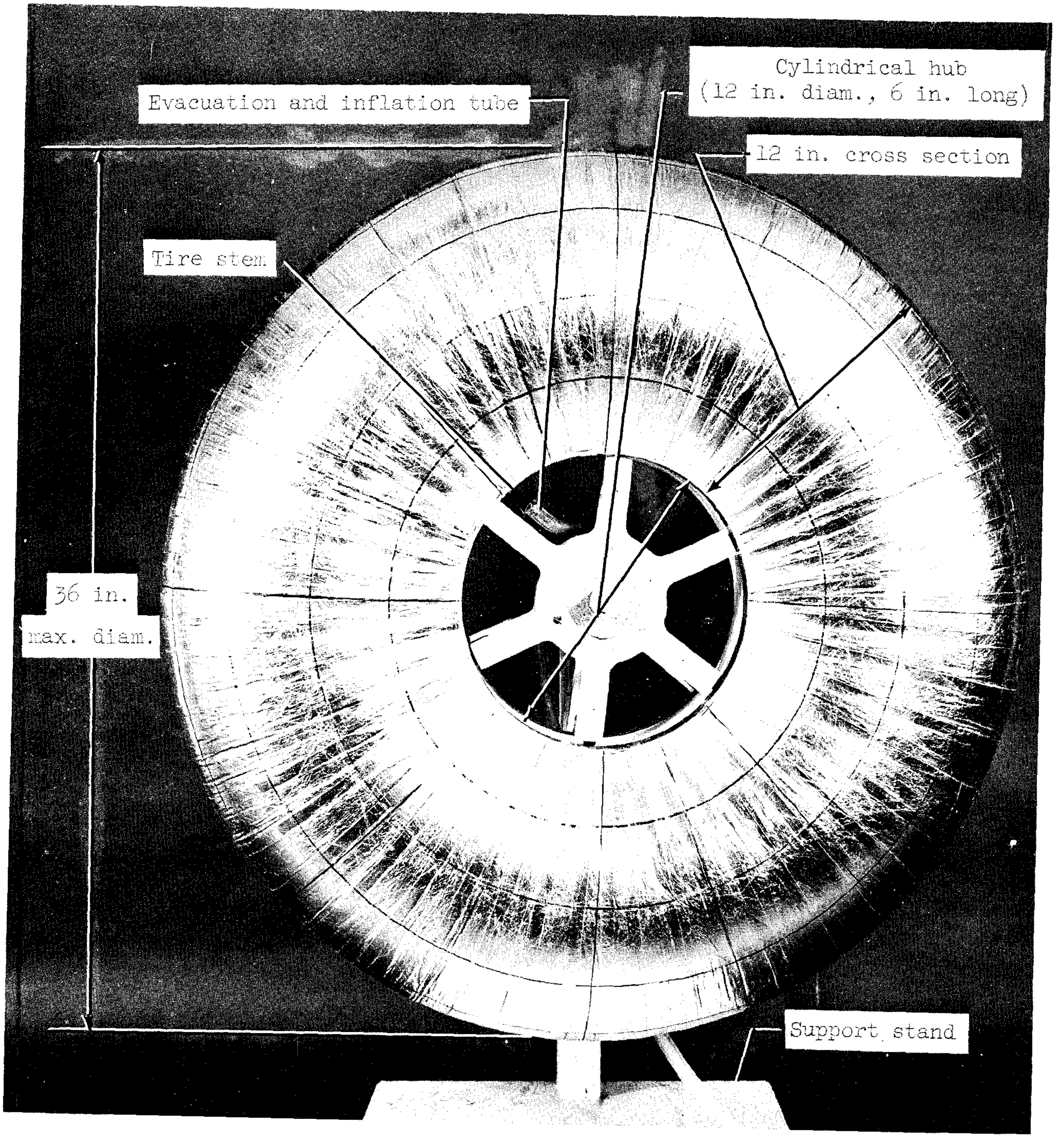
2. Houmard, J. E.; and Marketos, J. D.: Approximate Analyses of the Structural Stability of the C-Annulus Space Station Models. GER 10755, Goodyear Aircraft Corp., Sept. 18, 1962.



L-61-2891.1

Figure 1.- 1/8-scale model of inflatable space station used to develop folding procedures.

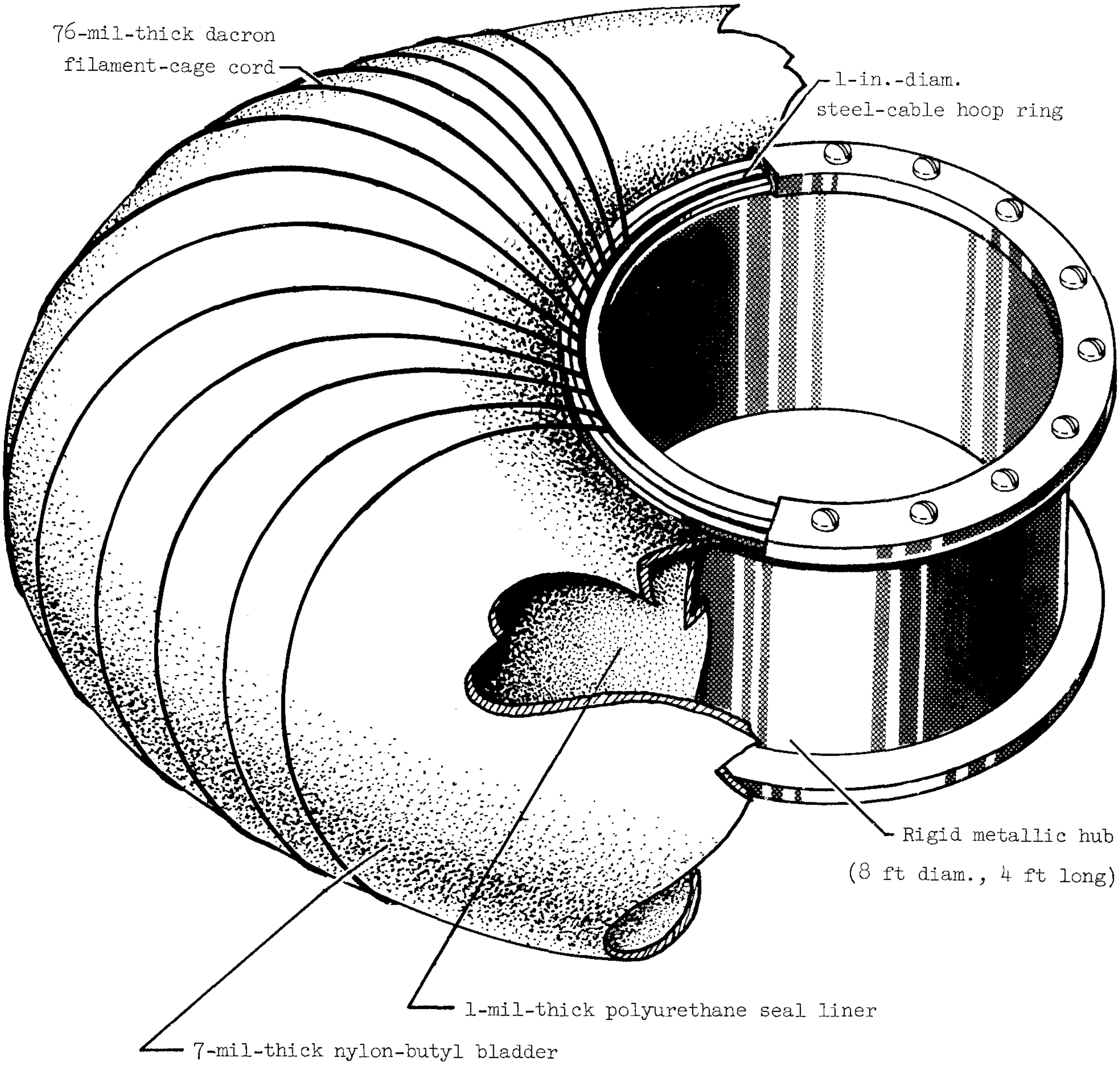
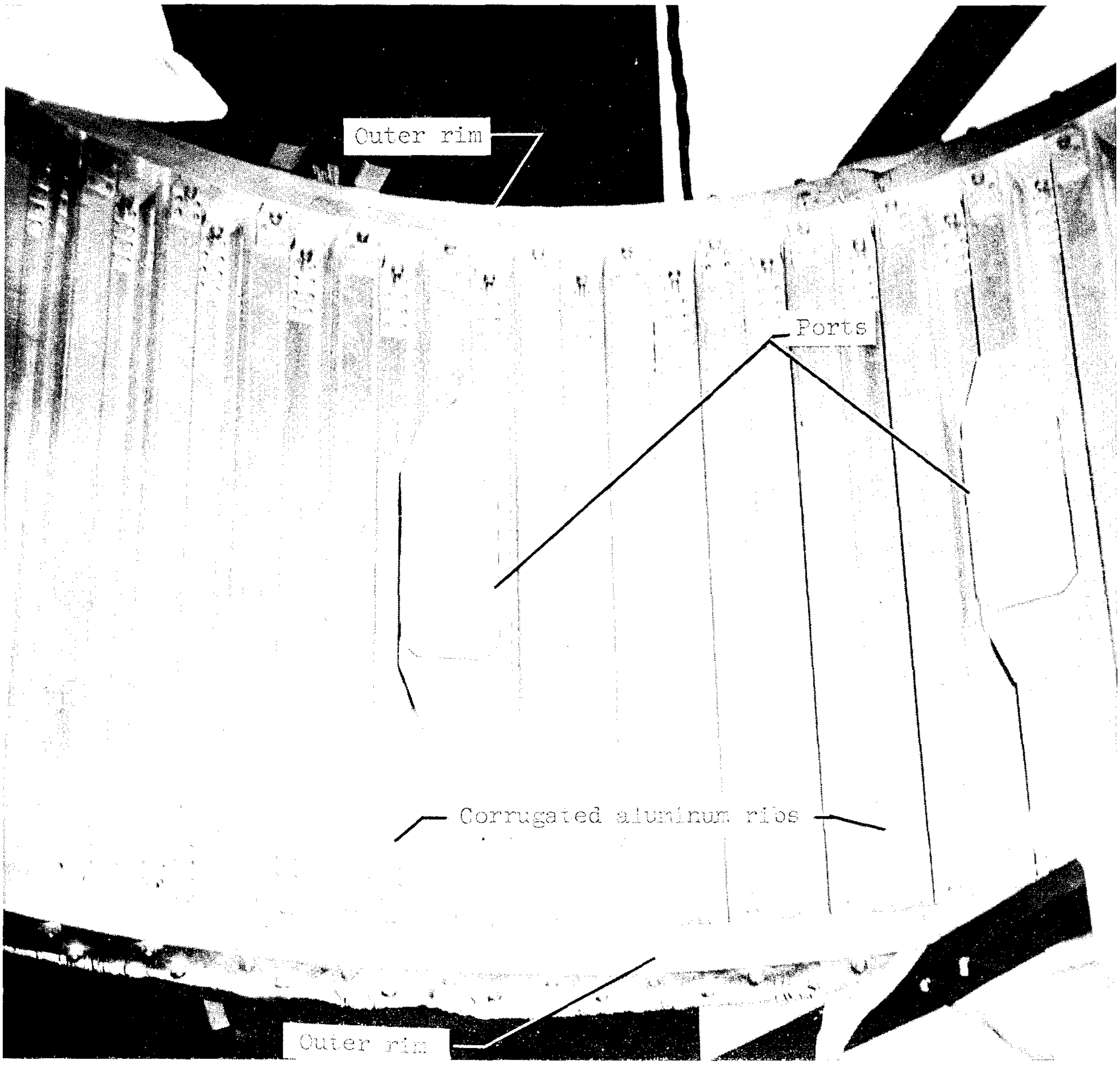


Figure 2.- Basic construction of 24-foot-diameter torus.

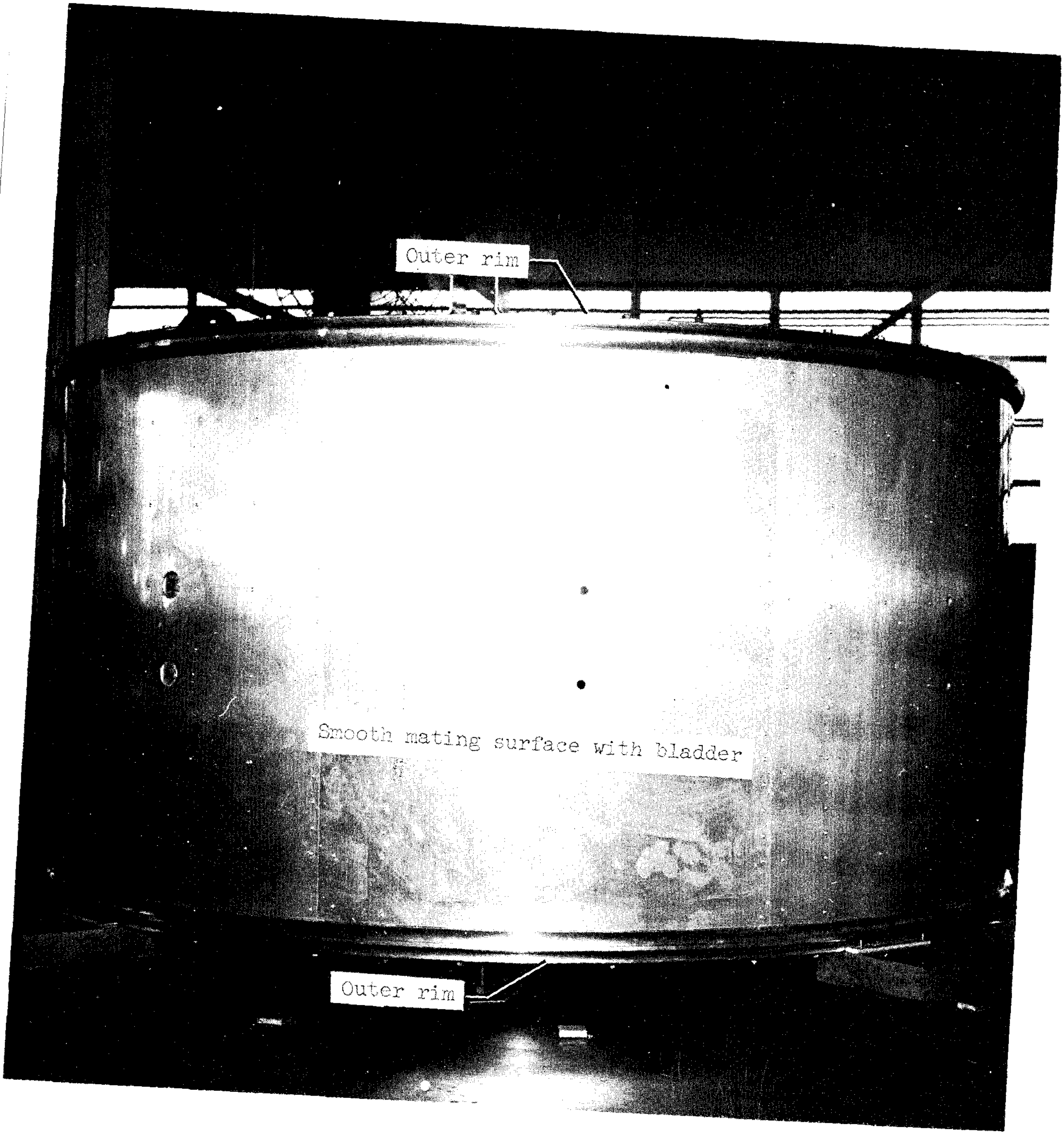
Figure 3.- Internal view of 24-foot-diameter torus. L-62-3016.1



(a) Inner construction.

