A PREDISTRIBUTED FOAM FOR RIGIDIZING MEMBRANE STRUCTURES IN SPACE

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INTRODUCTION

Early concepts of rigidizing membrane structures involved the generation of the rigidizing material in space and its distribution over the membrane structure in space. The rigidizing material was a urethane foam. This method is illustrated in Figure 1, which shows an egg-shaped membrane structure. The portion attached to the hub is a paraboloid (or solar concentrator); the opposite portion is a hemisphere that completes the pressure envelope. A film jacket attached to the paraboloid forms a space between the paraboloid and the film.

When the structure is inflated to a specific pressure, it takes on a specific contour. Then the rigidizing material is generated and injected into the space between the solar concentrator and the jacket. After the foam has set and cured, the spherical portion is cut away, leaving a rigid paraboloid in space (Figure 2).

A problem exists, however, in the even distribution of the rigidizing material. Because distribution problems have occurred in ground applications, it is not unreasonable to presume a low probability of accurate distribution with large structures in space. Such structures in this instance are the size of the Echo I satellite, with a paraboloid of 40 to 50 ft in diameter.

The objective of a program sponsored by NASA-Langley* was to develop and analyze a material that could be predistributed over the surface to be rigidized in space. The resulting material was an azide-base polyurethane foam, which was used in rigidization experiments performed in vacuum chambers on solar concentrators up to 2 ft in diameter.

A thermally activated urethane foam system was selected because it did not require an auxiliary blowing agent and because the urethane technology had already been developed to a high degree. The urethane system also offered flexibility in the selection of a foam formulation that would produce the desired physical characteristics.

In this program, various azide structures were investigated, and an optimum one selected for use in this application; a foam formulation was developed

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*Contract No. NAS 1-3301 from the National Aeronautics and Space Administration, Langley Research Center, Hampton, Va.

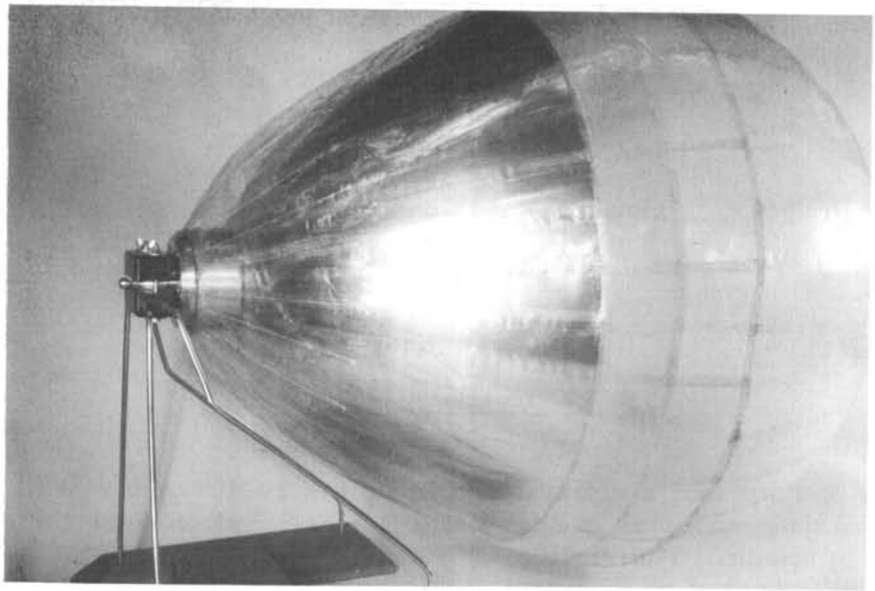

Figure 1 - Inflatable Solar-Concentrator Model

and made adaptable to the space-rigidizing of solar concentrators; the physical properties of the foam product were determined and their effectiveness in space was established; and the effects of this rigidizing process on the paraboloidal contour were determined.

The azide-base polyurethane foam offered promise, because it could be produced in vacuum with only the application of heat and because it offered a solution to the problem of distributing foam in space. But additional work is needed to advance the state of the art of this new predistributed foam.

This paper discusses the development of the process conditions, the production and testing of the foam product, the rigidizing of 2-ft models in vacuum, and contour measurements of the models.

