DEVELOPMENT OF SPACE EXPANDED AND RIGIDIZED SOLAR ENERGY COLLECTORS

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INTRODUCTION

The largest problem in the use of inflatable solar concentrators in space programs is the development of a feasible technique for their fabrication. This technique must produce concentrators that are light in weight and easily packaged in a small volume. More important, it must be possible to inflate and rigidize them in a space environment and the rigidized concentrator must have a specified form suitable for its function.

The Hughes Aircraft Company, under NASA Contract 1-3244, undertook to develop the techniques and produce concentrators that would meet the following general requirements. The concentrator should be packageable in a small volume and be automatically inflated in space to form a rigid paraboloid. The reflecting surface of the concentrator was to be aluminized polyester film formed by the Hughes "no master stress-relaxation" process. The back surface of the aluminized film was to be covered with a flexible reinforcement coating that would become rigid after the concentrator was inflated in the space environment.

Originally it was planned that the reinforcement would be a polyester-resin-fiberglass laminate, activated by ultraviolet radiation. After a number of tests had been made, however, it was decided that this reinforcement system possibly would not result in the highest quality optics. Therefore a coincident investigation was also made into the use of an epoxy syntactic foam as a reinforcement. With either type of reinforcement it was planned that the final assembly weight would be approximately 0.4 lb per sq foot.

This report covers the experimentation and testing which led to the production of concentrators able to meet the contract requirements. Three major problems were involved. First, techniques had to be optimized for inflating the paraboloid assembly to the specified form. A second problem was the development of a suitable rigidizing layer, one which would also produce an acceptable optical surface on the polyester film. The third problem concerned a method for bonding the rigidizable layer to the film,

which normally acts as a parting agent. Complicating all these problems was the requirement for inflation and rigidization in the high vacuum of a space environment. This was a particularly difficult requirement for the chemical rigidizing process, since such processes normally occur in a pressurized, terrestrial environment.

CONCENTRATOR DESIGN

The general design and configuration of the paraboloid fabricated is illustrated in Figure 1. The paraboloid is five feet in diameter and is encircled by a torus six inches in cross section. The reflective surface of the paraboloid is 2-mil aluminized polyester film and the outer, clear pressure retaining membrane is 2-mil clear polyester film.

As shown if Figure 1, both film surfaces are formed of a series of hexagonals, joined by a heat-sealing technique. This mosaic surface eliminates the gored construction usually employed for such structures and has several other advantages. First, most proposed space collectors are very large, with diameters of from 30 to 100 feet. Since aluminized polyester film is currently not available in widths greater than five feet, the mosaic technique provides a means of making uniform surfaces of unlimited size.

A second advantage of the mosaic construction lies in its suitability for the technique developed to form the paraboloid. This technique is a Hughes proprietary process, in which a film is formed to the desired parabolic curvature by a combination of stretch and relaxation techniques, without using a costly master form. When using this technique with conventional pie-shaped gore construction, the unequal stresses throughout the surface, due to the concentration of seals at the center, prevent attainment of the correct curvature. Use of the mosaic surface, with its equally distributed seals, eliminates this difficulty.

The five-foot diameter paraboloids and torus assemblies were ordered from an outside vendor. The torus assemblies attached to the paraboloids were also made of 2-mil polyester film, since preliminary 2.5 psi would not buckle when acted upon by the internal pressure of 0.5 psi needed to form the paraboloid.

It was planned then, after receipt of the assemblies from the vendor, to inflate them to the required shape, then apply the rigidizing layer. On subsequent curing, in a vacuum environment, the part should assume the correct shape permanently.

In previous, Company funded efforts, Reference 1, a technique had been developed to form polyester film materials to a paraboloidal shape without a master form tool. This technique consists, in brief, of overstretching a film by pressurization, or vacuum. Then on relaxation, the film in returning to its original shape goes through a number of curves, including a paraboloid. Establishing the correct pressure to result in a paraboloid was then a relatively simple task. The paraboloidal shaped film could then be used as a master for subsequent layup of the rigidizing layers. However, after layup of the first few trial parts it was found that the paraboloid had to be formed, in the relaxed state, with an absolute minimum of residual stresses, or gross, physical distortion would result as soon as the cured part was removed from the fixture.

POLYESTER RIGIDIZATION

The rigidizing technique initially utilized was an ultraviolet activated polyester resin system originally developed on a NASA contract, as a possible successor to the Echo II balloon, Reference 2. After making a few sample parts, however, it was found that the use of this technique gave rise to several problems. First the polyester resin, as is characteristic of most polyesters, showed very poor adhesion to the underlying film. This adhesion was so poor that the initial samples delaminated partially due to the stresses in the film. More serious than the delamination, however, was the fact that wherever the film did adhere to the fiberglass laminate the optical surface was quite poor. This degraded optical surface had two forms, a patternless, uneven, distortion and a uniform, regular distortion in which the fabric weave was visible on the optical surface.

Polyester resins, when impregnated into a fabric, inherently do not result in a good surface, because of the relatively high volumetric shrinkage. Since fabric "show-through" is a well known phenomena with polyester resins, it is common commercial practice to utilize a heavily filled gel coat between the mold and the fiberglass laminate. An investigation was therefore made into materials which could act as a gel coat to help hide the fabric pattern.

