SESSION V

DEVELOPMENT OF AN EXPANDABLE AIRLOCK UTILIZING THE ELASTIC RECOVERY PRINCIPLE

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INTRODUCTION

Recent studies of expandable structures have been centered around several manned space mission applications. Some of these applications as shown in figure 1 include: lunar shelters, space hangar, access tunnels, and expandable airlocks. The purpose of this paper is to discuss research on the latter application, namely, the expandable airlock.

The basic function of an airlock in a space vehicle is to permit crew and cargo transfer between the pressurized space vehicle and the vacuum of space. The principal advantages of a flexible expandable airlock as opposed to rigid internal concepts are reduced weight and increased useable volume. An expandable airlock is lightweight since it is constructed of high-strength filaments or fibers in an isotensoid design. Deployment in a favorable pressure differential (usually a vacuum) allows the airlock to be designed for internal pressure loads only. The absence of the requirement for resisting external loads is thus another weight reduction factor. An expandable airlock provides increased useable spacecraft volume because it is deployed external to the space vehicle when required and is compactly packaged during the launch phase of the mission, or when its extension would adversely affect extravehicular operations or experiments. Rigid internal airlock concepts, on the other hand, sacrifice valuable internal volume. If the airlock must be used internally, however, the expandable airlock has the advantage of being able to be stored in a minimum volume and erected only when actually needed.

Expandable airlock applications for advanced space station concepts such as the proposed MORL are shown in figure 2. Airlock A is an external airlock application which could be packaged in a recessed port in the wall of the space station during launch and later externally deployed as required. This airlock could be retracted, if necessary, either to meet operational requirements or to better protect the airlock. This airlock requires a protective wall system to make it compatible with the space vacuum, thermal, micrometeoroid, and radiation environment. A flexible transparent composite wall material located at eye level in the expanded airlock could serve as a viewing station for external experiments, thus reducing extravehicular activity.

Airlock B is what might be classified as an internal expandable airlock since it is located in the interior of the space station in the experiment and docking hangar compartment. The airlock is not exposed directly to the space environment and thus does not require the environmental protective wall required for external application (airlock A). Here again a flexible transparent window section in the airlock would permit direct viewing of experiments in the unpressurized hangar compartment without space exposure of the astronaut. The airlock would be collapsed for storage when not in use.

The access tunnel shown connected to the resupply or crew ferry spacecraft would be an expandable structure similar in design to the expandable airlock. The tunnel would provide direct transfer from the space station living compartment to the stored ferry vehicle, either as the primary supply or astronaut transfer tunnel, or as an emergency escape tunnel. Its flexible and expandable characteristics would provide easy alinement. It is, of course, exposed to the space environment and would require a protective wall system.

EXPANDABLE AIRLOCK COMPONENTS

An expandable airlock is basically composed of three-component systems: (1) structural pressure vessel, (2) environmental protective wall, and (3) a deployment system. The structural pressure vessel is that part of the airlock wall which resists the applied pressure loads. It includes both the structural wall and end enclosures. It must be impervious to leakage and for most flexible composite materials requires the use of a bladder. The optimum design of a filamentary structure requires isotensoid fiber orientation, i.e., the fibers lie along geodesic paths and transfer loads in tension only. In the case of a structure that folds, the fibers must retain the designed orientation in the expanded configuration. A matrix is usually required to perform this function.

The environmental protective wall is that part of the airlock which shields and protects the airlock's integrity against the environmental hazards of space. It includes micrometeoroid protection, radiation shielding, and a thermal insulating wall and surface coating. The desirability or necessity for all or some of this protection is related to the function of the airlock. For example, an internal airlock application does not require micrometeoroid protection; whereas, reliability demands that a parmanent cargo transfer tunnel have this protection. In general, the protection required for the airlock is for airlock materials protection rather than for the protection of the astronaut, since in most transfer operations the astronaut will have his own independent life support and space environment protection system and will be in the airlock for only short periods of time.

The airlock deployment system is that part of the airlock which deploys the airlock from the packaged configuration and stabilizes it in both the pressurized and unpressurized modes of operation. It is important that the airlock remain deployed in the unpressurized mode to insure that the astronaut's movements are not restricted by the airlock's collapsed walls. A reliable deployment system is, of course, essential to the successful operation of any expandable airlock. There are numerous possible systems for performing the deployment operation. Most systems, however, can be classified by one or combinations of the three categories shown in figure 3: (1) air pressurization, (2) mechanical actuation, or (3) elastic recovery.

Air pressurization of the airlock chamber is possibly the simplest method of deployment. It, however, does not provide a stable configuration in the unpressurized mode of operation. A second concept of deployment by air pressurization is pressurization of a spiral annulus located in the airlock wall. A stable configuration is then achieved even for the unpressurized mode. A modification of the spiral annulus is the pressurization of several straight tubes located symmetrically about the airlock circumference.

Mechanical deployment systems include various ingenious concepts. Among these are telescoping tubes which essentially jack the airlock into place, and concentric cylinders which telescope to form the airlock structure. The hemispherical configuration is included to illustrate that expandable airlocks are not necessarily limited to cylindrical configurations. This airlock could be hand deployed and has merit for internal auxiliary, or emergency, airlock application. The success of a mechanical deployment system depends on the successful solution of problems associated with mechanical operations in the space environment. Vacuum welding and vacuum lubrication are technical areas which require thorough investigation.

The elastic recovery concept utilizes the stored potential energy of a strained elastic material for deployment. Elastic recovery concepts include the use of stress memory materials, springs encased in the airlock wall, and thick-walled structures constructed of resilient open-cell foam.

For external airlock application, a thick-walled structure constructed of a resilient foam material is a promising approach. The foam, in addition to providing deployment actuation, also affords micrometeoroid protection and insulation for thermal control. It maintains a stable configuration in the deployed mode of operation and it is well suited for multiple deployment.

A typical compression stress-strain curve for a polyester open-cell foam is shown in figure 4. For this plot, a constant compression strain rate of 1 inch per minute was experienced by a 4-inch cube of polyester foam with a density of 1.30 lb/ft^3. Curve A is the initial loading and unloading curve. The area under the loading portion of the curve is a measure of the work required to compress the sample, and the area under the unloading portion is a measure of the energy available for restoring the material to its original configuration. The area between the curve is, of course, a measure of the energy lost in the compression cycle, either through heat, viscous flow, or plastic deformation. A compression set in the foam is indicated by the offset from zero on the abscissa corresponding to zero load. For this viscoelastic material the compression set decreases with time.

Curve B is a plot of the fifth cycle of a continuous cyclic load on the material. The loading portion of this curve is lower than that for the initial curve, indicating that less energy was required to compress the foam for this cycle than for the initial cycle. The unloading curves, however, are almost identical, indicating that the potential energy available for restoring the material to its original configuration is not severely affected by continuous cyclic loading.

Curve C is a plot of the sixth hysteresis cycle on the foam. A time interval of $27\frac{1}{4}$ days elapsed between cycles number 5 and number 6. This plot shows a tendency for the material to recover, with time, some of its original characteristics as indicated by the upward shift of the loading portion of the plot.

Curve D is the stress-strain curve for a second 4-inch cube of the same material. This sample was loaded to the same maximum load as was the first sample, and then left compressed for a period of 7 days. After this period the load had relaxed to approximately 54 percent of its initial value. The difference in the loading portion of the two samples (curves A and D) is probably due to the nonhomogeneous property of the foam material. The significantly lower position of the unloading curve, however, indicates that long-term storage in the packaged configuration of an elastic recovery expandable structure will cause the structure to lose some of the energy available for deployment. The time required for deployment is also related to the length of time compressed as indicated by the larger compression set of curve D. These various characteristics of the foam material must be considered in the design of an elastic recovery deployment mechanism.

ELASTIC RECOVERY AIRLOCK DESIGN*

Guidelines

The remainder of this paper will discuss the design of an expandable airlock which utilizes the elastic recovery principle for deployment; specifically, a resilient foam. Guidelines for this design are shown in table 1. These guidelines specified a cylindrical configuration with sufficient volume for the transfer of a pressure-suited astronaut (approximately 4 feet in diameter and 7 feet in length). Deployment from the packaged mode was to be achieved through utilization of the stored potential energy of a compressed foam. Provision for multiple deployment was required since this offers additional environmental protection to the airlock and allows an unobstructed spacecraft exterior. The airlock was assumed to operate in a 200 n. mi. circular orbit with a 28.7° inclination. Passive thermal control was required to hold the internal temperature of the airlock within 50° F to 80° F. A 10-psi operating pressure was assumed for structural design with a safety factor of 5. A 30-inch-diameter hatch which could be opened with a force of 40 pounds or less was required. A maximum leakage of 0.01 lb/day with 1 atmosphere pressure differential was the allowable leakage rate. A requirement of 0.995 probability of zero penetration was specified for micrometeroid protection. Radiation protection was not specified since the astronaut would be in the airlock for only short periods of time and since he has his own independent space suit protection. Some radiation protection is, of course, inherently afforded by the airlock wall.

