NASA CONTRACTOR REPORT

NASA CR-254

NASA CR-254

N65-27947
(ACCESSION NUMBER)
91
(PAGES)
(NASA CR OR TMX OR AD NUMBER)
/
(THRU)
(CODE)
63
(CATEGORY)
FACILITY FORM 602

RIGIDIZED INFLATABLE SOLAR ENERGY CONCENTRATORS

by S. Schwartz and J. Bagby

GPO PRICE $
CFSTI
~~OTS~~ PRICE(S) $ 3.00

Hard copy (HC) [redacted]

Microfiche (MF)

Prepared under Contract No. NAS 1-3244 *by*
HUGHES AIRCRAFT COMPANY
Culver City, Calif.
for

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

NASA CR-254

RIGIDIZED INFLATABLE SOLAR ENERGY CONCENTRATORS

By S. Schwartz and J. Bagby

Prepared under Contract No. NAS 1-3244 by
HUGHES AIRCRAFT COMPANY
Culver City, Calif.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $3.00

FOREWORD

This report was prepared by Hughes Aircraft Company as one phase of NASA contract NAS 1-3244, "Rigidized Inflatable Solar Energy Collectors." The work was administered under the direction of the Structures Research Division, Langley Research Center, National Aeronautics and Space Administration, with Mr. Atwood Heath as project engineer.

This report covers work from 1 August 1963 to 25 December 1964.

ABSTRACT

27947

~~This report describes~~ the development of two processes for fabrication in a space environment of five-foot diameter inflatable, rigidizable solar energy concentrators is described. The reflective surface of each concentrator was two-mil aluminized polyester film formed to the desired paraboloidal shape by the Hughes stress-relaxation process, which does not require a master tool. One process uses an ultra-violet activated polyester-fiberglass laminate for rigidization. The other process uses an epoxy syntactic foam activated by infrared radiation. Prior to rigidization either type of concentrator can be packed in a small volume.

A demonstration was made in which a precoated paraboloid of each type was erected and rigidized in vacuum. The ability to package either paraboloid in a small volume and then to automatically eject and expand it to shape was also demonstrated.

Tests were run on samples of rigidized material and on five-foot paraboloids. Physical property tests run on samples of each rigidized material included mechanical and thermal tests. Optical and calorimetric tests were made on a five-foot paraboloid of each type. Both structures were found to be near paraboloids with efficiencies of 40 to 45% at area ratios of 900. The target weight of 0.4 lb per sq. ft. and reflectivities of 80% were achieved.

author

CONTENTS

CONTENTS (Cont'd)

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

TABLES

INTRODUCTION

The use of inflatable solar concentrators in space programs requires 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 NAS 1-3244, undertook to develop the techniques and produce concentrators that would meet the following general requirements. The concentrator could be packaged 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 ultra-violet 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 developed 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.

Also covered in this report are the experimentation and testing which resulted in satisfactory solutions to these problems and produced satisfactory concentrators. It describes preliminary tests on the use of polyester-fiberglass laminate as a rigidizing material, gel coat investigations for improving film-polyester resin adhesion and experimentation on polyester-fiberglass laminate and syntactic foam rigidizers. It also describes polyester film studies, developmental work on paraboloid fabrication and demonstrations of concentrator erection and rigidization in a space environment. Finally the report presents recommendations for additional work directed at optimizing the fabrication of space inflatable concentrators.

EXPERIMENTAL PROCEDURE

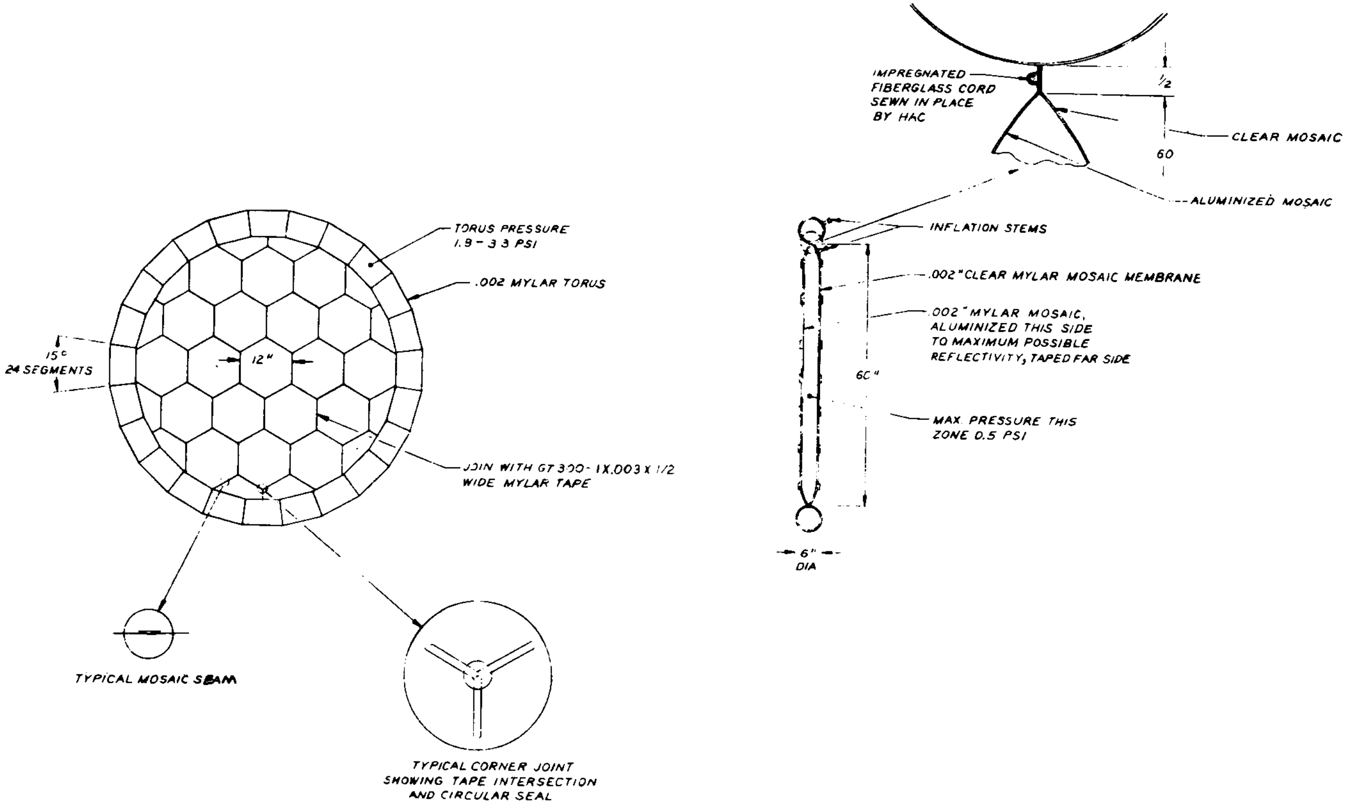
CONCENTRATOR DESIGN

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. A clear "photolyzable" film recently developed could not be used as originally planned because raw stock was not available when needed.

As shown in 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 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. In addition to complete assemblies, a number of five-foot diameter mosaic membranes, made of 2-mil aluminized film, were also ordered. The torus assemblies



IF 5 FT FLAT HEX MEMBRANES ARE FURNISHED <u>SEPARATELY</u> FROM TORII, THEN THERE MUST BE AN EXTRA 2 IN. ON THE RADIUS SO THAT THE O.D. OF THE HEX MOSAIC MEMBRANES ARE 64 IN. IN THIS CASE THE BASIC HEX SIZE SHOULD REMAIN 12 IN. AS SHOWN ABOVE, AS THE EXTRA 2 IN. LIP IS FOR CLAMPING ONLY.

Figure 1. Print showing construction of mosaics and paraboloid assemblies.

attached to the paraboloids were also made of 2-mil polyester film, since preliminary stress-calculations indicated such a torus, inflated to approximately 2.5 psi would not buckle when acted upon by the internal pressure of 0.5 psi needed to form the paraboloid.

TOOLING FIXTURES

The first samples, made to test gel coats, were one-foot diameter paraboloids made as simple diaphragms in an aluminum fixture shown in Figure 2. After fabrication of the first few samples, with relatively poor optics, it was realized that using this fixture it was impossible to tell at what stage the optics deteriorated. Accordingly an acrylic window was built into the bottom plate of the fixture as shown in Figure 3. This window made it possible to examine the concave aluminized surface of the film and observe changes in the surface condition on application of each coating. This was of great value in determining the fabrication technique which would produce the best optics.

With only one fixture it took several days to fabricate each test sample, since all coatings were being cured at room temperature. Therefore, to accelerate sample production, three more small test jigs were built to make six-inch diameter samples. As shown in Figure 4 these fixtures were made using an acrylic block, an "O" ring and an aluminum clamp ring. Their use provided a clear view of the inner surface and made it possible to immediately observe the effect of every coat applied. Enough jigs were made to test a number of fabrication variations concurrently.

In addition to the improved small fixtures, a 24-inch and a five-foot diameter fixture were constructed. Both of these fixtures also have viewing ports.

POLYESTER REINFORCED PARABOLOIDS

Preliminary Tests

The technique used in forming the paraboloid was developed to eliminate the need for using a form in fabricating very large paraboloids. In this method, known as the stress-relaxation process, a film

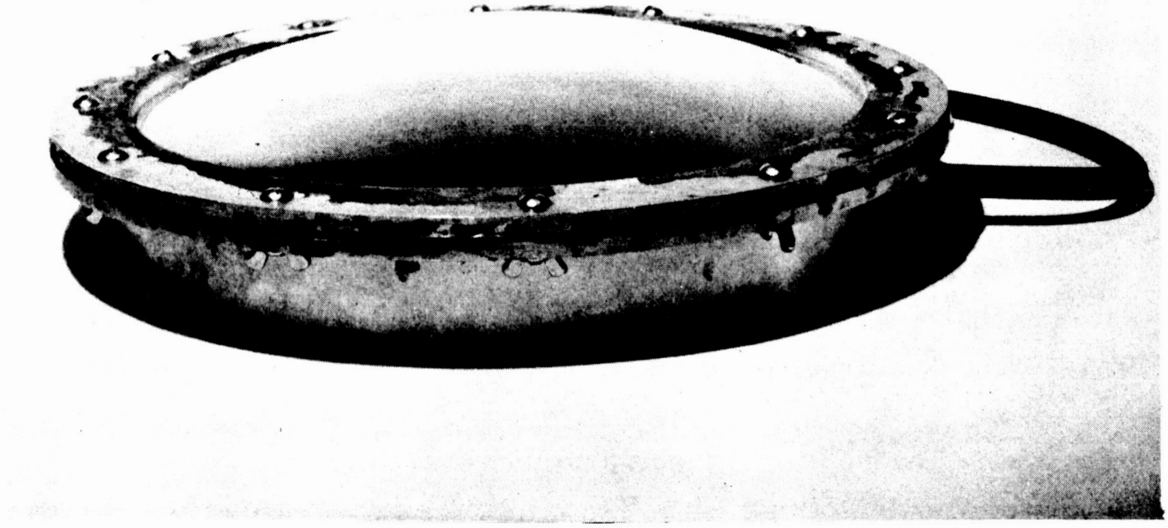


Figure 2. One-foot diameter forming fixture.

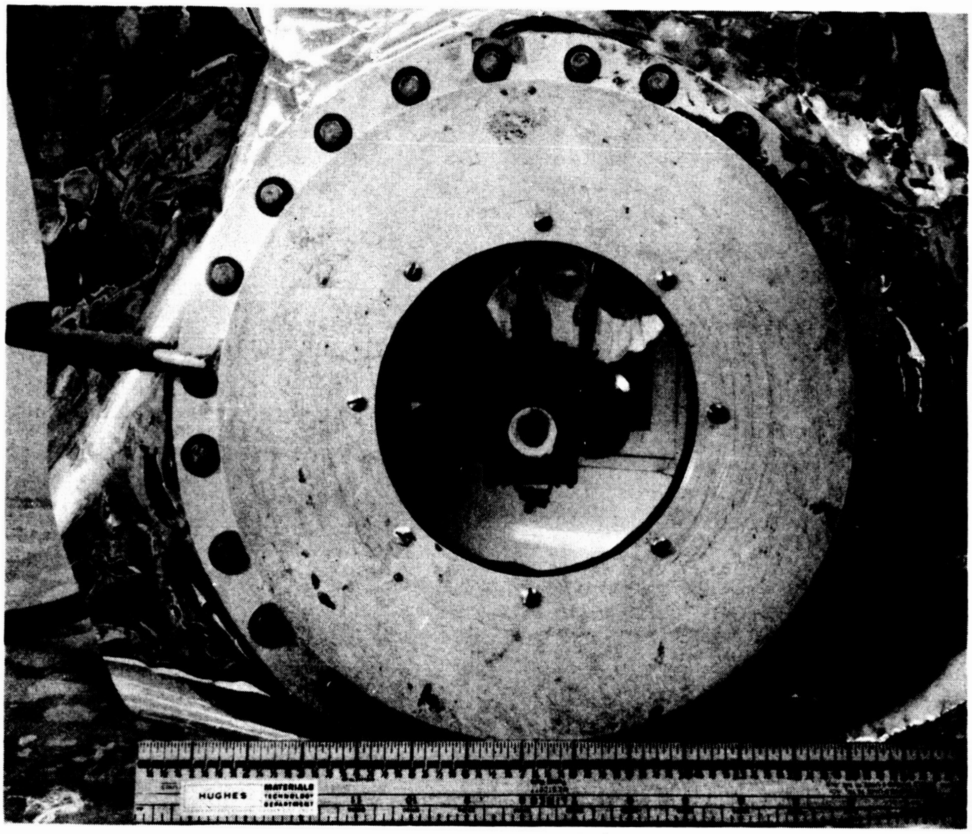


Figure 3. Window in the 12-inch diameter fixture.

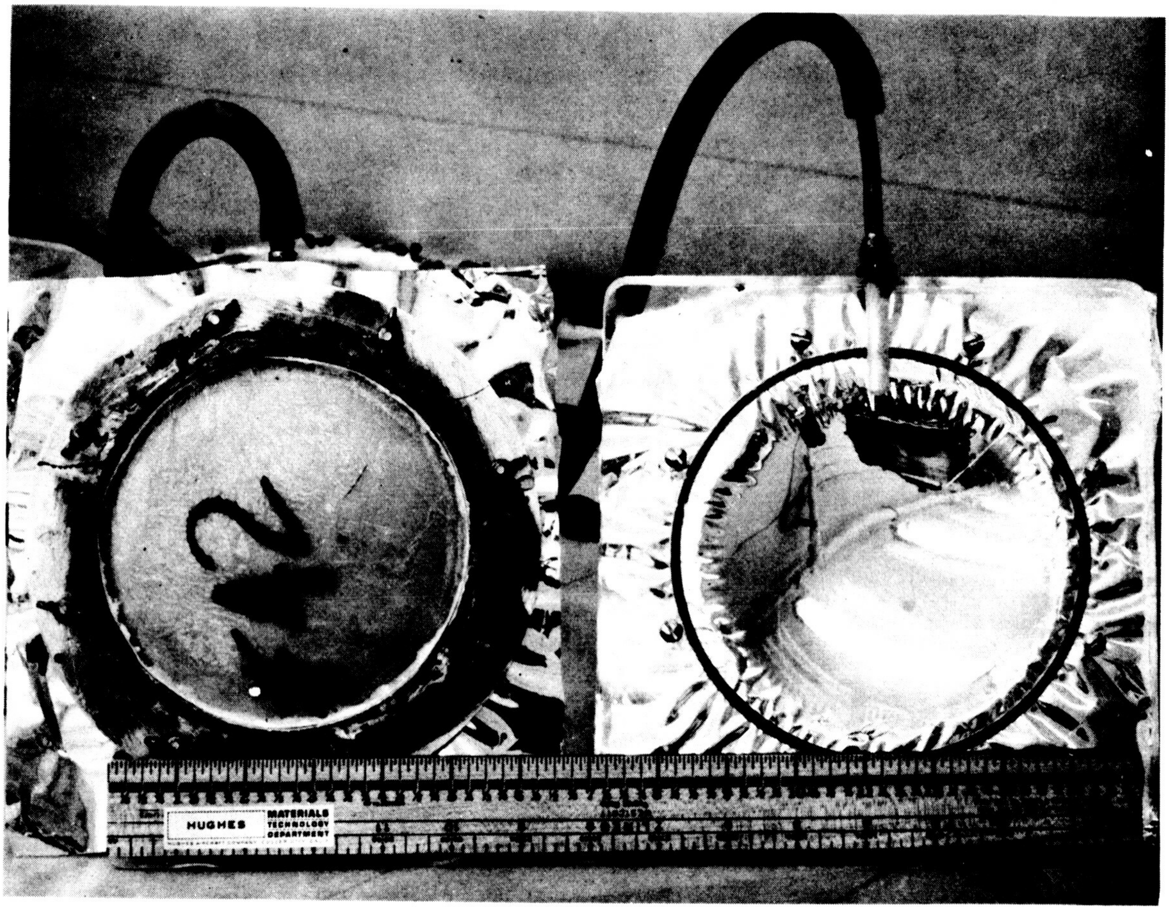


Figure 4. Transparent six-inch diameter fixtures, showing both surfaces of part.

membrane is first stressed, in a fixture by internal pressurization, to a curvature in excess of the final value required. The membrane is kept in the "overstretched" condition for a short period of time. The pressure is then released. On repressurizing to a known, experimentally determined lower value, the membrane assumes the desired parabolic curvature. The rigidizing layer is then applied to the convex surface of the film after the initial stretching. Rigidization then takes place while the membrane is maintained at the lower pressure.

The first exploratory tests were made with a one-foot diameter fixture and 2-mil aluminized film. The initial pressure of 105 mm Hg was followed with a relaxed pressure of 80 mm Hg. A six-layer #112 glass fabric-polyester resin laminate was applied to the convex surface of the film and allowed to cure at room temperature and pressure. When the rigidized part was removed from the fixture, residual stresses in the film caused severe overall distortion and the film delaminated extensively from the backing. Moreover, where delamination did not take place, the optical surface was relatively poor. That this distortion is due to stresses in the film is shown conclusively by the fact that when the film was removed completely from the polyester laminate, the laminate regained its original paraboloidal shape and showed very little sign of distortion.

Additional tests indicated that initial stressing to 205 mm Hg and a relaxation to 62 mm Hg would also result in the desired paraboloid. A second laminate made in this manner showed slightly less distortion, slightly less delamination, and an equally poor surface. These tests did, however, demonstrate the necessity for using the lowest possible relaxation pressure during rigidization.

The results of the preliminary tests then indicated that there were considerably more stresses in the film than had been anticipated, as evidenced by the distortion of the rigidized paraboloid upon removal from the jig. The poor adhesion of the film to the rigidizing layer was not unexpected since this type of film is normally a parting agent and polyester resins usually exhibit poor adhesion.

While the use of a thicker laminate would help reduce distortion, it was decided to use a circular rim around the paraboloid for this purpose. This decision was based on experience with laminates of different thickness and on tests in which the circular rim was used.

Gel Coat Investigations

Preliminary Survey. Since the initial tests showed the need for improved adhesion between the film and the reinforcing laminate the efforts were directed toward this objective. It was believed that the best method of improving the adhesion to the film, and also the optical surface, would be to provide an intermediate coating or coatings between the film and the polyester. Such a coating, or coating combination, would act as a primer coat to improve the adhesion and at the same time, if thick enough, act as a gel coat to compensate for the shrinkage effects of the polyester-fiberglass laminate. In the event that the gel coat functioned as conventional gel coats do with polyester laminates then the optical properties would be improved.

The required properties for a primer-gel coat combination are (1) good adhesion to the polyester film and to the polyester resin, (2) good flexibility in the cured state, (3) ability to be spread in a fairly thick, even coating, and (4) resistance to the space environment. Desirable, but not absolutely necessary, is the ability to dry or cure at room temperature.

Once these requirements were established a number of materials were tested. These materials included urethanes, modified polyester adhesives, modified synthetic rubber, a flexible epoxy, a flexible polyester, a silicone RTV rubber, and several polysulfides. In all cases the coatings were tested first for their efficiency in adhering to the polyester film and then as undercoats for the polyester laminate. In some cases, where a coating showed promise as a film adhesive, but could not be built up sufficiently to function as a good gel coat, a combination of two coatings was tested. The materials tested and the results secured are shown in Table I.

Material	Adhesion		Optical	Remarks
	Mylar	Polyester	Surface	
Urethane No. 1	Good	Poor	Poor	Difficult to spread to an even thick film by brush. Sprayed well.
RTV Silicone	Good	Poor	Fair	Easy to make an even film by spraying. Low film strength.
Urethane No. 2	Poor	Poor	Fair	Easy to make a good film by brush or spray.
Polyester No. 1	Fair	Poor	Poor	Spreads to an even film by brush. Sprays well.
Polyester No. 2	Good	Fair	Fair	Somewhat difficult to apply by brush. Sprays well. Attacked by polyester.
Synthetic Rubber	Good	Poor	Poor	Brushes on well. Sprays well. Attacked by polyester.
Flex. Epoxy	Poor	Fair	Fair	Not too flexible. Used silica filler to reduce shrinkage.
Flex. Polyester	Poor	Poor		Not too flexible. Used silica filler to reduce shrinkage.
Polysulfide No. 1	Good	Fair	Fair to Poor	Material spread well.
Polysulfide No. 2	Good	Good*	Good	Material spread well. Cured very slowly.
Polysulfide No. 3	Good	Good*	Good	Material spread well. Cured nicely in 24 hours.
Polysulfide No. 4	Good	Good*	Fair to Good	Material spread very well. Cured well in 24 hours.

*Mechanical fabric "lock" coat was used.

Table I. Primer-gel coat test results.