The gel coat to be useful for the particular paraboloid fabrication problem would have to be more than a heavily filled material to which the polyester resin would adhere. It would also have to have good adhesion to the polyester film, normally a parting agent, and would have to be flexible in the cured state. A number of materials were tested which appeared to meet the requirements. These include several urethane coatings, a silicone RTV and a Butyl rubber cement, a flexible polyester and a flexible epoxy coating and several types of polysulfide coatings. These latter materials were found to give the best combination of properties, and so were selected as the intermediate coating between the polyester film and the polyester rigidizing layer.

TOOLING

Even with the use of the polysulfide gel coat, a great deal of irregular, patternless distortion occurred in the small, one-foot diameter, rigidized samples which were made initially. These first samples were all made at normal room pressures, in order to first develop an optically satisfactory technique. The type of fixture used for these first test samples was a simple metal fixture in which the film was inflated as a diaphragm. With this fixture, obviously the reflective surface could not be examined until the part was removed. It was therefore impossible to determine if the distortions in the reflective surface were due to the gel coat application or occurred with the application of the final polyester rigidizing laminate, or on cure of this laminate. In order to determine at what stage the distortion commenced, then, the original fixture was modified to include a transparent window, Figure 2. This worked so well that a number of smaller, (6 in. diameter) solid acrylic fixtures were also made, Figure 3.

OPTICAL TESTS

With the use of the transparent fixtures it was possible to observe the effect of each coating on the aluminized polyester film. No discernable

distortion was found on application of the gel coat. Distortion, however, did become noticeable with the onset of polyester gelation. A number of types of polyester resins, and fabric combinations were tested. In general, it was found that materials known to have low shrink characteristics, such as the diallyl phthalate based materials, combined with the finest, practicable weaves of cloth, resulted in the best surfaces. Non-woven reinforcements such as felts, mats and overlay veils were also tried without, however, any noticeable improvement. In each case, of course, the resin was one which was ultraviolet catalyzed, so it could be automatically set up in space.

After preparing a great number of samples using the various polyester combinations, several samples were prepared using room temperature cured epoxy resins. An immediate improvement was noted, Figure 5. It was therefore concluded that the inherently large shrinkage of the polyester system would always act as a barrier to attainment of the highest optics. Tests were therefore made to determine if an epoxy system could be developed to result in both rigidity and satisfactory optics.

EPOXY RIGIDIZATION

The first tests made with an epoxy system utilized an epoxy resin and a finely powdered silica filler. Excellent optical results were secured. However, the resulting cured structure, approximately 0.1 inch thick, was both too heavy and much too brittle. Further tests, made to develop a more satisfactory coating, resulted in a syntactic foam utilizing an epoxy resin, and phenolic microballoons as the filler. A special catalyst system was developed which cured in several hours at 240° F, but gave a room temperature shelf life of approximately two months. The use of syntactic foam gave much improved optical results, Figure 5. Because of the success of the epoxy syntactic foam some tests were also made to develop an ultraviolet cured polyester syntactic foam. However, because of the opacity the phenolic microballoons could not be used with this system. Glass microballoons were tried, but were also too opaque if used in the thickness required.

FILM HEAT TREATMENT

With the advent of the heat cured epoxy system another problem arose; that of shrinkage of the polyester film after heating. It was found that the film, as received from the vendor, shrank as much as 1 1/2 percent on heating for a short period at 325° F. This shrinkage, during cure of the rigidizing coat, could then interfere with obtaining optimum curvature in the heat cured epoxy rigidized parabola or might cause distortion, in service, of the polyester cured parabola.

A series of tests were made on the aluminized film and it was found that 16 hours at 250° F caused the shrinkage rate to be reduced to an almost asymptotic value. The 16 hour treatment at 250° F was therefore used to "pre-shrink" all the film used for later fabrication tests.

For maximum results, the pre-shrinking should take place at 325°F. However, visual examination of the aluminized film heat treated at this temperature indicated a slight decresas in the brilliant luster, so the 250° F temperature was chosen for use.

VACUUM TESTS

All of the above tests of the polyester and epoxy ridigization systems were made with the rigidizing layer maintained at normal room pressure conditions. (The reflective film of course, was pressurized as required to obtain the parabolic shape). With the development of the syntactic foam system a series of tests were made to determine the behavior of each system under vacuum conditions.

The first tests made with either system indicated that, under vacuum conditions, the optical results would be considerably degraded. When rigidization was attempted in the vacuum with the polyester system the volatiles in the resin, plus dissolved air, caused considerable delamination, with resultant degradation of the optical surface. Tests of a syntactic foam covered surface gave approximately the same results, since dissolved air and other volatiles in the foam caused considerable bubbling of the foam. (The foam was de-aerated as much as possible prior to application on the paraboloid).

A number of inflation-pressurization techniques were tried in an effort to impose a back pressure on the laminate or the foam during the cure cycle. None were particularly effective or automatic, until a mechanical back-pressure system was developed. In this system two perforated, non stretched, 1/2 mil polyester film diaphragms were placed over the reinforcing layer when the assembly was in the deflated position. Later, on inflation, the perforated diaphragms acted as mechanical restraints on the laminate at the same time the perforations allowed the volatiles to escape, thus preventing bubbling or delamination. In addition to acting as a back-pressure media the diaphragms were used as parting agents to prevent sticking and/or delamination when the entire structure was packaged. Figure 6 illustrates the back pressure membrane technique.