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*The elastic recovery concept was studied by the Whittaker Corporation, Narmco Research & Development Division under contract NAS7-283, entitled "Research On An Expandable Airlock Utilizing the Elastic Recovery Principle." Mr. N. O. Brink was project engineer.

Materials

The materials which comprise the airlock wall may be divided into four major functional categories as shown in figure 5: (1) the outer thermal control surface, (2) layers for micrometeoroid protection and thermal insulation, (3) the structural fabric, and (4) an inner impervious liner. The composite wall must also incorporate in its design sufficient foam thickness to actuate deployment by the elastic recovery principle. In addition, the resulting composite wall must maintain flexibility to insure that it can be packaged and deployed.

Thermal Control

The use of polymeric composite structure materials presents very definite temperature limitations on the airlock. The maximum allowable temperature of the foam material in a space vacuum environment is approximately 250° F. Above this temperature, the foam will lose its elastic recovery properties and above 300° F will lose its structural integrity. The necessity for maintaining the temperature within the airlock between 50° F to 80° F further required an extensive and accurate thermal analysis.

The passive thermal control capability of the airlock was determined from a parametric study of temperature levels as a function of surface optical properties and insulation thickness. The thermal environment of an orbiting vehicle is established by radiation heat influx on the external surfaces. In a low earth orbit, solar radiation, earth-reflected solar radiation, and earth-emitted thermal radiation are the contributing factors to the total heat influx. In the case of an airlock structure which is not an independent vehicle, the effects of reflected and emitted radiation from the surfaces of the space vehicle on the airlock must also be included. The heat influx to an orbiting vehicle varies greatly from point to point around the orbit because of the dependence on the vehicle's altitude, its attitude with respect to the sun and the earth, and whether it is in sunlight or shadow.

The complexity of an accurate analysis of the thermal environment as influenced by all of these variables necessitated the use of a computer program. For this calculation, the cylindrical airlock was divided into an octagonal body having eight flat surfaces and an end plate as shown in figure 6. The bottom surface in contact with the space vehicle was assumed to be a nonheat-transfer surface. The computer program then determined the geometric shape factors between each surface of the orbiting airlock and the heat sources, and solved the pertinent finite difference heat-transfer equation at 5° intervals around the orbit. The heat influx to each surface included reflected solar radiation and thermal radiation from a 260-inch-diameter circular base. Two extreme heating conditions were assumed for the analysis: (1) a maximum heating condition in which the airlock was considered to be constantly orientated toward the sun during an orbit of maximum time in sunlight exposure, and (2) a minimum heating condition in which the airlock was considered to be constantly in the shadow of the space vehicle for an orbit of minimum time in sunlight exposure. The condition for maximum heating was found to be when the axis of the airlock was oriented at an angle of approximately 30° with the sun vector.

Results for the maximum heating condition indicated that a surface coating with an absorptivity of 0.19 and an emissivity of 0.25 combined with a 2-inch-thick foam layer would maintain the internal temperature of the airlock within the specified limits of 50° F to 80° F for the condition of maximum heating. In addition, the external surface temperatures would be maintained within the allowable limits for the composite materials. However, for the minimum heating condition, the internal airlock air temperature for this same design would drop rapidly. The internal air temperature would drop to 50° F in approximately 35 minutes and after several orbits would stabilize around -40° F. The corresponding lowest external surface temperature would be approximately -85° F. These extreme temperatures were considered to be within reason of feasibility since they would not adversely affect the airlock materials and would be tolerable for a pressure-suited astronaut.

Micrometeoroid Protection

Micrometeoroid protection is provided by an outer cloth bumper which acts to break and fragment the hypervelocity micrometeoroid particles, a layer of foam which retards the fragmented particles, and an inner cloth main wall (see fig. 7a). An analysis showed a requirement for: a bumper laminate weight of approximately 0.27 lb/ft^2, a 1.35 lb/ft^3 density foam thickness of approximately 2.0 inches, and a main wall weight of approximately 0.12 lb/ft^2. Preliminary hypervelocity impact tests in which 10-milligram polyethylene terephthalate disks struck composite wall samples at velocities of approximately 7,000 and 18,000 feet per second indicate that a lower bumper weight may be sufficient. A typical cross-sectional view of a sample taken from these tests is shown in figure 7b.

Structural Design

Since the airlock was a cylindrical configuration with a relatively thick composite wall, improved folding and packaging characteristics were provided by designing a corrugated bellows-shape configuration in the cylindrical airlock section. The deployed and packaged configurations are illustrated in figure 8.

Two design approaches were considered for the airlock load-carrying structure: (1) a filament wound structure and (2) a filament reinforced knitted structure. The filament wound approach initially appeared attractive since a helically wound cylinder constitutes one of the most efficient structures; i.e., the lightest weight for a given internal pressure load. However, filament winding a corrugated cylinder requires elaborate fabrication techniques. In addition, the matrix required to maintain filament orientation tends to stiffen the structure.

A filament reinforced knitted structure is shown in figure 9. Axial loads are carried by continuous fibers woven back and forth in the knit with the knitted material used simply as a matrix to position the load-carrying fibers. Circumferential loads are carried by circumferential hoop bands located at the points of corrugation and spaced uniformly along the length of the cylinder. The advantages of this approach are: (1) the knitted matrix is easy to fabricate, lightweight, and extremely flexible and (2) the loops formed by the longitudinal fibers as they traverse back and forth form a natural and efficient means of attaching the airlock to the space vehicle and to the end hatch. For this purpose, the longitudinal fibers can be woven around a rigid mounting ring during the knitting process or later threaded by a rigid ring. For these reasons, the filament reinforced knitted structure was the selected structure.

An inner liner was designed to retain the air within the airlock. Desirable characteristics for the liner material included flexibility, toughness, low permeability, and low toxicity. A review of candidate materials showed polyvinylidene chloride film to possess the best properties. The thickness of film required to prevent extrusion through the structural fabric was determined experimentally. The results of this test indicated a 3/4-mil thickness would sufficiently prevent extrusion through the structural fabric mesh under a pressure differential of 45 psi. To provide additional safety, a liner thickness of 2 mils was recommended. A scuff pad may also be desirable to resist abrasion and puncture from abusive treatment by the astronaut's equipment. The liner attachment was so designed that the liner could be removed and replaced if punctured or for preventative maintenance.

Packaging Study

The requirement of flexibility of the composite wall of an expandable structure cannot be overemphasized. It is absolutely necessary for successful packaging and deployment of such a structure. A wall structure built up of several flexible components and bonded together to form a composite structure can so easily turn out stiff and inflexible. Several basic principles, however, if followed can give the desired flexible characteristic. These principles include: (1) prevent binder impregnation of the laminate materials, (2) use a low modulus binder, (3) use a minimum of adhesive material, and (4) reduce the number of plies to a minimum. Limiting the binder impregnation of the foam and cloth proved to be the key factor to improved flexibility in this study. A successful technique which was developed for this purpose is a transfer technique. This technique is a two-step procedure, whereby the resin (in this case a polyurethane) is first spread out in a thin film, and allowed to advance to a tacky state. The cloth or foam material is then laid on the resin to pick up enough to cover the surface. The laminate materials are then bonded together with contact pressure and cured at room temperature. A sample of composite flexibility achieved by this technique is shown in figure 10. The cloth and foam layers represent the thickness required for micrometeoroid protection.

Folding and packaging characteristics of the airlock were studied through the use of scale models. Complete scaling of a composite structure is problematical because of a difference in scaling laws. Geometric scaling is a linear function of the airlock dimensions and wall stiffness is a cubic function of the wall thickness. For this study, the airlock dimensions were scaled geometrically by one-quarter and the wall thicknesses by one-half. This produced a model which was 1 foot in diameter and $1\frac{3}{4}$ feet in length with a 1-inch wall thickness. The folding model study began with simple cylinders and progressed to more complex configuration including models with flexible or rigid hoop bands and simulated convolutions.

A simple cylindrical model is shown in the deployed and packaged configurations in figure 11. The large major folds or buckles visible under the shroud are typical for this type of cylinder. This type of fold is not optimum from a deployment standpoint, since the best recovery characteristics for a flexible composite structure are exhibited when the resilient form is uniformly compressed. This suggests, to insure that large portions of the foam do not remain uncompressed, the use of many minor folds in the composite wall rather than a few major folds. The use of many minor folds also provides faster deployment, since shallow creases "pop out" more readily than deep creases.

The approach taken for improving the folding pattern of the composite wall was to restrict the folding pattern through the use of hoop bands uniformly spaced along the length of the cylinder. (See fig. 12.) Both flexible and rigid hoop bands were evaluated. It was found that flexible bands had little effect on decreasing the number of large folds. (See fig. 13.) These major folds or buckles are essentially the same as those observed for a cylinder without hoop bands.

Rigid hoop bands, however, constructed of filament wound impregnated glass rovings were found to be effective in restricting folding to the desired pattern. This model is shown in figure 14 in the deployed and packaged configurations. The use of rigid rings is also compatible with structural requirements for the airlock since hoop rings are required to resist the circumferential loads.