As shown in Table I there were only a few materials which met the requirements described above. Some of the first materials that appeared promising were the two adhesives based on polyester resins. Both of these materials showed good adhesion to the film, however bonding was very inconsistent between the polyester laminate and either coating. Tests showed that both materials were attacked by the styrene in the wet polyester laminate. In an effort to correct the deficiencies, these materials were applied as thin primer coats, and then thicker coats of either urethane, flexible epoxy or the polysulfide were applied to act as a gel coat. In no case was really good polyester laminate adhesion secured. Figure 5 shows typical delamination of a primer and gel coated film from the polyester laminate. In this case

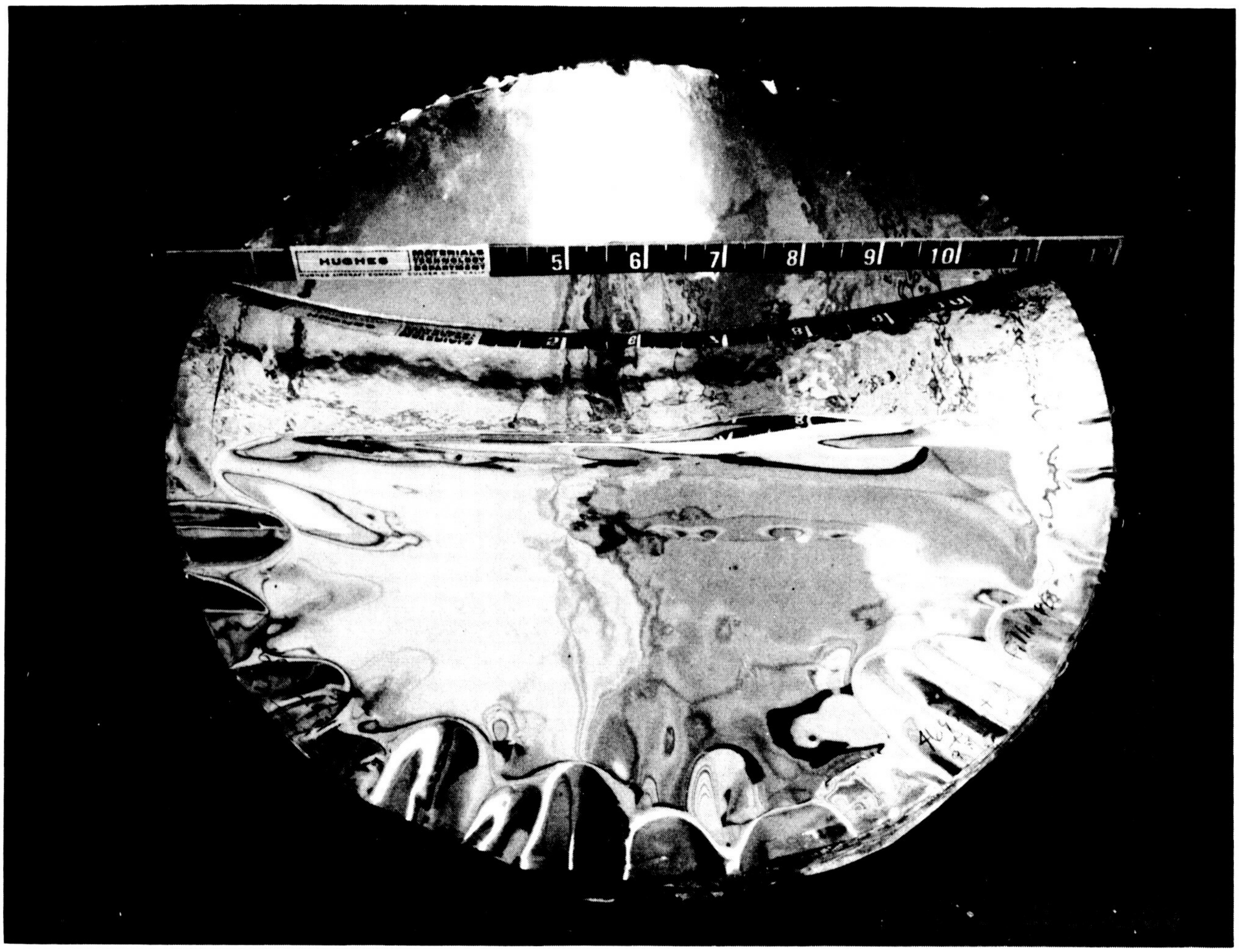


Figure 5. Typical film-polyester delamination.

the entire convex surface of the film was coated with a layer of polyester adhesive #1 and then one-half of the surface was coated with urethane coating #2 as a gel coat. On removal from the forming fixture delamination commenced immediately. The urethane coated surface delaminated as shown in several hours.

Polysulfides. The preliminary tests demonstrated the need for a gel coat. It serves as a primer to improve adhesion of the polyester-fiberglass laminate reinforcement and helps compensate for the shrinkage effects of the polyester resin. In testing a number of different types of materials for use as gel coats, the polysulfide based coatings appeared superior in their adhesion to the polyester film and in flexibility. It was therefore decided to retest these materials using the transparent fixtures. A number of other coating materials were also procured or prepared for comparison testing.

Each material was tested by brushing one coat or spraying four thin coats on the outer surface of a six-inch diameter inflated diaphragm. Using the transparent test fixtures, the optical properties of each coating were observed as the material cured. The optics proved uniformly good except in the case of several heavily applied brush coats. On these heavy coatings, slight optical distortions in the form of brush marks were evidenced. Tests using one- and two-foot inflated diaphragms showed similar results.

All the tests indicated that with the exception of heavy brushed coats, the polysulfide gel coats produced very little distortion. Moreover there was little difference between any of the polysulfide coatings. Each appeared to have good adhesion to the film and showed good flexibility when cured. Adhesion to the polyester resin, however, was only fair to poor. It could be improved by using a fabric "lock" coat as was demonstrated in tests described later in this report. The various properties did differ somewhat in initial viscosity and general workability. In these respects, polysulfide coating #3 proved best. However, polysulfide coating #2 appeared to have somewhat better adhesion, and therefore it was used in all following tests.

Epoxy-Polyamides. Since the polysulfides did not prove entirely satisfactory from the standpoint of adhesion to the polyester layer, several epoxy-polyamide mixtures were tested. The first mixture tested was as follows:

Epoxy Resin	30 pts
Polyamide	70 pts
Pyrogenic Silica	5 pts

Fair to good adhesion to the film was achieved and adhesion to the polyester was fair. The optical surface, however, was poor. The surface, while not showing a fabric pattern, did have a fine "orange peel" effect. A 50-50 epoxy-polyamide mixture was somewhat less flexible than the 70-30 mixture, but did show a finer "orange peel" surface. Later samples using 40 parts of epoxy resin to 60 parts of polyamide produced optics that were approximately the same or slightly superior to those of the 50-50 mixture. These later samples, however, were not as brittle as the former and could be rolled up for storage when necessary.

Epoxy-Polysulfides. Gel coats were also made with epoxy-polysulfide mixtures. The initial mixture consisted of:

Epoxy Resin	100 pts
Polysulfide	50 pts
Diethylenetriamine	8 pts

Adhesion to the polyester was good and the surface optics using the above formulation were at first quite satisfactory. However, after three days of room temperature curing, with the diaphragm under pressure, a good deal of patternless distortion appeared. Moreover, the optics of the completed polyester-fiberglass paraboloid were quite poor.

In an effort to improve the epoxy-polysulfide gel coat optics 325 mesh silica powder was added to the previous mixture in the ratio of 2 parts of resin mixture to one part of silica. This improved the optics considerably but the cured mixture was much too stiff and brittle to be used. This effort did emphasize the fact that heavily filled coatings have less shrinkage and less distortion than unfilled coatings.

Urethanes. A new urethane elastomeric gel coat material was also tested. A 10-mil application produced only fair optics. Adhesion to the film surface was inferior to the polysulfides in that the coating could be readily peeled off. Also, adhesion to the polyester was only fair. No further work was done with this material.

Polyesters. One of the drawbacks to the use of a heavy gel coat is the additional weight involved. A series of tests were therefore made to determine if the need for a separate gel coat could be eliminated by using a fully cured, single layer, glass fabric laminate that could serve as its own gel coat. The intent was to obtain a hard,tough layer which would still be flexible after curing because of its thinness and the natural flexibility of the cloth reinforcement.

The tests unfortunately did not produce favorable results. The film was primed with polyester base adhesive #2. It was then covered with a single layer of polyester impregnated #103 (0.001-inch thick) fiberglass fabric. The cured samples were indeed very flexible and showed very little evidence of distortion as long as the pressures were kept constant. However, when the pressure was reduced, distortion appeared. On repressurization to the identical pressure used for curing, however, no or very little distortion could be seen. Unfortunately, when additional layers of impregnated #103 fabric were added, distortion immediately commenced with the onset of gelation.

The explanation for this distortion appears to lie in shrinkage stresses. It is surmised that in curing, the polyester resin inevitably shrinks. However, when only one layer is present, the shrinkage stresses are not high enough to overcome the pressurization stresses. Therefore distortion does not show up until the pressure is released. On the other hand, with several layers of polyester-fiberglass, there is enough stress to produce readily visible distortion even when the diaphragm is pressurized.

"Lock" Coat Tests

Since it appeared that satisfactory adhesion could not be obtained between the wet polyester lay-up and any of the gel coats, it was decided to test a mechanical "locking" system. In the first tests a synthetic rubber coating was applied to the aluminized film. When this coating was partially dried, a layer of #181 glass fabric was laid on its surface. After a number of tests, to determine the right time for fabric application, it was found possible to so apply the fabric that its bottom surface adhered firmly to the adhesive coating, while its top surface remained dry and unimpregnated. After the underlying coating was completely cured, the glass fabric was impregnated with a brush coat of the filled polyester resin. Two more layers of polyester resin impregnated glass fabric were then applied. Figure 6 shows the resulting configuration. The adhesion resulting from use of this technique was considerably better than had been secured previously. Adhesion of the polyester laminate to the underlying substrate was good in almost all cases.

The application of a smooth, dry glass fabric layer to a tacky surface proved to be quite difficult. Therefore a series of tests were made to determine if the solvent dried adhesives (polyesters and rubber base) could be reactivated by simply brushing acetone over dry fabric placed on a dried coating. This technique was found to work very well. However, as previously stated inconsistent results were secured when the polyester laminate was applied. The cause was eventually traced to the attack on the adhesive by the styrene in the polyester used. Work on these adhesives was therefore discontinued.

Several types of polysulfide coatings were then tested in conjunction with the mechanical "lock" fabric. Adhesion (film-to-coating-to-polyester) was uniformly good and fair optical properties were achieved. Figure 7 shows the appearance of the best polysulfide gel coated paraboloid made with the "lock" fabric. Specular reflectivity tests on the central portion of this parabola indicated a reflectivity of 80.5 percent.

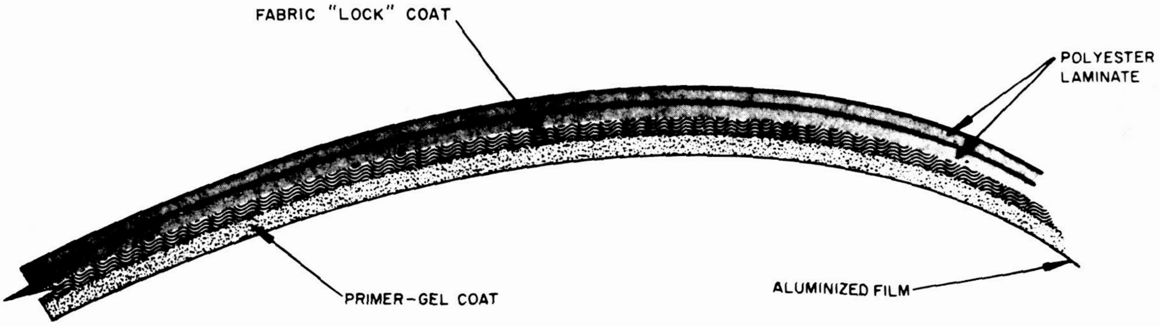


Figure 6. Cross-section of collector configuration incorporating a "mechanical lock" coat.

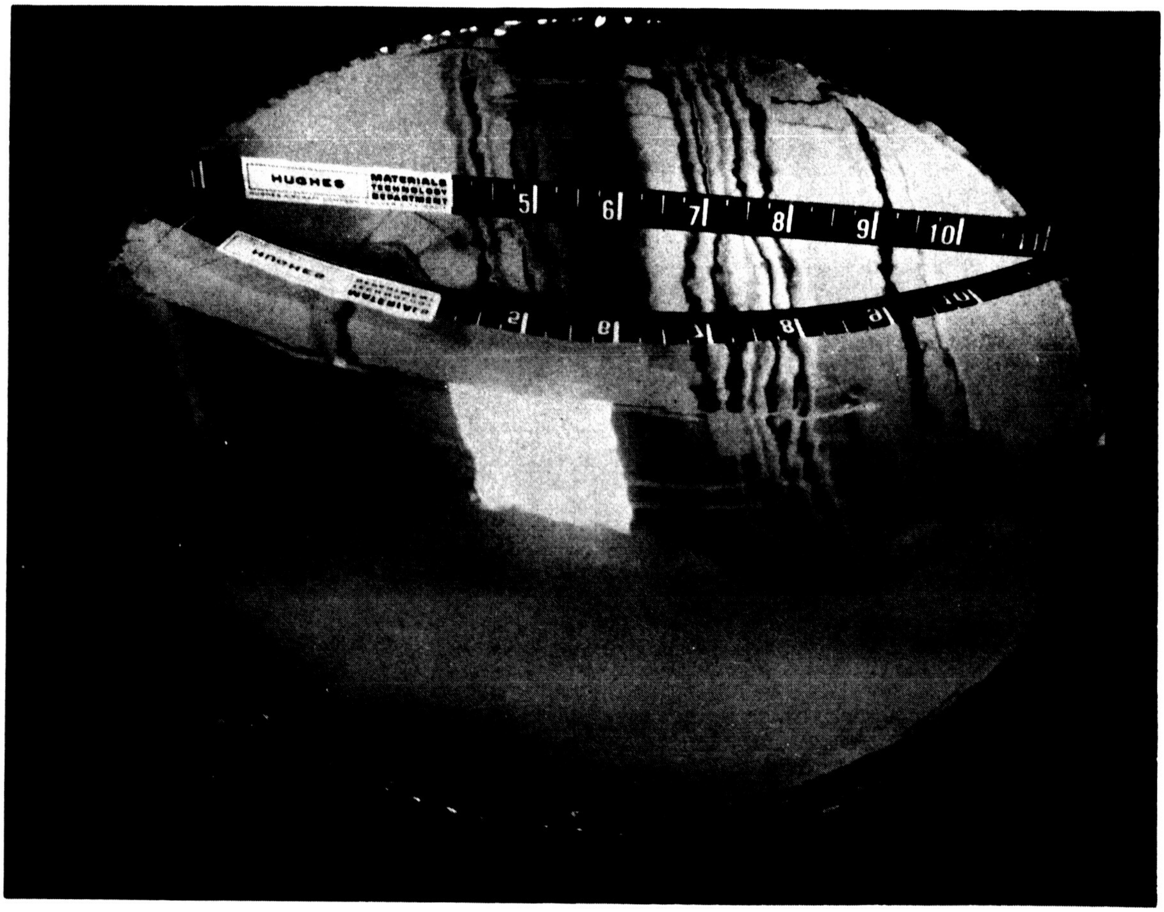


Figure 7. Polysulfide coated paraboloid incorporating a "lock" coat.

Additional investigations of the fiberglass "lock" fabrics showed that to obtain good optics, the "lock" fabric and the reinforcement must be applied at identical pressures. If the diaphragm pressure is reduced after applying the lock fabric, it must be restored to the original value before adding the reinforcement. Any variation, above or below, will result in distortion. In tests, underpressure produced an irregular distortion, overpressure produced a "lock" fabric pattern type of distortion. These effects are attributed to minute wrinkles in the fabric at low pressures and to the very low stretch at high pressures.

Attempts were made to eliminate the need for precise pressure control without too much success. Non-woven and two-way stretch nylon fabrics were tested and some improvement in optics was obtained when pressure control was not precise. However, bonding of the nylon substrate to the polyester was not satisfactory. Increasing the Mylar thickness to three or five mils helped, as did increasing the gel coat thickness. Unfortunately this increase in thickness would produce a parabola weight in excess of that required.

Polyester Resins Investigation

A polyester resin-glass fiber laminate system was chosen for rigidizing the parabola because this system offers a number of advantages over other resin systems for space applications. One advantage is that it is completely automatic, utilizing ultra-violet radiation in space for triggering the reaction. Other proposed systems such as urethanes or epoxies require vapor catalysis or heat, with attendant problems of special containers, valves, and means for reducing the heat when the reaction is completed. Another advantage of the polyester system therefore is that its weight is minimum since no extra components are required.

There are, however, two major problems involved in the use of a polyester for this application. The first of these is the poor adhesion of the polyester laminate to the film. Work on this problem has already been described. The other major problem of the polyesters is in the relatively high shrinkage of the resin, which is inherent in this type of material.

In the fabrication of other types of polyester-glass fabric structures, shrinkage is shown on the surface of a part as an optical phenomenon. In this phenomenon the resin shrinks back into the glass during cure. This produces a surface with a fabric pattern that is unacceptable for a reflector surface.

The usual method for eliminating this effect is to use a heavily filler-loaded polyester gel coat next to the mold, on which the polyester laminate is laid. The gel coat then becomes the outer surface of the part. This method was investigated to see if it could be used to minimize the surface defects appearing on the aluminized film. The solution was complicated because the mold in this problem is not a rigid body as is usually the case, and also because the gel coat must be very flexible after cure, rather than hard and rigid as is common.

During the initial tests, which were mainly concerned with satisfactory adhesion of the film to the polyester laminate, when the polyester laminate was applied directly to the film the fabric pattern was clearly visible wherever adhesion took place. Addition of silica filler to the polyester resin helped reduce this pattern, but not markedly. Later, when relatively heavy gel coats were used, the distinct fabric pattern was no longer visible.

The optical surface formed ranged from nearly perfect to badly distorted. Figure 8 illustrates the varying degrees of quality in optical surfaces obtained with the gel coat-mechanical fabric "lock" techniques. It is significant to note that the two best samples, #1 and #2, were rigidized with room temperature curing epoxy coatings, rather than the polyester. These two samples were prepared to determine whether the patternless distortion was due to polyester shrinkage, since the epoxies exhibit considerably less shrinkage than do the polyesters.

Additional optical investigations were made using the one- and two-foot diameter transparent fixtures. Polysulfide and epoxy-polyamide gel coats were used. The film was stretched, relaxed, and then examined through the fixture. If the surface appeared optically perfect the coating was applied to the diaphragm by brushing and/or spraying. The effect on the surface was then observed

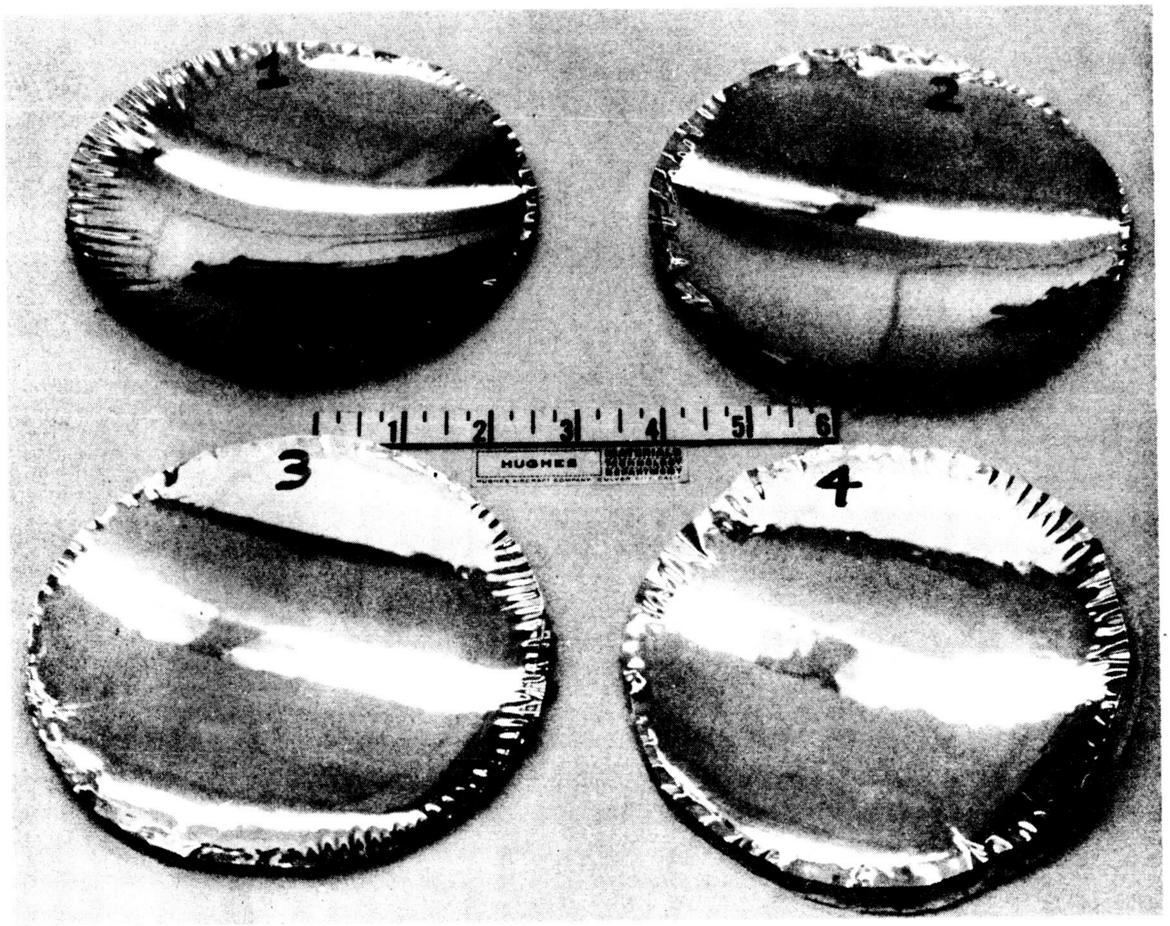


Figure 8. Variations of quality in optical surfaces produced by using gel coats and lock fabrics.

immediately and also as the cure progressed. Both single heavy coats and light multiple coats were tested.