Another problem brought out when vacuum tests were initiated was the difficulty in maintaining the required curvature during the cure cycle. This was particularly true with the epoxy syntactic foam paraboloid since, as heat was applied, the internal pressure increased and at the same time all the components in the structure softened slightly. Control of the curvature therefore could not be done simply by pressure control. A system was finally developed in which movement of the paraboloid surface actuated solenoid valves which in turn either admitted pressurizing air or vented the paraboloid interior to the vacuum. This control system was based on the use of fixed reference wires, attached to a ring holding the structure, and a sensor contacting the paraboloid's apex. In actual service, of course, another system would probably be used, possibly based on variation of focul length.

With the development of the back pressure membrane and the electrical position sensor it was then possible to prepare the five foot diameter paraboloids of either type and to demonstrate their packaging abilities and the automatic expansion and rigidization techniques.

PACKAGING

The packaging demonstration was made using the syntactic foam reinforced paraboloid, since it was the stiffest and the bulkiest of the two paraboloids. The paraboloid was rolled into an approximately 8 inch diameter roll, 5 1/2

feet long. The rolled up structure had a hollow space 4 inches in diameter into which could be placed air bottles, valves, etc. In the demonstration, illustrated in Figure 7, plant air lines were used, instead of independent air bottles, however. As shown the structure automatically released itself from the container and inflated to full size. The torus pressure used was 2 1/2 psi and the paraboloid pressure was .1 psi (note: as shown in the illustration this was not enough to cause full inflation, since it was desired not to stretch the structure).

PARABOLOID FABRICATION

Two demonstrations were made of the expansion and rigidization capabilities of each system. The first paraboloid demonstrated consisted of the preformed two mil aluminized polyester film and was reinforced with a laminate consisting of seven fiberglass layers and a diallyl phthalate resin. In addition the two unstretched, 1/2 mil perforated back pressure diaphragms were installed. The structure was placed in the altitude chamber, unpressurized, and brought to the correct curvature automatically and maintained at that curvature during the cure period. To cure the polyester laminate eight 40 watt tubular ultraviolet lamps were preinstalled in the chamber. Despite the relatively low powered radiation source the parabola appeared fully cured after a four hour period, at a simulated altitude of 113,000 feet.

The second demonstration paraboloid was a pre-coated epoxy syntactic foam paraboloid. The rigidizing layer of syntactic foam was 0.1 inch thick, and included two 1/2 mil perforated diaphragms. Because the heat could not be applied evenly on this structure it was cured very slowly, the curing cycle was 24 hours during which time the edges of the aprt were gradually raised to 200° F while the center reached 248° F. During this period the curvature also was continually monitored.

In both the demonstrations a good paraboloid was obtained, and as in previous tests, the optical surface of the syntactic foam reinforced paraboloid appeared to be somewhat the better. Figure 8 shows an informal test of the syntactic foam reinforced paraboloid. The weight of the five foot diameter polyester paraboloid was 7.88 lb, with a unit weight of 0.40 lb per sq ft. The epoxy paraboloid weighed 8.11 lb, with a unit weight of 0.42 lb per sq ft.

After removal of the paraboloids from the forming fixture it was found that neither type was rigid enough for mounting on an optical test fixture at the three specified points, without gross distortions in curvature. The lack of rigidity in each case was due to the weight of the structure, since when the paraboloid was uniformly supported on the edges, by being placed on a table, each structure appeared uniformly curved. To correct this weakness, a light ring of epoxy impregnated glass braid was bonded to each structure. This produced the necessary rigidity.

In addition to preparation of the required five foot diameter paraboloids, several other paraboloids were prepared during the course of checking out the equipment, determining the cure procedure, etc. From these test paraboloids, physical test specimens were cut so that a quantitative measure of the physical properties might be obtained. The results of these tests are shown below in Table 1.

Physical Properties of Rigidization Layers

Test Type	Temp. °F	Epoxy Str., psi	Foam Mod., psi	Polyester Str., psi	Laminate Mod., psi
Tensile	72	593	336,000	13,300	655,000
Tensile	240	282	143,000	4,460	156,000
Flexural	72	721	-	17,000	-
Flexural	240	518	-	299	-
Edgewise	72	625	-	593	189,000
Compression	240	140	89,600	335	-

TABLE 1

The values shown in Table 1 are very low in comparison to laminates made under normal pressurization conditions. For the purpose intended, however, the strengths appear to be adequate.

Two specimens approximately 2 1/2 x 4 inches of each material were placed in quartz vacuum chambers to determine the effects of high vacuum and infrared and ultraviolet radiation. Each specimen had a small thermocouple mounted on the rear (non-aluminized surface) with the junction imbedded in the specimen, in contact with the aluminized surface.

The samples were maintained at a vacuum of approximately 10^{-6} mm Hg for 240 hours. The surface temperatures were maintained at 180° F using five infrared heating lamps. (This was the maximum temperature which could be obtained.) The ultraviolet lamp (in the housing) maintained one solar equivalent radiation on the samples for the duration of the test. After the exposure period the samples were tested for loss of weight and change in physical appearance. The loss in weight amounted to approximately 4 1/2 percent for the epoxy and 7.0 percent for the polyester samples. There was no apparent change in the appearance of the epoxy reinforced samples. The polyester samples, however, showed a small amount of surface wrinkling, due no doubt to degradation of the polysulfide gel coat.

A number of tests were also made to determine the optical characteristics of the completed paraboloids. The reflectivity of the polyester paraboloids averaged 79.3 percent while that of the epoxy foam paraboloids averaged 82.0 percent. Surface angular deviations and axis intercepts were also determined on the paraboloids made at the simulated 113,000 ft altitude. The results indicated that the surfaces were generally parabolic, but with some astigmatism present. The surface angular deviation from a true paraboloid was within ± 1.0° for both structures.