A full-scale cylindrical section of the airlock was constructed to determine the packaging ratio and the load required for packaging. This section as seen in figure 15 was 4 feet in diameter and 3 feet in length. The thickness of the walls was 2 inches, approximately that required for the airlock. Loads were applied to the cylinder by means of weights suspended from the center of the top end plate. A load deformation curve for the cylinder is seen in figure 16. Since this cylinder did not have rigid hoop bands to restrict the folding pattern, a major circumferential buckle occurred at a load of approximately 130 pounds. When the load was removed this major buckle was not completely relieved; consequently, the cylinder returned to only 66 percent of its original height. It is anticipated, however, on the basis of the one-quarter scale tests, that a cylinder constructed with a corrugated surface and rigid hoop rings would fully deploy. However, even if the airlock did not completely deploy, air pressurization would complete the deployment. Once deployed it would maintain the expanded configuration. On the basis of the packaging tests, an $8\frac{1}{2}$ to 9 expanded volume to packaged volume ratio is considered feasible.

Assembled Airlock

An artist's concept of the assembled airlock is seen in figure 17. A cutaway section exposes the inner liner, the corrugated structural fabric, and the protective outer wall. The cover cap serves as a shroud for the airlock during launch and as protection when the airlock is not deployed.

Retraction cables are designed to provide multiple deployment capability. These cables are attached to the hatch flange and separated from the flexible walls by a spacer. Torque applied to a winding ring at the base provides equal displacement of the cables, thus insuring uniform retraction of the airlock. The airlock in its retracted configuration is shown above.

The end closure hatch is a rigid structure held in place by three spring-loaded bullet-type catches. The top of the hatch is covered with foam and a cloth bumper to provide micrometeoroid protection equivalent to that afforded the flexible walls. It is designed for inward opening thus providing a positive pressure seal. Underwater zero gravity simulation studies have shown an inward opening hatch to be a feasible approach. A detail of the hatch components is shown in figure 18.

A weight estimate for the expandable airlock system is shown in table 2. The total weight is 101 pounds. Not included in this weight estimate are the valving system, retraction ring drive unit, and base closure plate. The material weight for the airlock of 43.4 pounds is based upon an assumed area of 95 square feet and upon the weights of actual composite samples. The end rings, hatch, hoop rings, and inner liner accounted for 41.8 pounds. The remainder of the 101-pound airlock system weight consists of the retraction mechanism.

CONCLUSIONS

In conclusion, an expandable airlock which utilizes the stored potential energy of a compressed foam for deployment appears to be a feasible approach for manned space mission applications. It will maintain a stable configuration in the deployed mode of operation and it is well suited for multiple deployment. The foam in addition to providing deployment actuation, also provides micrometeoroid protection and insulation for thermal control. Adequate packaging characteristics can be achieved through the use of a corrugated bellows-shape configuration supplemented with rigid hoop rings designed to restrict the folding to the desired pattern. A filament reinforced knitted structure is not only lightweight and extremely flexible, but provides a natural and efficient means for attaching the airlock to the space vehicle and to the end hatch.

REFERENCES

1. Brink, N. O.: Research On An Expandable Airlock Utilizing the Elastic Recovery Principle. Final Rept. (Contract NAS7-283), Whittaker Corporation, Narmco Research & Development Division, April 1965.
2. Brink, N. O.: Development and Evaluation of the Elastic Recovery Concept for Expandable Space Structures. NASA CR-121, 1964.
3. Loisch, J. A.: Design of Inner Pressure Shell for Airlock Structure. Astro Research Corporation Report 159, Aug. 1964.
4. Olson, M. W.: A Research Study To Investigate the Application of Filament Winding for Sections of an Erectable Space Station. Final Rept. (Contract NAS1-2317), U.S. Rubber Co., April 1963.
5. Schuerch, H.; and Kyer, A.: Structural and Folding Analysis of the Airlock. Astro Research Corporation Report 169, Oct. 1964.

TABLE 1.- EXPANDABLE AIRLOCK DESIGN CRITERIA

Configuration	Cylindrical, 4-foot diameter, 7 feet long
Deployment	Elastic recovery, multiple
Orbit parameters	200 n. mi. circular orbit 28.7° inclination
Thermal control	Passive system
Internal temperature range	50° F to 80° F with a design temperature of 64° F
Structural design	10-psi design pressure with a safety factor of 5
Hatch design	30-inch diameter opening with an opening force of 40 lb or less
Leakage	Maximum of 0.01 lb/day at 1 atmosphere pressure differential and 60° F temperature
Meteoroid protection	99.5 percent probability of zero penetration
Radiation protection	Not designed into the airlock wall due to the short period of time astronaut is in the airlock

TABLE 2.- AIRLOCK WEIGHT ESTIMATE

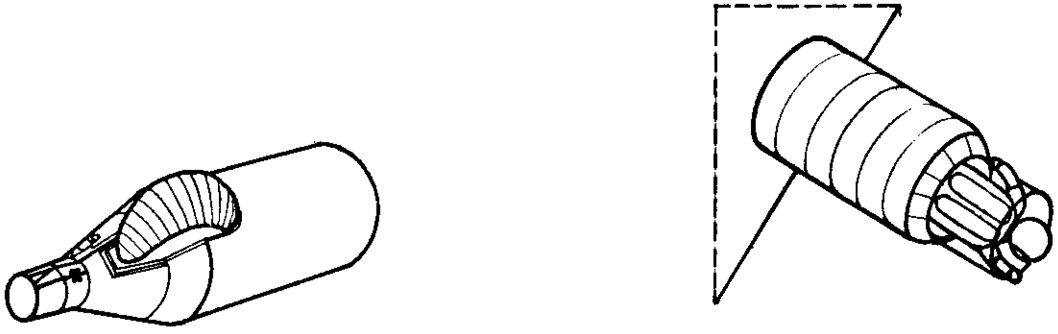
Item*	Materials	Weight, lb
1. Hatch	Laminate, ring and foam	10.5
2. Upper end ring	Aluminum	18.9
3. Cap	Laminate	3.0
4. Composite wall**		
a. Protection layers	Foam and cloth 38 lb	43.4 (total)
b. Structural fabric	Dacron and monofilament 5.4 lb	
5. Hoop rings and drawstrings (2)	Wound fiberglass	6.5
6. Airtight liner	Polyvinylidene chloride	2.5
7. Bottom end ring	Aluminum	3.4
8. Retraction mechanism	Various	
a. Cable hanger (4)		4.0
b. Cables and eyes (4)		1.0
c. Pulleys (8)		.8
d. Winding ring		4.0
e. Winding ring retaining assembly (4)		1.0
f. Shield assembly	Laminate	2.0
	Total weight	101.0

*Valves, tubing, retraction drive unit, or attachment plate not considered.

**Composite wall weight based on a surface area of 95 ft^2.

(a) LUNAR SHELTER

(b) SPACE HANGAR



(c) ACCESS TUNNEL

(d) EXPANDABLE AIRLOCK

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Figure 1.- Space applications for flexible expandable structures.