L-61-7362.1

Figure 4.- Equipment module of the 24-foot-diameter torus.



(b) Outer construction.

L-61-3920.1

Figure 4.- Concluded.

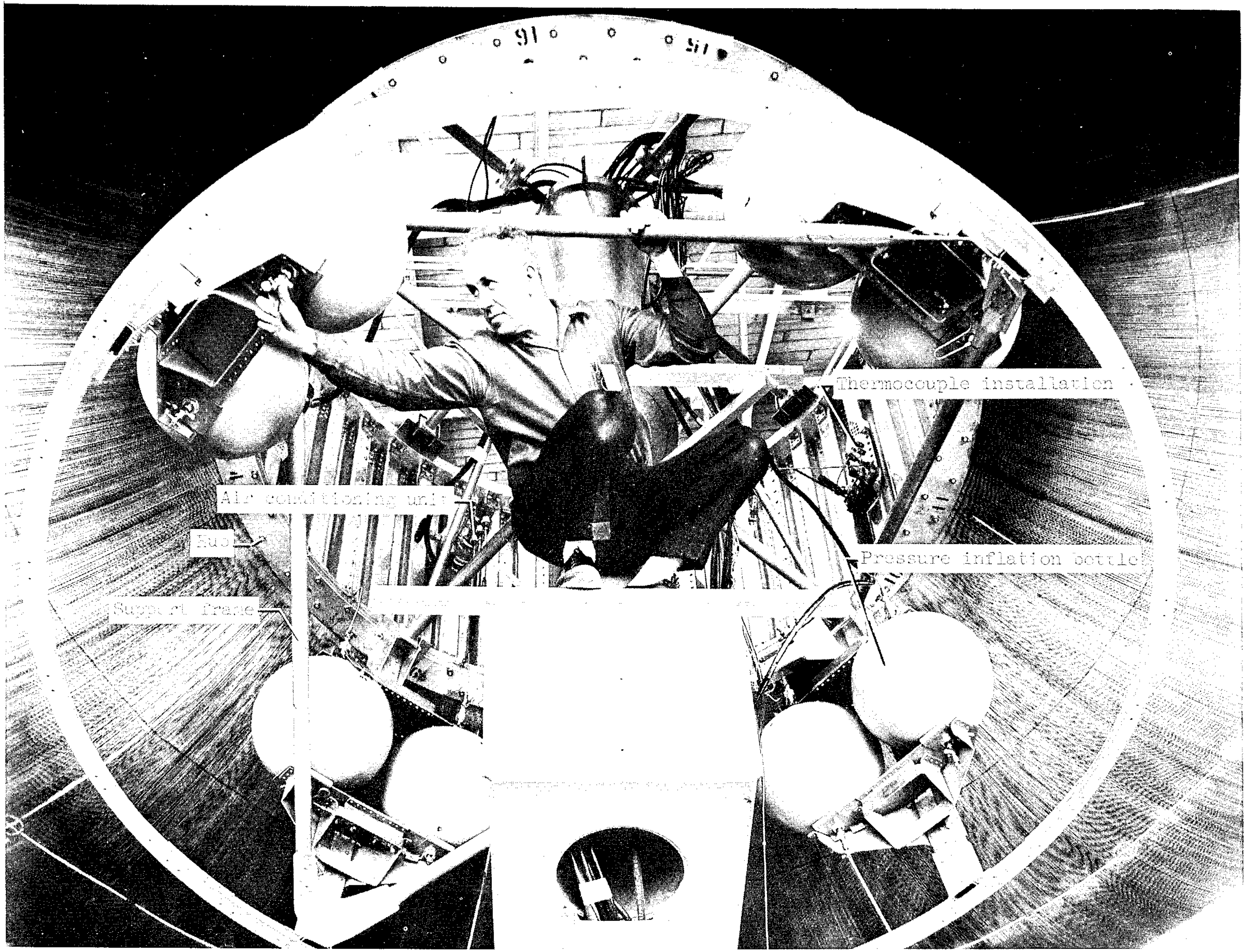


Figure 5.- Inflation-system assembly for the 24-foot-diameter torus. L-62-3431.1

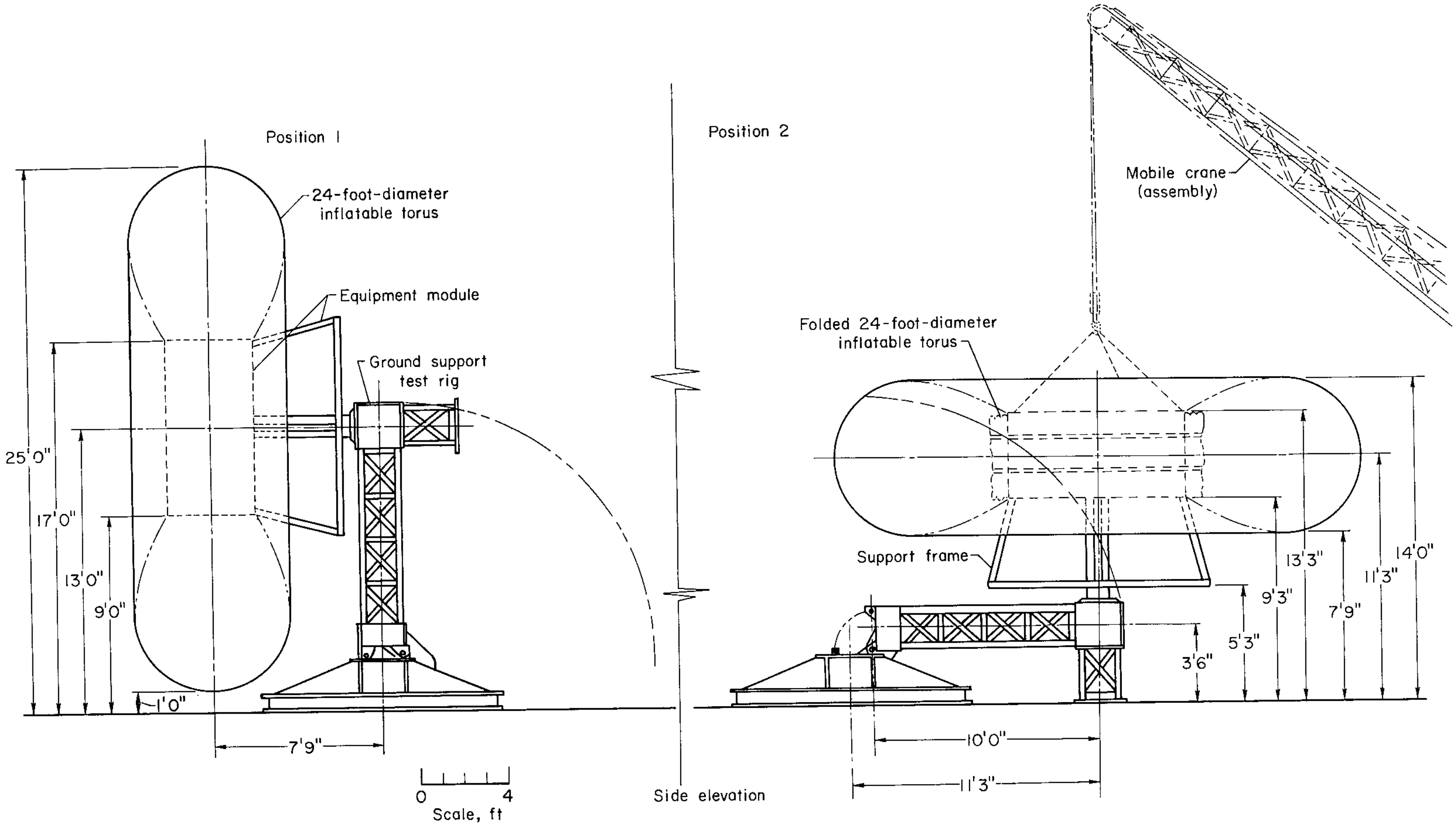
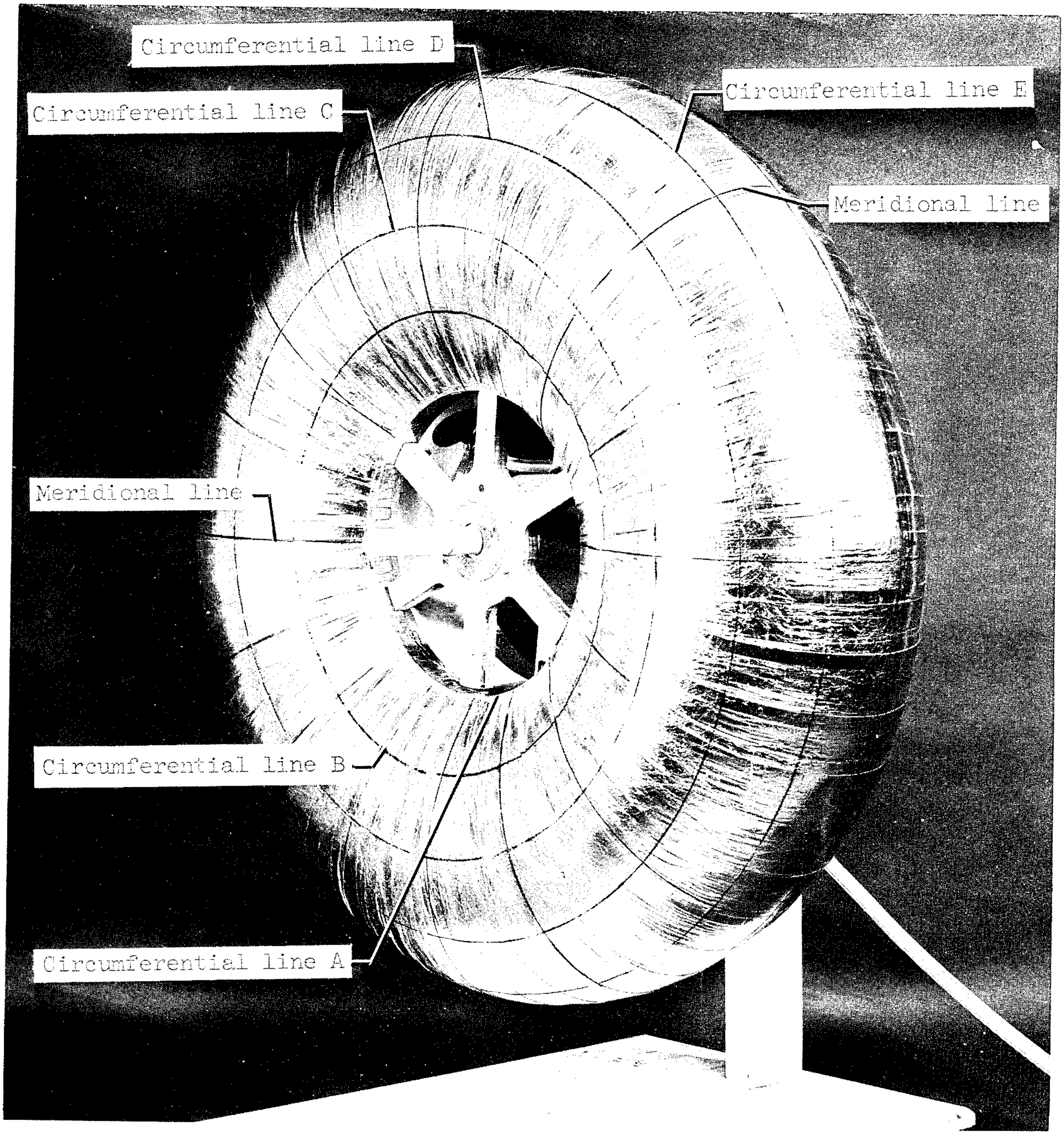
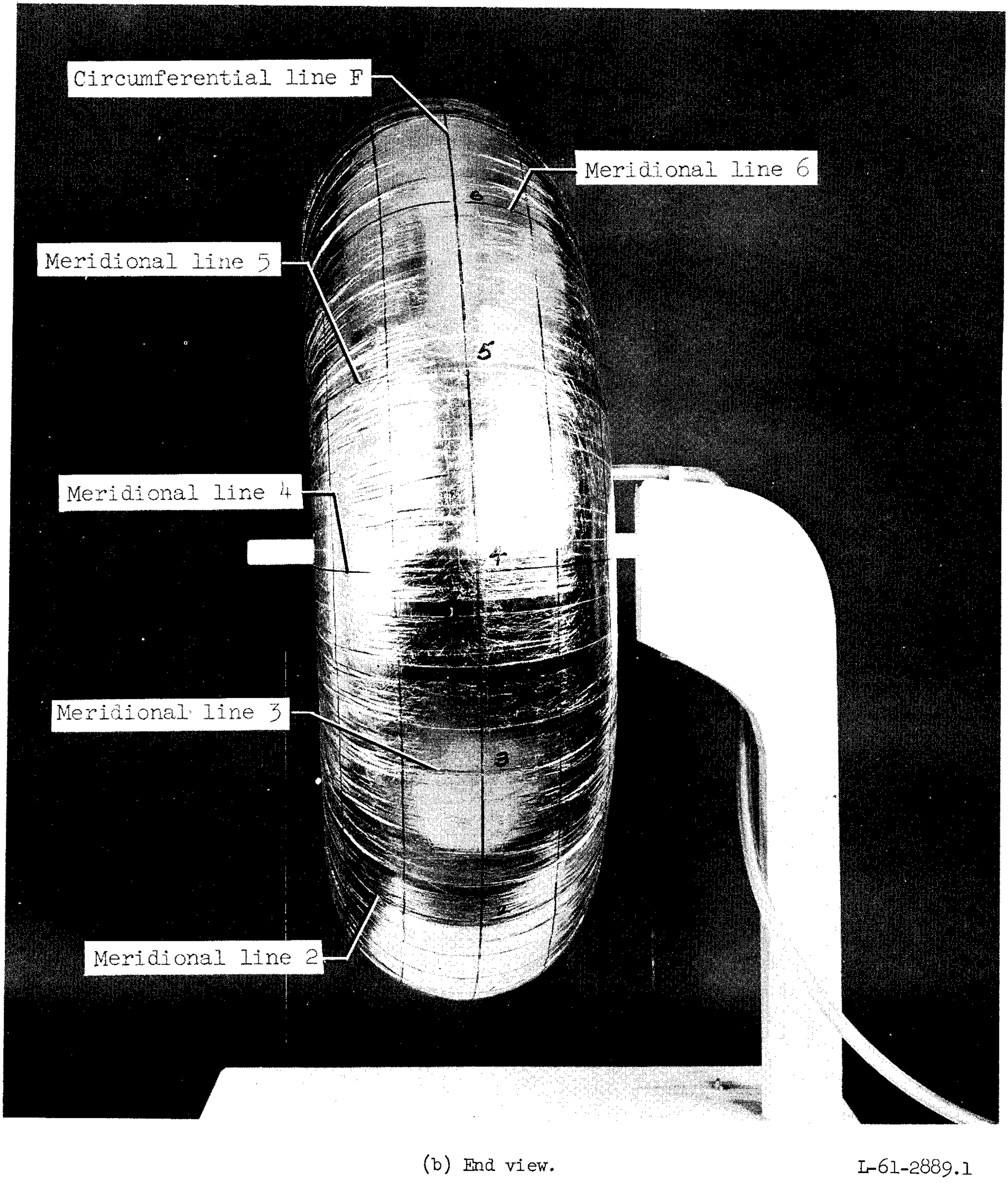


Figure 6.- Support equipment configuration for the 24-foot-diameter torus.