Calorimeter tests were also made to determine the efficiency of the completed paraboloids. A water cooled calorimeter with various sized asbestos aperture plates was used. The ambient solar flux was monitored with an Eppley pyrheliometer. Figure 9 illustrates the test setup. The results of the tests indicated that the epoxy paraboloid had an efficienty of 45 percent at an area ratio of 900 and an efficiency of 19 percent at an area ratio of approximately 6500. The polyester reinforced paraboloid had an efficiency of 41 percent at an area ratio of 900 and an efficiency of 27 percent at an area ratio of 3600.

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2. "Final Report - Space Structure Rigidization," Hughes Aircraft Company, Report P 61-13, Sept. 1961

3. S. Schwartz and J. P. Bagby "Rigidized Inflatable Solar Energy Concentrators," Hughes Aircraft Company Report P 64-123, Dec 64

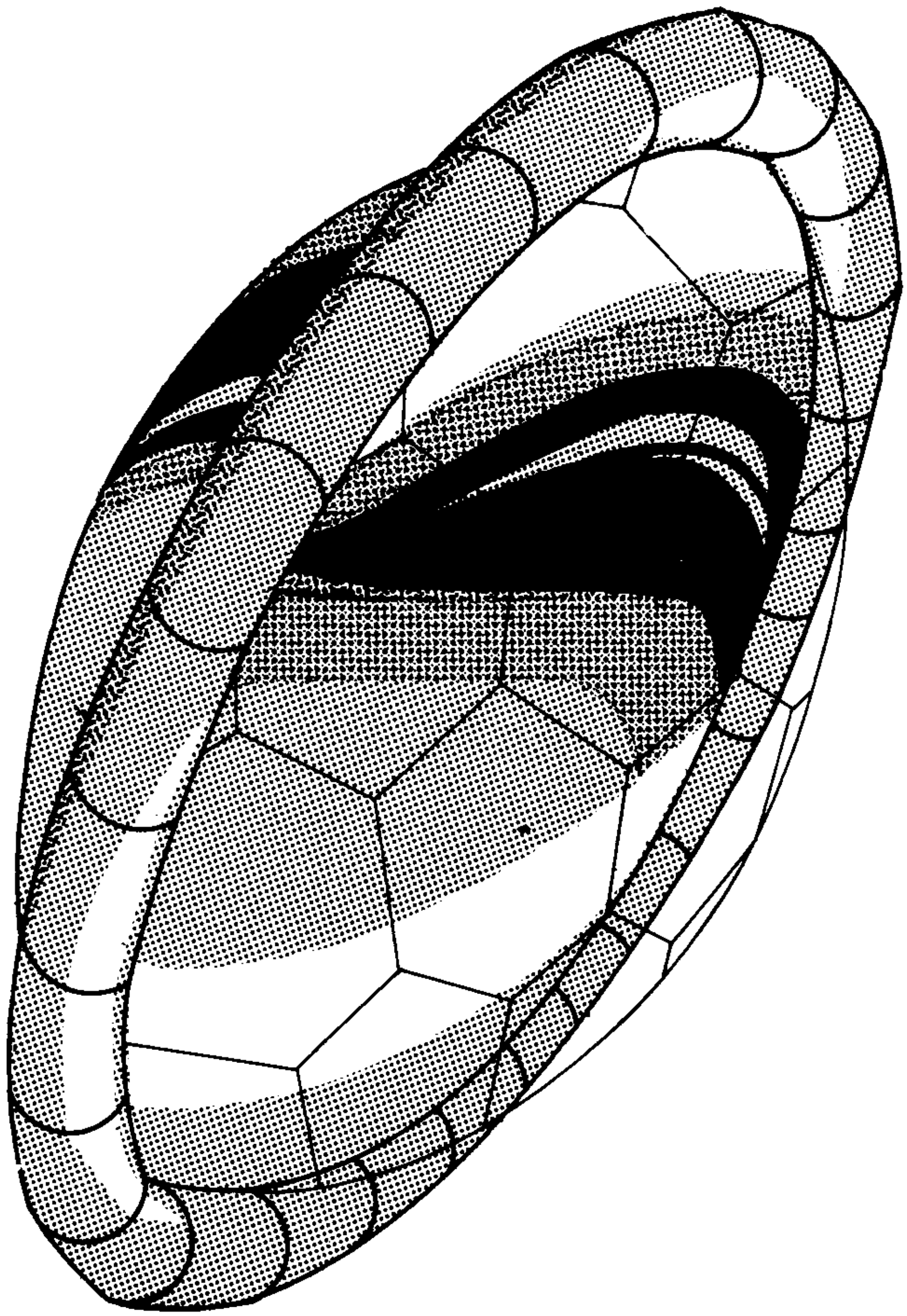

Figure 1. General Configuration of Solar Concentrator

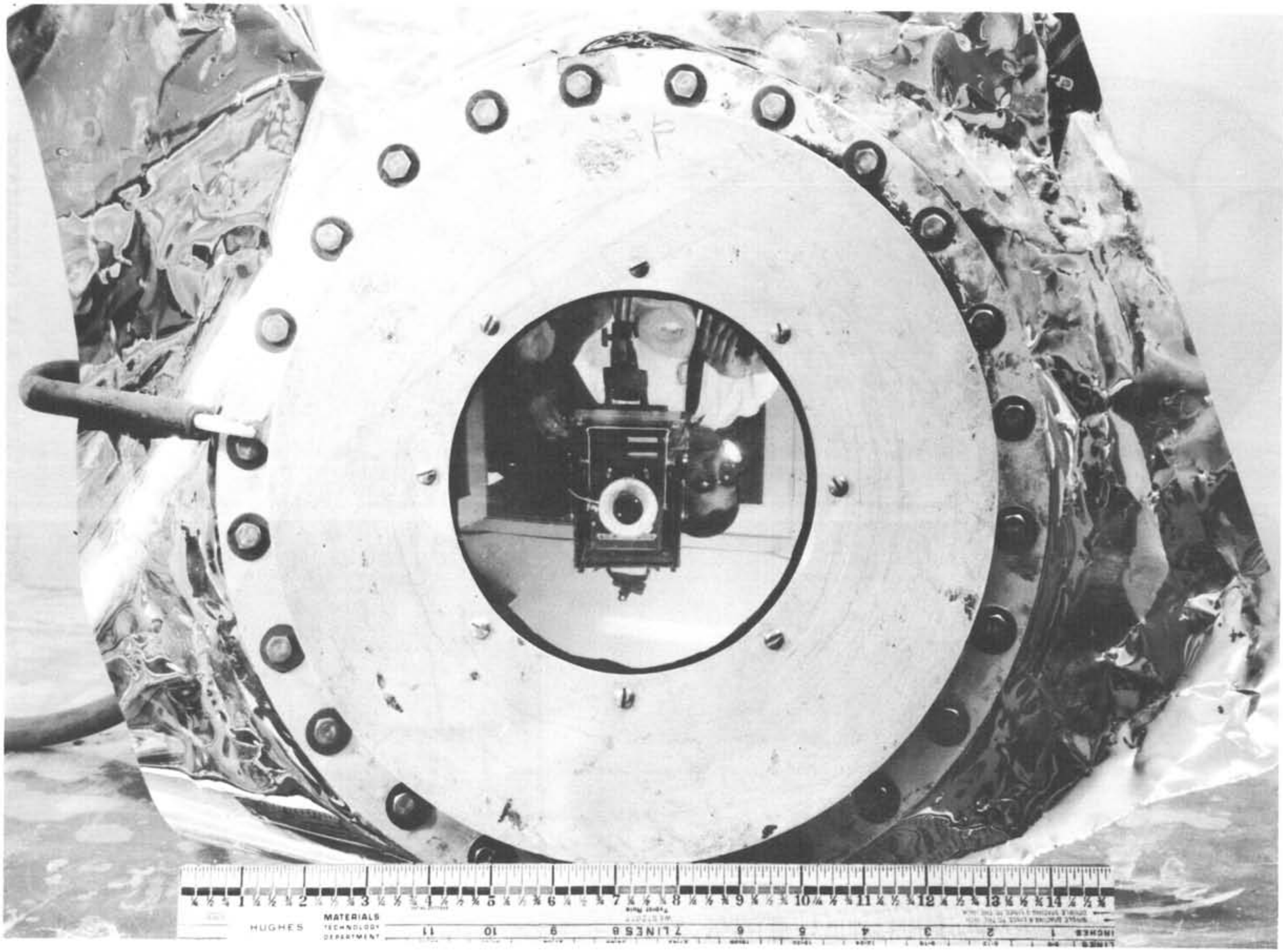

Figure 2. Reflectivity of Inflated Aluminized Film

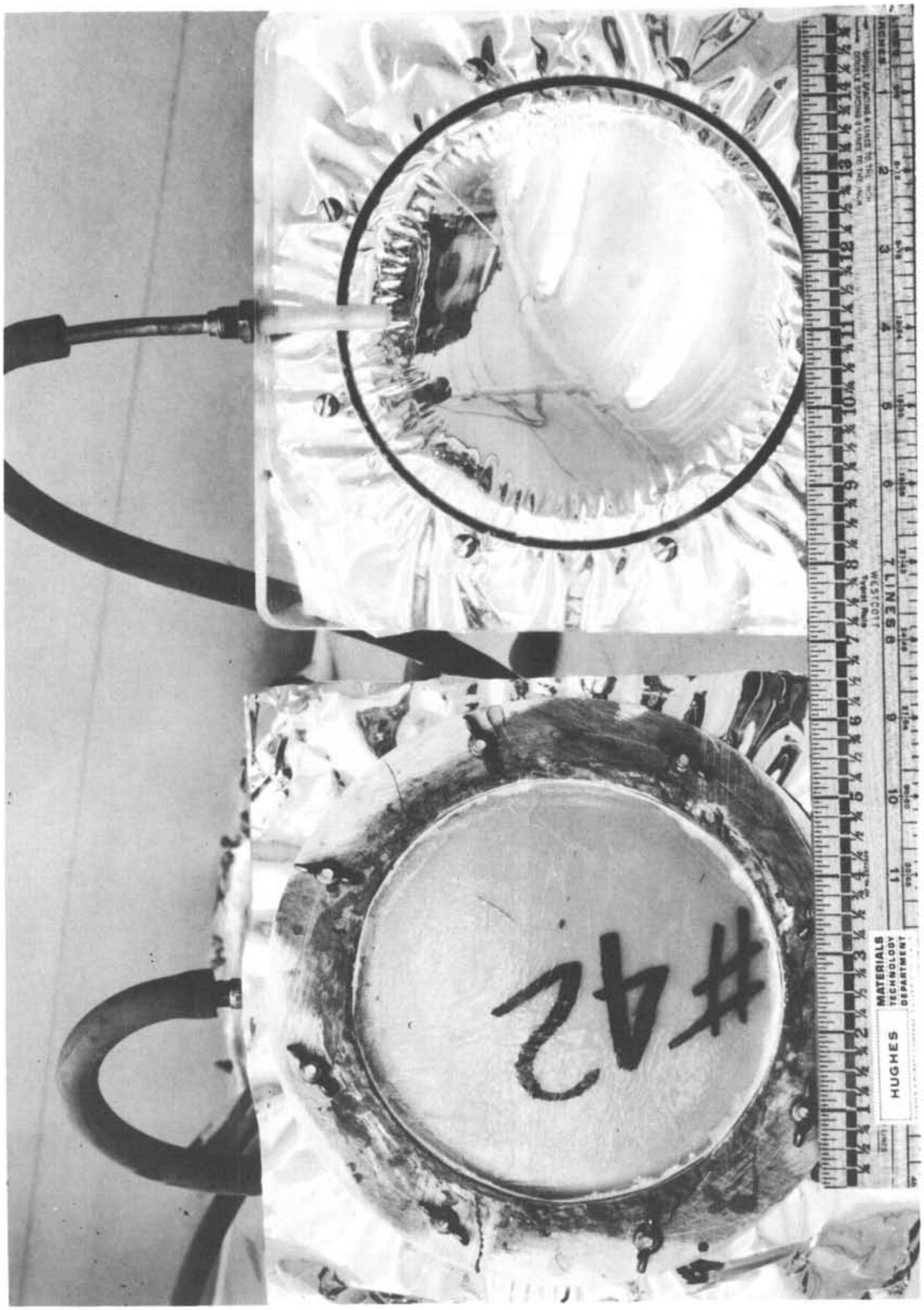

Figure 3. Small, Transparent Acrylic Forming Fixtures

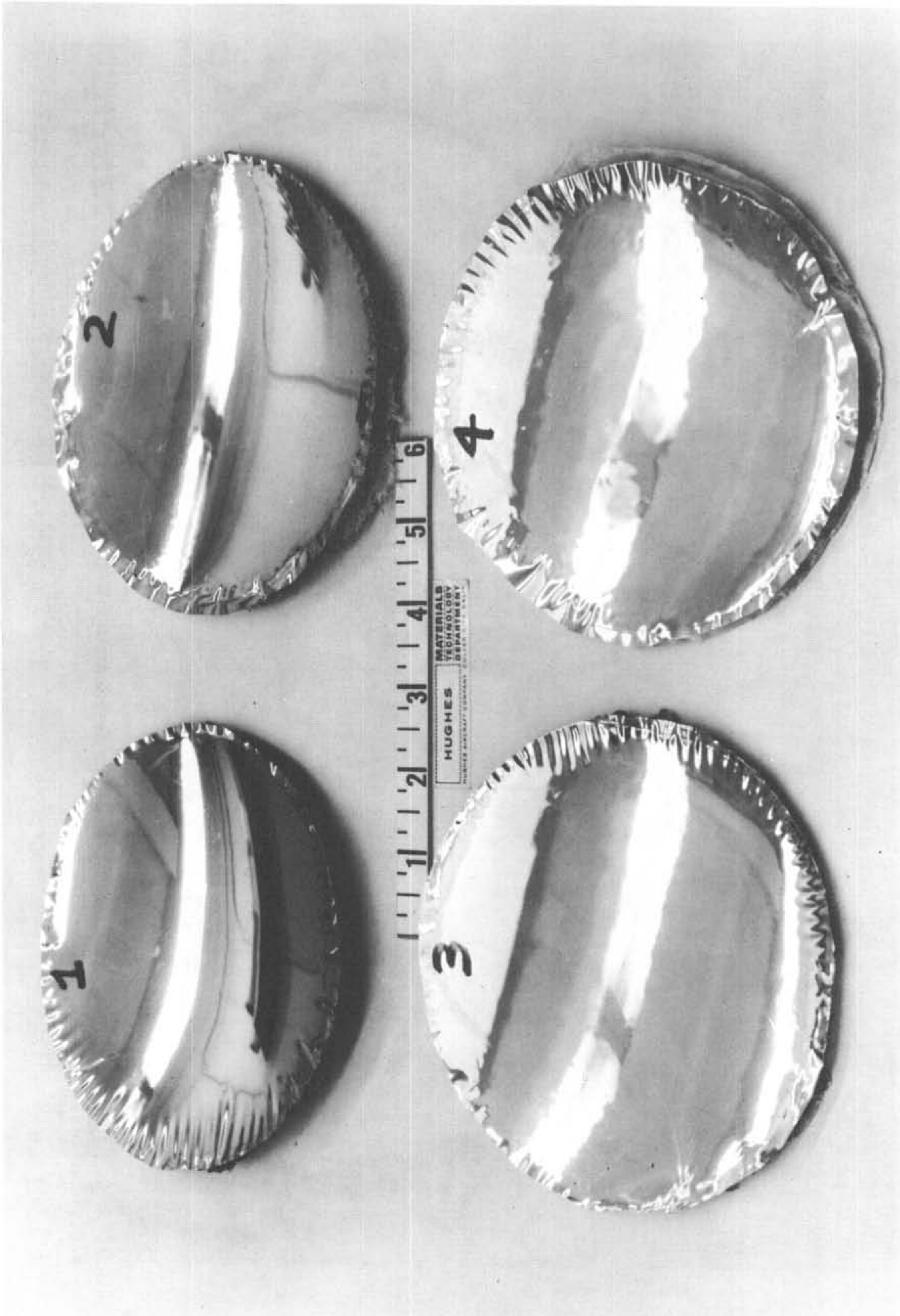

Figure 4. Comparisons of Optical Quality of Polyester vs Epoxy Rigidized Paraboloids