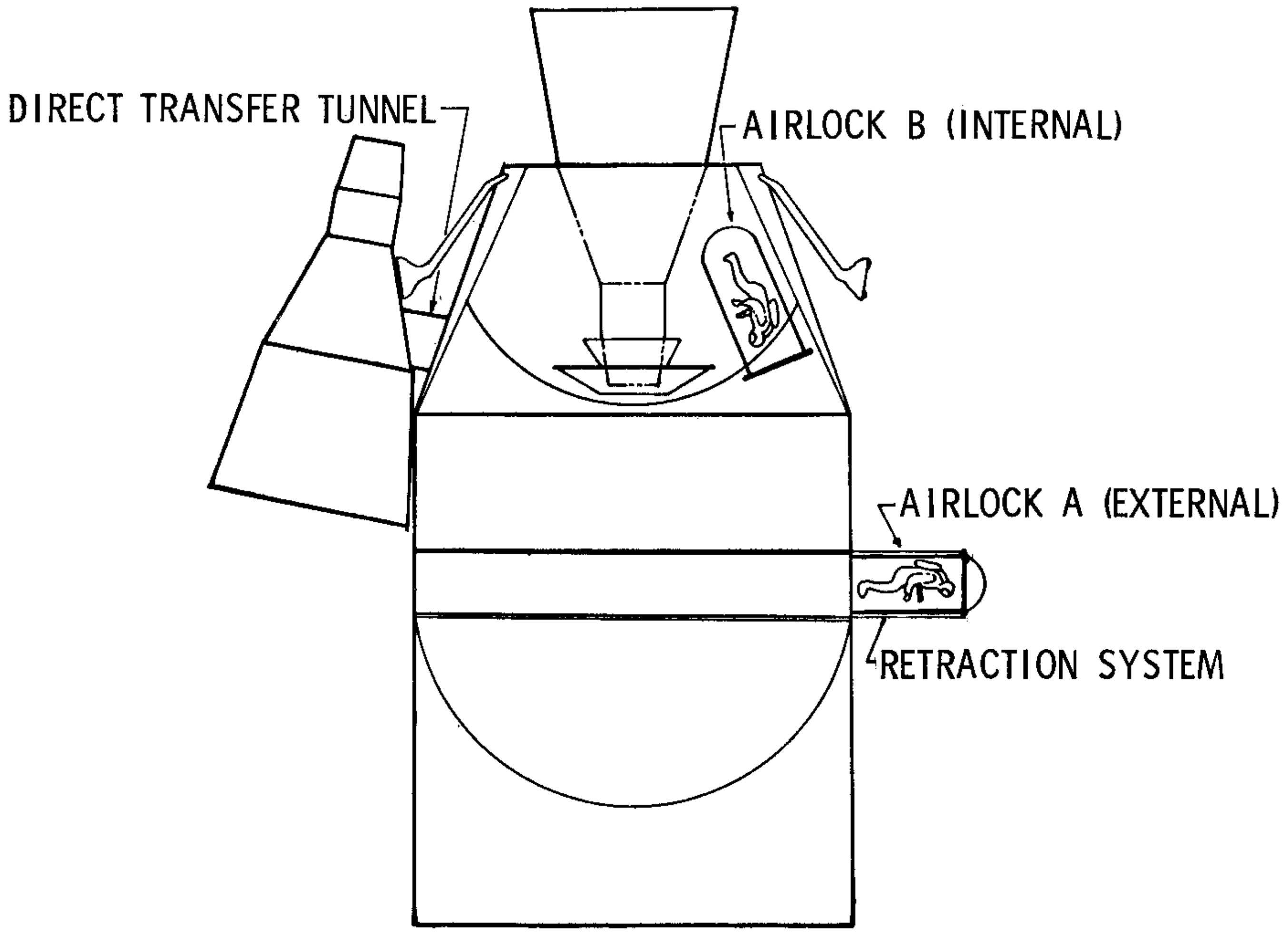

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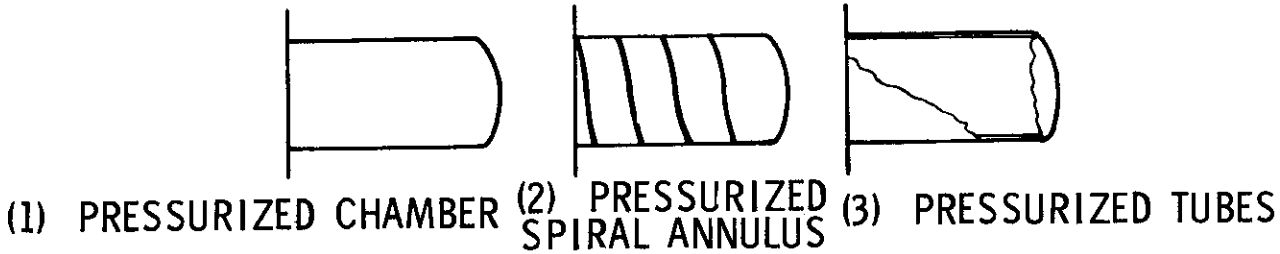
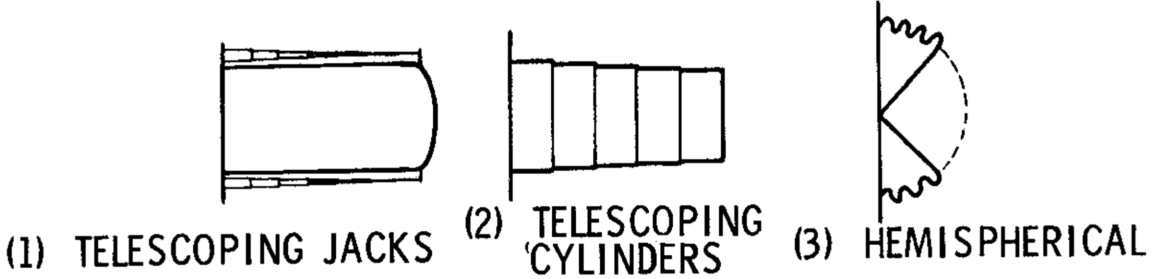
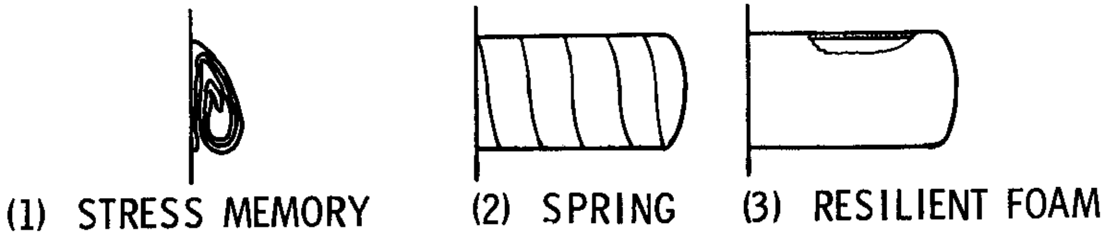
Figure 2.- MORL expandable airlock application.



(a) AIR PRESSURIZATION.



(b) MECHANICAL ACTUATION.



(c) ELASTIC RECOVERY.

NASA

Figure 3.- Deployment system.

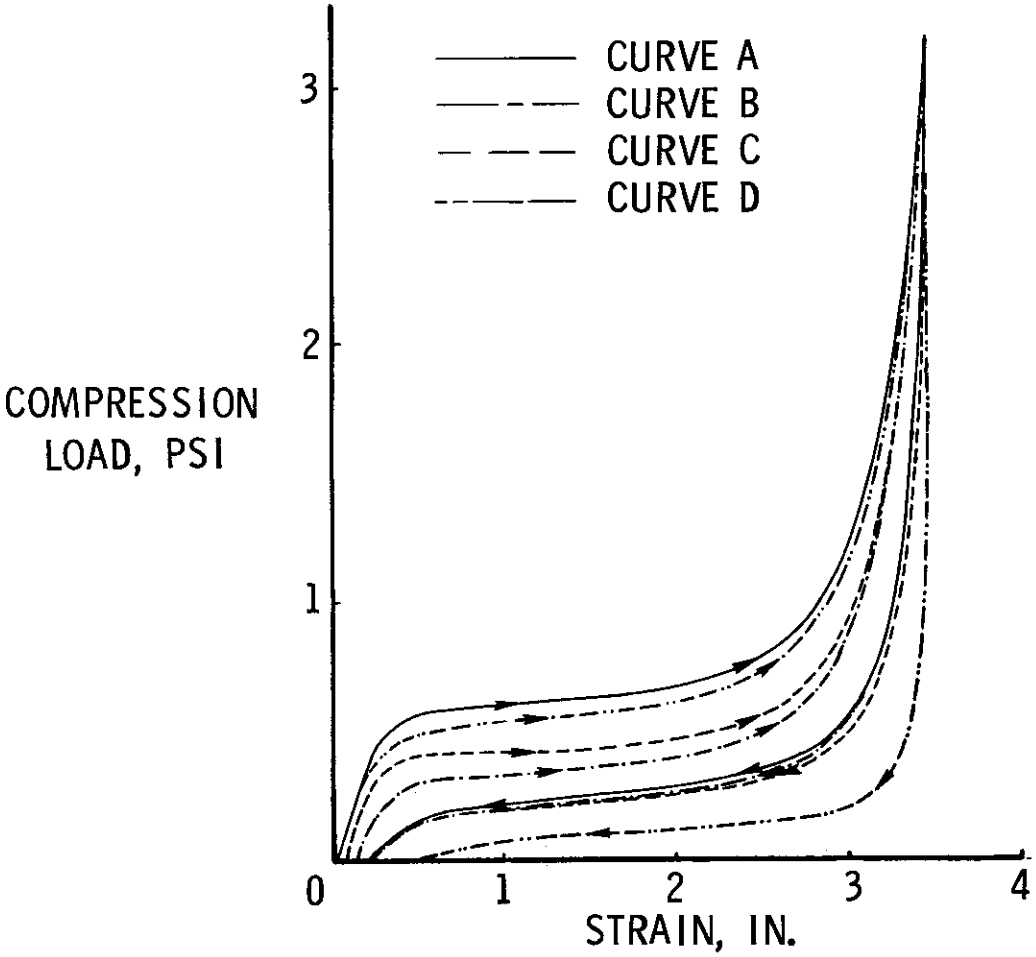


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Figure 4.- Compression stress-strain curve for 4-inch cube of polyether open-cell foam.