(a) Front view. L-61-2890.1

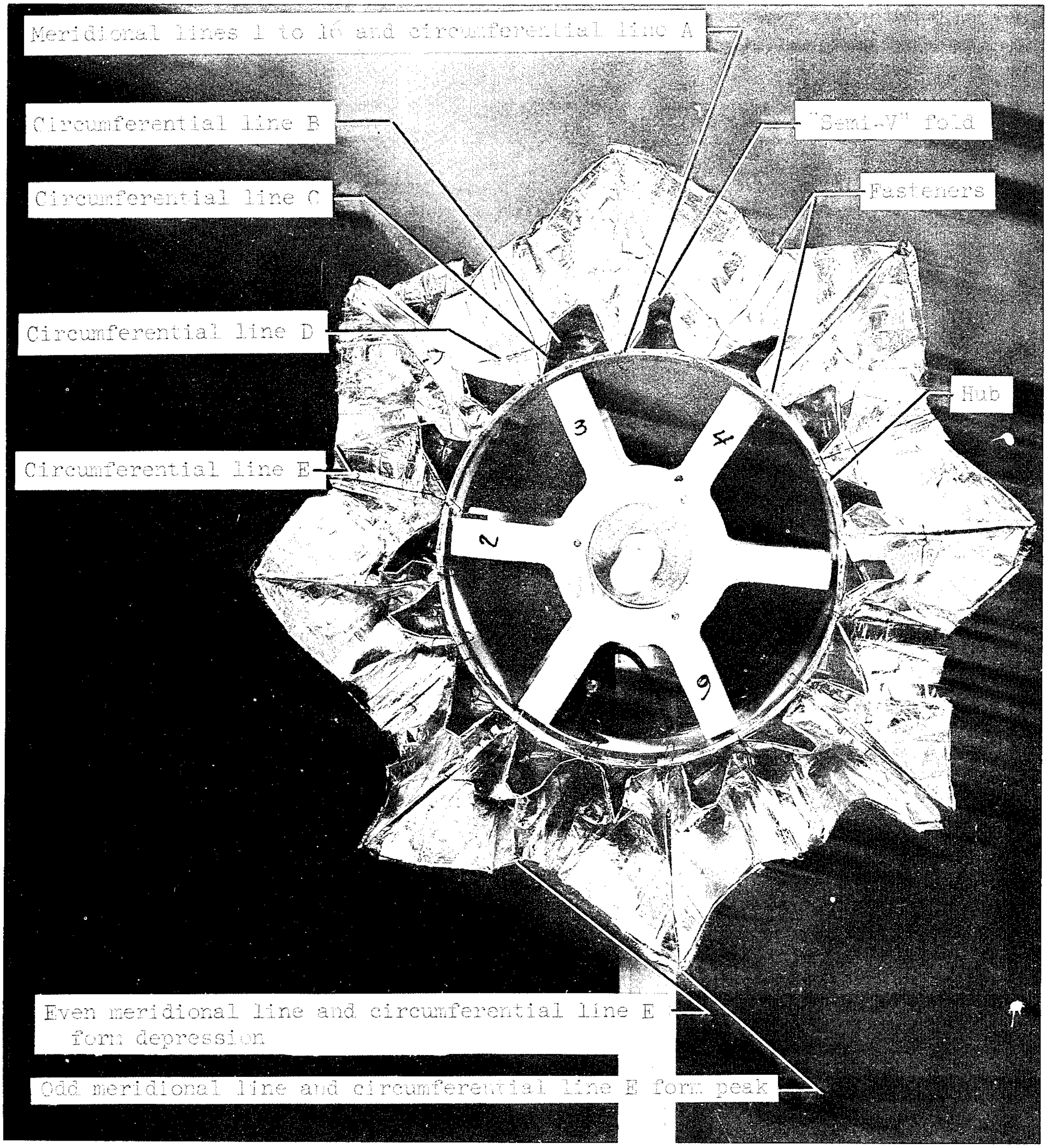
Figure 7.- 1/8-scale model showing fold markings.



(b) End view.

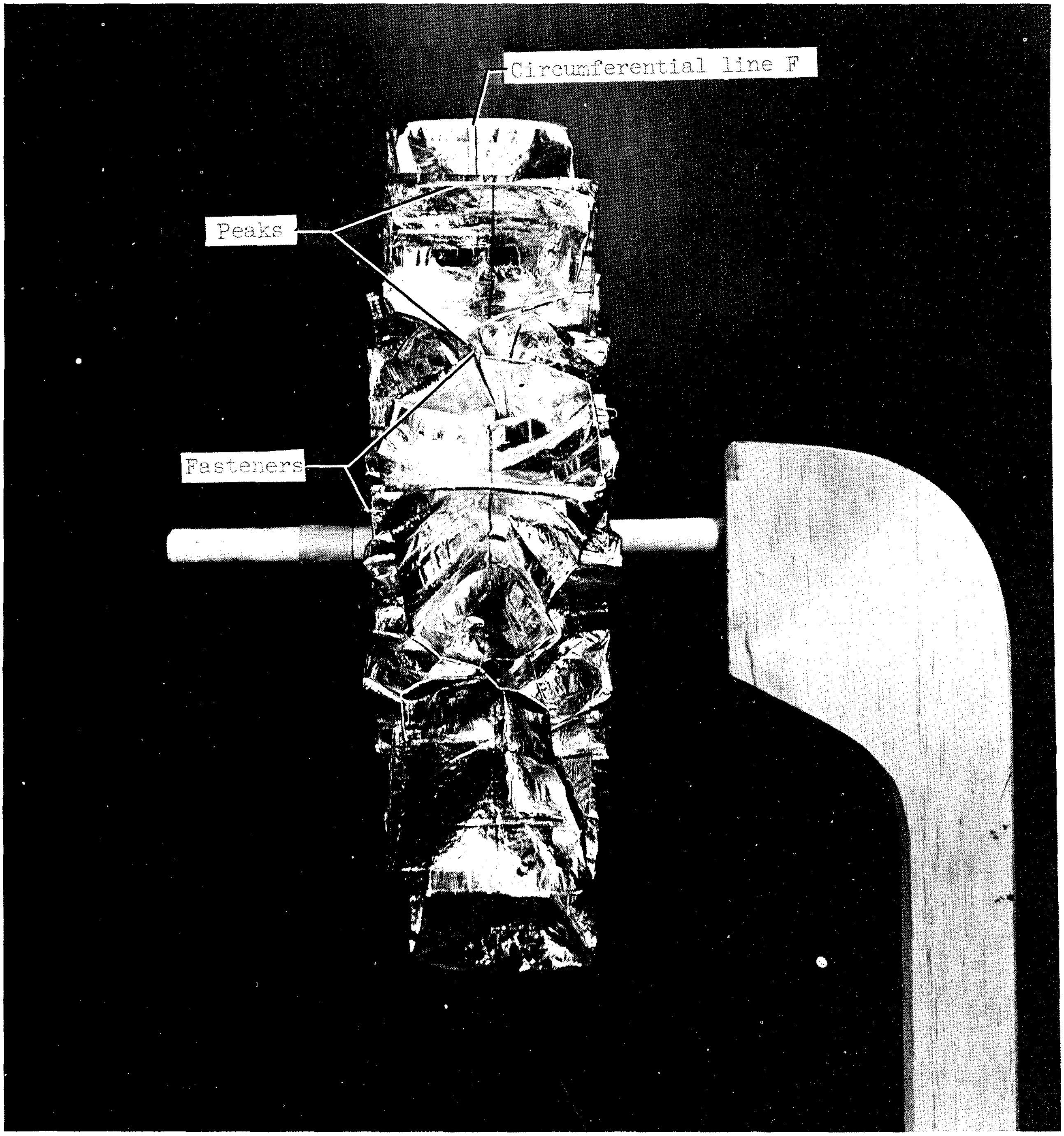
L-61-2889.1

Figure 7.- Concluded.



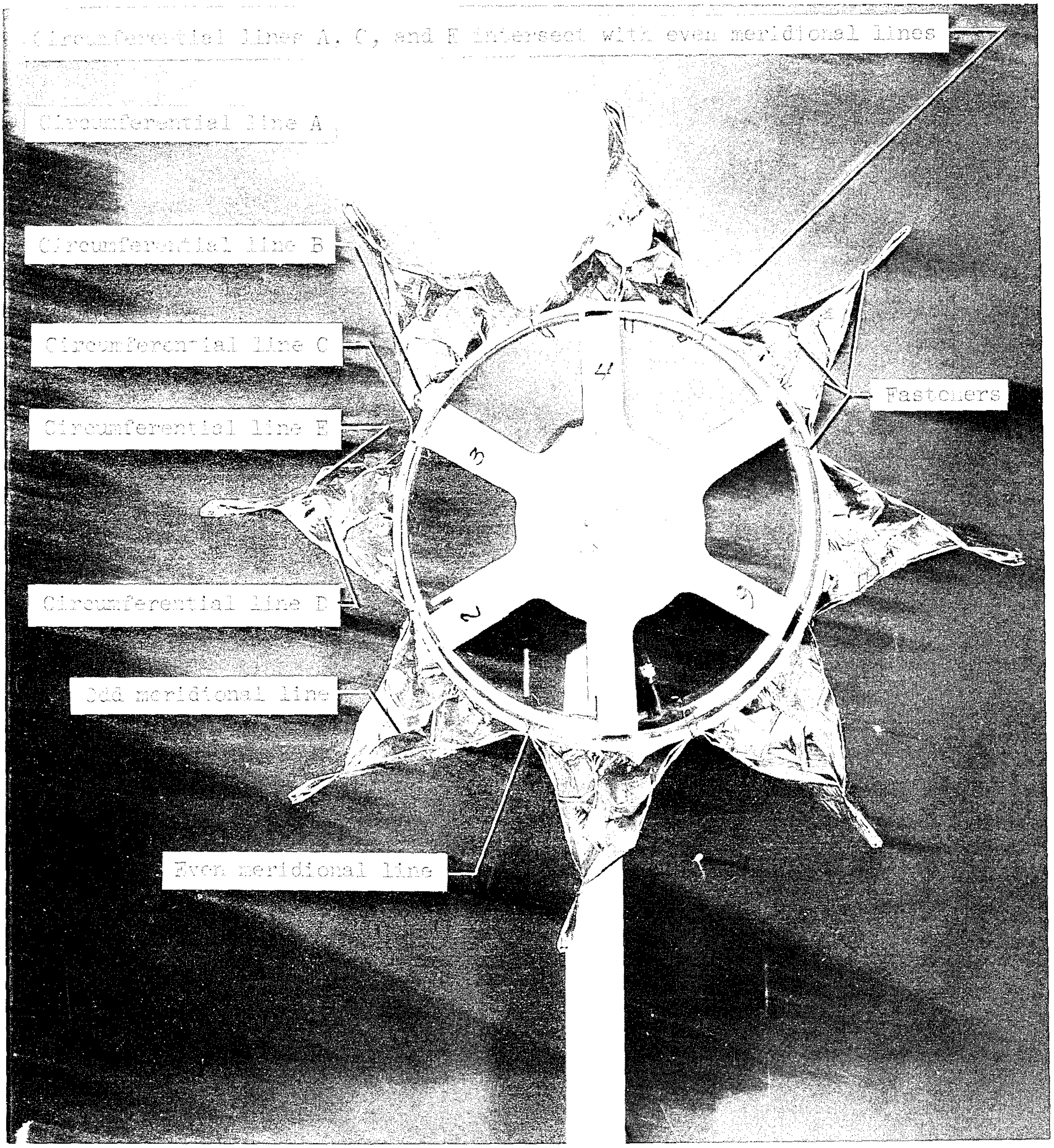
(a) Front view. L-61-2846.1

Figure 8.- Step 2 in folding procedure with 1/8-scale model.