Very little distortion appeared after application or cure of gel coats of either type when applied by brush or spray. The heavy brush coat did, however, produce slight optical discrepancies in the form of brush marks. It was found that two thin gel coats gave better optics than one thick one. It was concluded that substantially all the distortion, both fabric pattern and the "patternless" kind, resulted from the cure of the polyester resin-fiberglass laminate.

Tests were then made to determine how and when the polyester reinforcing laminate caused the distortion. It was discovered that when the gel coat was too thin or when the fabric next to the gel coat was of too coarse a weave, the resultant cured mirror surface showed a definite fabric pattern. Both the pattern distortion and the irregular distortion appeared when the polyester resin started to gel and cure. The conclusion is that both types of distortion are related to resin shrinkage and to the differential stresses set up in the resin and the glass fabric and in the substrate. Figure 9 shows typical distortion in a two-foot diameter polysulfide gel coat and polyester fiberglass reinforced paraboloid.

The investigation included experimentation with various types of resins. The polyester resin used in the preceding tests was a styrene monomer resin. The resin was catalyzed with 1-1/2 percent methyl ethyl ketone peroxide and 1/2 percent cobalt napthenate to result in a room temperature gel time of approximately 30 minutes. The majority of the samples were filled with 325 mesh silica powder, in the ratio of one part resin to one part filler. The filler, of course, was used to reduce the shrinkage as much as possible. Tests were also made with unfilled resin, but with 2 percent of a pyrogenic silica to impart thixotropy. The filled resins in all cases appeared to show slightly less distortion, as was expected. The serious disadvantage in the use of the heavily filled resin, however, was the additional weight imparted and the loss in strength and adhesion caused by the excess filler.

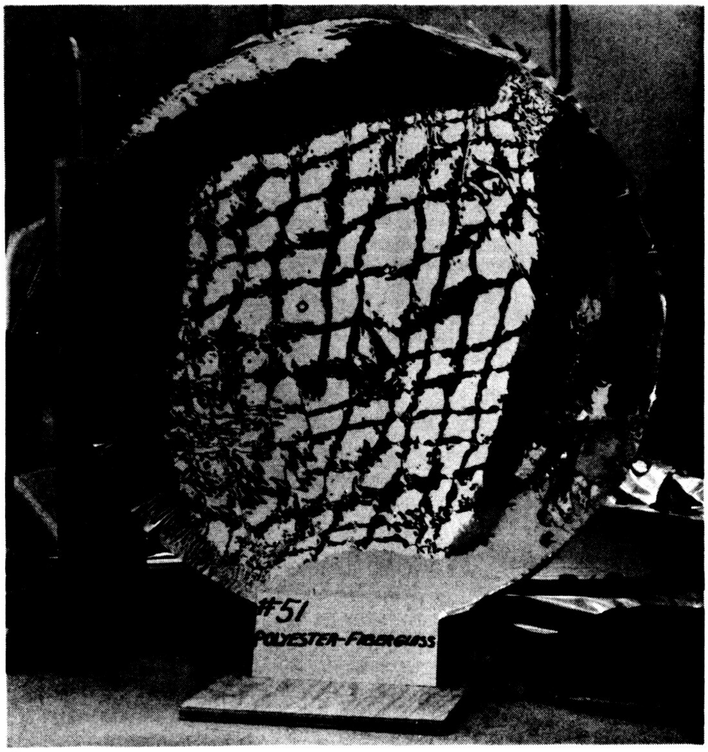


Figure 9. Test grid reflection in two-foot diameter polysulfide-polyester-fiberglass reinforced paraboloid. (Two layers 181 fabric for reinforcement.)

In addition to the first resin, a number of other commercially available polyester resins were tested, both for UV catalyzed reactivity and for possible lower shrink rate. An attempt was made to obtain all three cross-linking monomer types of resins, i. e., styrene, diallyl phthalate and triallyl cyanurate in order to make comparisons. The vendors were also requested to supply their lowest shrinkage materials. Emphasis was also placed on securing non-accelerated resins (the first resin contained 0. 06 percent of cobalt napthenate accelerator as supplied by the manufacturer). The resins obtained initially for test are shown in Table II.

Resin	Monomer
#1	Styrene
#2	Styrene
#3	Diallyl phthalate
#4	Styrene
#5	Triallyl cyanurate
#6	Diallyl phthalate

Table II. Polyester resins tested.

The diallyl phthalate based resins showed the lowest distortion, corresponding to the lower shrinkage rates claimed for them. The resins containing styrene monomer cured in approximately 20 to 30 minutes, in bright sunlight or under a 1-KW UV lamp, to a Barcol hardness of approximately 50 when catalyzed with a 2-percent benzoin-tri-cresyl-phosphate mixture. The diallyl phthalate and the triallyl cyanurate monomer resins with the same catalyst took approximately three times as long to gel, and took approximately 24 hours at room temperature to reach a Barcol hardness of approximately 30.

Since the optical results were better with resin #6 (a diallyl phthalate monomer resin) than with the styrene modified materials, a number of solid resins were procured and materials were formulated with DAP as the reactive monomer. Three types of materials were formulated and used in tests. The first of these was a NPW solid, polychloroester, previously tested with styrene; the second was a partially polymerized diallyl phthalate; and the third were several isophthalic-maleic mixtures. In this last type, the isophthalic component is the low shrink member and the maleic resin is used to increase reactivity. The following resins were obtained; (a) a 1:1 mixture, (b) a 1:2 mixture of isophthalic and maleic and (c) a 1:3 mixture.

The initial tests were made of the polychloroester and isophthalic maleic resins using 40-percent DAP as the monomer with 2-percent benzoin and 2-percent benzoyl peroxide as the catalyst. The polychloroester in approximately 24 hours out of doors set up to a Barcol harness of 35 to 40. The isophthalic-maleic resins after approximately 48 hours set up to a Barcol hardness of approximately 20 for the most reactive (1:3), to a hardness of 10 to 15 for the other resins. Since these resins were apparently not reactive enough no further work was done with these materials.

Tests were also made with the partially polymerized diallyl phthalate resin and the polychloroester resin, with DAP monomer contents as low as 18 percent. In both cases the viscosity was extremely high and acetone was used to reduce it so that fabrics could be easily impregnated. Laminates of either resin with a 25-percent content of DAP cured outdoors to a Barcol hardness of approximately 30 to 40 in approximately 24 hours. Laminates were also made with an 18-percent DAP content. With this low a monomer content the diallyl phthalate materials only attained a hardness of approximately 10-20 in a two-day sunlight cure. The polychloroester resins with this monomer content obtained a hardness of approximately 30.

Room temperature storage tests were also made of the diallyl phthalate and the polychloroester resin. Twenty-five gram samples of each catalyzed resin were stored with varying amounts of hydroquinone as an inhibitor. Inhibitor contents were approximately 0.015, 0.030, and 0.045 percent as well as noninhibited samples for controls. The diallyl phthalate resins commenced gelation in one week, whereas the polychloroester was stable for approximately two months of storage. Small sample laminates were made from time to time from the storage resins to check the activity. In these tests the polychloroester materials appeared to set up satisfactorily in a 24-hour outdoor exposure.

Shrinkage Tests. An effort was made to measure the shrinkage of Fiberglass laminates made with partially polymerized diallyl phthalate and the polychloroester resin, but no conclusive results were obtained. For the measurements a 15-ply #103 glass fabric laminate was laid on a Teflon coated polished ferro type plate. On the plate were two sets of orthogonally placed fine scratch marks. In one set the marks were seven inches and in the other eight inches apart. By measuring the original distances on the plate very accurately, and then measuring the reproduced marks on the laminate, the coefficient of shrinkage could be calculated. Measurements were made of the laminate after room temperature UV curing and after a 16-hour elevated temperature cure. Table III shows the results.

Material	Seven-Inch Dimension		Eight-Inch Dimension	
	Original Shrinkage Inches/ Inch	Post-Cure Shrinkage Inches/ Inch	Original Shrinkage Inches/ Inch	Post-Cure Shrinkage Inches/ Inch
Polychloroester	.0001	.00094	.0003	.0015
Diallyl phthalate	.0016	.00190	.00216	.00235
Styrene monomer	.0019	.00067	.00026	.00070

Table III. Polyester shrinkage.

In general there was lack of agreement between measurements in each of the two directions. There were also conflicting measurements, for example, the standard styrene based resin shrank less than either of the test resins. For these reasons it was concluded that some error exists in the measurement. It should be pointed out that the laminate after fabrication is only approximately .033 inch thick and usually shows a small amount of warp. This could contribute to the difficulty of making accurate measurements. Thicker laminates were not desired, however, since these would not be representative of the reinforcement actually used.

Since results of the shrinkage test were not conclusive, it was decided to test the reactivity of the various diallyl phthalate based resins. The resins tested included a commercially available DAP material (Resin #6), a Hughes formulated partially polymerized DAP material and the polychloroester resin. Using 2 percent of benzoin and 1 percent of benzoyl peroxide it was found that 8-ply laminates of Resin #6 cured in four hours of sunlight to a Barcol hardness of 40-45. Under the same activation conditions, and with the same amount of catalyst, both the other resins took two to three times as long to reach the same state of cure.

Additional tests on the resins included catalyzed storage tests, and general handling properties. In all cases the resin #6 appeared to be as good as or better than either of the other materials. This resin was therefore used for all further tests, and was used for production of the required five-foot paraboloids.

Adhesion Tests. A major problem in the use of the polyester resins is the poor adhesion of the polyester resin to the film surface. The use of a primer gel coat offered a considerable improvement in most cases. A series of tests were therefore made to determine which of three gel coat materials would show the best adhesion. Flat panel specimens were made up using polychloroester resin-glass cloth laminates on a primed film surface. Each laminate was 3 x 10 inches with 2-inch film tabs on the ends. The film was peeled from the laminate using a climbing drum peel test fixture in accordance with MIL-STD-401A, "Sandwich Constructions and Core Materials; General Test Methods." The primers tested and the results of the tests are shown in Table IV.

Primer	Average Peel Load, lb	Type of Failure
#1	14.9	90% adhesive
#2	13.2	100% cohesive
#3	21.5	100% cohesive

Table IV. Polyester-gel coat adhesion tests.

These tests show that the primer #3 (a polysulfide) is considerably better than the other materials. Unfortunately, in later tests made at elevated temperatures of 240° F very poor adhesion was found in the primer-to-film bond and in the primer-to-laminate bond. In an effort to obtain a better bond a number of tests were made with a room temperature curing silicone adhesive. Excellent bonds were obtained, and the resulting coating was quite flexible at both room temperature and at elevated temperatures. However, since the polyester resin would not adhere to the silicone coating it appeared that a fabric "lock" coat is needed if this coating is to be used.

Previous tests had already established that the use of a Fiberglas "lock" coat was not too satisfactory. With Fiberglas "lock" fabric it was found very difficult to deflate a paraboloid and then reinflate without a good deal of distortion appearing unless the pressure was very carefully controlled. This effect was attributed to the very low stretch of Fiberglas fabrics. Samples of a nylon "two-way stretch" fabric were therefore obtained, and it was found relatively easy to install a "lock" fabric which would allow deflation and inflation without appreciable distortion. Unfortunately, in the few tests run it was not found possible to obtain consistently good bonds from the polyester laminate to the nylon substrate. Tests were also run with other "loose" fabrics including several felts, and several cotton waddings. Optical results in all cases were not as satisfactory as with the nylon stretch fabric.

Coincident with the tests on the silicone adhesive and the nylon stretch fabric the vendor was apprised of the inconsistencies found in primer #3 material. They recommended use of a material designated primer #4. Tests of this material did result in much better adhesion, as compared to the later batches of #3 primer. Since this system would result in a considerable saving in weight as compared to the silicone adhesive - "lock" fabric technique, it was decided to concentrate on this process.

Additional tests were run on 8-ply laminates placed on bare polyester film on a #2 primed surface and on a surface primed with primer #4. It was then found that primer #4 caused inhibition of the resin cure. This was true of all the other resins previously tested. Under the same conditions of exposure used in earlier tests, it took approximately 8 hours to reach a Barcol hardness of 30-35 and approximately 16 hours to reach a Barcol of 40-50, using the Hetron resin. The #2 primer surface apparently caused no inhibition. However, on prolonged storage the primer #2 was badly softened by the wet resin thus rendering it impractical for actual usage.

Three five-foot diameter paraboloids were prepared using three-mil diaphragms made at Hughes and using the Resin #6 resin. Two of the paraboloids had a brushed-on coating of the primer #4 primer and a third a coating of the primer #2. The optical results were poor with the #4 primed surfaces, due to brush marks, and inhomogeneities in the primer, which were plainly visible after the aluminized coating had been removed from the optical surface. (The surface of the brushed-on primer #4 appeared very smooth and homogeneous when examined from the top.) The third paraboloid made with the brushed-on primer #2 was also quite poor since the fabric showed through in a pronounced manner. Since the #2 coating, at approximately 1/2 mil, was considerably thinner than the #4 coating this demonstrated the need for an appreciable thickness of coating.

Tests were then made with the #4 material to determine techniques for spraying the coating to appreciable thicknesses. It was found that the material could be sprayed, when catalyzed with 8-1/2 percent catalyst, and thinned with toluene, in the ratio of 100 parts of polysulfide to 120 parts of thinner. In order to build up a uniform coating approximately 7 to 5 mils thick four coats were necessary, with approximately 20 minutes between coats. Such a coating, when sprayed on clear polyester film and viewed by transmitted light appeared smooth, homogeneous and of uniform thickness. A five-foot paraboloid, using a three-mil diaphragm, made at Hughes, was produced with fair optics, but practically no brush marks.

Additional tests were also made with a urethane coating said to be useful as a primer to increase adhesion of polyester coatings. This coating, showed no inhibition, but unfortunately a very poor bond was obtained from the polyester to the coating. No further work was therefore done on this material.

In all the work which had been done with the primer #4 the ratio of resin to catalyst was 100:7-1/2. Increasing the catalyst to 8-1/2 parts per 100 of resin appeared to give a "tighter" cure and resulted in a coating which appeared to cure harder and faster and showed less inhibiting effect on the polyester. This catalyst-resin ratio was consequently used for all further tests.

With the completion of these adhesion tests, it was concluded that the polyester system could be used for producing paraboloids that would meet contract requirements. Distortion tests had been made. The polyester resins had been compared with other materials. Hetron 103 had been selected after comparison with other polyesters. Shrinkage measurements had been made and adhesion had been investigated extensively.

SYNTACTIC FOAM INVESTIGATIONS

After completing the tests using the powdered filler reinforcements with either polyester resins or epoxies it was quite apparent that the optical quality of these parabolas far surpassed any paraboloids untilizing resin impregnated fiberglass. However, the extreme fragility and relatively heavy weight of the filled resin reinforcement definitely indicated that some other materials should be used. Consequently, epoxy as well as polyester syntactic foams were investigated.

Epoxy Syntactic Foam

To combine the advantages of a powdered filler with a lightweight material, phenolic microballoons were mixed into an epoxy resin. Sufficient microballoons were added to form a paste-like mixture. This material was light in weight and had the necessary bulk to increase its stiffness. The initial formula used is shown below:

Epoxy resin	100 pts
Phenolic microballoons	23 pts
Pyrogenic silicy	1.5 pts
Diethylenetriamine (DTA)	8 pts

The paste reinforcement of this material was hand spread over the inflated film, which had previously been primed with a thin brush coat of primer #2. The paraboloid was cured overnight at room temperature and at the relaxation pressure. Pressure was released after 16 hours of curing. The paraboloid formed was extremely good. The optics were very good and adhesion of the reinforcement to the film was excellent. Several six-inch and one-foot diameter paraboloids were made using the above techniques, all with uniformly good results.

Since the reinforcements were still not too strong after cure, tests were made to determine the feasibility of incorporating a single layer fabric reinforcement in with the syntactic foam. In two tests the fabric was laid on top of the paste and was slowly wet with resin as the material cured. In both cases the optics were considerably inferior to those samples made without the fabric reinforcement (see Figure 10). In another test a fabric was applied to an already cured part (initially with excellent optics). Again there was a marked deterioration in the optical quality. This conclusively demonstrates the role of the fabric in causing optical deterioration.

At first, uniformity of the coating was a problem. The first samples using either the powdered filler or the microballoon filler were made by simply troweling the paste over the inflated dome. Since both materials were opaque and did not flow to any extent, it was quite difficult to spread the paste to a uniform thickness. This lack of uniformity was clearly visible in the first samples, and in fact was the major defect in these otherwise very satisfactory paraboloids.

In an effort to obtain more uniformity in the coating several paste spreading techniques were tried. A blade spreader method (doctor blade) using a spacer was not successful since the paste could not be spread evenly and would hang up in some areas and pull away in other areas. Another technique tried was a roller which covered the entire

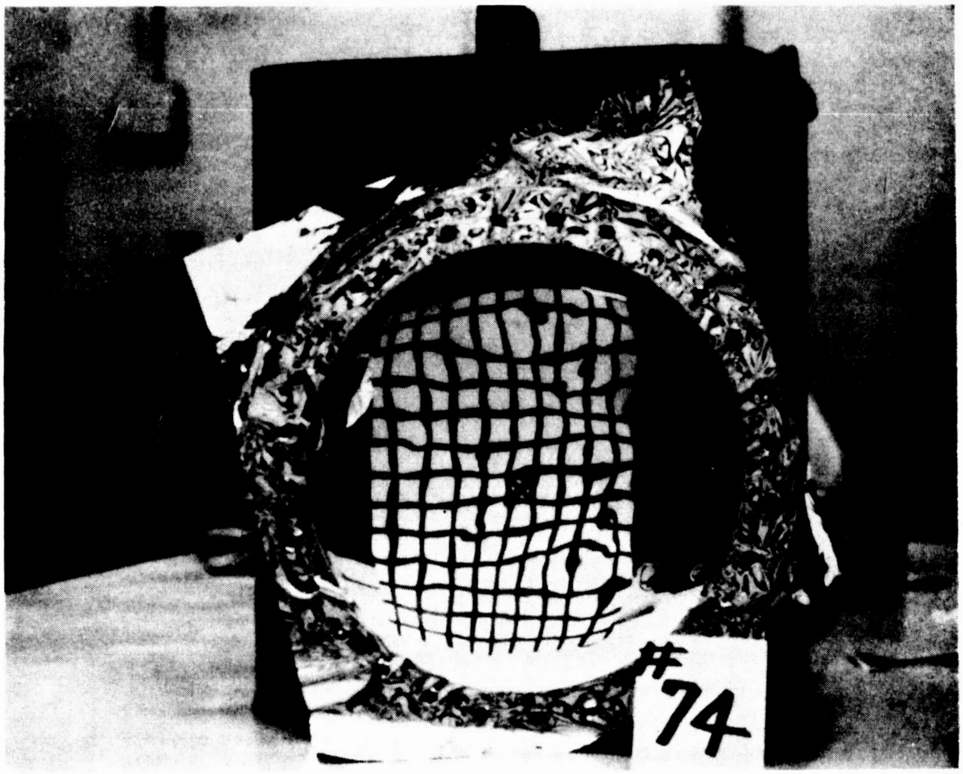


Figure 10. One-foot diameter epoxy-phenolic microballoon paraboloid reinforced with one layer of fabric.

diameter of the membrane. By means of a ring spacer around the circumference of the membrane the paste could be rolled down and spread over the entire surface to a fairly uniform height. Using this technique, however, it was not possible to coat the inflated membrane. The film was therefore coated in the flat condition and then subjected to the stretch and relaxation treatment with the paste in place. No appreciable effect was noted from the weight or resistance of the paste to the pressurizing treatment, and the paraboloids made this way showed excellent properties both from the standpoint of the optical surface and the figure obtained (see Figure 11).

Three techniques were finally developed which appear to be satisfactory. In one method a ball of foam paste is placed on top of the film and a metal plate is placed on top of the foam and another under the film. The entire assembly is then placed in a polyethylene bag and a vacuum is drawn. Depending on the stiffness of the foam the material can be forced down to a uniform thickness in one to three hours. Such a system can be used for any size part, if a stiff enough plate is used, or if a large enough plate is available.

Another system tried is theoretically applicable to five-foot or larger paraboloids. A wedge shaped spreader bar is used in a manner similarly to a doctor blade, except that the bar, when drawn across the film, is held at a 45 degree angle to the surface. This carries the paste in the direction of motion and it simultaneously forces the paste down onto the film. Using this technique very uniform spreads were obtained on paraboloids of one- and two-foot diameter, but it was very difficult to obtain the same results in coating a five-foot paraboloid.