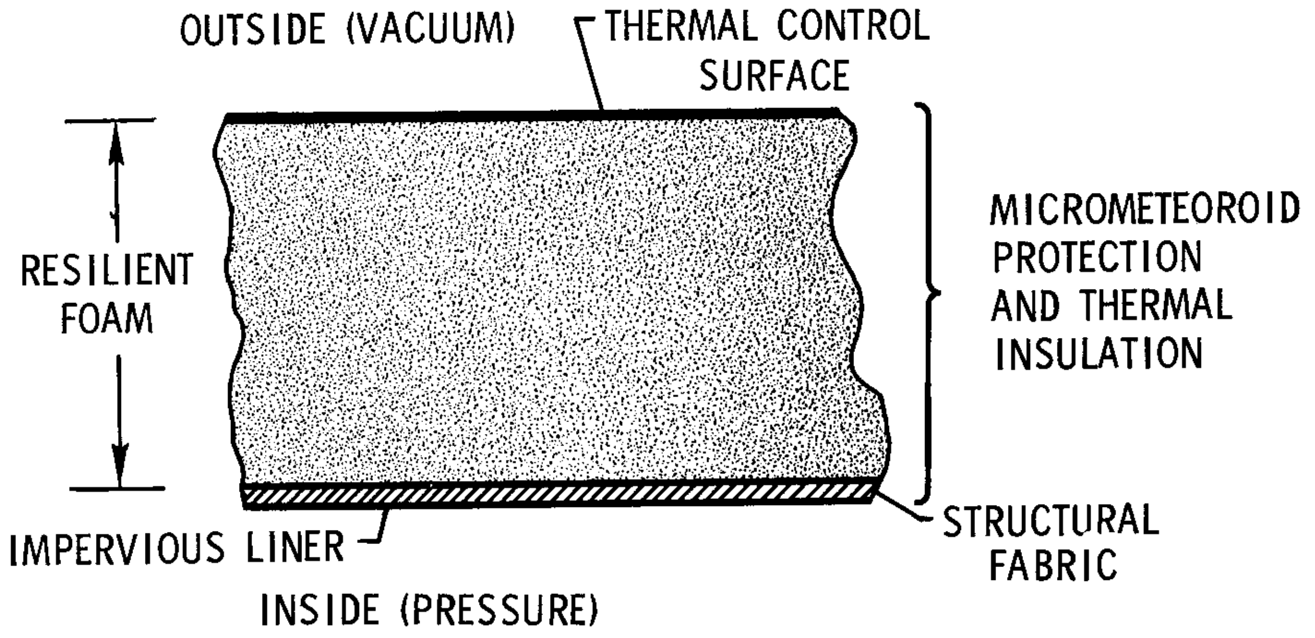

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Figure 5.- Typical wall section.

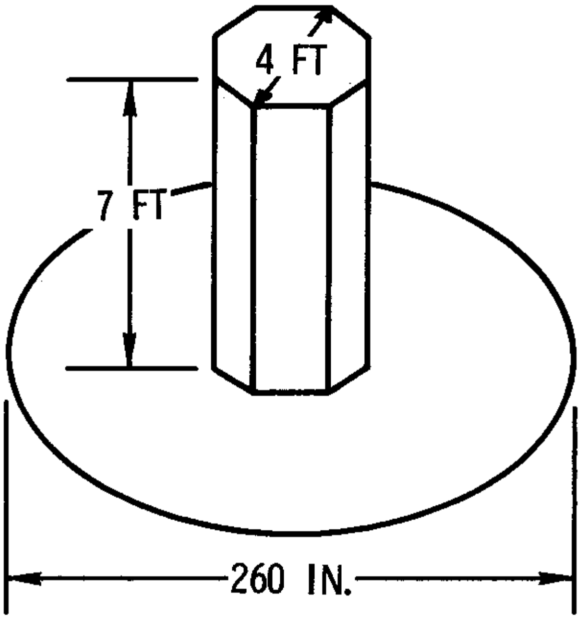

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Figure 6.- Octagonal thermal model of airlock.

(a) WALL MODEL

(b) HYPERVELOCITY IMPACT
TEST SAMPLE

NASA

Figure 7.- Micrometeoroid protective wall.

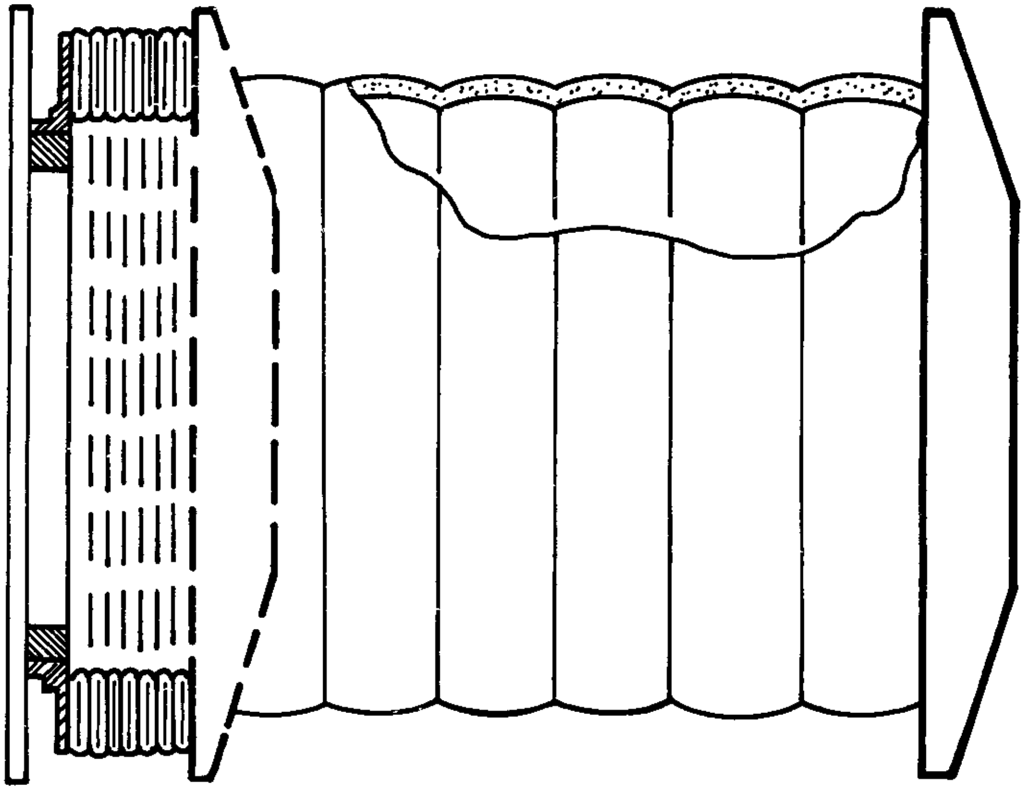

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Figure 8.- Corrugated bellows configuration.