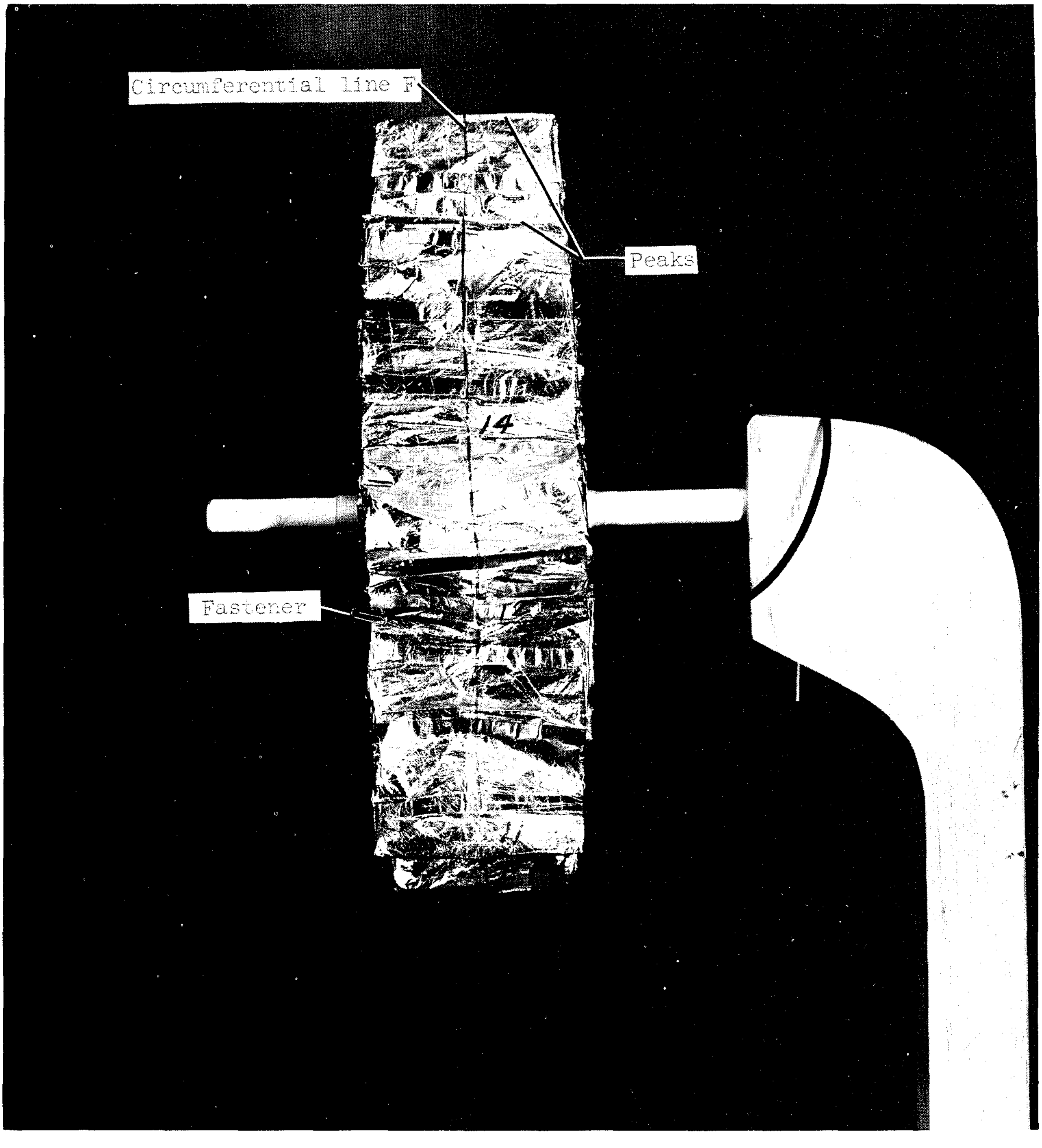
(b) End view. L-61-2845.1

Figure 8.- Concluded.



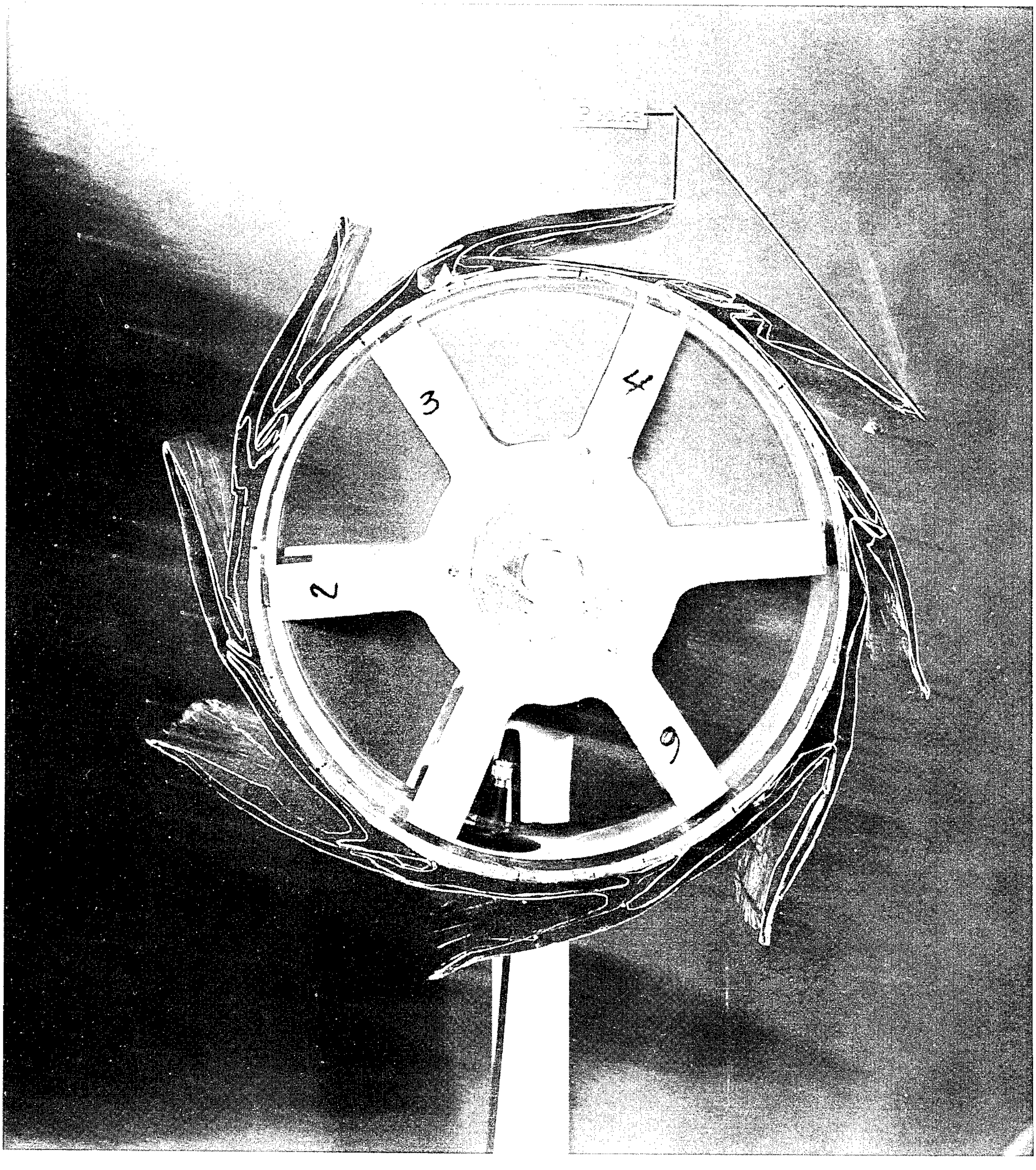
(a) Front view. L-61-2847.1

Figure 9.- Step 3 in folding procedure with 1/8-scale model.



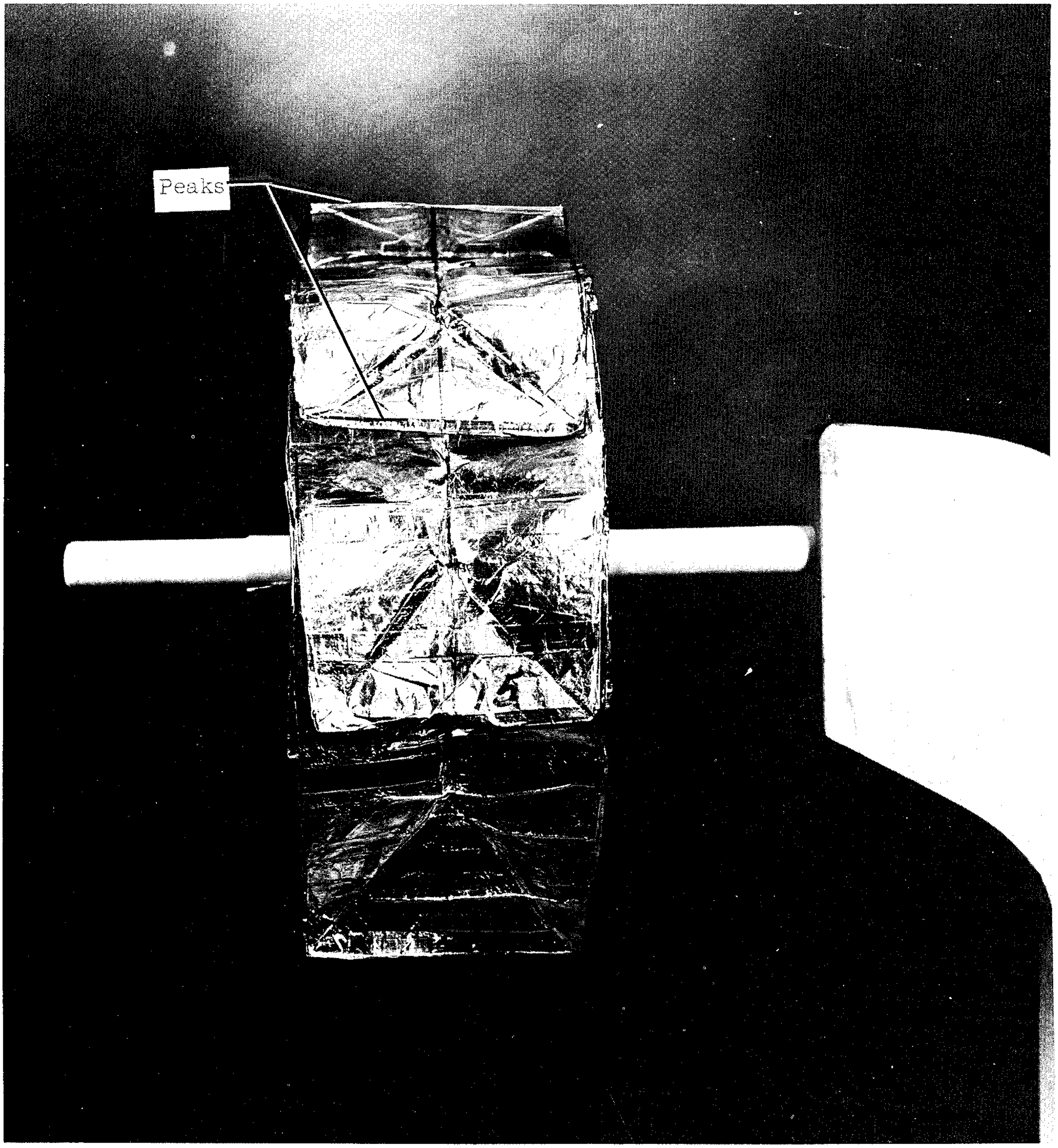
(b) End view. L-61-2850.1

Figure 9.- Concluded.



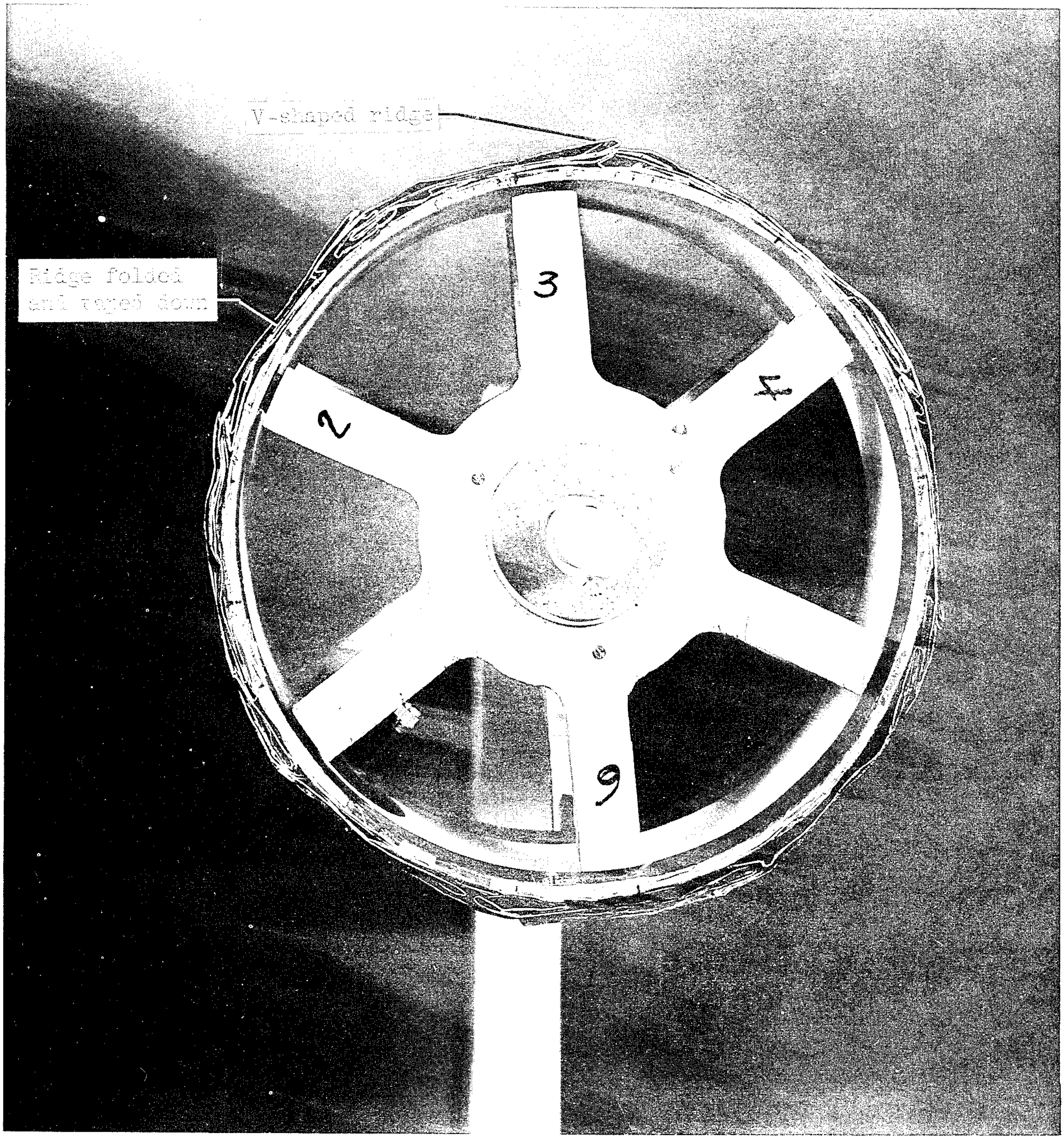
(a) Front view. L-61-2849.1

Figure 10.- Step 4 in folding procedure with 1/8-scale model, showing eight peaks folded clockwise.