The technique finally chosen consisted of making an approximately 4- to 6-inch diameter ball of foam and then flattening this ball to an approximately 24-inch diameter disc between heated (120-140° F) platens of a hydraulic press. By using 0.1-inch thick spacers it was relatively easy to make the discs to a uniform thickness. These discs were initially made between cellophane sheets, cooled with dry ice to reduce sticking to the cellophane and then transferred to the aluminized film. The discs were butt joined to each other and the spaces between the discs were filled in with additional foamant. By using a small

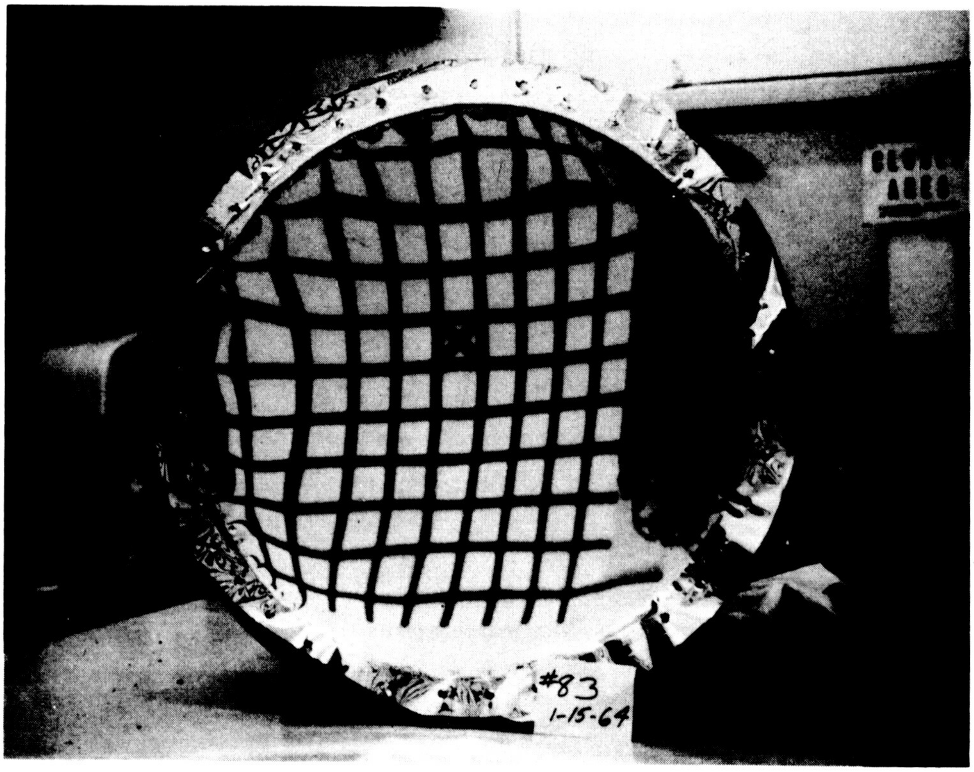


Figure 11. Two-foot diameter epoxy-phenolic microballoon paraboloid made with "flat" paste spread technique.

hand-held heat gun it was possible to soften the foamant material and press the edges together to form a large, homogeneous sheet.

In addition to tests on the spreading technique, tests were made on a series of samples to determine the optimum percent of microballoons used in the foam. Approximately 50 percent by weight of phenolic microballoons can be incorporated into the epoxy resin without the aid of a thinner such as acetone. However, such a mixture is extremely dry and is almost impossible to spread. When cured, this mixture has quite a low density and, because of its bulk, has a relatively high stiffness-to-weight ratio. The optical surface, however, is slightly grainy. Mixtures made with as low as 15 percent microballoons, on the other hand are soft, are easily spread, and have the disadvantage of flowing easily before final cure. The optical surface with such a mixture is somewhat better than the highly filled mixtures. Samples were accordingly made up with 15, 22-1/2 and 30 percent of microballoon content. These mixtures were all applied to approximately 120-degree segments of a one-foot diameter paraboloid so as to obtain identical conditions in the film, during cure, etc. After cure, the 22-1/2 percent mixture appeared to be the best from the standpoint of optics, and adhesion to the primed film.

Latent Catalyst Tests. All the preceding tests were made with resin systems using room temperature catalysts for convenience. Such catalysts would, of course, not be practical for ultimate usage because of their extremely limited shelf life. An investigation was made of epoxy resin systems which could be catalyzed and which would remain flexible for at least one month at room temperature, and which could then be cured in a moderate time at temperatures not exceeding 240° F. Currently, two such systems are available. One system, in two types, designated XW-100 and XW-101 was procured. Both are one-component materials with a claimed shelf life of at least two months at room temperature. In the first preliminary tests good laminates were made by heating for approximately 24 hours at 250° and for approximately 72 hours at 180°F. While these cure times may be somewhat excessive, the material did appear to offer promise of being usable for this application. However, since both materials were supplied with approximately 50 percent of thinner incorporated into the resin, neither was judged too suitable for space application.

The second system investigated simply utilized a new catalyst with the epoxy resins previously used. This catalyst, a borate, 2-(β - dimethylaminoethoxy) -4 methyl 1, 3, 2-dioxaborinane, can be mixed with the resin with no reaction at room temperature, other than a slight viscosity change. Preliminary tests with the catalyst and two resins, each with an epoxide equivalent weight of 175-200, and viscosities of 500-600 and 10, 000-20, 000 indicated that at 240°F cure took place in approximately 24 hours and approximately 48 hours at 200°F.

Attempts were then made to find an accelerator which would "kick over" the reaction in a shorter period of time at 200°F, and also result in a material with an adequate room temperature storage life.

A number of different amines were tested as accelerators. In each case the standard mixture was 100 parts of epoxy resin and 10 parts of the borinane catalyst. To 25 gm batches of this "standard" then were added from 1/2 to 4 percent of the following; (a) diethylaminopropylamine, (b) benzyl dimethylamine, (c) triethylenediamine, and (d) ethylene diamine. The last two were incorporated in silica molecular sieves. The results of the tests indicated that the most satisfactory material was the diethylaminopropylamine. With 1/2 percent of this material incorporated in the 10:1 "standard" mixture satisfactory cures appeared to take place in 4 to 6 hours at 225°F, and somewhat longer at 200°F. Storage tests of this material indicated that the material would be flexible for at least three weeks when stored at room temperature. The formulation which was developed and used in all subsequent tests was as follows:

Epoxy Resin	100 parts
Phenolic microballoons	27-1/2 parts
Pyrogenic silica	4-1/2 parts
Borate catalyst	10 parts
Diethylaminopropylamine	0.55 parts

Polyester Syntactic Foam Tests

Since very definite improvement in optics resulted from the mixing of phenolic microballoons in an epoxy resin, the same filler was tried in a UV catalyzed styrene monomer polyester resin. As anticipated practically no cure took place because of the opacity of the phenolic microballoons. Substitution of glass microballoons for the phenolics was somewhat more successful in that initially a cure was obtained approximately .030 inch deep in a few hours. Because of these initial successes further efforts were made to develop a UV activated polyester syntactic foam which would cure throughout its thickness.

The first tests with glass microspheres and polyester resins utilized silica "microballoons." This material was used in conjunction with a styrene based resin, #1, and benzoin as a catalyst. It was found with this combination that a rapid surface cure took place, followed by a further cure to a depth of approximately 0.030 inch. It was felt that the opacity of the particular microspheres might be causing the poor cure. Samples of glass microballoons appeared to be more transparent when examined under a low power microscope. However, tests with the styrene modified resin and the glass microballoons gave approximately the same results as tests with the silica microballoons.

Tests were than made with the diallyl phthalate based resin, #6, which, perhaps because of a slower curing rate, showed less tendency to a "skinning" effect and a more complete cure. The addition of benzoyl perioxide as a secondary catalyst, then resulted in a mixture which would cure nearly completely (0.093 inch thick) in a 24-hour period left outdoors in the sunlight. The optics obtained, while not quite as good as with the epoxy samples, were nevertheless fair. A good figure was obtained (visually judged); however, a good deal of local "patternless" distortion was found. The formulation found to be the most satisfactory is as follows:

Diallylphthalate polyester	100 pts
Glass microballoons	30 pts
Benzoin — TCP mixture	2 pts
Benzoyl peroxide — TCP	2 pts

This mixture (excluding the glass beads) showed very little sign of gelation for as long as two weeks. With the addition of the glass microspheres the mixture showed signs of gelation in 24 hours. However, the mixture did remain usable for several days.

Since the above mixture, in an .093 to .125 inch thickness did not cure completely at room temperature, it was placed in an oven and cured at 180° F. If the temperature was raised to 180° F slowly (over a 1/2-hour period) and then maintained at this temperature for two hours, a much stronger paraboloid resulted. Since this process probably simulates the process that would occur in space, it was considered justifiable. A rapid rise in curing temperature resulted in a deteriorated optical surface, marred by warpage and "orange peel" formation. The weight of the syntactic foam produced is another disadvantage to the use of the glass microballoons. These microballoons have a bulk density of 10-11 pound/cubic foot, approximately three times that of the phenolic microspheres. In an attempt to make lower weight syntactic foams another type of spheres was obtained. These beads, had a density of approximately 3-1/2 pound/cubic foot. However, in tests with the diallylphthalate resin an adequate cure was not obtained, in thicknesses of approximately 0.100 inch, when the samples were left in the sun for as long as 48 hours. This filler then either inhibited cure, or prevented adequate absorption of the UV radiation. Work was therefore discontinued on the polyester based syntactic foam.

FILM TESTS

Surface Treatments

Coincident with experimentation on the optimum gel coat-to-film bond, work was started on a technique for etching the film surface in order to improve the gel coat-to-film bond, or perhaps to make possible a reinforcement-to-film bond. A 75- to 95-percent sulfuric acid solution swabbed on the film for 20 to 30 minutes at room temperature did etch the surface. Somewhat similar results were obtained with fine emery paper. However, simple peel tests with polyester resins gave very inconsistent results. Since this process was considered somewhat impractical for a large surface, no further work was done at this time.

Heat Treatments

The first post cure tests of a paraboloid indicated that there were shrinkage stresses in the film which were produced by the heat treatment. To relieve these stresses the film was preshrunk in several 3- to 6-hour heat treatments at temperatures varying from 240° to 300° F. No visual effect on the reflective surface was seen after the prolonged heating at temperatures up to 300° F. Shrinkages as high as 1.6 percent were obtained in one hour at 325° F. At 250° F the shrinkage was approximately .68 percent in one hour with an increase to .82 percent in 16 hours. Since this last value is almost an asymptotic value, this procedure was used to "preshrink" all the film used in later tests, and in paraboloid fabrication.

For maximum results, the preshrinking should take place at 325° F. However, visual examination of the samples heat treated at this temperature indicated a slight decrease in the brilliant luster, so the 250° F temperature was chosen for use.

Protective Coating

As a consequence of the various operations performed on the film, it was virtually impossible to avoid damaging the aluminized surface. A water soluble protective strippable coating, was found to give excellent protection to the surface. This material, however, will not withstand the preshrink heat treatment operation. It was therefore arranged to have the mosaic fabricator apply this coating to the film immediately after pre-shrinking. The coating is kept on as film during the mosaic fabrication and during the paraboloid fabrication. It is believed this procedure will produce a considerable improvement in the final product.

Effect of Film Thickness on Optics

Tests indicated that increasing film thickness improves optics. Three- and five-mil aluminized film was tested both with polyester laminates and with epoxy syntactic foams. In every case the optics were better. However, since the use of the thicker materials had not been originally called for, the large hexagonal mosaics received contained the two-mil material. Moreover, a change to the heavier gages would have necessitated changing the stress relaxation pressures, and also the torus assemblies. Therefore, work with the heavier material was discontinued.

TORUS ASSEMBLY TESTS

Tests were made with the complete torus and paraboloid assemblies received from the vendor, to determine if the "stretch and relaxation" process could be carried out satisfactorily as planned. It was possible to pressurize the torus assembly safely to approximately double the designed maximum pressure of 3.3 psi. However, when the paraboloid was inflated to its relaxed pressure of 17 mm Hg, the torus resisted the radial load for only a few minutes, before buckling in one or more places; the paraboloid then distorted badly. (The paraboloid had been previously pressurized to the 42 mm Hg stretch pressure using a metal reinforcing ring on the assembly.)

Analysis revealed that this type of structure, with opposing compressive radial and hoop tension loads, is difficult to stress with high accuracy. Furthermore the structure was analyzed as a perfectly circular torus. However, in actuality, since its construction is of flat sheet material, it was made in a number of segments. The segment joints act as local reinforcements, setting up unequal stresses and buckling loads between the joints. These concentrated stresses combined with the compressive radial load of the inflated paraboloid cause buckling failure when the torus is under load.

It is believed that a satisfactory torus-paraboloid structure can be designed and fabricated. Such a structure will probably require a considerably heavier torus of cloth reinforced material which would be pressurized to a much higher pressure than the 2-mil film torus. For the current project, therefore, it was decided that the demonstration of release from the container, expansion, and deployment to the approximate shape could be made with the torus assemblies procured. Actual ridigization to the required shape would be done by using a metal reinforcing ring in conjunction with the torus assembly or with just the mosaic diaphragms. Simpler diaphragms made at Hughes were also used, since a number of joint failures occurred when the vendor fabricated mosaics were pressurized.

FIVE-FOOT PARABOLOIC DEVELOPMENT

Polyester-Fiberglass Paraboloids

Several five-foot paraboloids were prepared, using diaphragms made at Hughes. The diaphragms were made from "pre-shrunk" four-foot wide, two-mil aluminized Mylar. They contained one chordwise seam, approximately one foot from the edge. The seams were made with three layers of 1/2 inch wide, 2-mil heat sealing tape. After fabrication, each of the diaphragms was sprayed with four coats of primer #4 polysulfide coating, which was first air dried over-night then cured for eight hours at 160°F.

The diaphragms were then clamped to a plywood fixture and pressurized. Initial stretching was at an internal pressure of 42 mm of Hg (gauge). At this relatively high pressure the diaphragms appeared to distort uniformly, despite the presence of the relatively thick seam. The pressure was then reduced to the relaxed pressure of 17 mm Hg, and maintained at this level during application of the seven plies of #120 glass fabric saturated with polyester resin #6 in accordance with the formula previously given.

Final curing took place under a bank of eight 40-watt U. V. fluorescent tubes. The fluorescent tubes were installed in normal industrial reflectors, except that aluminum foil was used as the reflecting surface instead of the white enameled surface. The paraboloid was irradiated for approximately 16 hours (over-night), although gelation was observed to take place in 30 to 60 minutes. (The paraboloids distance from the lamps varied from 12 to 18 inches.)

The results indicated that in general this procedure for making paraboloids is quite satisfactory both from the standpoint of physical properties and of optical quality. It remained to determine if the same type of results could be secured in a vacuum.

Epoxy Syntactic Foam Paraboloids

Two five-foot diameter paraboloids were made from Hughes-fabricated 2-mil diaphragms and syntactic foam materials using the techniques just described. One paraboloid was cured in an oven for 4 hours at 225°F. After cure it was noted that all the joints in the syntactic foam sheets had merged together, so no joint lines were visible. However, because the oven had been heated too fast, the reinforcement ran down the parabolic surface under the influence of gravity. This resulted in an uneven distribution of the coating and consequently distortion. The other paraboloid was heated much more slowly, so that after 3 hours the temperatures had reached approximately 200°F. No running occurred, but the seam in the diaphragm broke and the part had to be cooled down for repairs. It proved possible to remove the foam, repair the seam, replace the foam, and then continue the cure. This part had a good figure and a fair surface, however, there were a number of "inward" facing bubbles on the film. These bubbles could well be a result of shutting down the cure in midcycle. Despite the somewhat poor results the tests nevertheless did indicate that the proposed syntactic foam system is practical. Several other tests were made, using the slow (approximately 200°F) oven cure, and satisfactory paraboloids were made.

It was noted that the syntactic foam rigidized paraboloids appeared to be somewhat more rigid than the corresponding polyester rigidized paraboloids. However, neither paraboloid could be supported at only three points on the edge without distortion. Installation of a simple ring around the edge of each paraboloid corrected this weakness.

Equipment Development

Coincident with the preceding work on paraboloid developments, tests were also made on techniques for forming the large paraboloids in the space chamber at approximately 100,000 feet. Since each sample part was to be processed for approximately 24 hours at a time, it was necessary to develop special sagitta variation sensing and automatic pressure regulation equipment in order to maintain the desired sagitta throughout the cure period. This was particularly important in the case of the epoxy reinforced assembly since considerable pressure variations would take place as the paraboloid was heated.

Sagitta changes were sensed by wires stretched above the inflated paraboloid and two sets of adjustable contacts that could be actuated by movement of the paraboloid. See Figure 12. In use the paraboloid was inflated to the desired sagitta. The contacts were then set so that the highest point of the paraboloid could vary ± 1/8 inch from the desired setting without affecting them. If the sagitta decreased beyond the allowable limit, the contacts would close and air would be automatically injected into the structure, while at the same time a buzzer and a green indicator light signaled the demand for air. If by chance the sagitta became too large, the second set of contacts would energize a buzzer and a red light. The paraboloid pressure could then be lowered manually, or in cases of emergency the chamber pressure could be increased.

The first tests with this indicating and control system utilized solenoid air valves with gravity actuated plunger returns. Intermittent malfunctions in the solenoid valve and in the actuating relay caused several of the first paraboloids to explode in the environmental chamber. Both conditions were remedied by using an alarm bell in the valve circuit to indicate a sticking relay and by substituting a spring-loaded solenoid valve for the gravity return valve previously used.

VACUUM TESTS

After establishing the configurations needed to obtain a rigidized structure for both the syntactic foam and polyester type paraboloids, tests were made to determine the best methods of making each structure in a vacuum environment. In the first tests small (approximately 8 x 8 inch) flat samples of both epoxy and polyester rigidized film were prepared to be used for mechanical, thermal and radiation testing by both NASA Langley and Hughes Aircraft. At a simulated 150, 000 feet altitude, it proved impossible to fabricate either type with a uniformly flat surface and with good optics. In the polyester samples the reinforcing laminate partially delaminated in small areas, and the entire surface became somewhat wavy due, no doubt in part, to the delamination. The epoxy reinforced samples also bubbled and foamed up in the

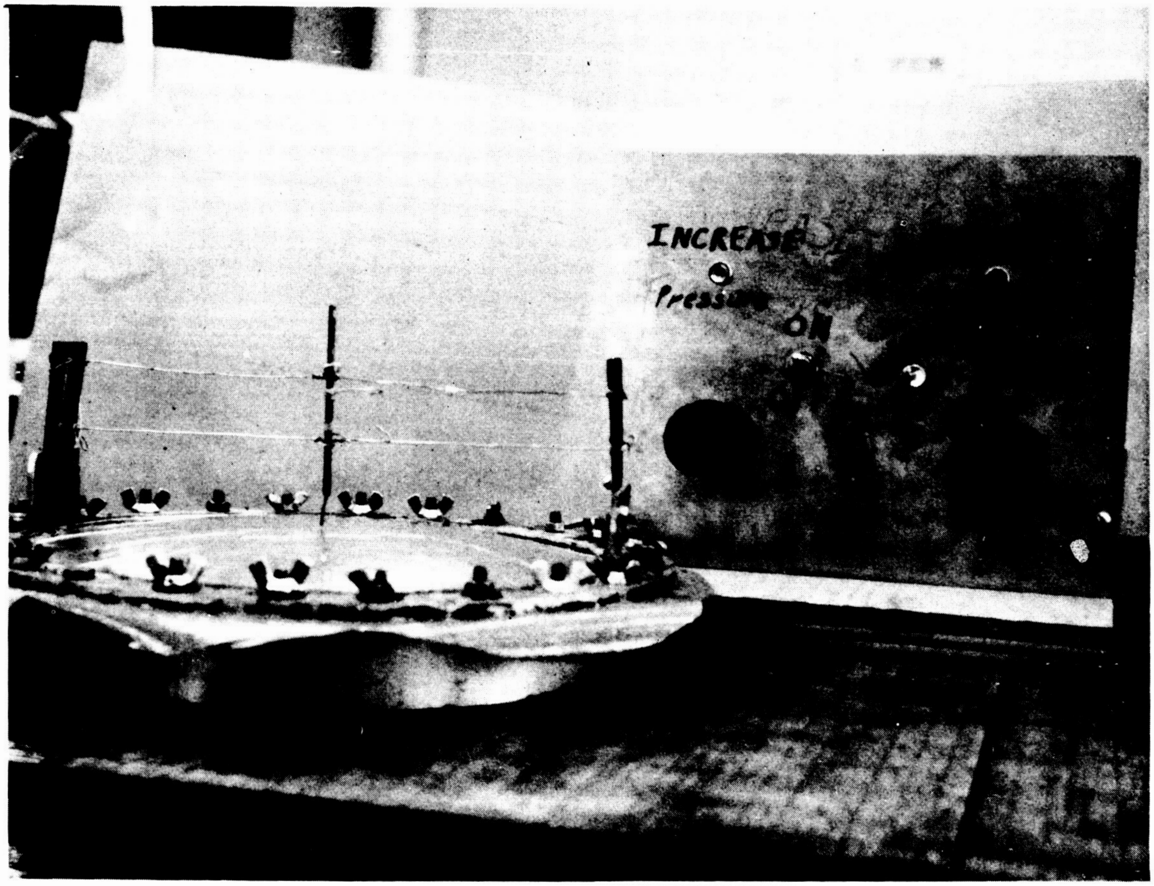


Figure 12. Sagitta variation sensing equipment.

the vacuum as they were heated to the softening point. Presumably this was due to the release of entrapped and dissolved air. In these samples the optical surfaces showed "macro" waviness and a somewhat dimpled surface.

A number of vacuum chamber tests were therefore run on the epoxy reinforced samples under varying conditions of heat input, to determine the optimum conditions of air release. The first samples were cured at 225-240° F for approximately six hours. The cure temperatures were gradually lowered, and the times were increased. The results of these tests indicated that a slow cure, of approximately 24 hours at minimum temperatures of 185-215° F produced the best optics in the epoxy reinforced paraboloid. The surface, however, was still not comparable to samples made at room pressures, with an oven cure, and was very inferior to paraboloids made at room pressure and temperature. It appeared quite evident then that dissolved air and other volatiles in the resin when rapidly liberated by heat and/or vacuum were responsible for the deterioration of the optical surface. This indicates the necessity of a slow cure for all paraboloids.

Back Pressure Technique. These tests showed the impracticality of using either the syntactic foam or polyester techniques under vacuum conditions. Earlier tests had already established that both were satisfactory at normal pressures. Therefore it was decided to test a back pressure system that would maintain the reinforcement at pressure while the outer surfaces of the assembly were simultaneously subjected to the vacuum environment.