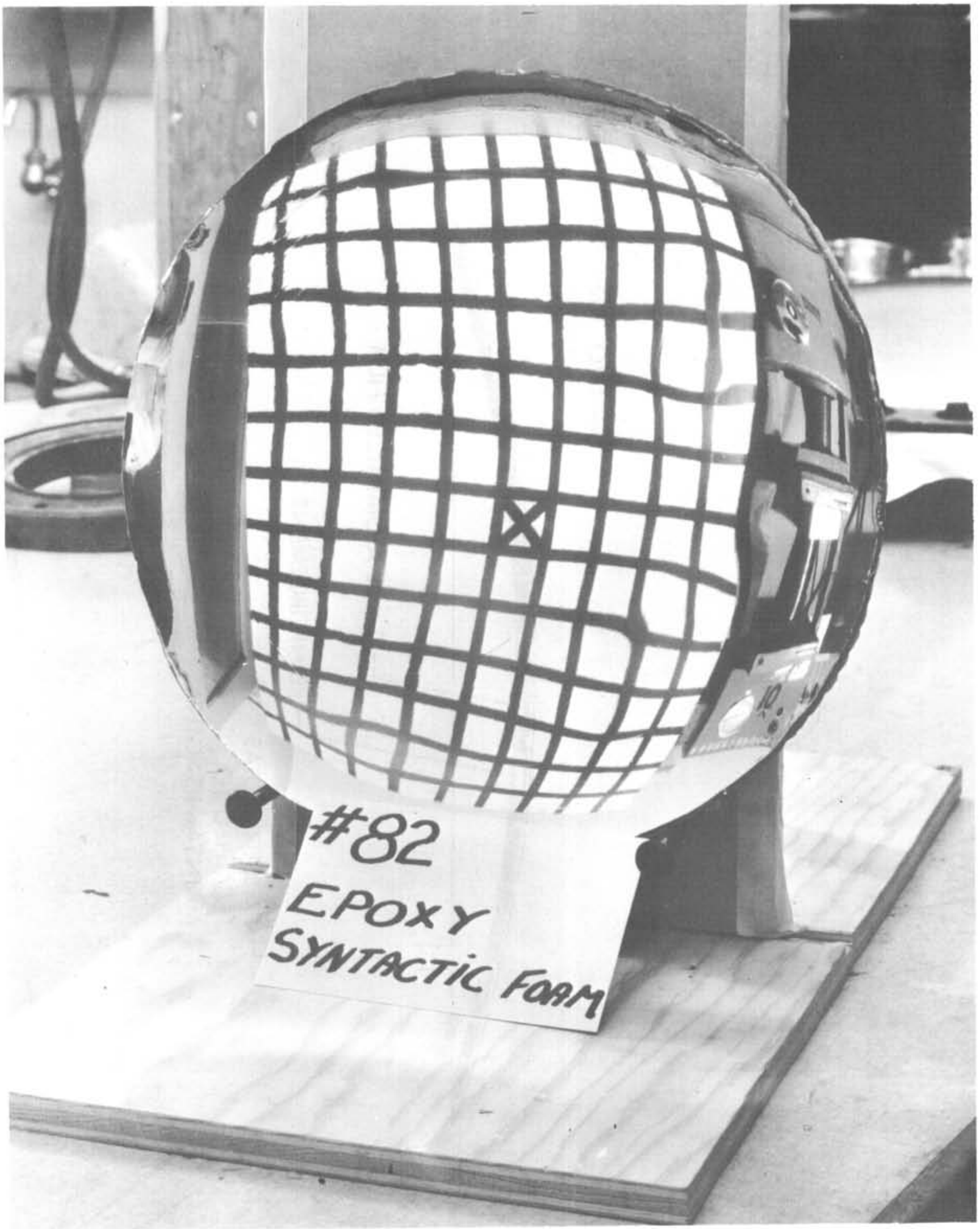

Figure 5. Two-Foot Diameter Parabola Rigidized with Epoxy Syntactic Foam

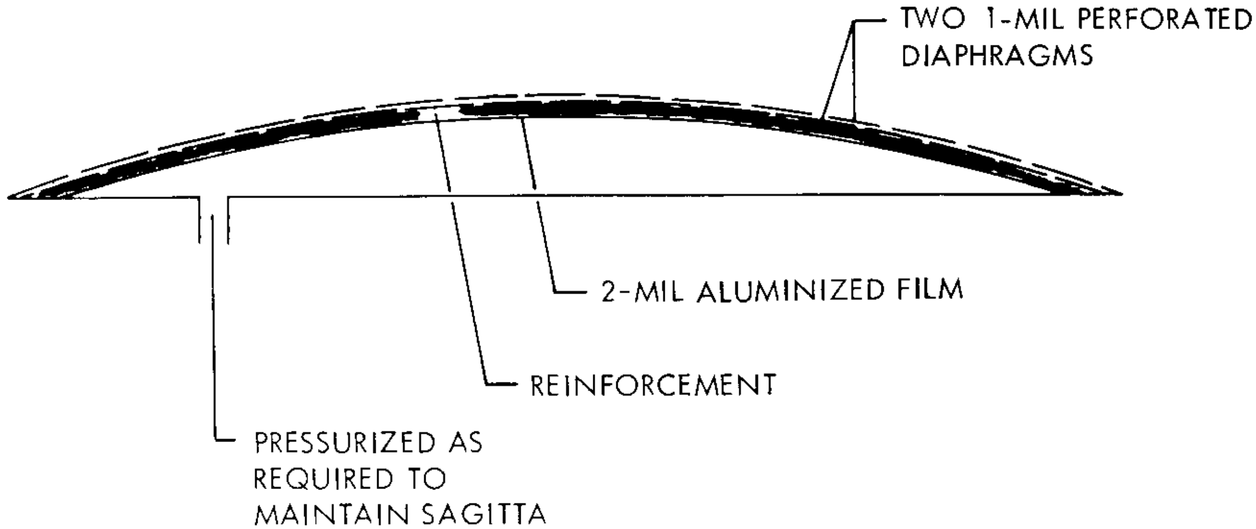

Figure 6. "Back Pressure" Membranes