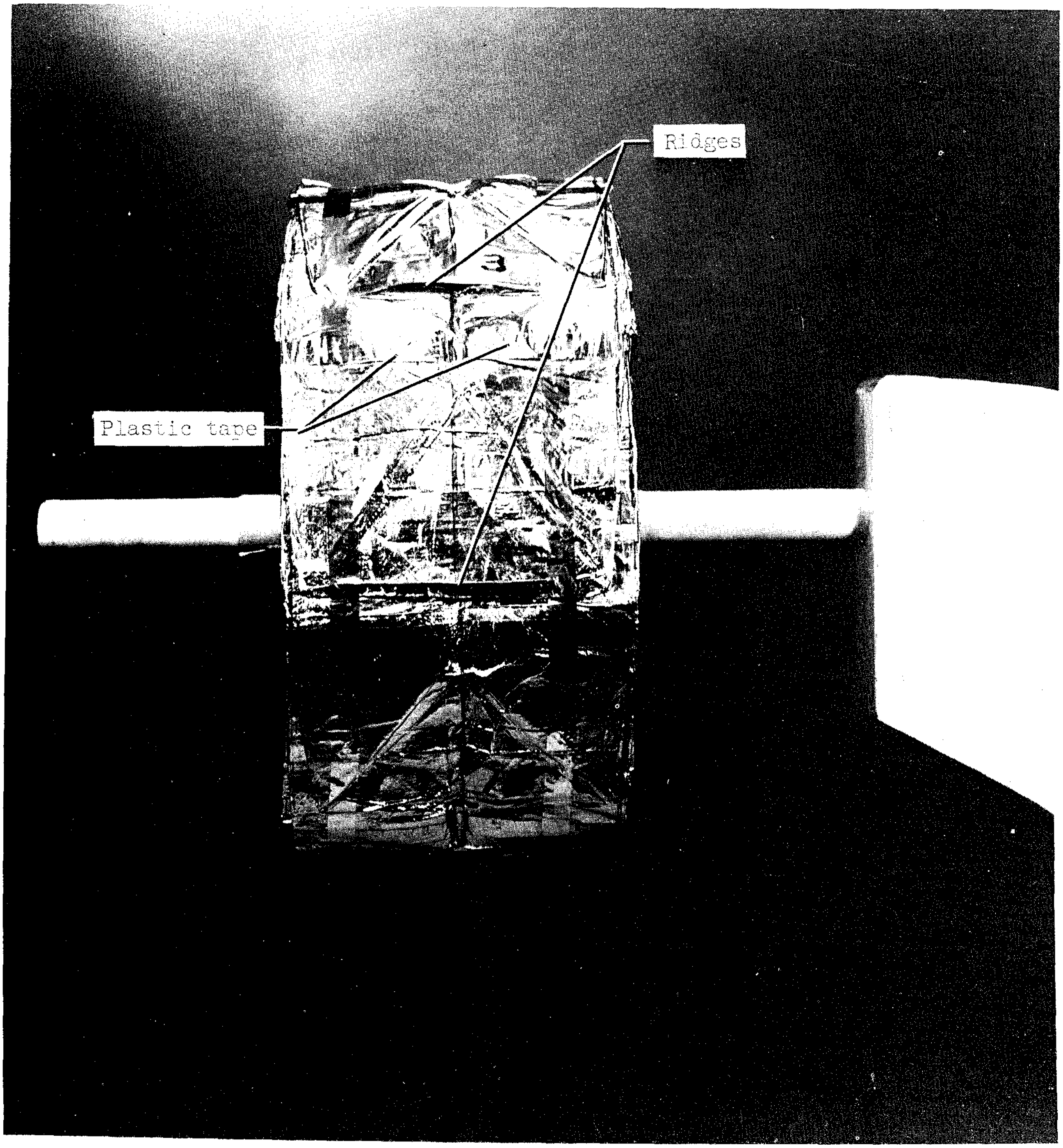
(b) End view. L-61-2848.1

Figure 10.- Concluded.



(a) Front view. L-61-2851.1

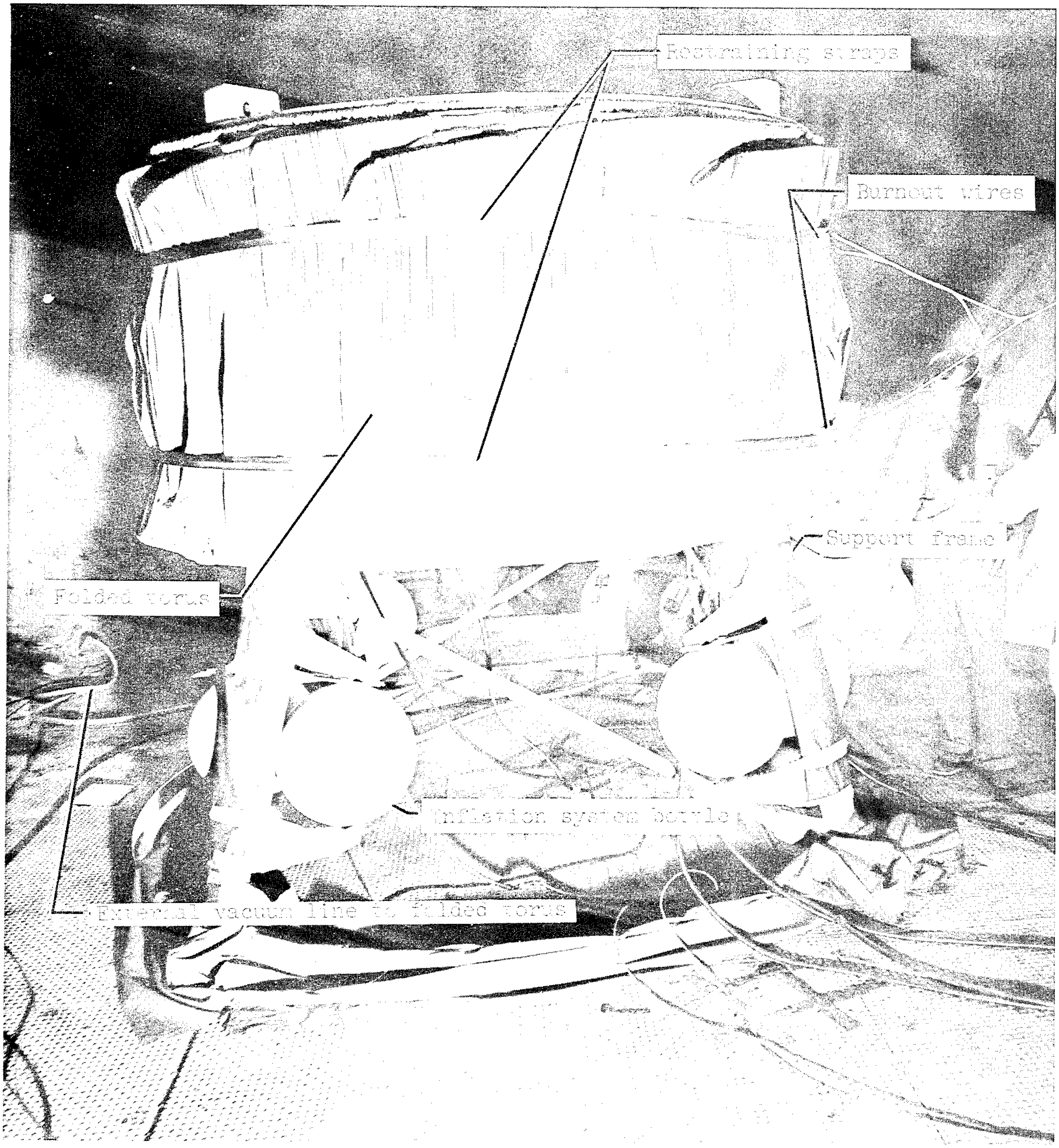
Figure 11.- Final folded configuration of 1/8-scale model.



(b) End view.

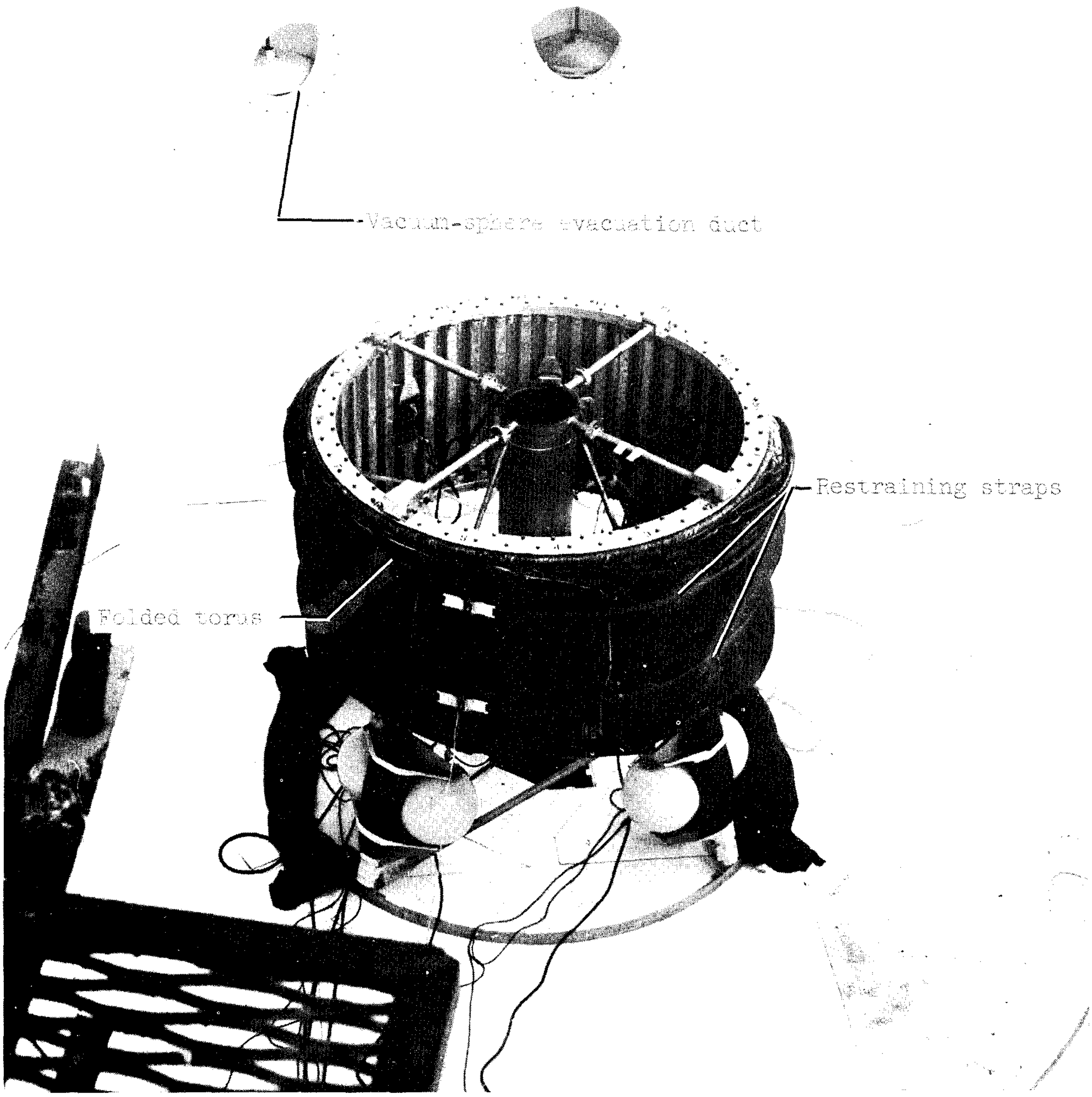
L-61-2852.1

Figure 11.- Concluded.



L-62-5207.1

Figure 12.- Folded 24-foot-diameter torus mounted in the 60-foot-diameter vacuum sphere at the Langley Research Center.



L-62-5811.1

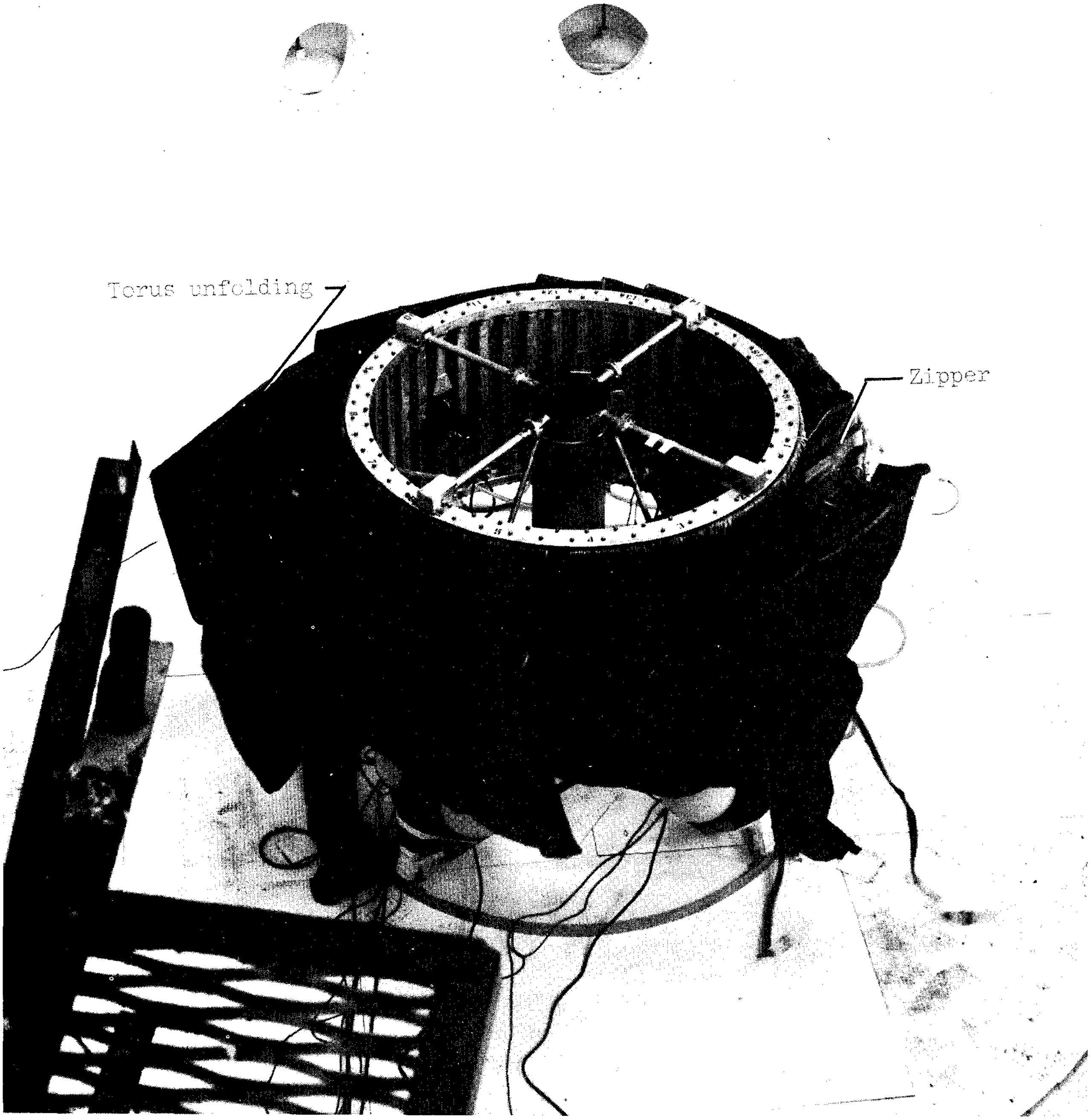
(a) Torus during vacuum-sphere pump down. T-5 sec; torus internal pressure, 2.90 mm Hg; vacuum-sphere pressure, 1.015 mm Hg.