The first tests, which proved unsatisfactory, used an assembly of three diaphragms, as shown in Figure 13. It was intended that the inner aluminized diaphragm would be maintained at whatever pressure was necessary for the correct sagitta. The pressure between the two outer diaphragms would then be maintained at whatever was required to prevent bubbling and/or delamination. In tests of this system on several one-foot diameter parabolas it was found extremely difficult to maintain the correct ratio between the two pressures, and it was also extremely

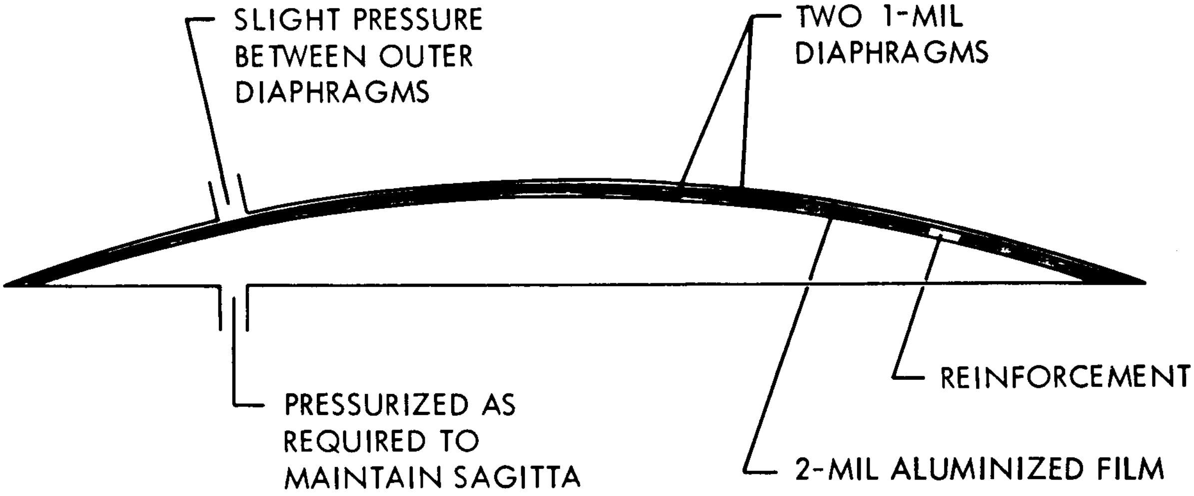


Figure 13. Initial "back pressure" system.

difficult to control the sagitta of the inner diaphragm. This approach was therefore discontinued in favor of a similar, but somewhat simpler, arrangement described below.

In this simpler and successful approach, an assembly was made up as shown in Figure 14. The two outer diaphragms, because of their perforations, acted primarily as mechanical restraints and not as pressure retaining diaphragms. In preparing the diaphragms care was taken to assure that the great majority of the perforations were not coincident. However, in use, the volatiles were released through the perforations. The liquid materials, because the diaphragms were pressed tightly together, were trapped and did not penetrate to the outer surface, except for small amounts which were mainly trapped between the two diaphragms. Tests made with this type of back pressure configuration gave quite satisfactory results.

In order to insure sufficient mechanical "back pressure" with the double perforated diaphragm technique, the following fabrication procedure was developed: The aluminized diaphragm is first stretched and then inflated at the relaxation pressure. Then the reinforcement, either epoxy or polyester, is applied to the inflated diaphragm. Next the assembly is deflated and the two perforated 1-mil polyester film diaphragms are placed on top of the reinforcement. The diaphragms are installed under the clamp ring in a smooth, but not stretched, condition. In subsequent pressurization the perforated diaphragms become tightly stretched over the convex surface of the parabola assembly. In tests on two-foot and five-foot diameter parabolas, the use of the "back pressure" diaphragms in the above manner not only minimized bubbling and delamination but also smoothed out the wrinkles which appeared in either reinforcement when the assembly was in the deflated condition.

Cross-section examinations of the structure of the polyester laminate reinforced paraboloid indicated that delamination was largely eliminated, and the assembly closely approximated one made by conventional vacuum bag techniques. The epoxy foam laminate, on the other hand, was somewhat changed after rigidization as compared to the uncured laminate. Prior to cure the assembly thickness was

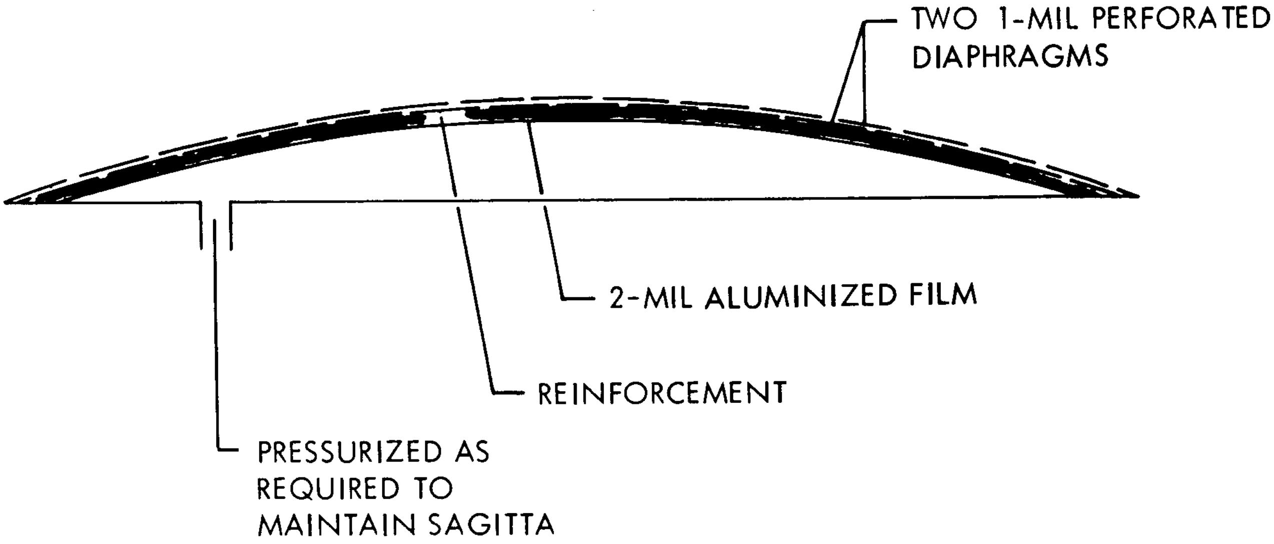


Figure 14. Mechanical "back pressure" configuration.

approximately 0.1 inch thick. After the elevated temperature cure it was found that the assembly was approximately 0.270 inch thick and the syntactic foam had expanded forming a number of internal voids. Also a firm bond had been established between the foam and the internal and external contacting films, forming a relatively stiff, lightweight sandwich structure. Figure 15 shows the cross section of a test sample cut from a paraboloid made in vacuum. The "foamed" structure is clearly visible, and the thickness is shown.

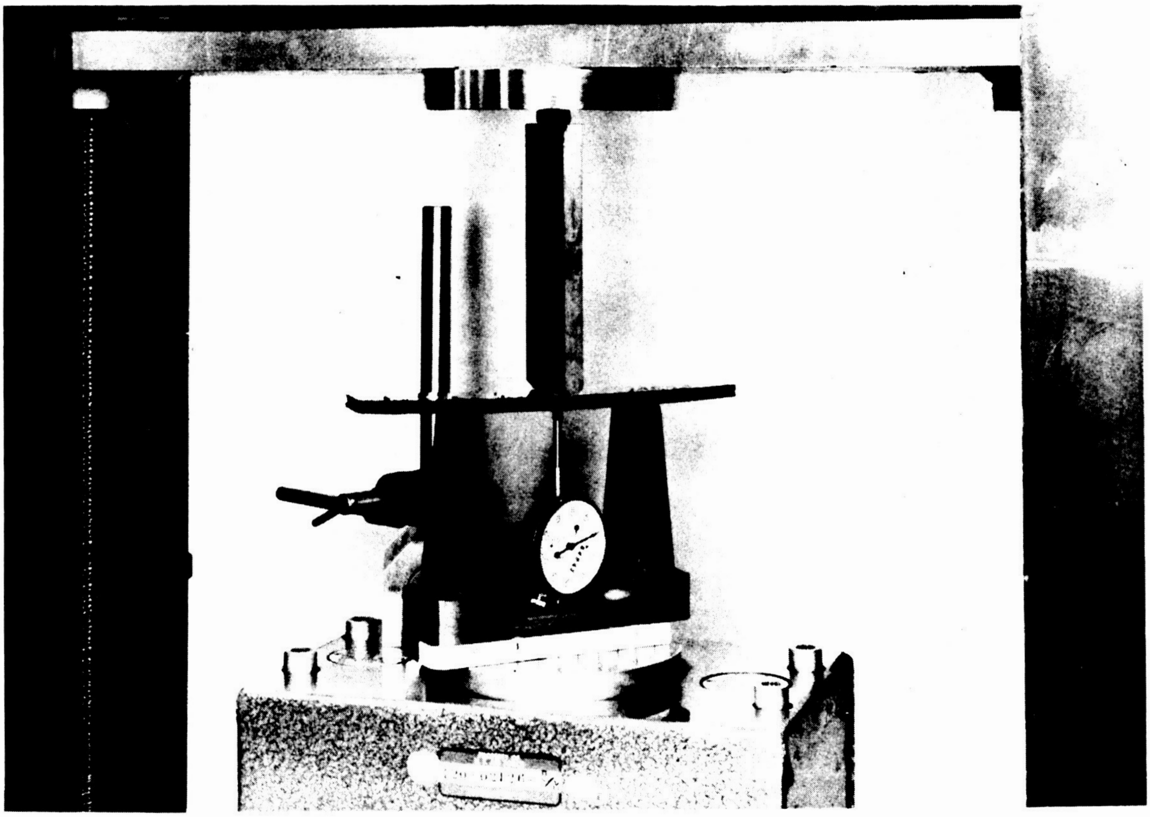


Figure 15. Cross-section of vacuum cured syntactic foam.

DEMONSTRATION

Demonstrations of erection, rigidization and packaging were conducted on 5, 6 and 7th of October. Two polyester and one epoxy paraboloids were demonstrated. The first, #161, utilized a Hughes fabricated diaphragm, seven fiberglass layers and two perforated "back pressure" diaphragms. It was pressurized in the chamber to the correct sagitta, but because of equipment failure was not rigidized perfectly. The second paraboloid, #162, made with a vendor fabricated mosaic and torus assembly, was pressurized to a five-inch sagitta, instead of the required 6-3/4 inch, to minimize the danger of rupture. This assembly was erected at a simulated altitude of 113,000 feet and was irradiated for 15 hours. Rigidization was perfect and thus demonstrated the feasibility of the polyester system. The curvature, however, was not suitable for demonstrating the optical characteristics of this type of structure.

The third paraboloid, #163, consisted of an epoxy reinforced assembly, a Hughes fabricated diaphragm and two perforated "back pressure" diaphragms. This part was erected and rigidized at a simulated altitude of 113,000 feet. The part was maintained in the chamber for approximately 24 hours and temperatures were gradually raised to 200°F on the edges of the part and to approximately 248°F in the center. The part had a good surface and curvature appeared to be within requirements. This part then adequately demonstrated the feasibility of the epoxy system. Figure 16 shows this paraboloid in the altitude chamber, with the radiant heater used for curing just above the assembly. Figure 17 shows the completed paraboloid undergoing informal tests.

Packaging of a complete rigidizable torus assembly was demonstrated by automatically ejecting and erecting the part from a hinged tubular container. The container was 8 inches in diameter, and 5-1/2 feet long. The structure was installed in the container in a folded and rolled condition, with an approximately 4-inch diameter longitudinal space which could presumably be used for pressure bottles, controls, etc.

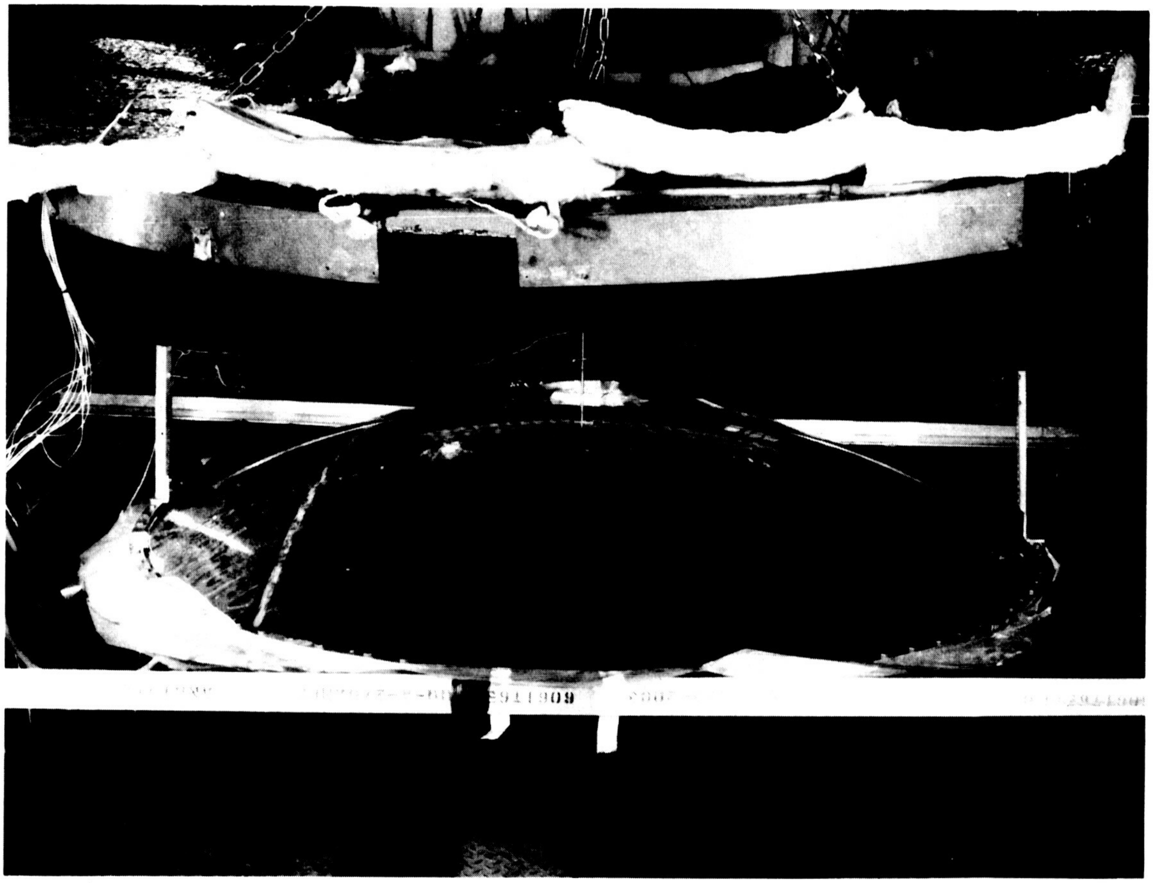


Figure 16. Method of curing five-foot diameter epoxy reinforced paraboloid.

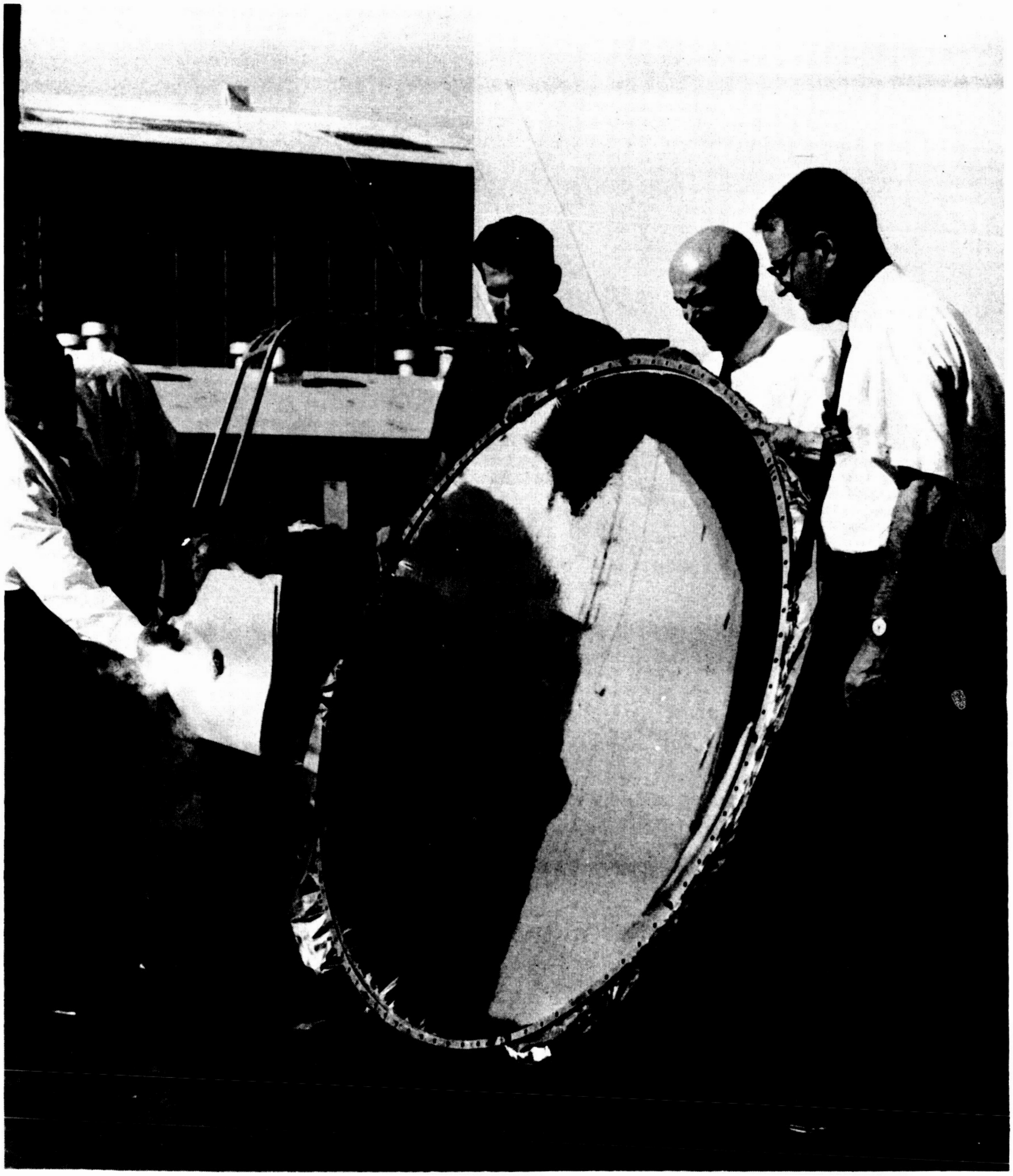


Figure 17. Five-foot diameter epoxy reinforced paraboloid.

This demonstration, it was believed, adequately established the packaging capabilities of the system. It was therefore not repeated using a polyester reinforced assembly. Figure 18 shows the ejection and erection sequence.

After demonstrating the erection and rigidization of both the epoxy and the polyester rigidized paraboloids, another polyester paraboloid was prepared. This was to be identical to the first two, but with a more accurate curvature. This paraboloid, No. 164, was made with a Hughes fabricated two-mil diaphragm. The paraboloid was formed at the desired sagitta height of 6-3/4 inches. After curing it was found that the diaphragm seam had opened up, which appeared to result in poor final curvature of the finished part. Figure 19 shows the appearance of paraboloid No. 164 with the seam repaired with transparent tape.

After removal of the paraboloids from the forming fixture it was found that neither type was rigid enough for mounting on the 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.

The final weight of the paraboloids, less the reinforcing ring, was very close to the originally estimated 0. 395 lb/sq ft. The epoxy paraboloid weighed 8. 11 pounds, with a unit weight of 0. 42 lb/sq ft. and the polyester paraboloid weighed 7. 88 pounds, with a unit weight of 0. 40 lb/sq ft. Since the paraboloids were quite rigid after the ring was added it may be assumed that these weights could be reduced further.

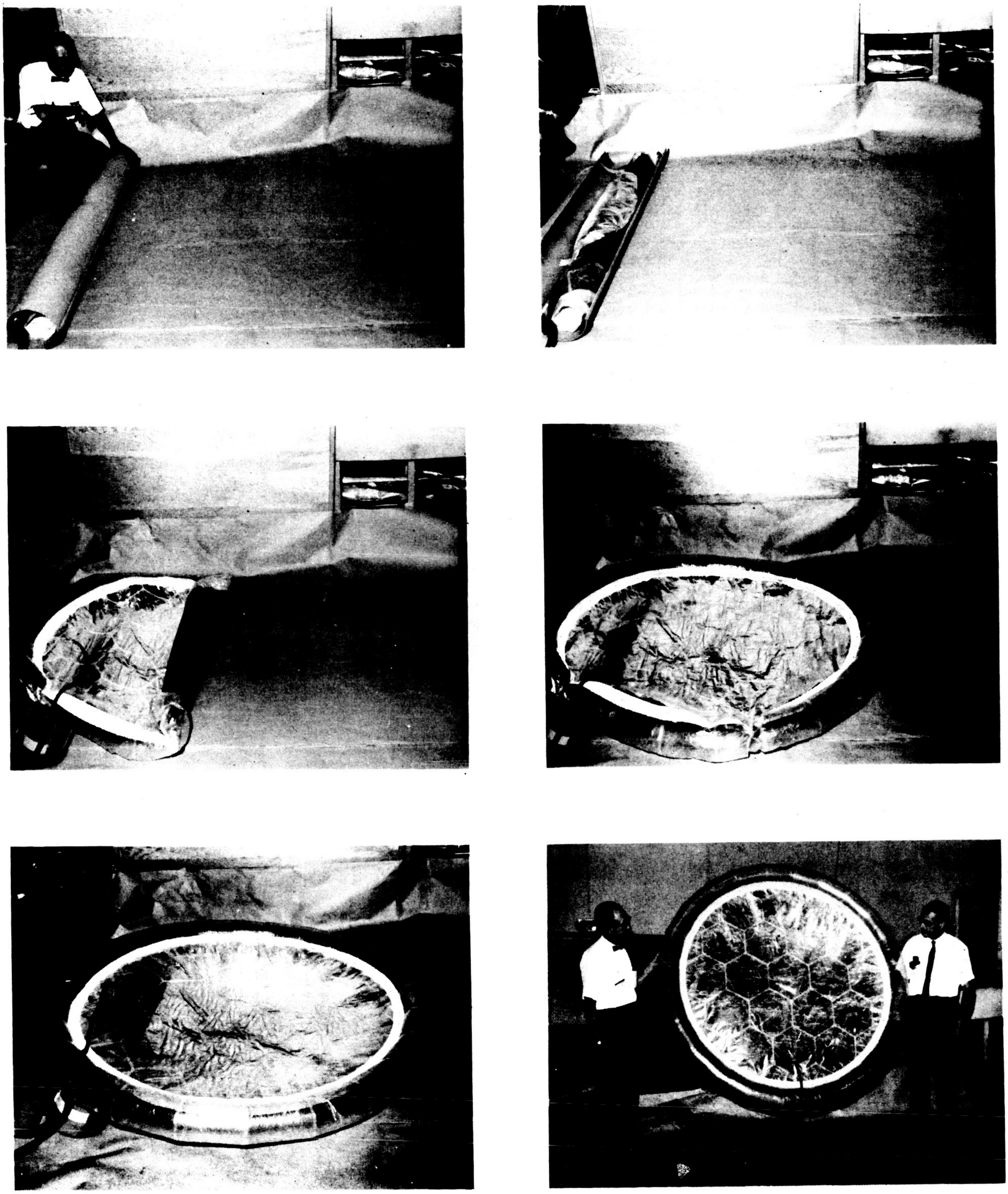


Figure 18. Ejection and erection sequence.