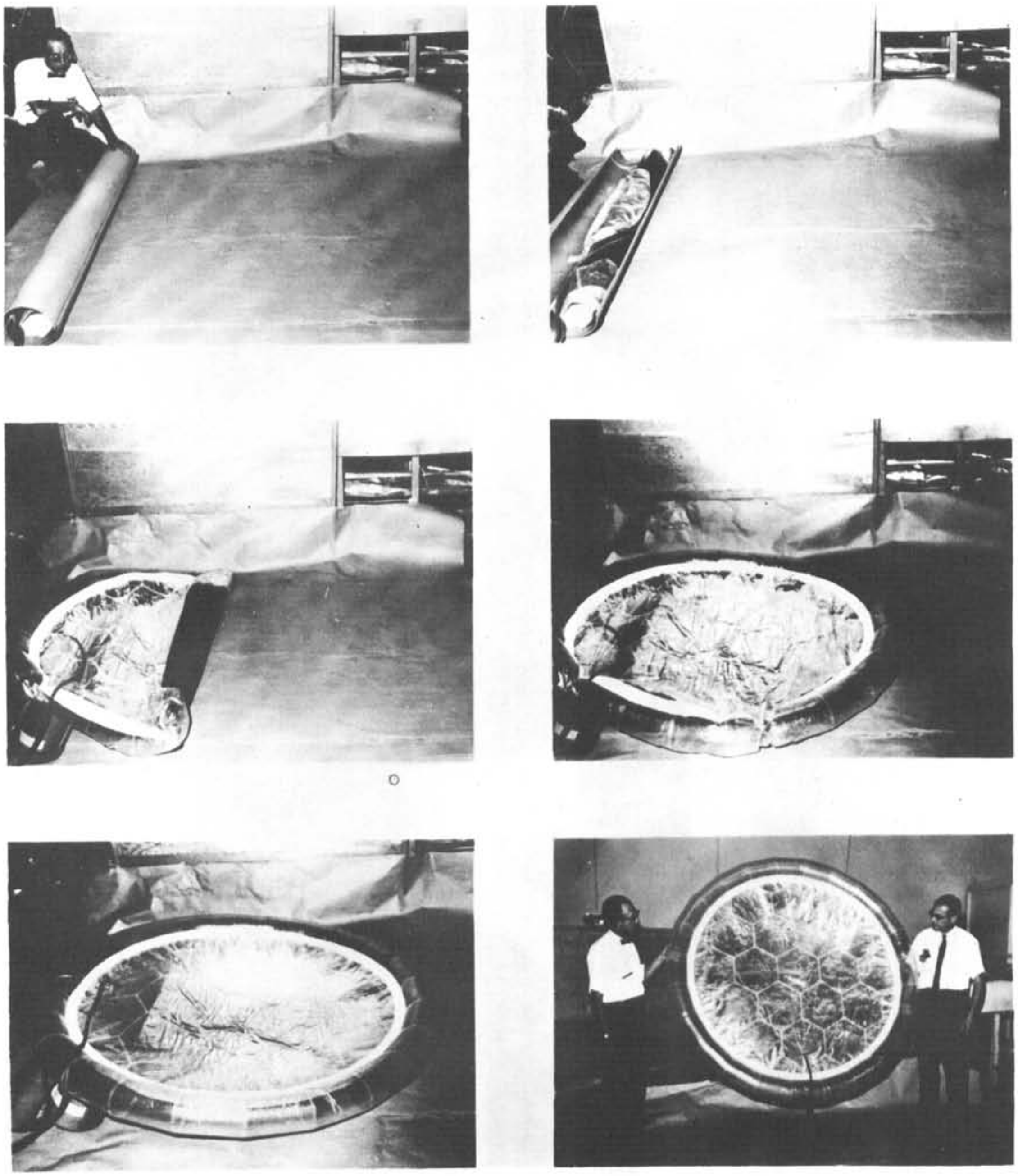

Figure 7 Packaging Sequence

Figure 8 Foam Reinforced Paraboloid

Figure 9 Test Set-up for Determining Calorimetric Efficiency