Figure 13.- 24-foot-diameter torus during vacuum-sphere tests.

L-62-5812.1

(b) Torus at instant of restraining straps release. T-3 sec; torus internal pressure, 2.95 mm Hg; vacuum-sphere pressure, 1.011 mm Hg.

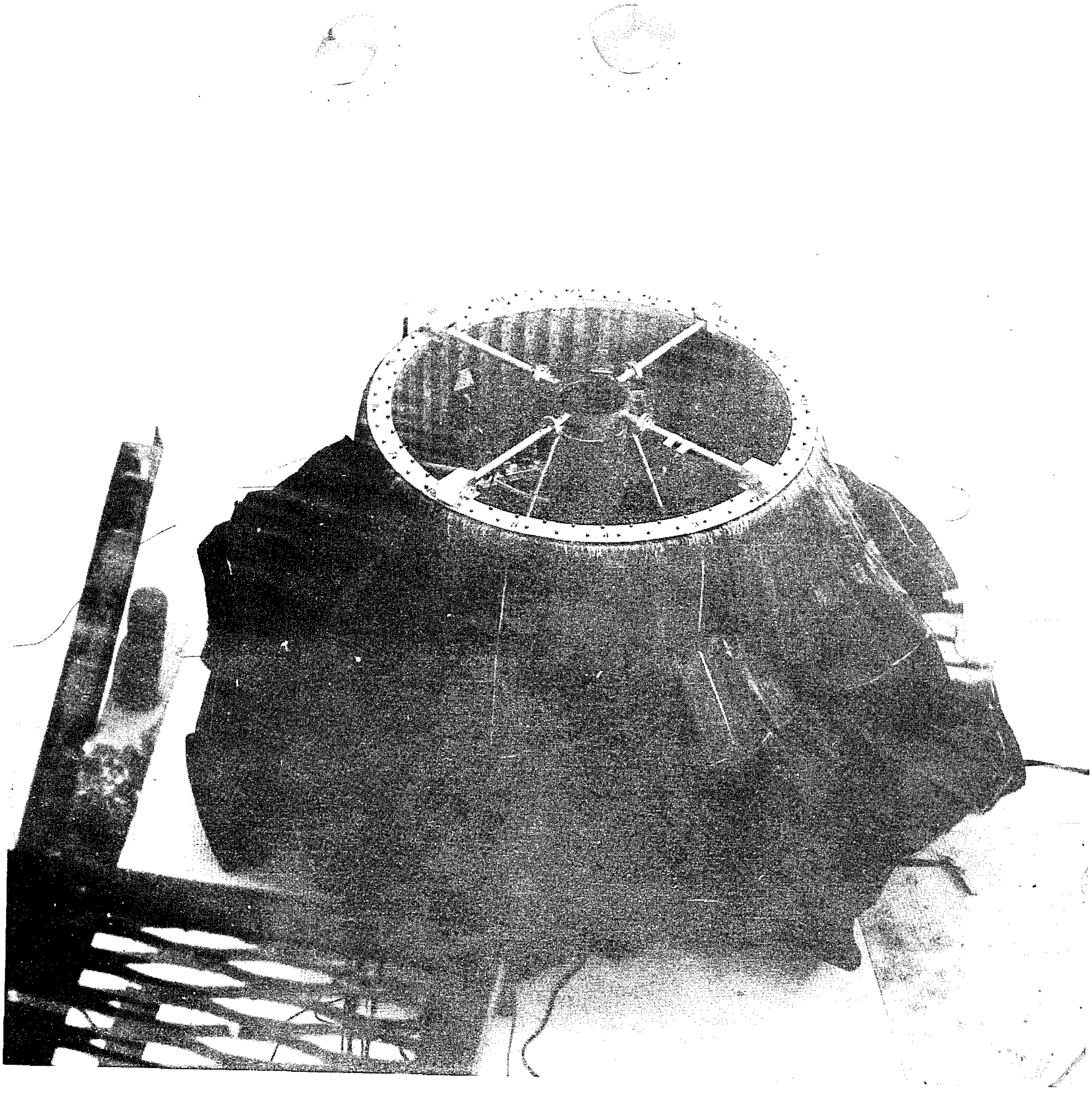
Figure 13.- Continued.



L-62-5813.1

(c) Torus unfolding. T-2 sec; torus internal pressure, 1.19 mm Hg; vacuum-sphere pressure, 1.010 mm Hg.

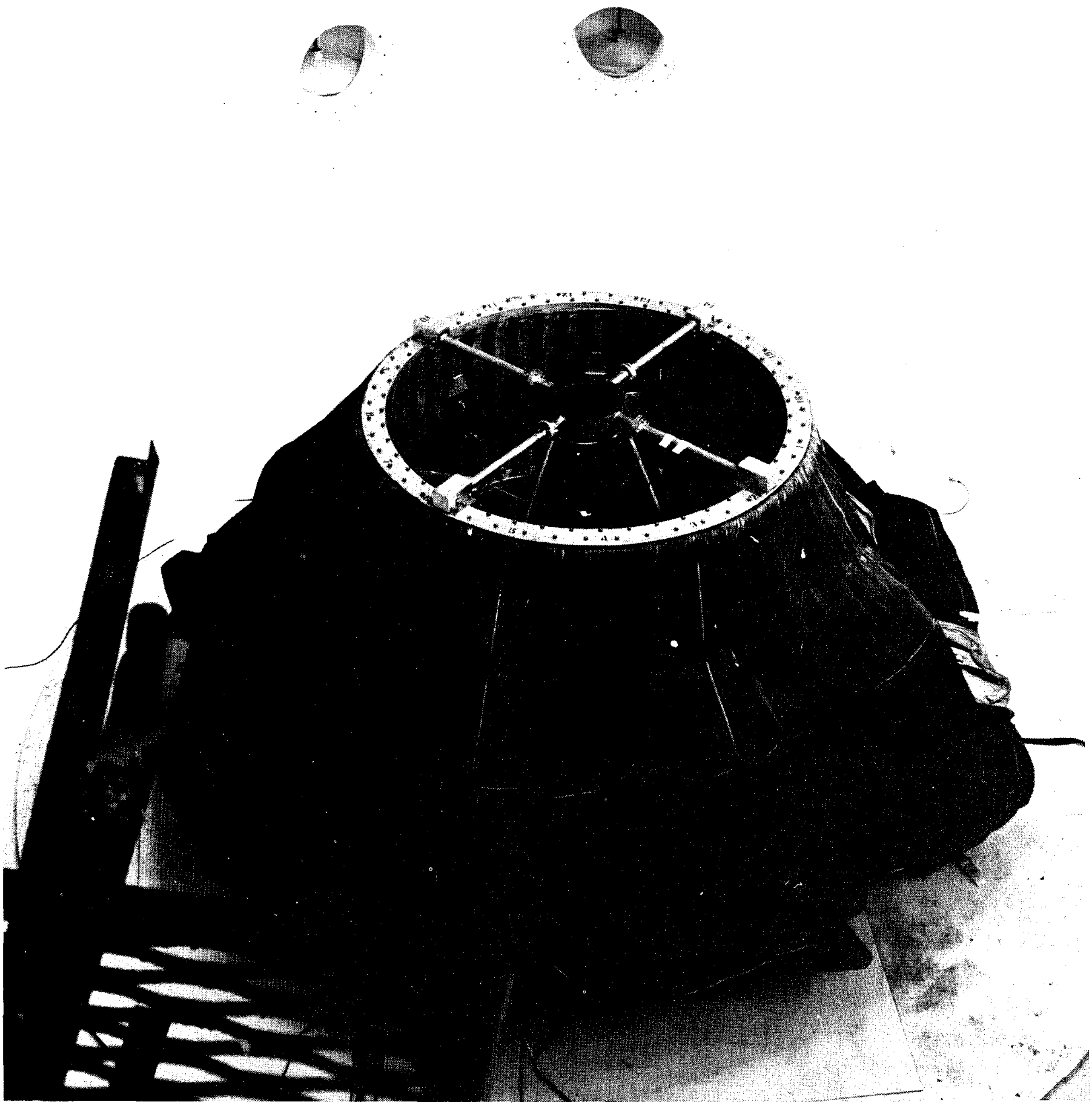
Figure 13.- Continued.



L-62-5814

(d) Torus in unfolded state before energizing of inflation system. T-0 sec; torus internal pressure, 1.35 mm Hg; vacuum-sphere pressure, 1.000 mm Hg.

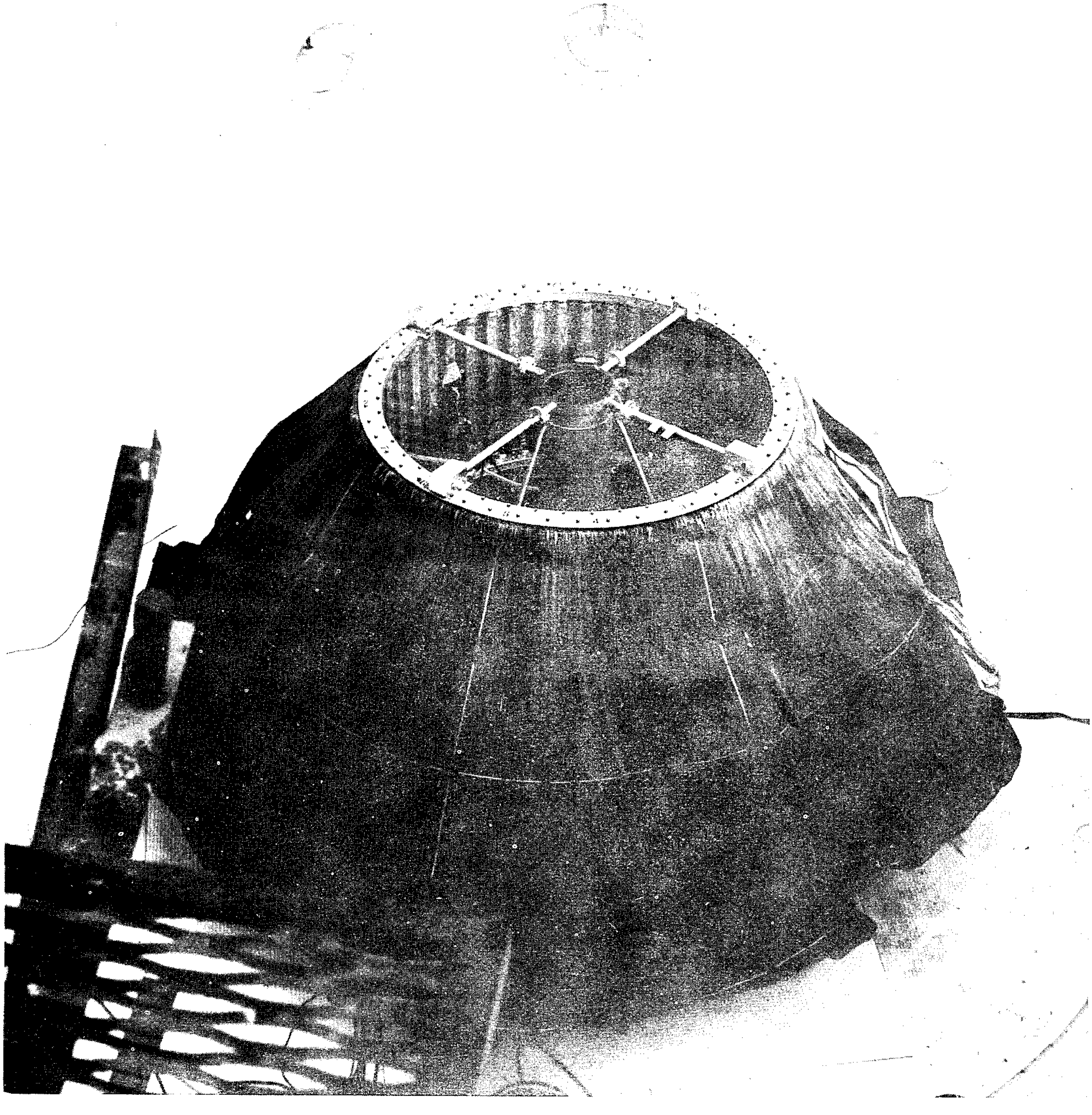
Figure 13.- Continued.



L-62-5815

(e) Torus immediately after energizing of inflation system. T+20 sec; torus internal pressure, 1.58 mm Hg; vacuum-sphere pressure, 0.985 mm Hg.

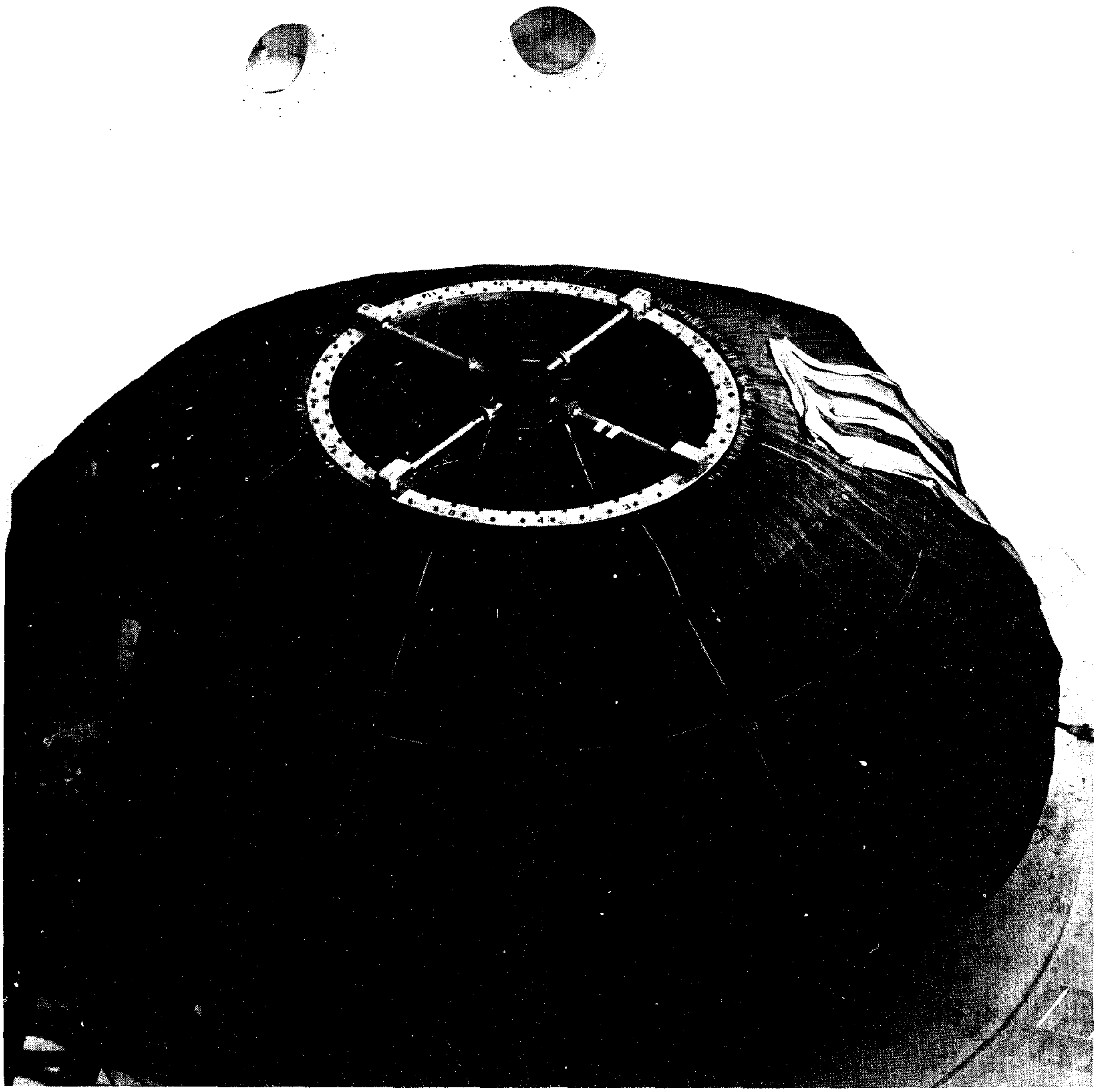
Figure 13.- Continued.