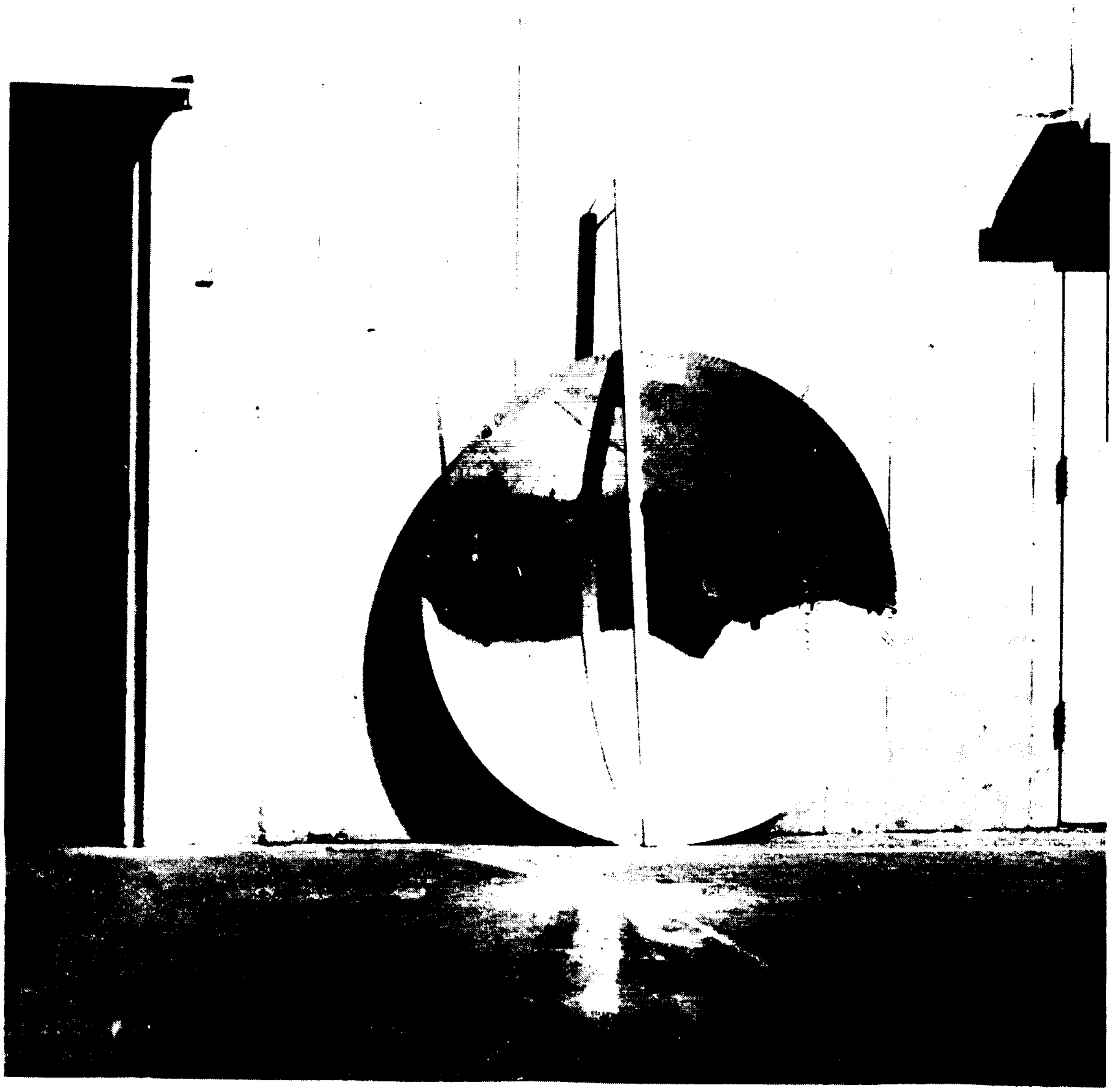


Figure 19. Five-foot diameter polyester reinforced paraboloid with seam repaired with transparent tape.

PHYSICAL PROPERTIES

MECHANICAL PROPERTIES

Samples of the epoxy syntactic foam and the polyester laminate reinforced material were cut out of paraboloids which had been expanded and rigidized in an altitude chamber. Standard tensile, flexural and edgewise compressive strength* tests were run on three samples of each at room temperature and at 240° F. The results of the tests are shown in Table V below.

Test Type	Temp °F	Epoxy Foam		Polyester Laminate	
		Strength, psi x 10^3	Modulus, psi x 10^5	Strength, psi x 10^3	Modulus, psi x 10^5
Tensile	72	.410, .990, .380 Av = .593	4.940, 0.458, 4.680 Av = 3.359	15.0, 12.1, 12.8 Av = 13.3	7.00, 6.70, 5.95 Av = 6.55
Tensile	240	.310, .300, .235 Av = .282	1.730, 1.480, 1.080 Av = 1.430	6.25, 3.50, 3.62 Av = 4.46	2.64, 1.01, 1.04 Av = 1.56
Flexural (4-1/2" span)	72	.915, .601, .647 Av = .721	Not run	16.56, 15.68, 18.78 Av = 17.007	Not run
Flexural (4" span)	240	.500, .561, .492 Av = .518	Not run	.23, .312, .305 Av = .299	Not run
Compressive Edgewise	72	.610, .690, .575 Av = .625	Not run	.650, 1.66, 4.70 Av = .593	2.10, 1.68 Av = 1.89
	240	.150, .150, .120 Av = .140	.938, .994, .756 Av = .896	.380, .380, .245 Av = .335	Not run

Table V. Mechanical properties of rigidizing materials.

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

---

*The compressive tests were run in a special North American Aviation type fixture which provided support to minimize column bending.

THERMAL COEFFICIENT OF EXPANSION

Specimens for thermal coefficient of expansion tests were cut 3-1/4 inches long by 1/2 inch wide to fit in the quartz tube of a standard ASTM D696-44 dilatometer, shown in Figure 20. Because the polyester samples were only approximately 0.050 inch thick instead of 0.5-inch diameter usually used it was felt that the samples might bend in column failure during the test, consequently small 3-inch by 1/4-inch wide brass shims were cemented edgewise on each side of the specimen, at one end. The shims then allowed free expension and contraction, but minimized the buckling tendency under load. Figure 21 shows a close-up of the sample inside the dilatometer tube.

The results of the tests are shown in Table VI.

Test Temp °F	Coefficient of Expansion, in/in/°F x 10^{-5}	
	Epoxy Foam	Polyester Laminate
-320	1.85	1.12
-118	2.63	1.37
+32	3.25	1.88
+150	2.07 (130°F)	1.17
+185	2.71	1.10
+240	Could not be run	.92

Table VI. Thermal coefficients of expansion of rigidizing materials.

In Table VI the thermal coefficients of expansion are shown increasing as the temperature increased from -320°F to +32°. Above this temperature the coefficients appeared to decrease in the case of the polyester and gave anomalous results with the epoxy. The polyester samples, it is believed, buckled under the load of the quartz rod in the dilatometer apparatus and thus the expansions were counteracted by the buckling failure. The extent of this failure was, of course, made worse as the temperature increased. The same effect was responsible for the epoxy results, it is believed. In this case at 240°F readings were

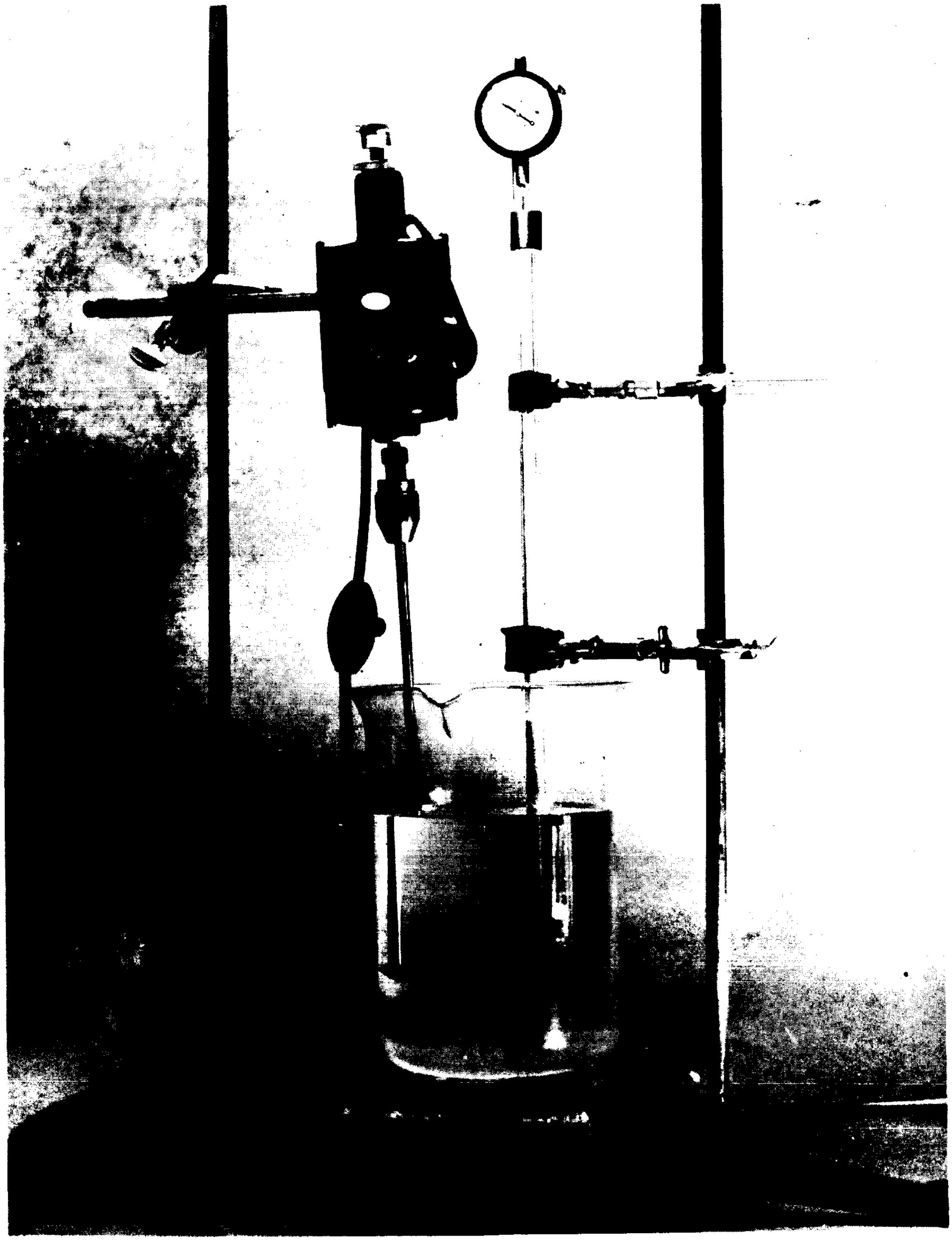


Figure 20. Quartz dilatometer used to determine thermal coefficient of expansions.

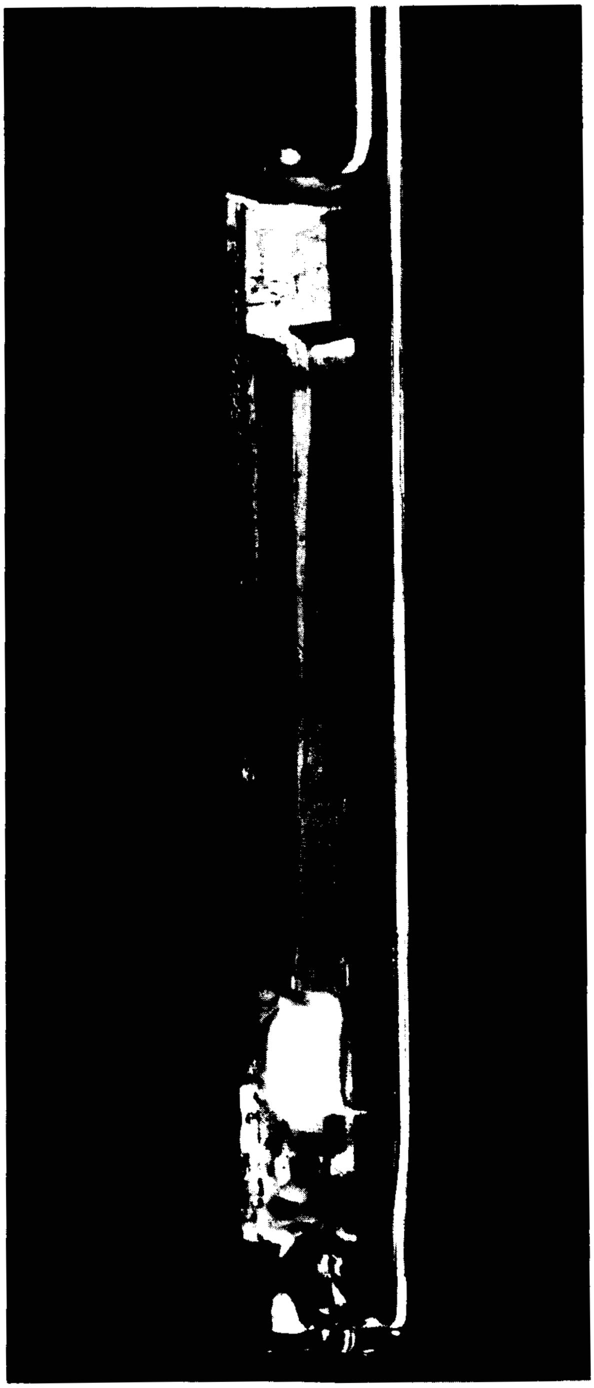


Figure 21. Expansion sample with brass anti-buckling reinforcement.

meaningless, since as the material increased in temperature the apparent coefficient of expansion decreased. This was also, no doubt, due to compression of the foamed sample by the weight of the quartz rod. Both samples were used in the "as cured" condition, with no post cure, which probably would have added strength.* An attempt was made to use 1-inch-long samples for the epoxy specimens at the elevated temperatures, instead of the approximately 3 inches x 1/4 x 1/4 samples used for the previous tests. The same results, however, were secured. Due to lack of time smaller samples were not made of the polyester materials.

VACUUM AND RADIATION EFFECTS

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 infra-red and ultra-violet 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 overall setup used is shown in Figure 22, and Figure 23 shows the specimens in the quartz chambers at the start of the test.

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 the five infra-red heating lamps shown. (This was the maximum temperature which could be obtained.) The ultra-violet 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. See Figure 24.

---

*Possibly the elevated temperature tests could have caused some post cure on the polyester samples, which then shrank slightly, thus lowering the values obtained.

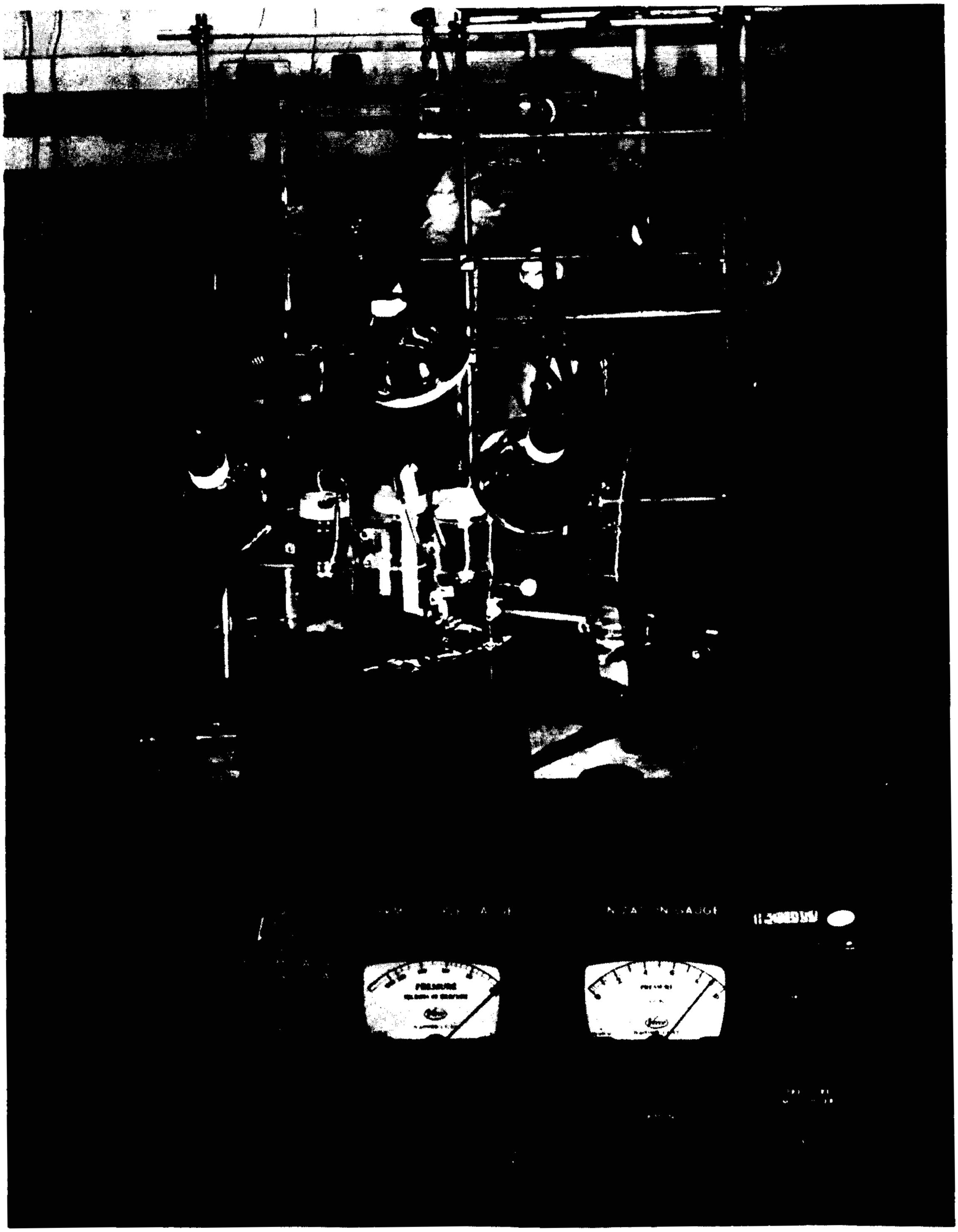


Figure 22. High vacuum and radiation test set-up (UV lamp in box covered with aluminum foil). (For clarity several IR lamps have been removed.)

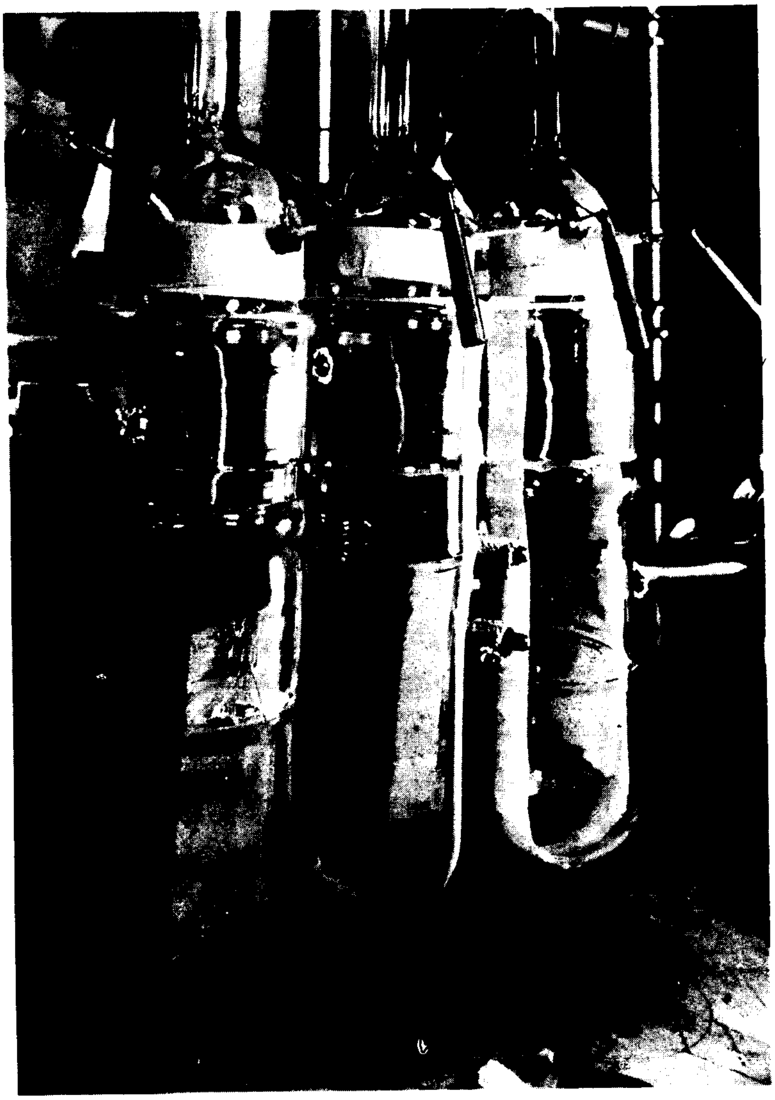


Figure 23. Appearance of samples prior to test. Polyester samples on left.