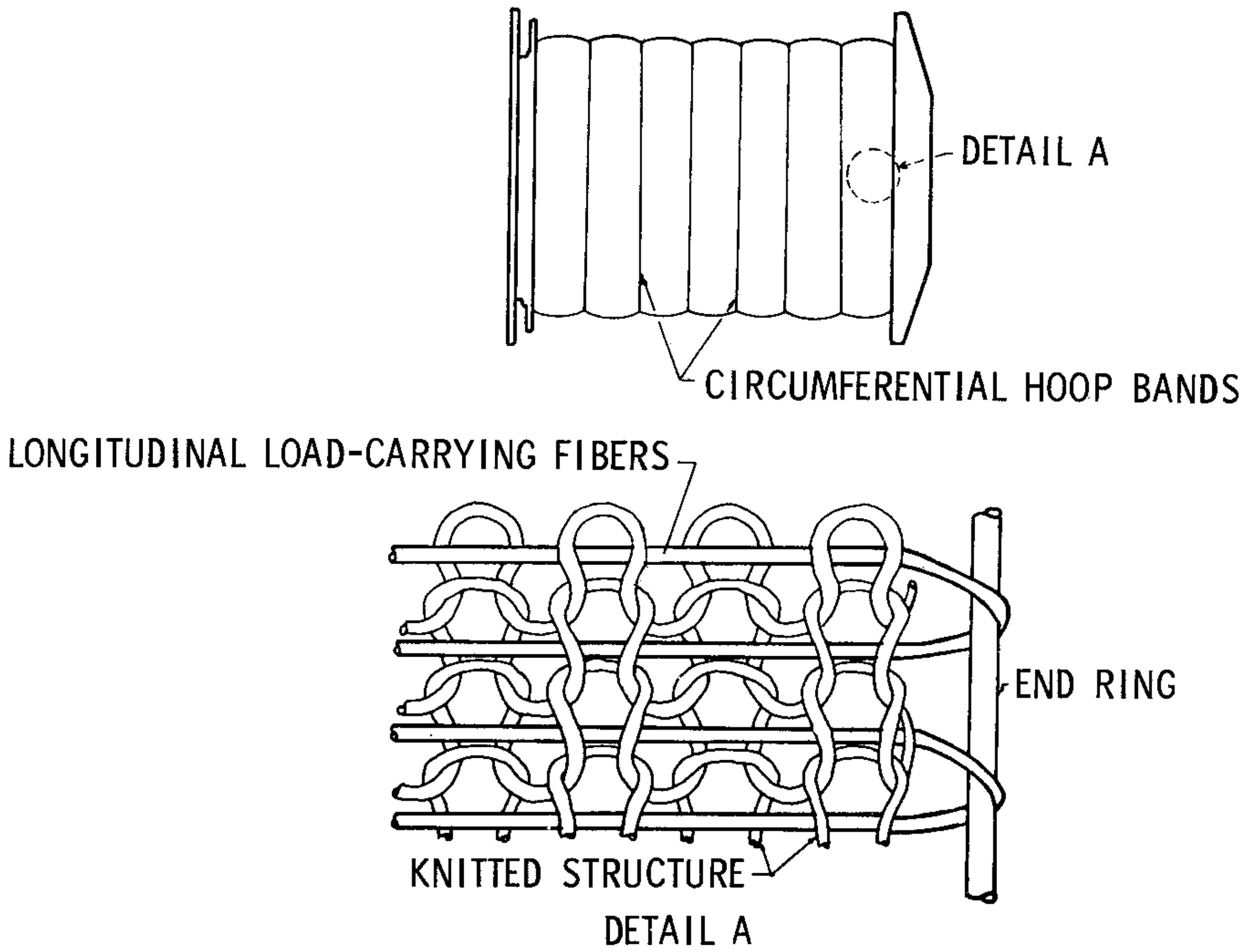

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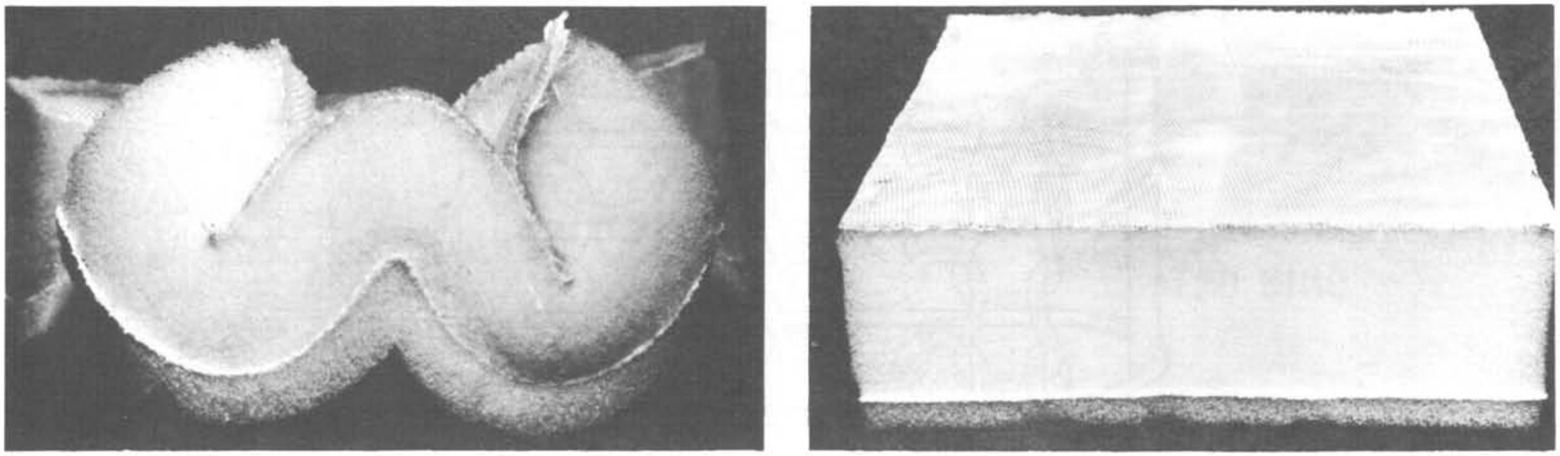
Figure 9.- Structural filament reinforced knitted fabric.



(a) FOLDED

(b) UNFOLDED

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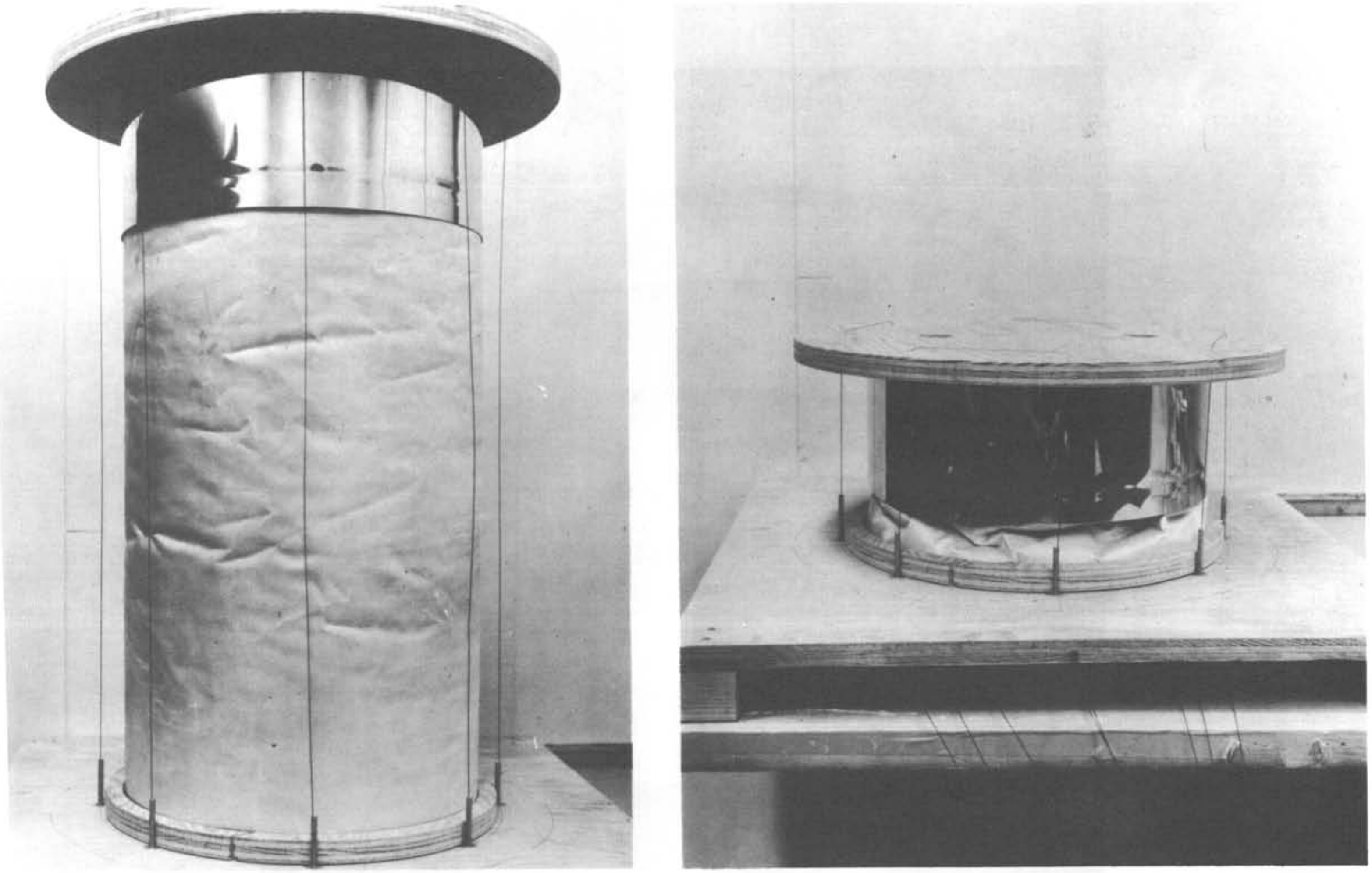
Figure 10.- Flexible elastic recovery composite.



(a) DEPLOYED

(b) PACKAGED

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Figure 11.- Cylindrical model.

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Figure 12.- Cylinder with hoop bands.