L-62-5816

(f) Torus beginning to fill with inflation gas. T+30 sec; torus internal pressure, 1.65 mm Hg; vacuum-sphere pressure, 1.000 mm Hg.

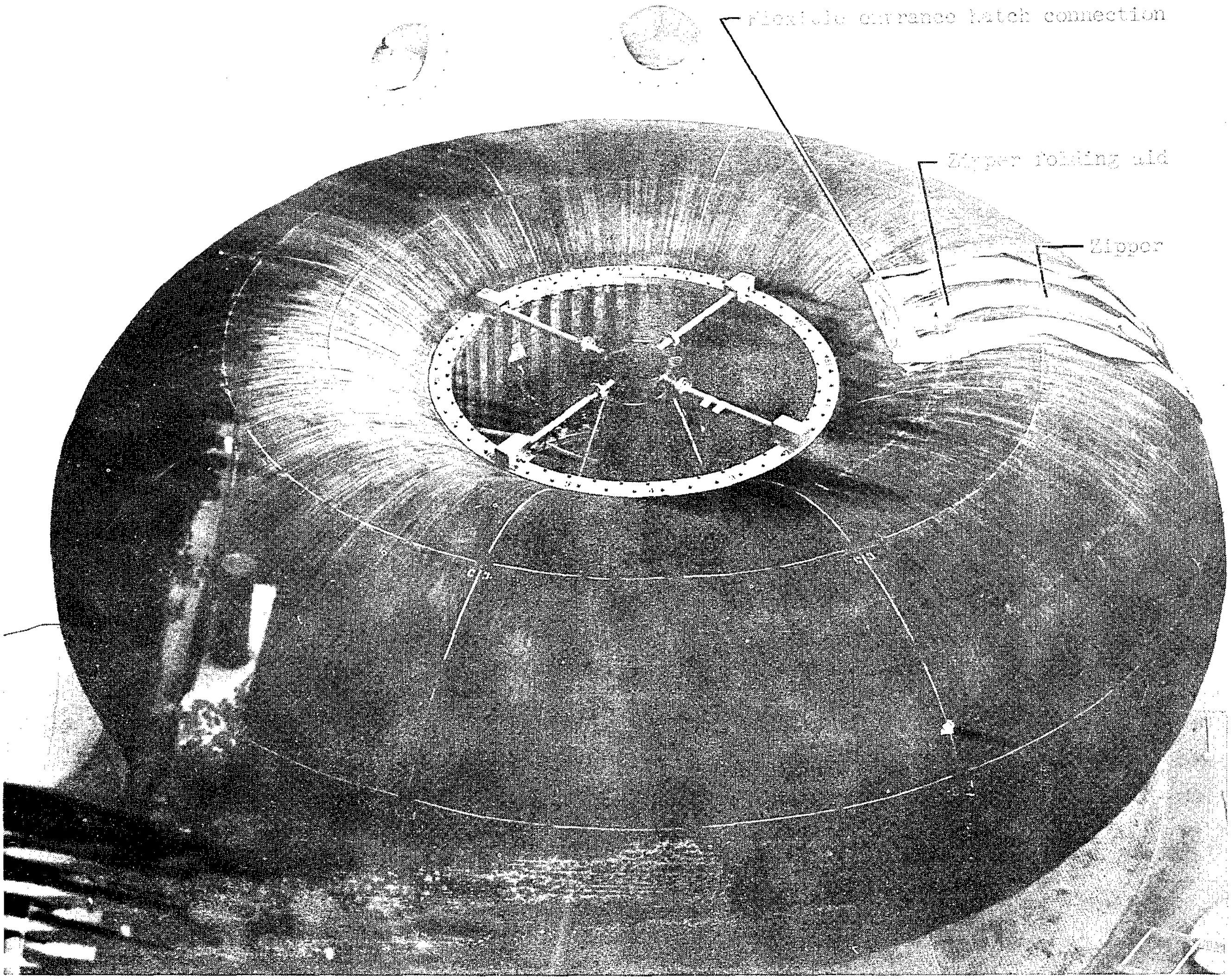
Figure 13.- Continued.



L-62-5817

(g) Torus assuming approximately final unfolded configuration after completion of shaping by inflation gas. T+62 sec; torus internal pressure, 13.00 mm Hg; vacuum-sphere pressure, 1.118 mm Hg.

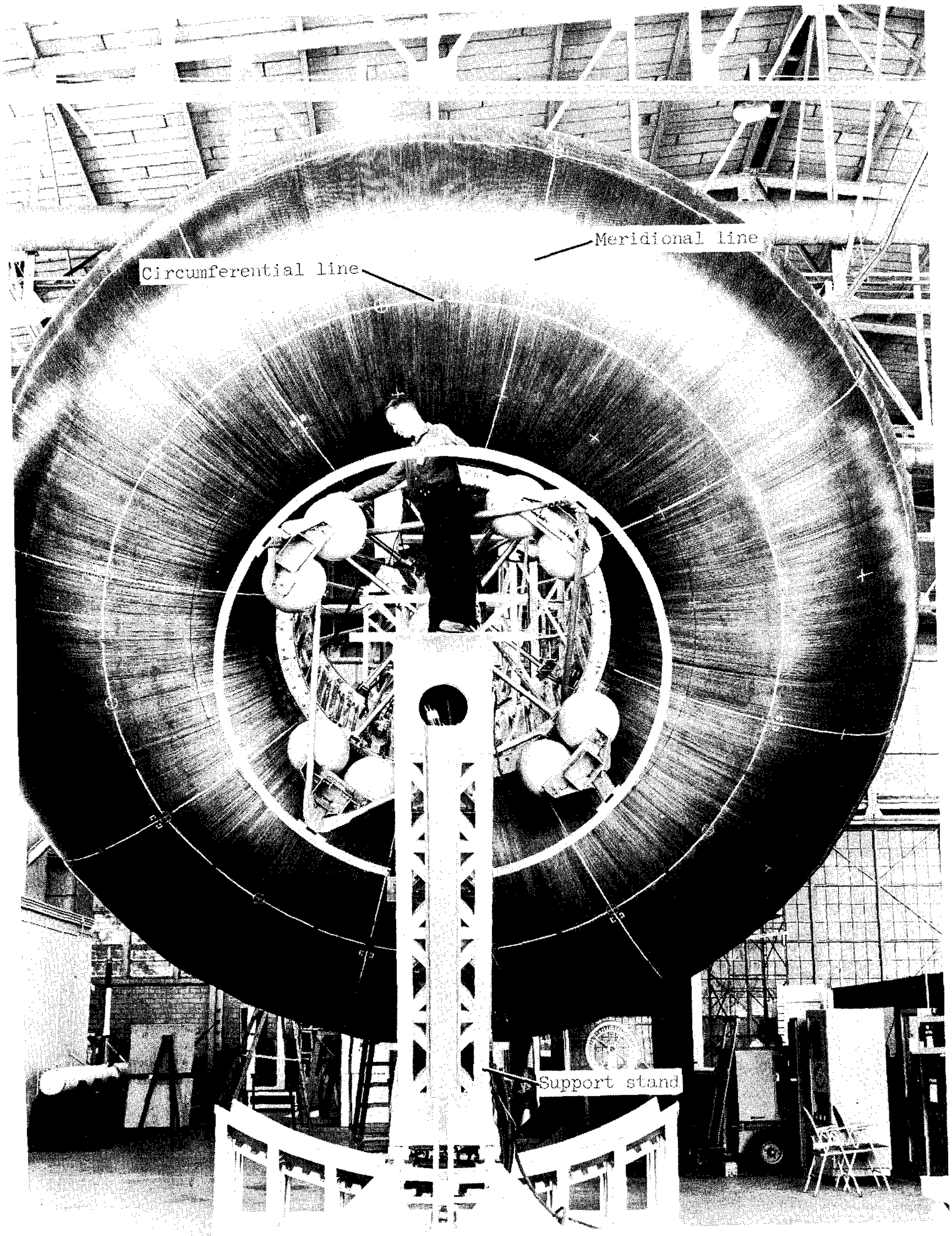
Figure 13.- Continued.



(h) Final inflated torus configuration.

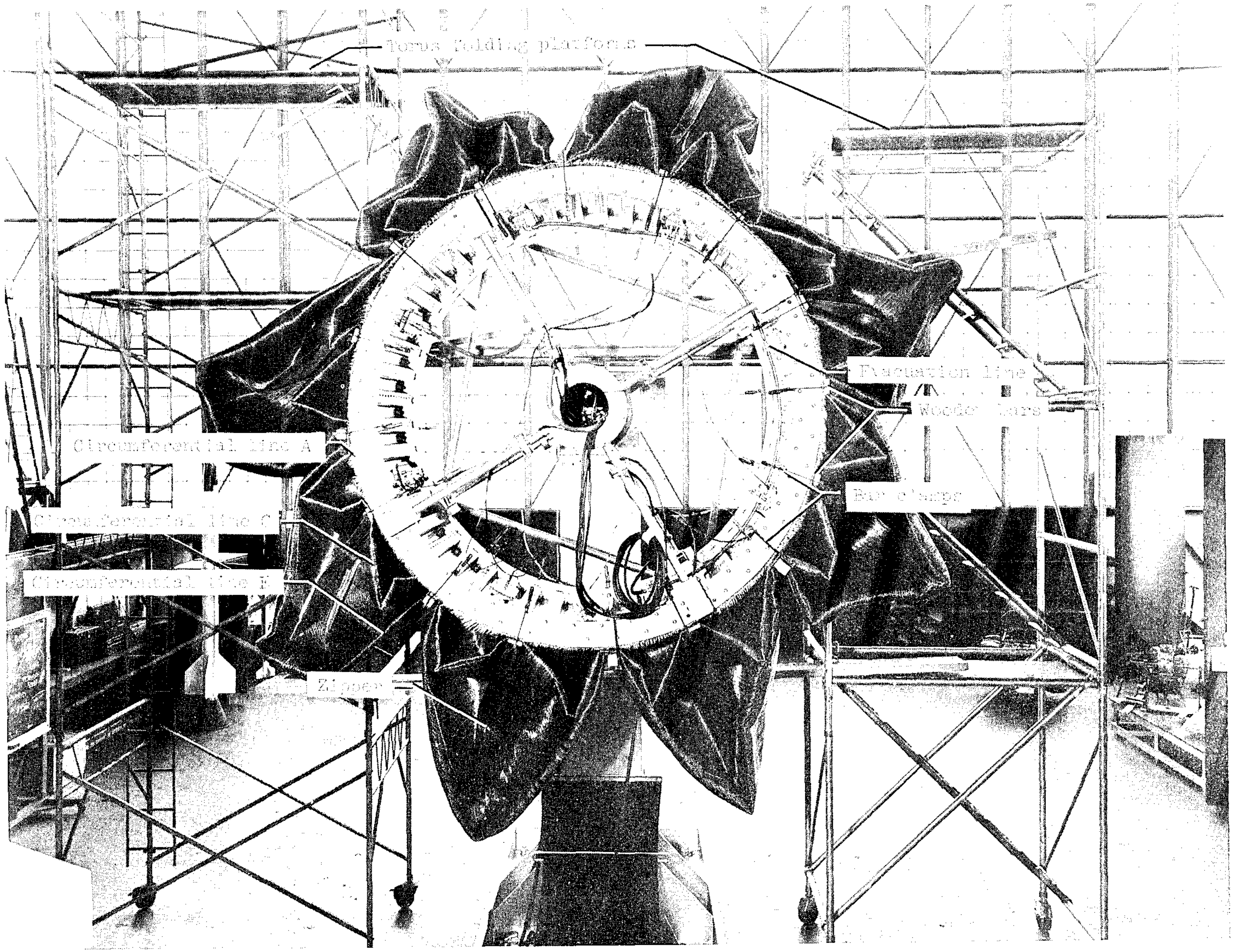
L-62-5818.1

Figure 13.- Concluded.