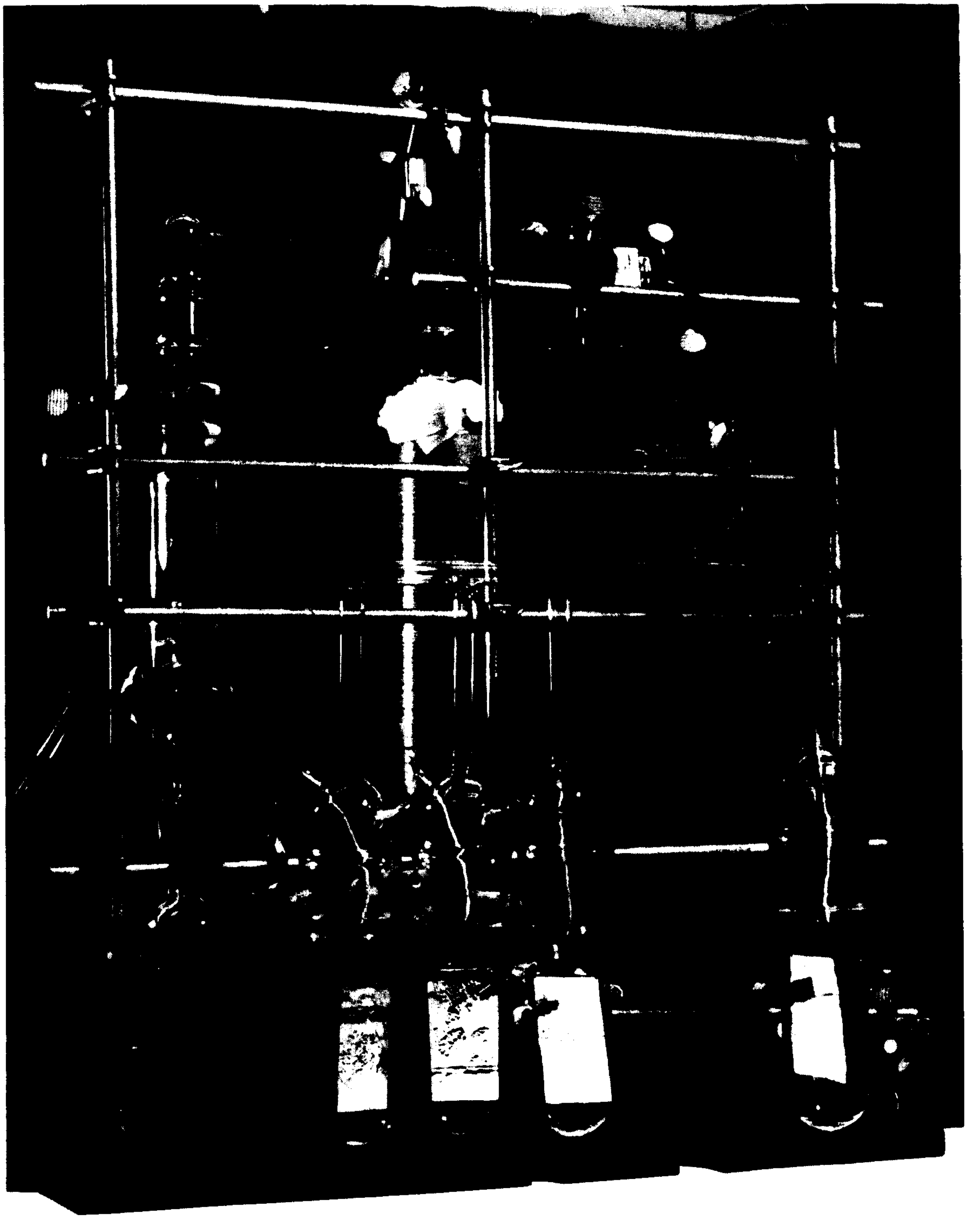


Figure 24. Appearance of samples after vacuum and radiation test. (Note changes in polyester samples.)

OPTICAL TESTS

Reflectivity Tests

Several paraboloids 1 foot in diameter were tested for reflectivity, using the techniques described in the appendix. The results of the tests are shown in Table VII.

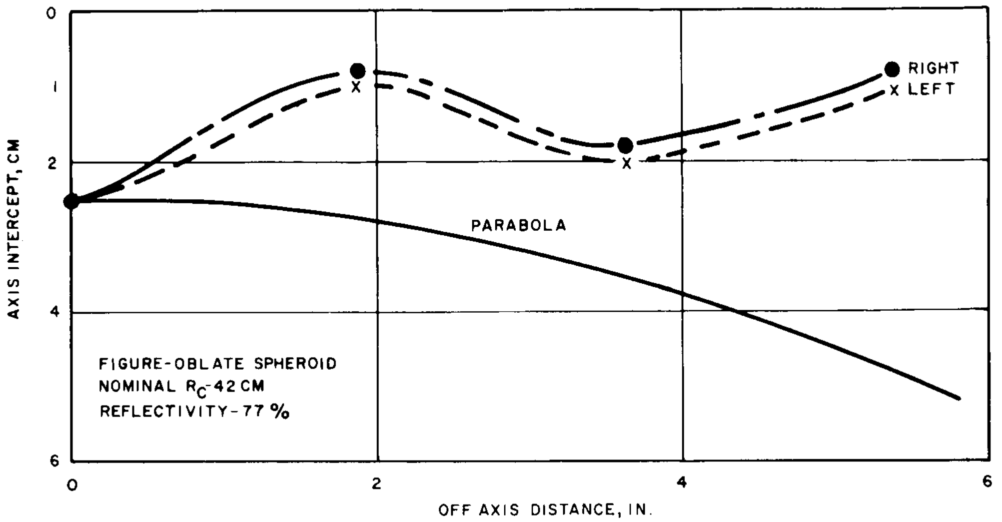
Sample No.	Type	Percent Reflectivity	
31	Polyester	80.5	Central 6-inch diameter
57	Polyester	77	
60	Epoxy	82	

Table VII. Reflectivity measurements.

Figure 25 shows the figures obtained on two of the above paraboloids. As can be seen, the process is capable of producing the required 80-percent reflectivity.

Surface Angular Deviation and Axis Intercepts

The tests for surface angular deviation and axis intercepts were made on the five-foot paraboloids made at the simulated 113,000-foot altitude. Both paraboloids were made using the Hughes fabricated 2-mil aluminized mylar two-piece diaphragms. The method of test is described in the appendix. Figure 26 shows the figure obtained on paraboloid #163, the epoxy reinforced paraboloidal made during the demonstration. The top portion of Figure 26 shows the axis intercept results and indicates that the surface was generally parabolic but with some astigmatism present. The lower part of the figure gives the surface angular deviation from the best fitting paraboloid. This was generally within ± 1°.



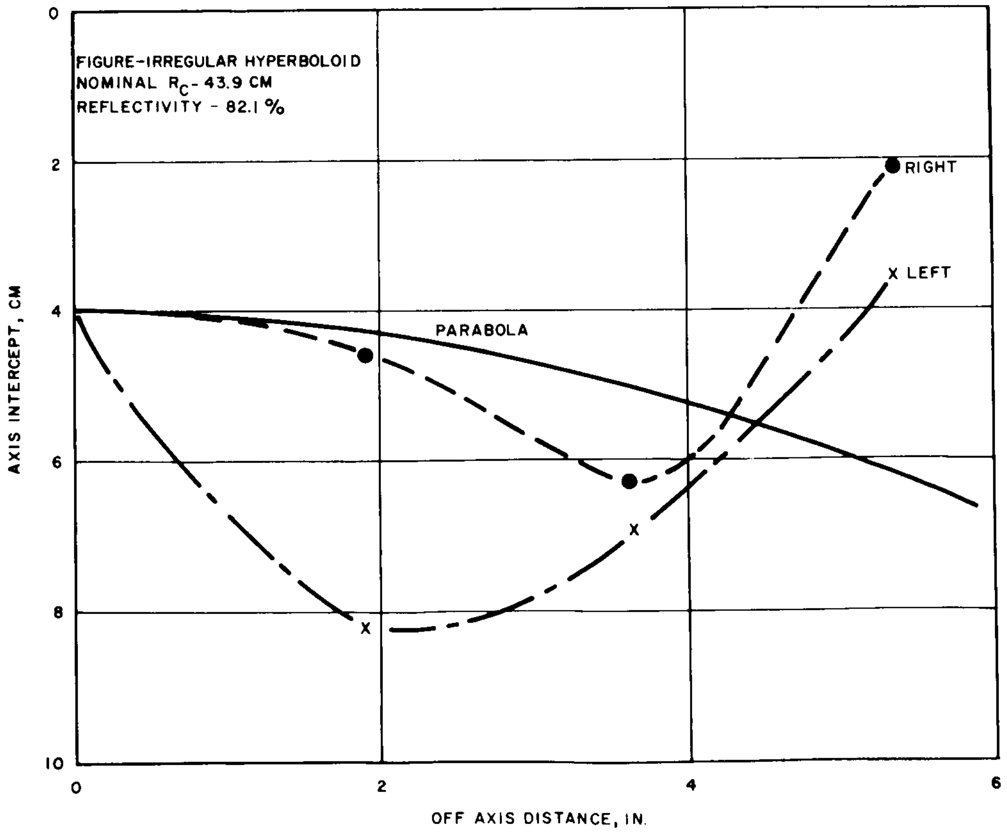


Figure 25. Figure determinations on small paraboloids made for reflectivity tests.

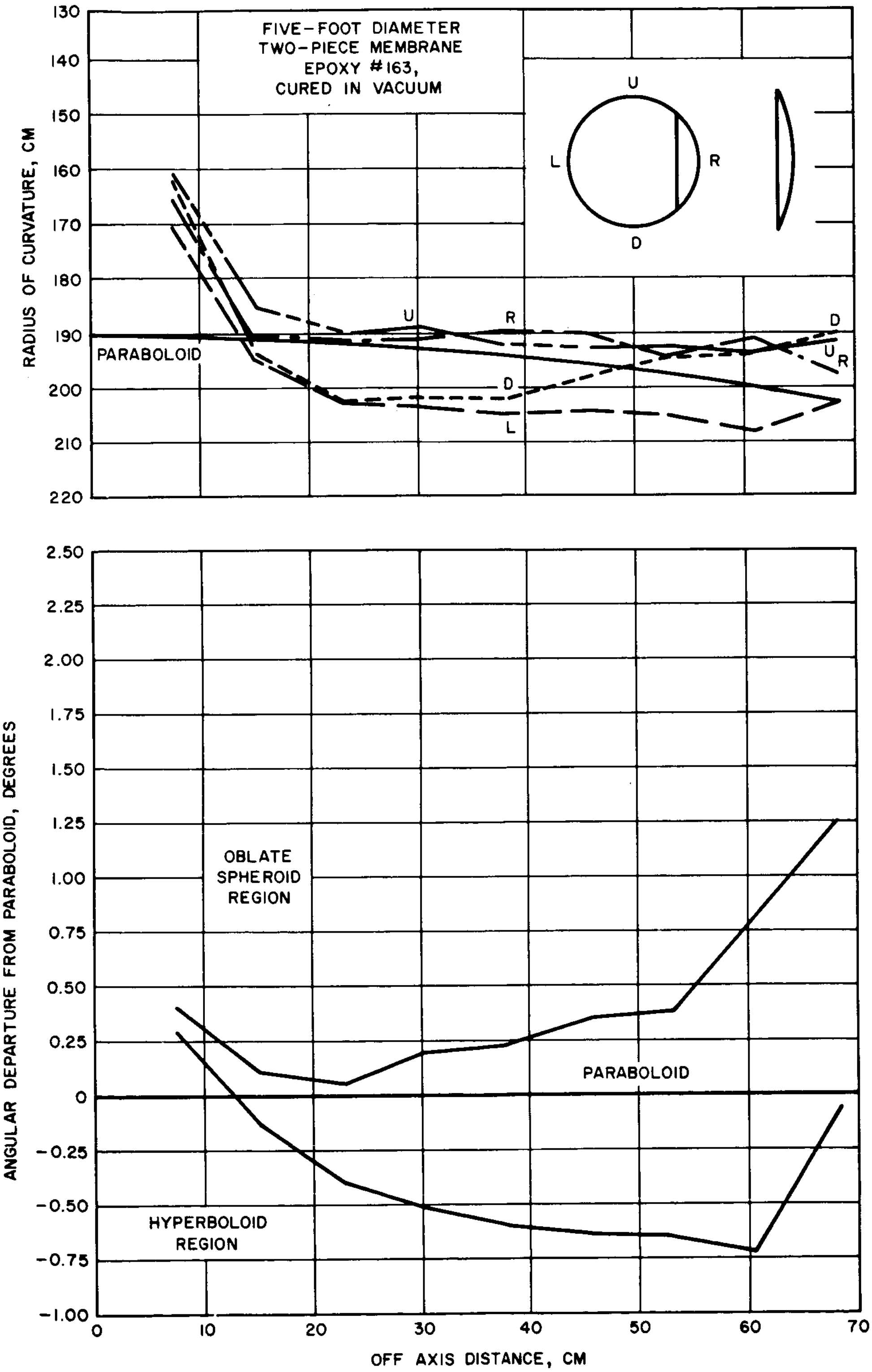


Figure 26. Figure determination of five-foot epoxy reinforced paraboloid.

In Figure 27 similar tests are shown for the polyester paraboloid. Here the figure was generally oblate with some astigmatism. The surface angular deviation was generally within ± 1.8°.

Calorimeter Tests

The rooftop facilities of the Power Systems and Test Operations Department at the Hughes El Segundo facility were used to perform calorimeter tests on two five-foot concentrators. A water-cooled calorimeter with various sized asbestos aperture plates was used. The ambient solar flux was monitored with an Eppley pyrheliometer. Figure 28 shows this apparatus.

The measured results for the two-piece epoxy concentrator #163 are shown in Figure 29. No allowance is made for the efficiency of the calorimeter itself. Figure 30 shows the results for the two-piece polyester concentrator #164. As shown the epoxy reinforced paraboloid had an efficiency 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.

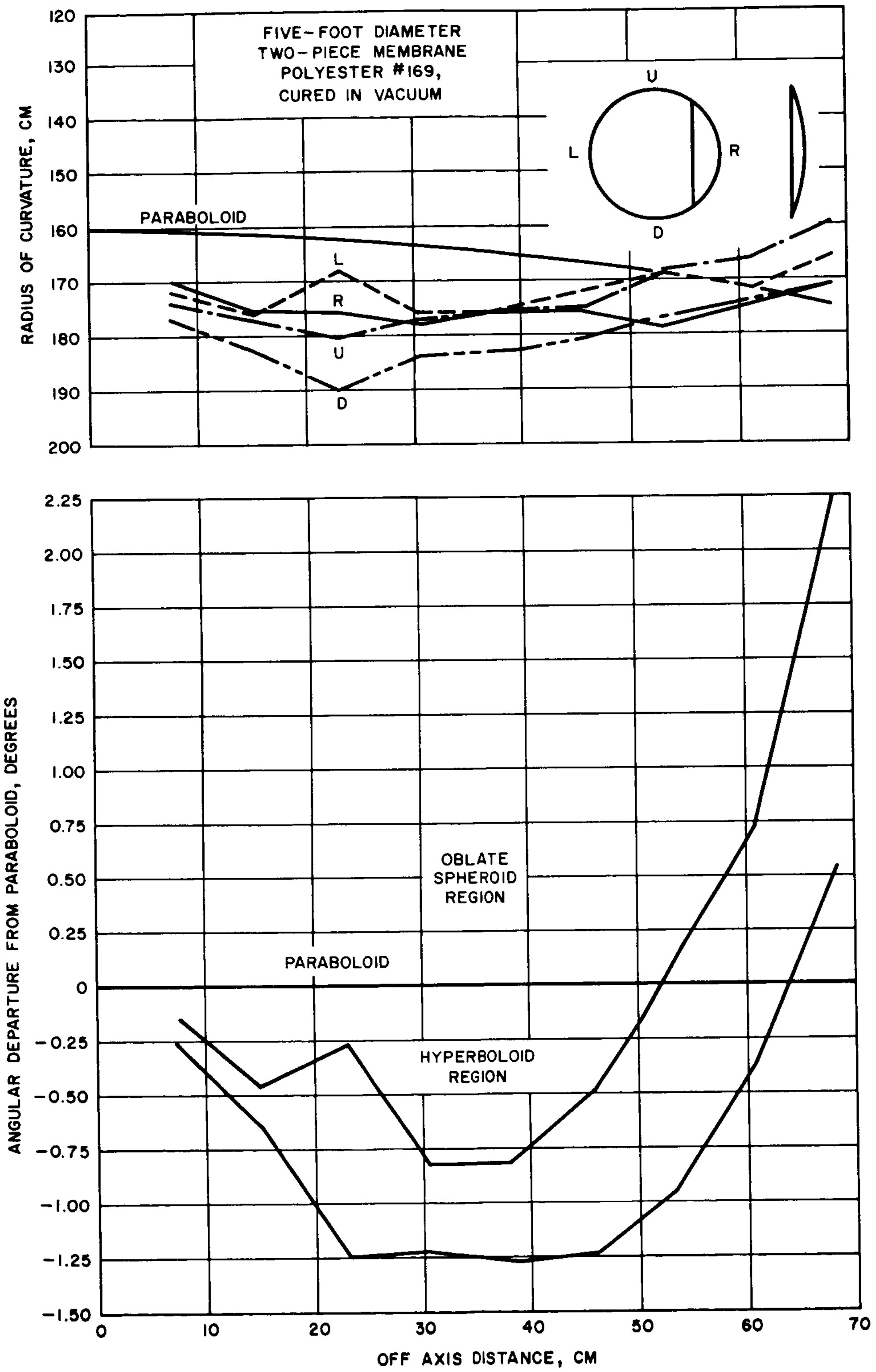


Figure 27. Figure determination of five-foot polyester reinforced paraboloid.

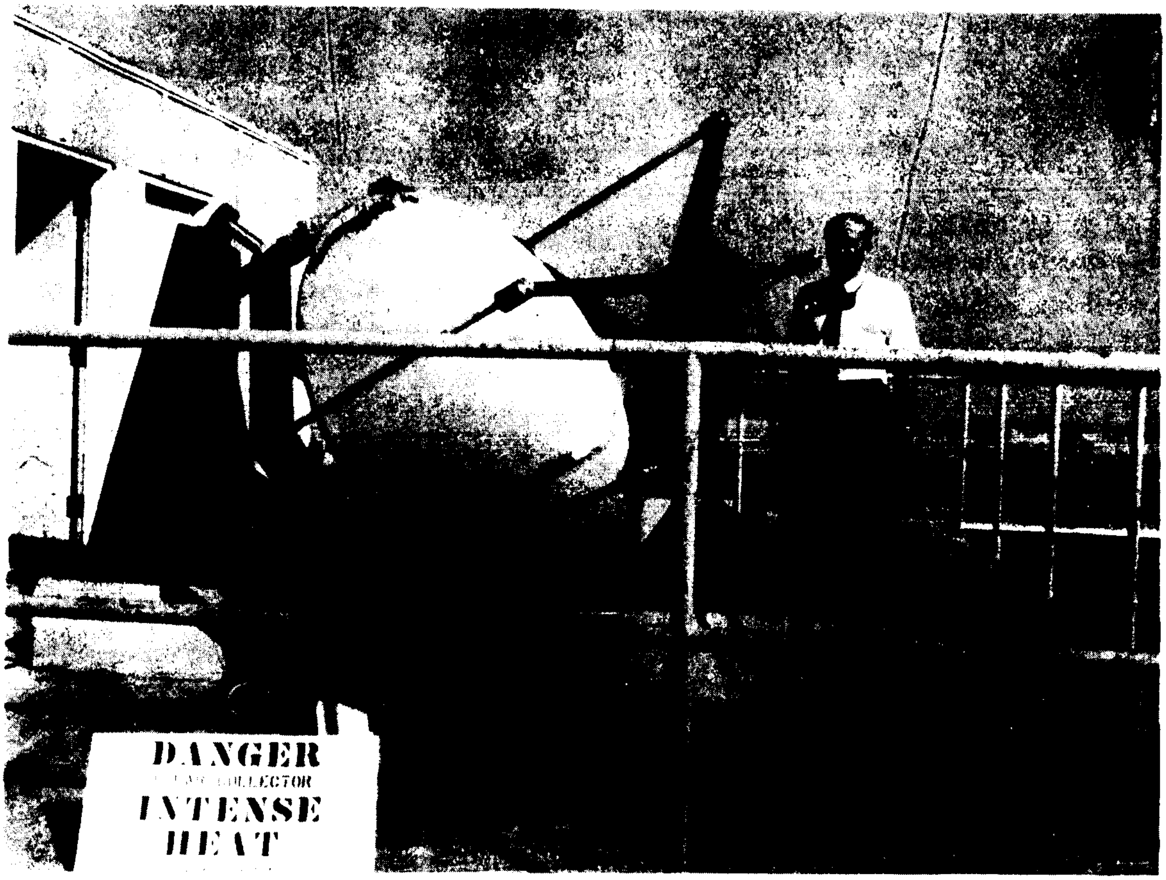


Figure 28. Calorimetric test apparatus used to determine paraboloid efficiency.