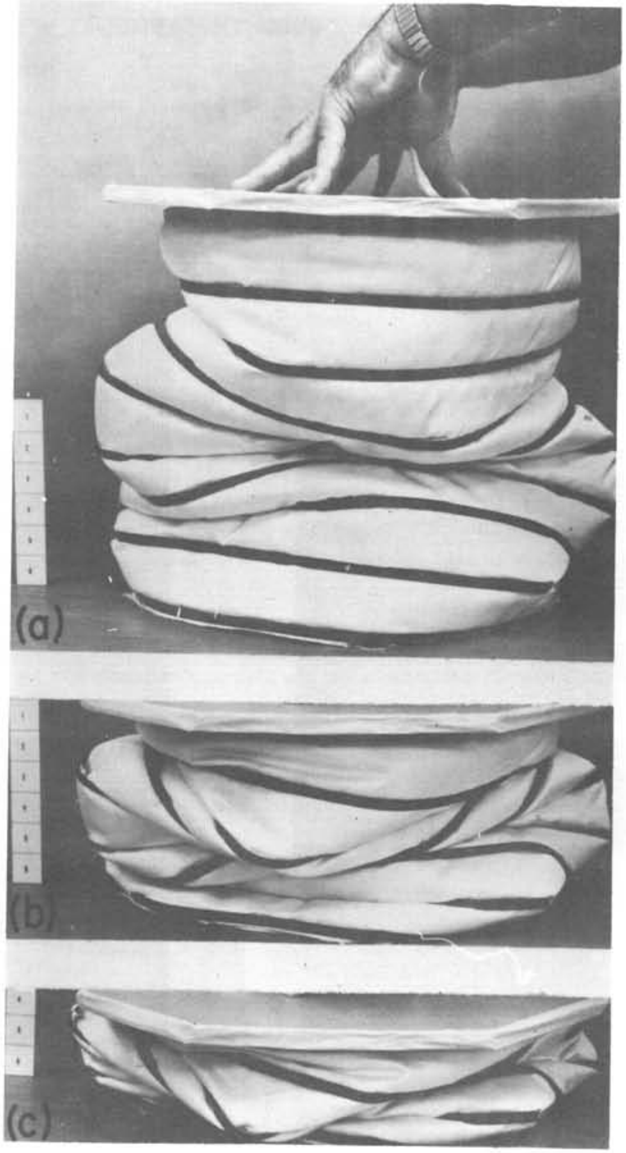

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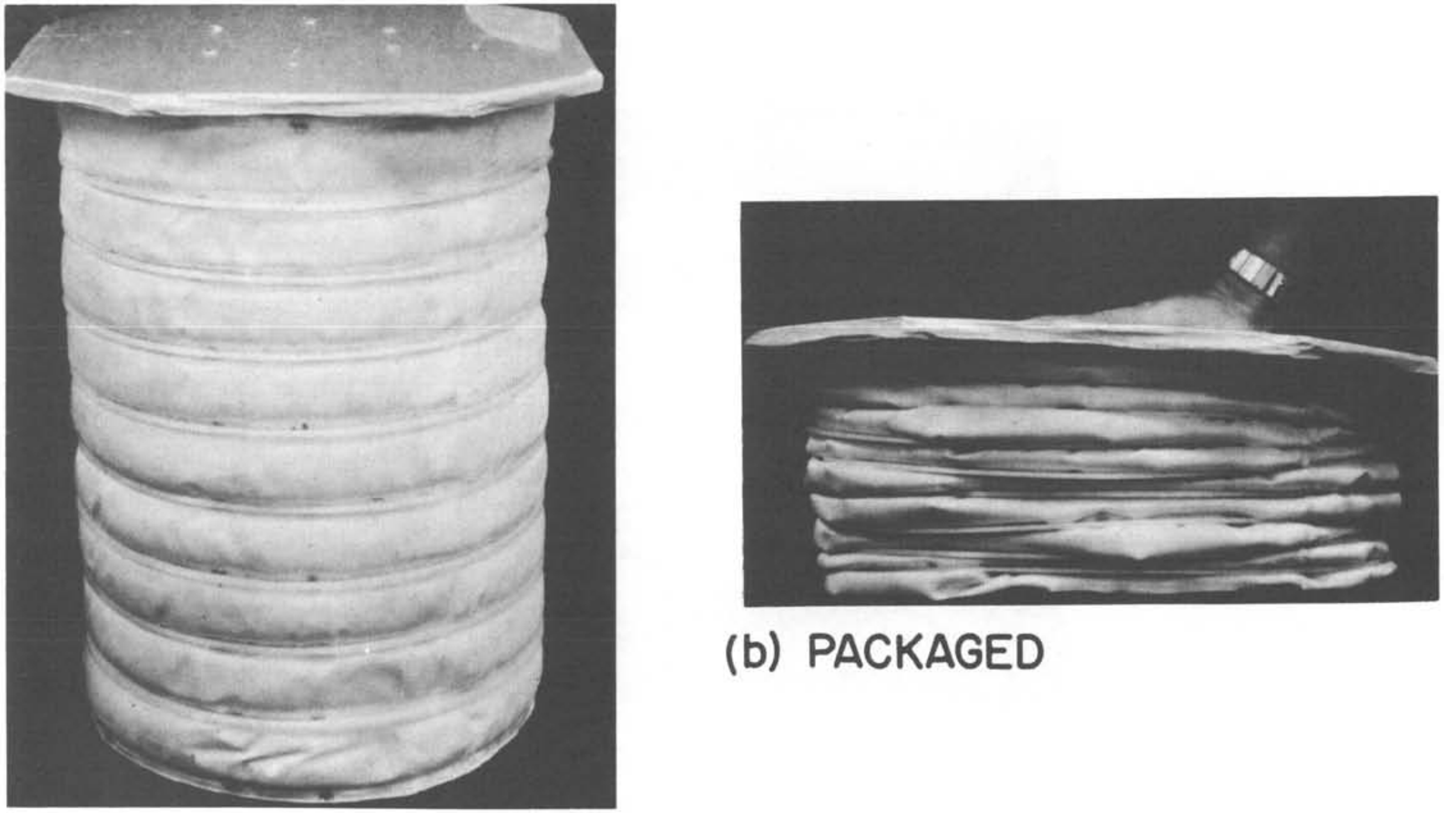
Figure 13.- Folding sequence for cylinder with flexible hoop bands.



(a) DEPLOYED

(b) PACKAGED

NASA

Figure 14.- Cylindrical model with rigid hoop bands.