(a) Fully inflated configuration. L-62-3430.1

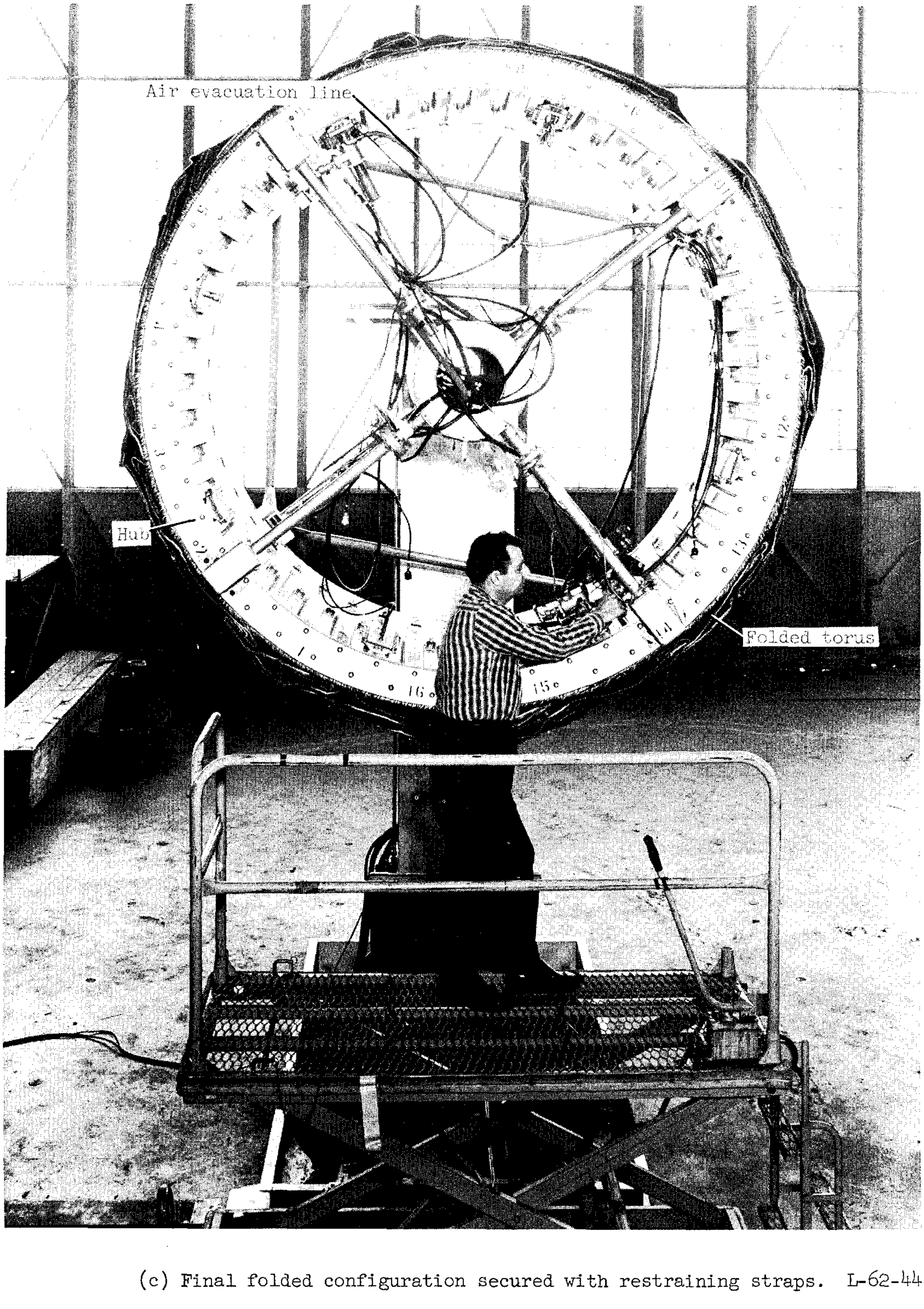
Figure 14.- 24-foot-diameter torus during folding process.



(b) Step 2 in folding process.

L-61-8029.1

Figure 14.- Continued.



(c) Final folded configuration secured with restraining straps. L-62-447.1

Figure 14.- Concluded.

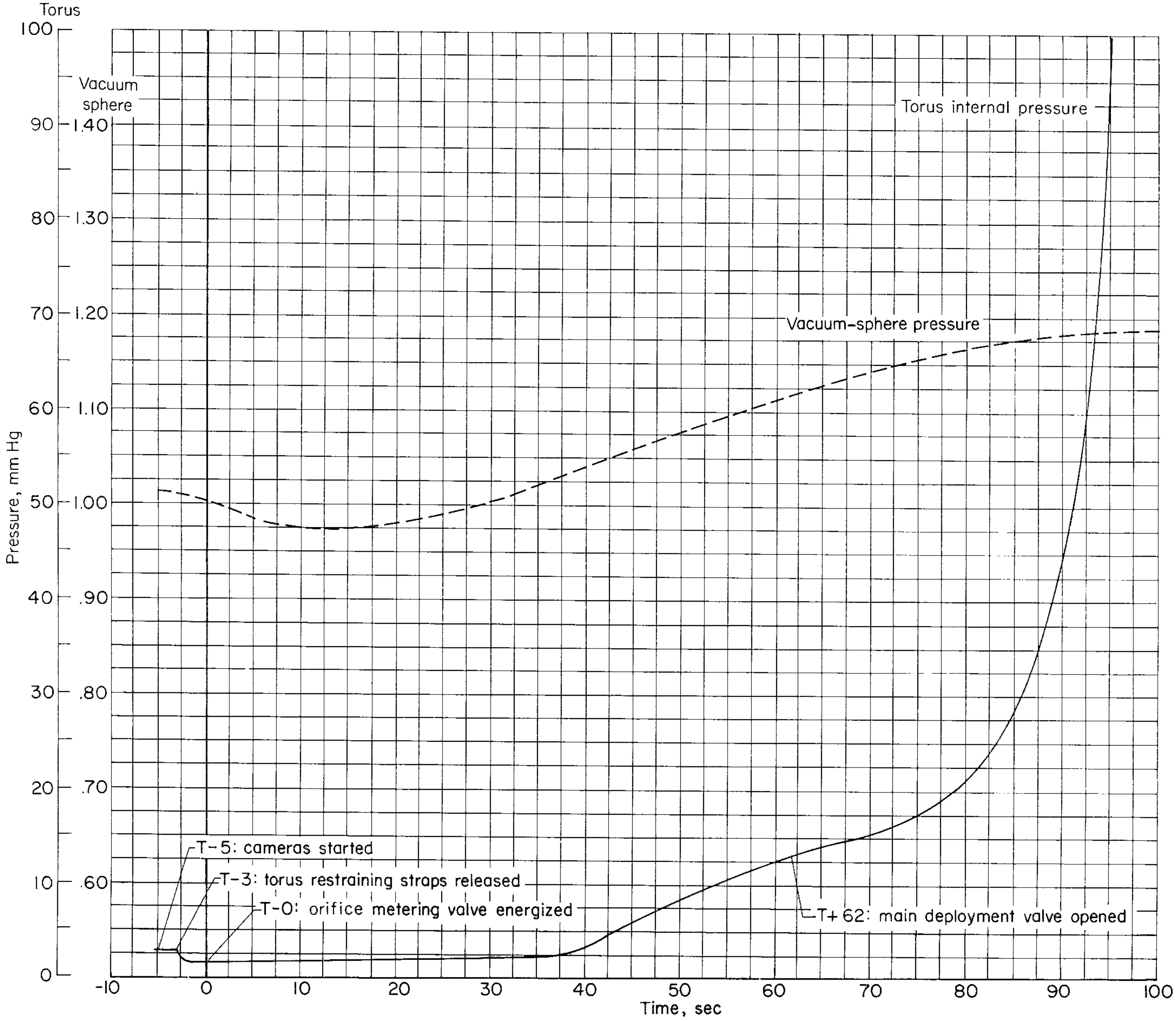
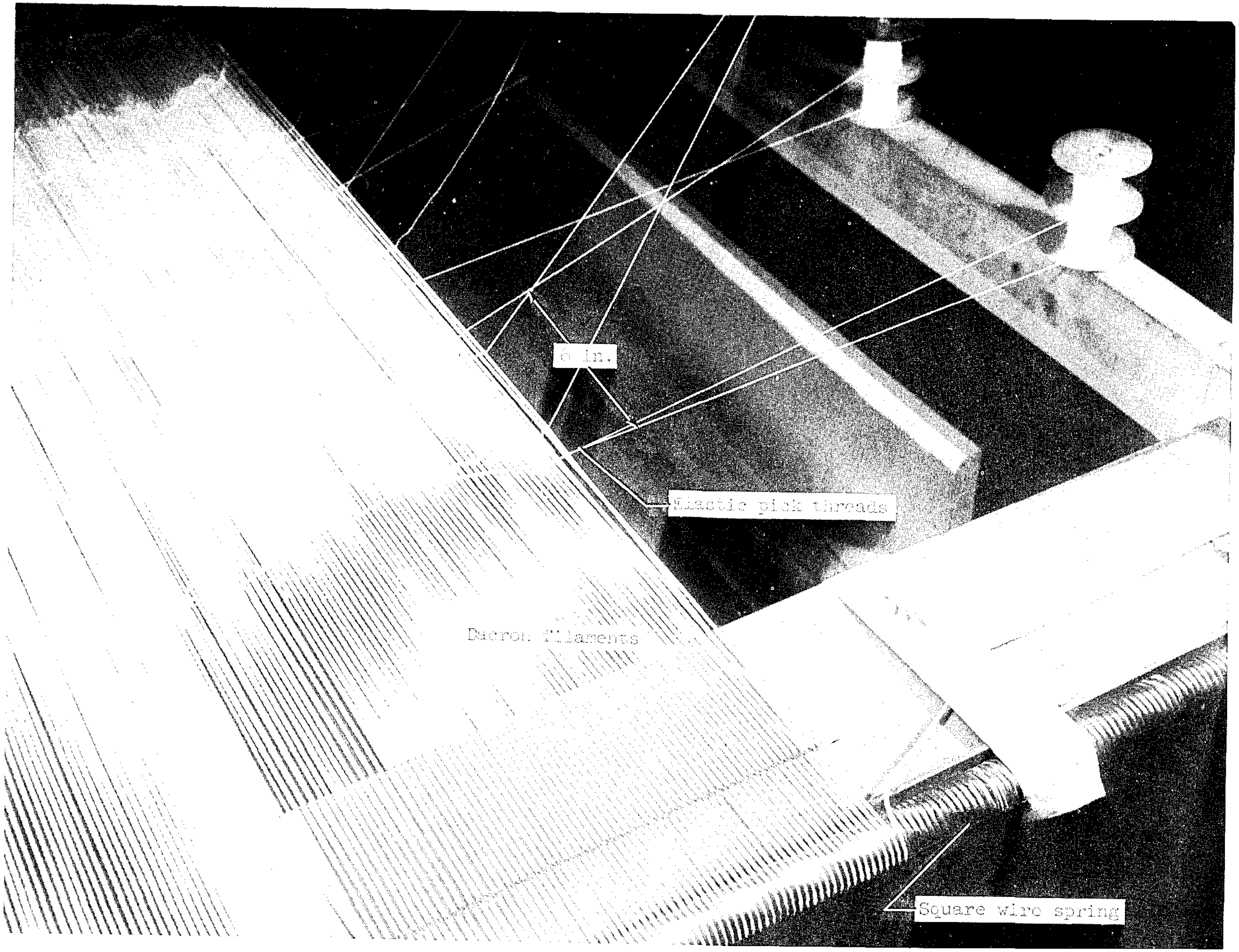


Figure 15.- Pressure time histories for 24-foot-diameter torus and 60-foot-diameter vacuum sphere.

(a) Final filament-cage construction. L-65-3

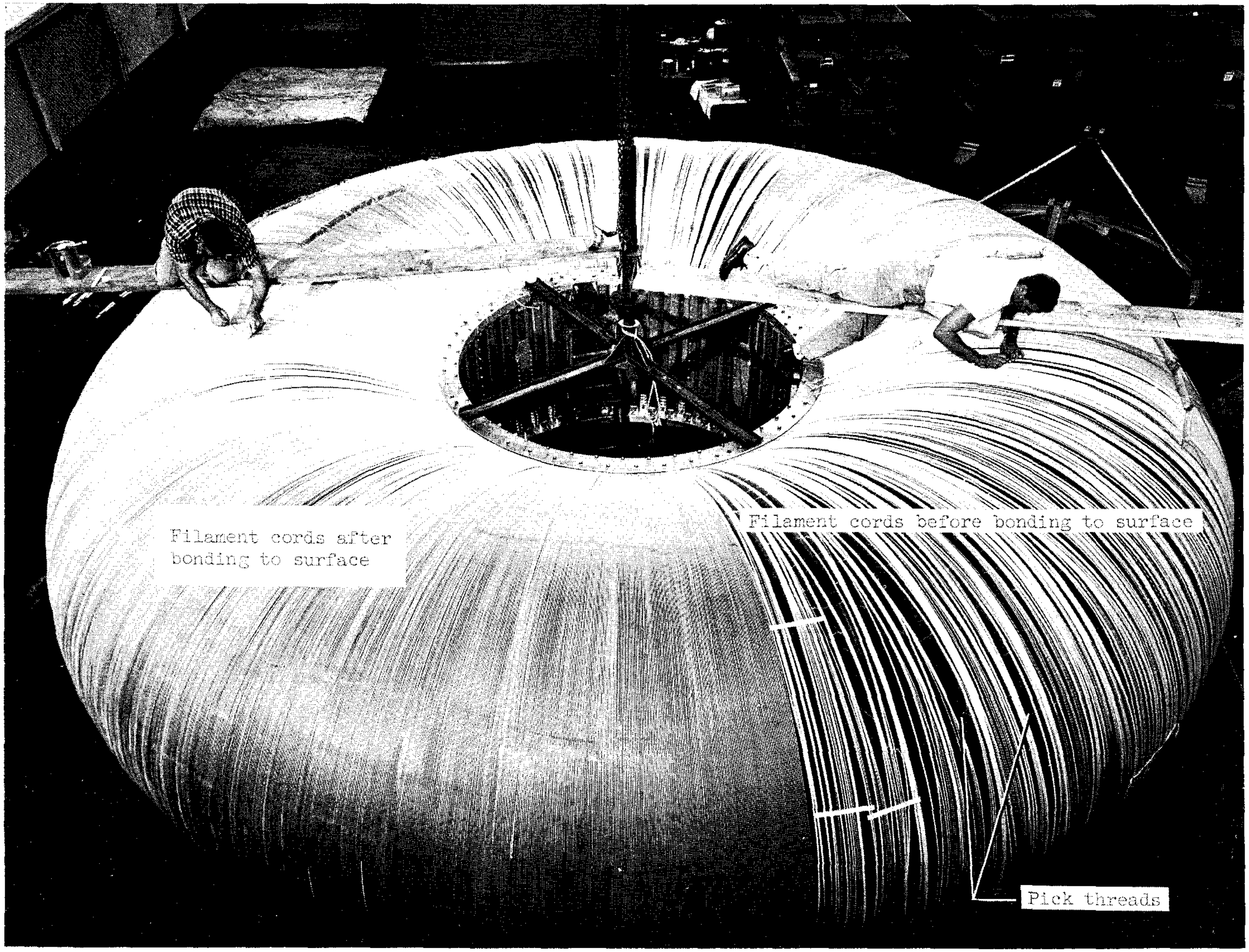
Figure 16.- Filament-cage construction and assembly for 24-foot-diameter torus.



(b) Filament-cage fabrication.

L-65-4

Figure 16.- Continued.



(c) Filament cage assembled with 24-foot-diameter torus bladder. L-65-5

Figure 16.- Concluded.

NASA-Langley, 1965 L-3960