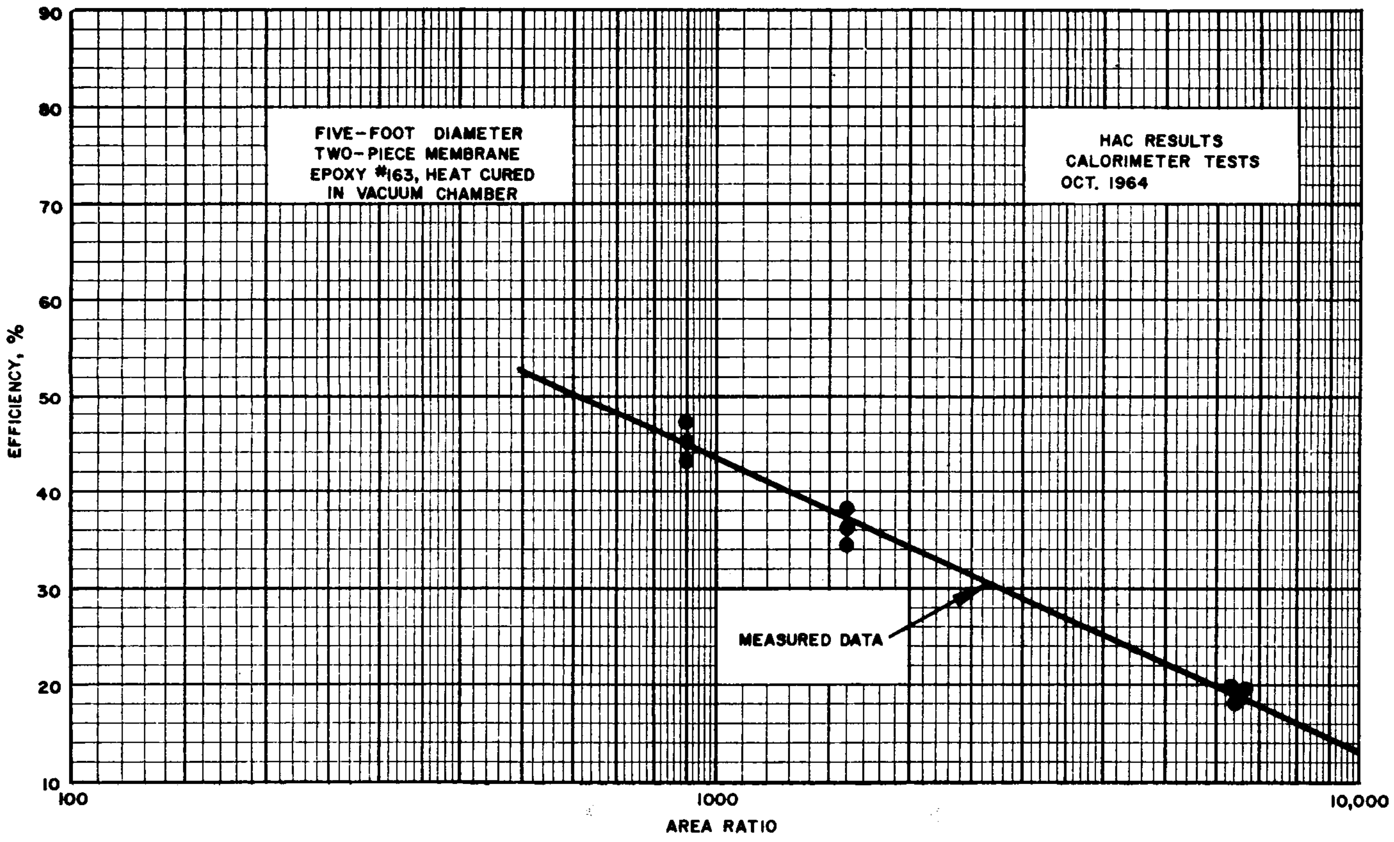


Figure 29. Calorimeter tests of five-foot epoxy reinforced paraboloid.

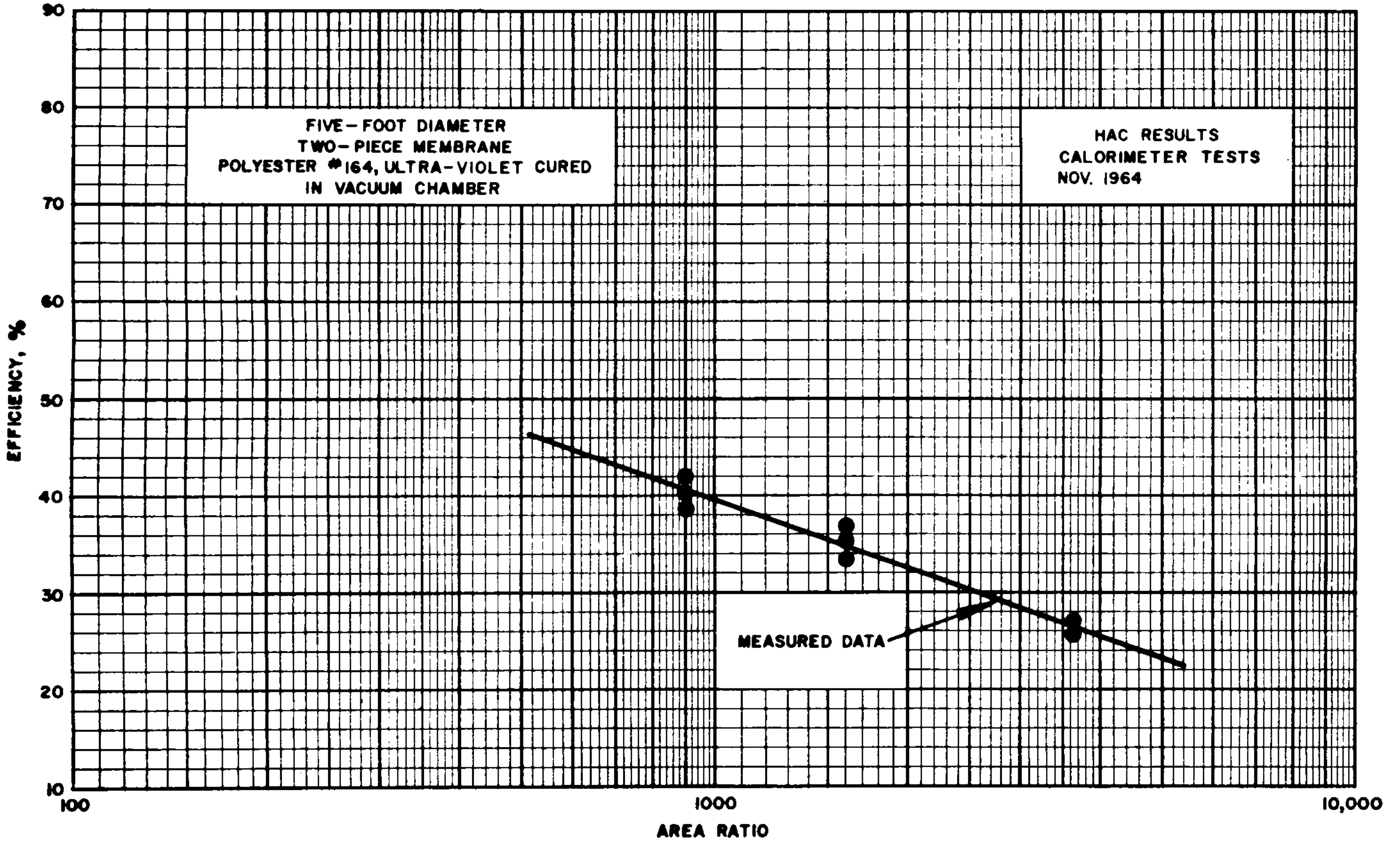


Figure 30. Calorimeter tests of five-foot polyester resin paraboloid.

CONCLUSIONS

Based on the work done and the results obtained the following conclusions may be made:

1. The contractual requirements have been met for a compactly packaged solar energy collector which can be automatically ejected, expanded and rigidized in a vacuum environment.
2. Two techniques are available for fabricating the required paraboloids; a diallyl phthalate based polyester laminate technique utilizing ultra-violet radiation for activation; and an epoxy syntactic foam rigidization technique utilizing infra-red radiation.
3. For both fabrication techniques the Hughes developed stress-relaxation system requiring no master forms is very practical. For optimum results, however, a system for "tuning" in space should be developed.
4. Either system can be used to make pre-coated parts which can be stored for at least a month at room temperature.
5. The epoxy syntactic foam is the better of the two systems from the standpoint of optics.
6. The finished paraboloids weighed approximately 0.4 lb. per square foot, not including the inflation apparatus, the torus, etc. Based on the performance of the finished paraboloids, however, it should be possible to reduce this weight.
7. It appears that the best optical results are secured through the use of the thicker films, .003 or .005 in. rather than .002 in. used.
8. The polysulfide gel coat used apparently breaks down when heated in the high vacuum. Some other gel coat material should be investigated.

RECOMMENDATIONS

While the techniques and materials previously described can be used to successfully fabricate full sized (50- to 100-foot diameter) concentrators, to obtain optimum results with such structures it is recommended that the additional investigations summarized below be carried out:

1. An investigation should be made to develop a high pressure resistant torus, or other techniques should be investigated to assure correct automatic expansion of the inflated paraboloid. These last might include making the paraboloid part of a sphere, which is later cut away.
2. The use of aluminized polyester film in gages as high as .010 should be investigated. The thicker film was found to provide better optics, and on larger paraboloids will prove more practical than the .002-mil material used for the five-foot paraboloid.
3. Even though the polyester reinforced paraboloids did not exhibit the better optics, their convenience in use, ready availability, and good storage properties merit further investigation. This additional work with the polyesters should concentrate on developing relatively heavy gel coats, and on the use of silicone RTV rubber and nylon stretch fabrics as "lock" coats. Preliminary tests indicated that such materials are considerably superior in a number of respects to the gel coats using polysulfide based materials.
4. A process should be developed for "tuning" the pressurized diaphragm to optimum curvature just before rigidization. Such a technique would not only serve to produce paraboloids, but would also assure placement of the final heat absorbing body in the best position for use in the rigidized structure.

APPENDIX

RELAXATION PROCESS OF CONCENTRATOR FABRICATION

A novel approach to the problem of making lightweight solar concentrators for space power systems has been developed at the Hughes Aircraft Company. The process is novel in that it eliminates the need for master forms and in that it can produce any desired second-degree shape: paraboloids, ellipsoids, hyperboloids, etc. Concentration ratios of 1000 have been measured with experimental models, and specific weights of concentrators of 0.5 pound per square foot have been achieved.

A thin membrane, in this case 0.002 film with a 10-molecule coating of vacuum-deposited aluminum, is placed in a circular fixture and clamped around its periphery. Next, a differential gas pressure is applied across the membrane so that it deforms to a particular curvature or sagitta. When the desired f-ratio is reached, a rigidizing agent is applied and allowed to set up. The differential pressure is maintained during the curing cycle. After curing, the pressure is removed and the finished lightweight concentrator is extracted from the jig.

The shape one would get with the simple straightforward procedure outlined is far from a paraboloid or even a sphere. It is, in fact, a very oblate ellipsoid (see Figure 31). However, a method of obtaining any particular conic of revolution desired has been perfected.

In this method the membrane is deformed in the fixture, first by the application of a differential pressure, to a curvature or sagitta somewhat in excess of the final value desired. Prior to rigidizing, the differential pressure is relaxed with the following results. As the differential pressure is gradually reduced, the shape of the membrane passes through all of the conic sections in the following order: oblate ellipsoid, sphere, prolate ellipsoid, paraboloid, hyperboloid (see Figure 32). When either testing or prior experience indicates that the desired shape has been assumed by the membrane, the rigidizing agent is applied while the pressure differential is maintained at the proper

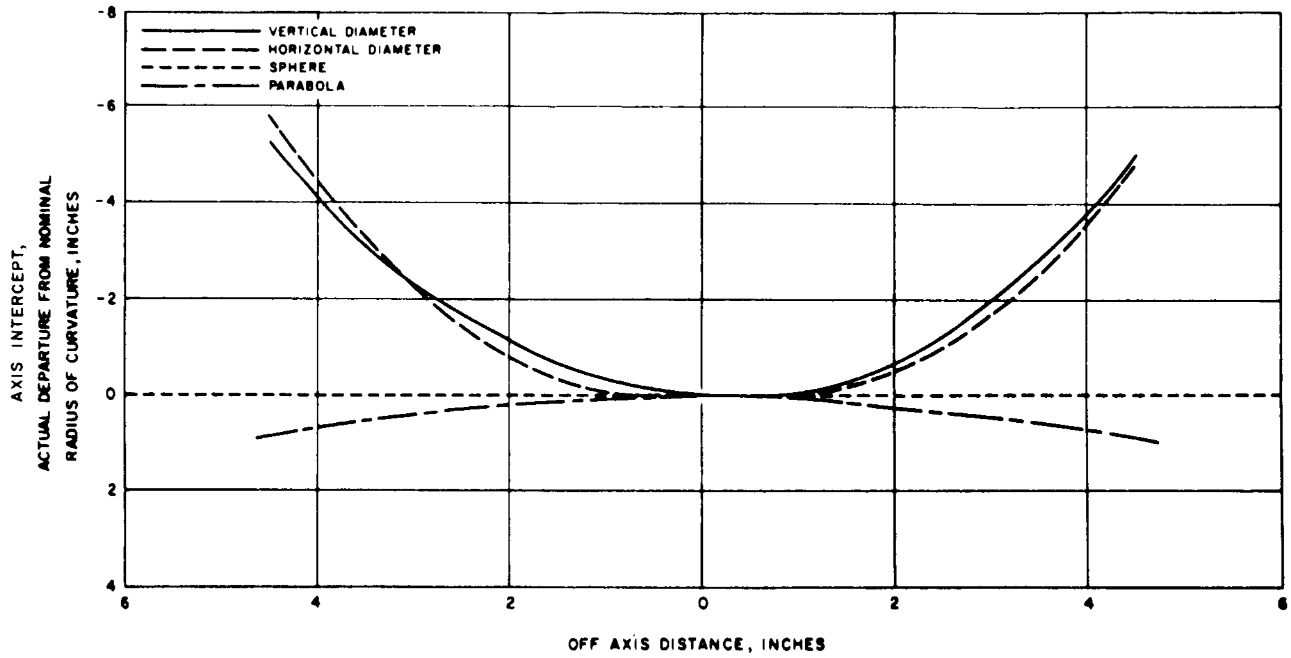


Figure 31. Results using 0.002 polyester film.

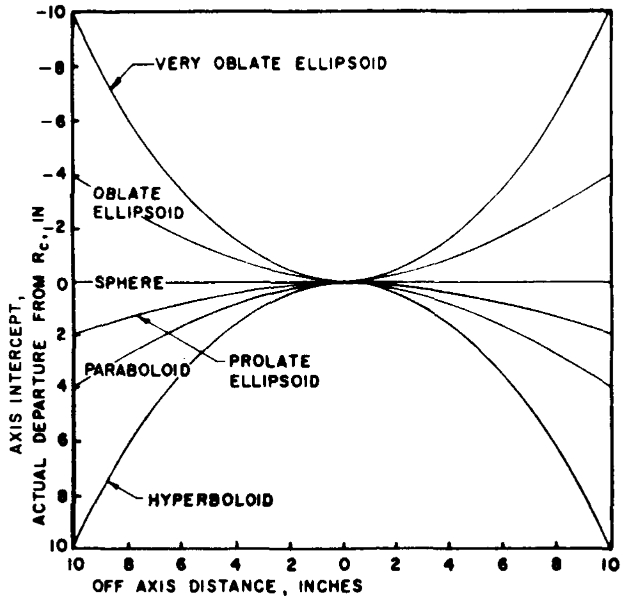


Figure 32. Axis intercept variation for conics of revolution.

value. The change in sagitta or curvature going from the original stretched position to the desired relaxed position is slight, but for precise work can be allowed for exactly.

Patent application has been made for the relaxation process.

DETERMINATION OF STRETCH RELAXATION PRESSURES

Figure 33 shows the axis intercept test results for a typical membrane after stretching and relaxing to various differential pressures. In this particular case the membrane was 0.003 film in a 20-inch diameter jig. The initial (stretching) differential pressure was 4.0 psi. When the differential pressure was relaxed to 106 mm Hg the membrane assumed the shape shown in the uppermost plot of Figure 33. When the pressure was relaxed further to 96 mm Hg the membrane took on the less oblate shape shown second from the top of the figure. This change in figure with lower differential pressures continued until at 24 mm Hg the figure was hyperbolic. In this particular case the proper relaxation pressure for a paraboloid was 36 mm Hg.

The five-foot mosaic membranes were similarly evaluated. The stretch pressure was finalized at 0.812 psi (42 mm Hg) and the best relaxed pressure was 0.329 psi (17 mm Hg).

REFLECTIVITY TEST METHOD

For these tests an accurate standard spherical mirror was obtained. Figured to an accuracy of plus and minus 1/8 wavelength (Na_D) and coated with pure aluminum of astronomical quality, this standard mirror will reimage a small source placed at its center of curvature with almost exactly 90% reflective and imaging efficiency. For very precise work the reference standard mirror itself can be calibrated. For our purposes this was not required since imaging efficiency was not being measured.

A small source aperture is next illuminated uniformly and the reimaged spot allowed to fall on a suitable sensor-meter combination. Similar measurements are then made using a test sample reflector of

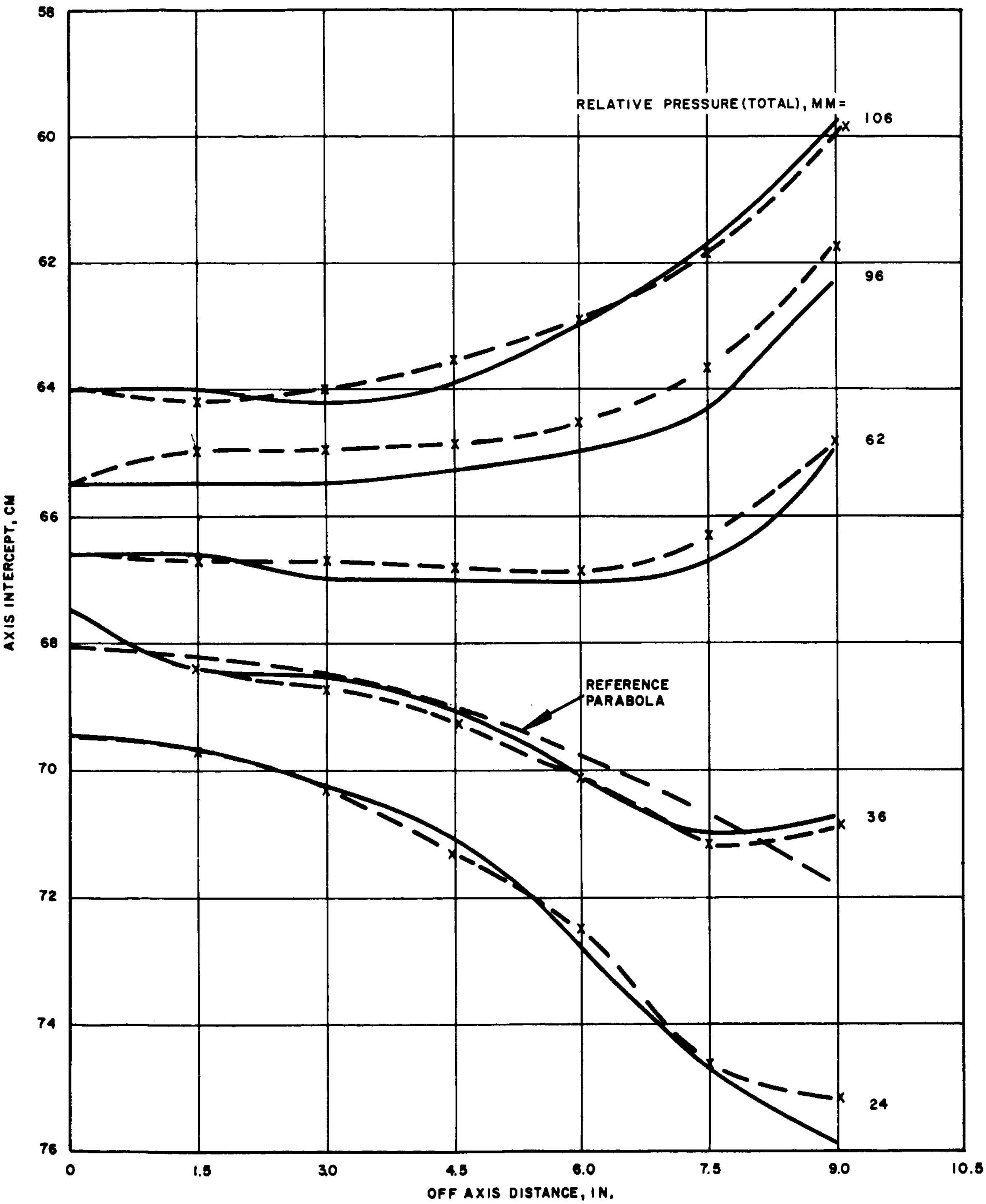


Figure 33. Sagitta variations with various relaxation pressures.

unknown quality. By comparing the meter readings for the standard and test mirrors, and allowing for the difference in the solid angle used for each, the reflectivity of the test mirror can be deduced.

SURFACE ANGULAR DEVIATION AND AXIS INTERCEPT TESTS

These tests can serve for an accurate, quantitative evaluation of the gross figure of a reflector. The test equipment consists of a sensible-sized source with an image card adjacent to it, moving together on a track parallel, and nearly coincident, with the optical axis. A mask is placed over the collector and various radial zones are exposed in turn. The zones' individual axial intercepts are measured by finding the position of the image card-source when the reflected ray intersects the optical axis at the source position. The central zone's "intercept" is determined by finding the position of best axial focus for that zone. Several radial traces are usually made; i.e., up, down, right, and left of center.

A plot can then be made of the departure of the various zones' axial intercepts - from that of the central zone - as a function of each zone's radial distance from the center of the reflector under test. This plot can be compared with the predicted differences for various reference conics of revolution. The angular deviation of the various zones from the best fitting paraboloid can be deduced from the above measurements by using simple trigonometry.

NASA-Langley, 1965