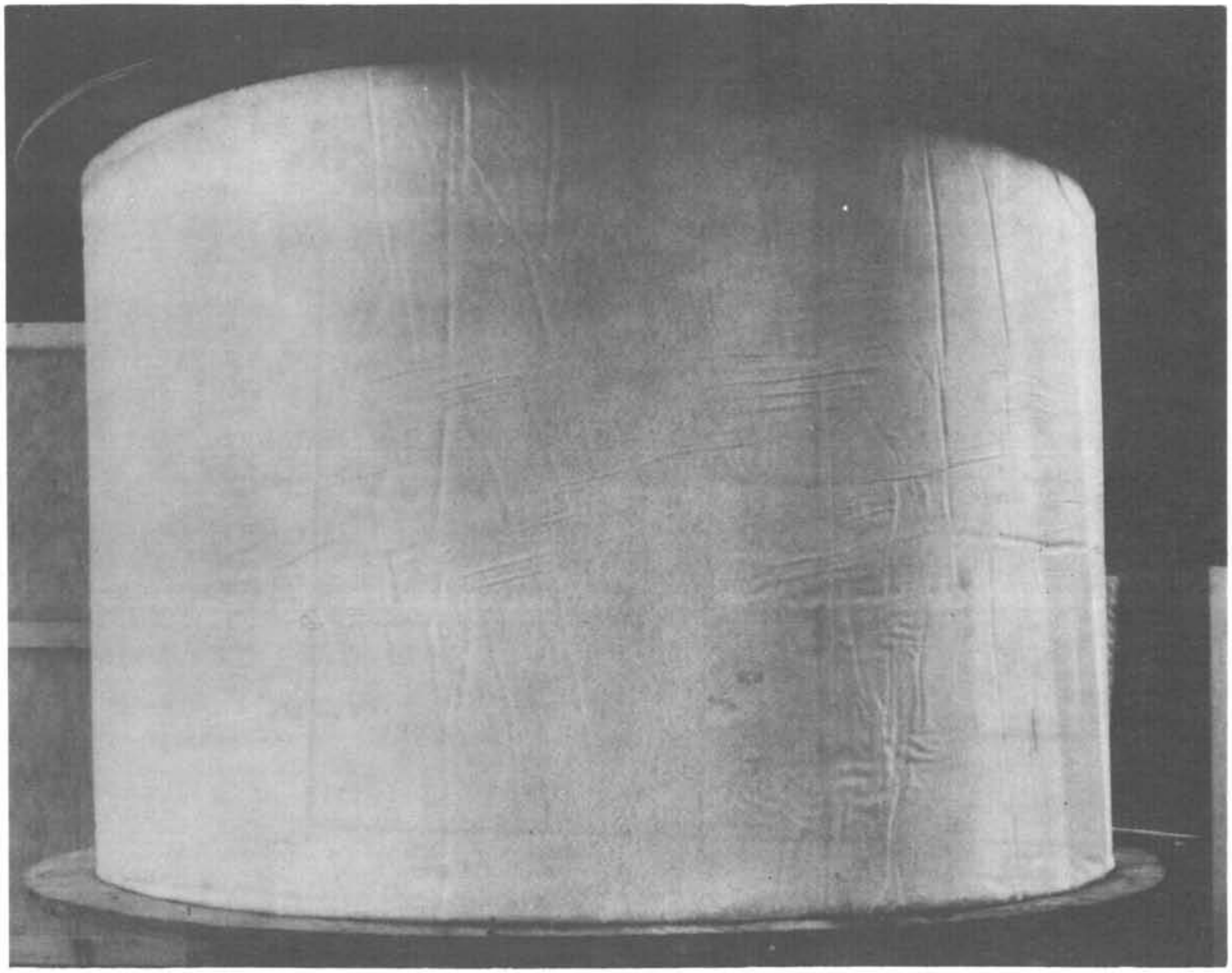


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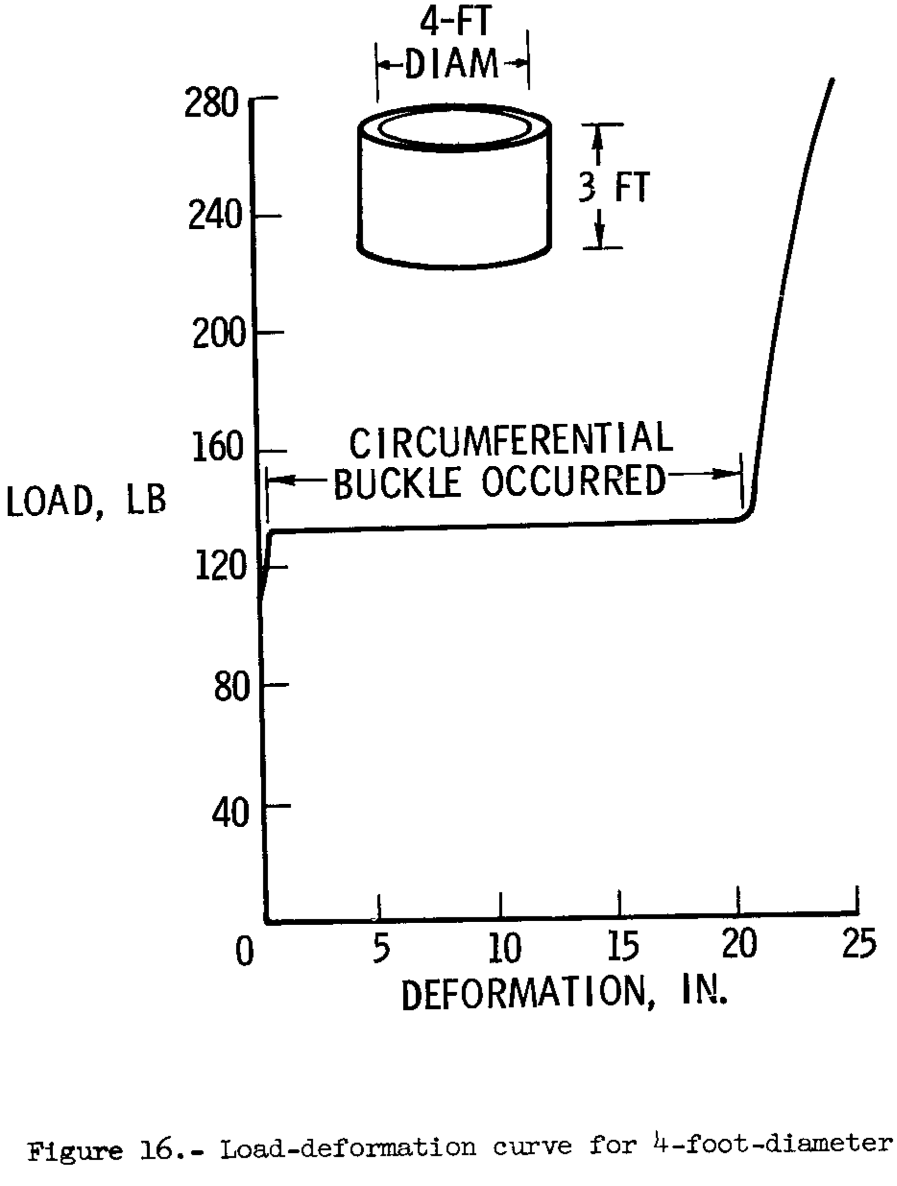
Figure 15.- Large test cylinder, 4 feet in diameter and 3 feet long.



NASA

Figure 16.- Load-deformation curve for 4-foot-diameter cylinder.

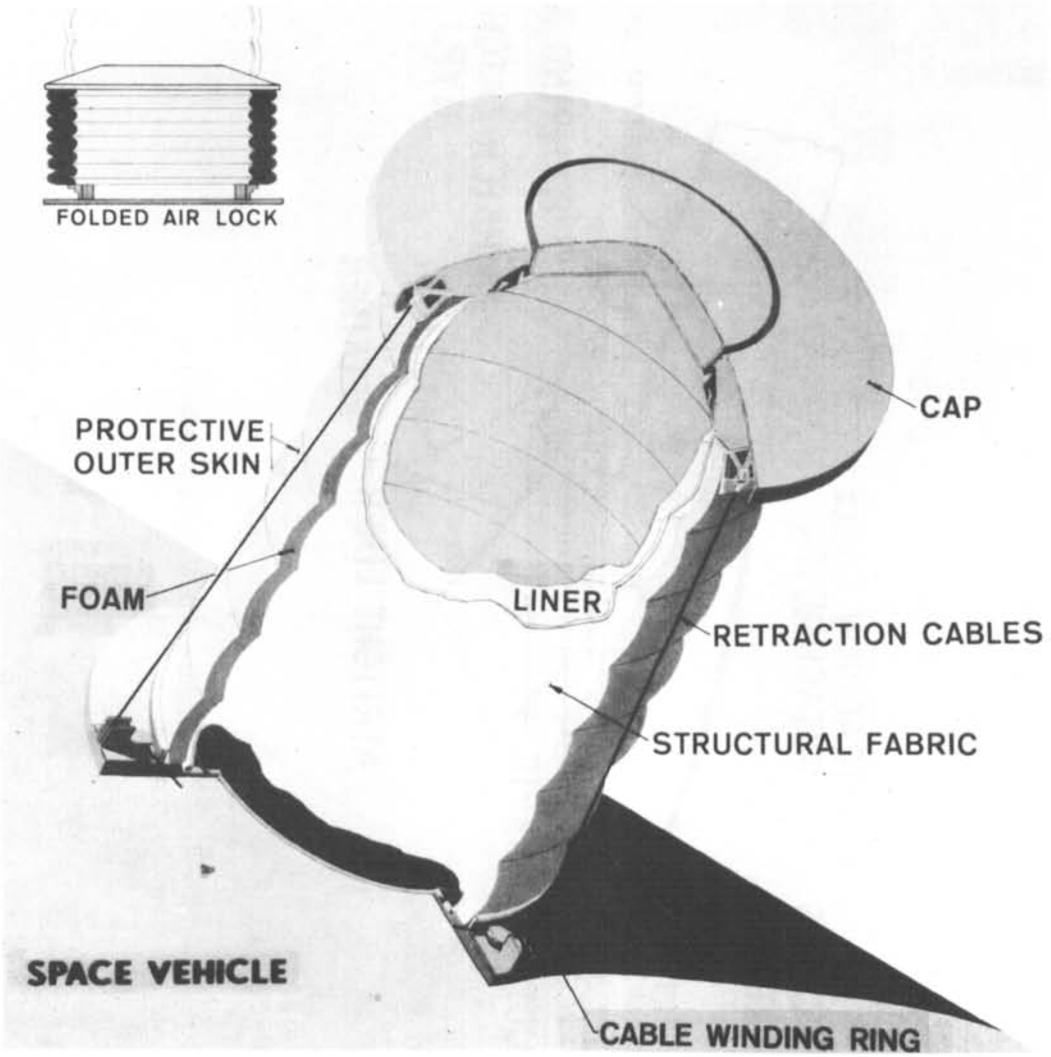


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Figure 17.- Expandable airlock.

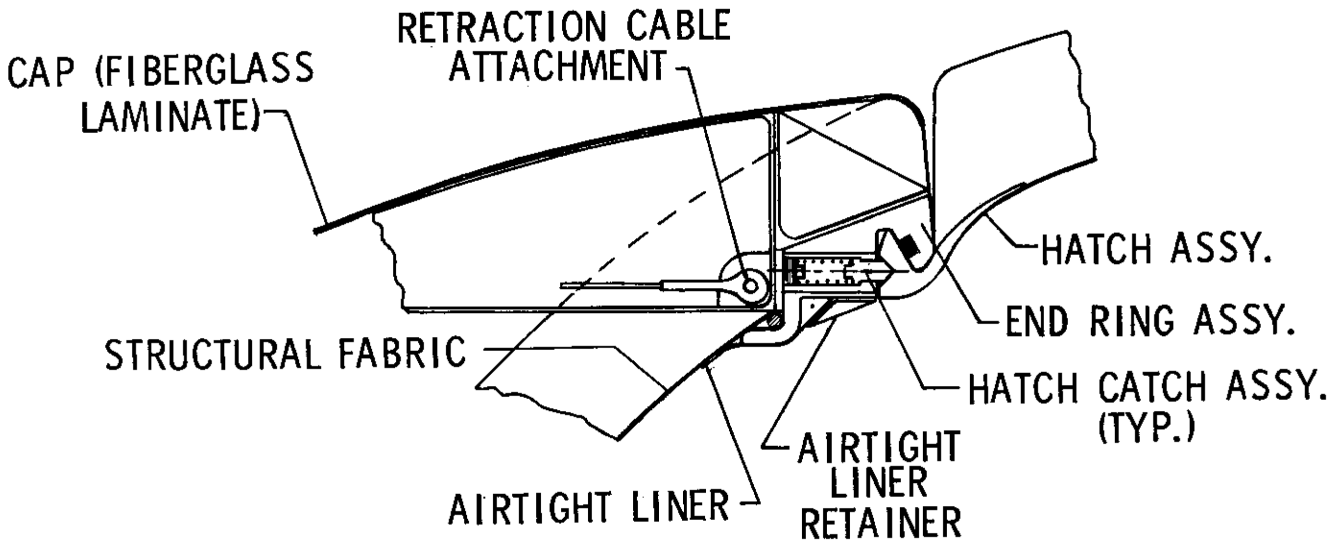

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Figure 18.- Hatch detail.