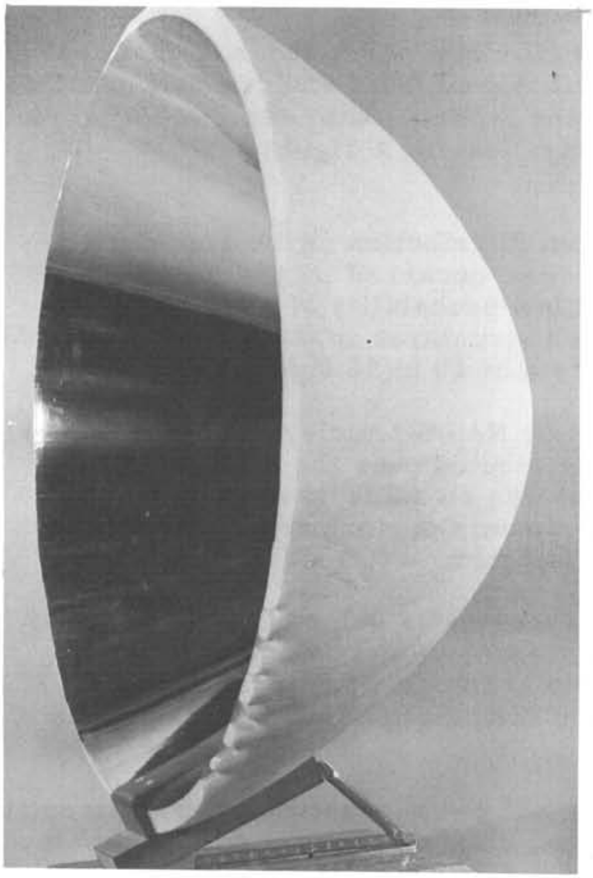

Figure 2 - Rigidized Inflatable Solar-Concentrator Model

FOAM PRODUCT AND PROCESS DEVELOPMENT

In the development of the foam product, a number of goals were set up for the production of a foam that will rigidize in the space environment. A hypothetical 300-naut-mi orbit was selected. Some of these goals are:

1. Triggering temperature: 175 F (the temperature should be high enough to prevent an inadvertent reaction and low enough to require a minimum heat input)
2. Sublimation tendency: 10 percent after 100 hr in vacuum (should be 10 percent or less after exposure to a vacuum of 10^{-5} torr so that the rigidizing process can react after a delayed period in orbit)
3. Rate of azide rearrangement: 50 min or less (this goal was set so that the ridigizing process would be completed in one orbit)
4. Reaction rate of isocyanate: set in 30 min; cure in 1 hr (this goal was set for the same reason as that in No. 4 to complete the rigidizing process in one orbit)
5. Heat release: 15 cal per square inch (this goal was set to minimize adiabatic temperature rise and to prevent distortion of a smooth mirror surface)

Figure 3 shows the foam processing sequence. The basic material applied to the space structure is shown in the dotted rectangle. A few catalysts and surfactants complete the formulation. As heat is applied, the first reaction is the triggering of the azide at 175 F in Step 1. Upon decomposition of the azide, or by Curtius's rearrangement, an isocyanate, additional heat, and some nitrogen are produced. The heat produced by the azide plus the heat supplied originally are now sufficient to release the blocked isocyanate in Step 2. The isocyanate then combines with the polyol resin in Step 3 to produce the polyurethane foam. This foam is of the rigid open-cell variety, which enables it to be removed from the vacuum chamber without damage.

Figure 4 shows the temperature history of the rigidizing process (in the change in scale on the abscissa, the shaded area represents 1 min of time). Heat is applied at the rate of approximately 12 F per minute. At 175 F, the azide is triggered. Its exotherm causes a temperature spurt to 350 F. At this point, the blocked isocyanate is released and combines with the polyol resin to produce the foam. The foam sets in less than 1 min and gradually cools to the environmental temperature.

Figure 4 is a typical temperature-history curve showing flexibility in the heating rate. A 100-percent "go" probability is obtained when the triggering temperature is reached in from 4 to perhaps 30 min. Slower heating periods are possible, and some have been tried with somewhat less than a 100-percent go probability.

How can this required heat be applied to a large surface? One approach could be by the use of selected surfaces. If the space vehicle can be presumed

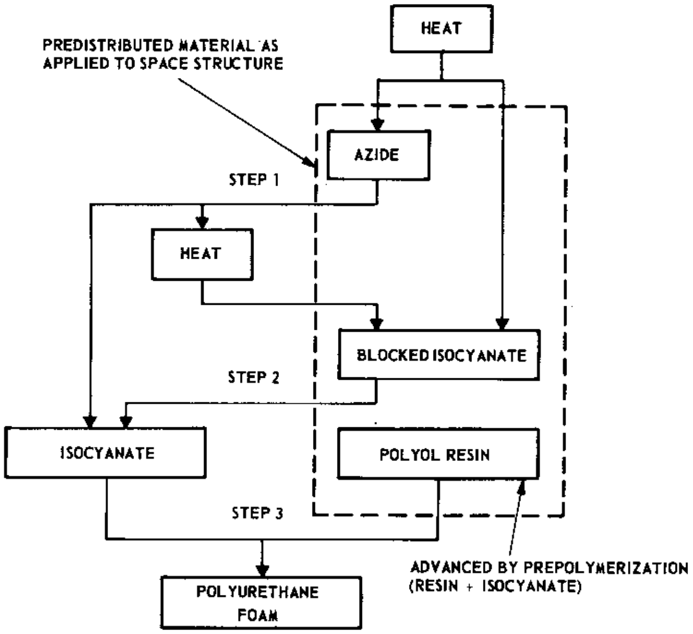

Figure 3 - Block Diagram of Rigidizing Process

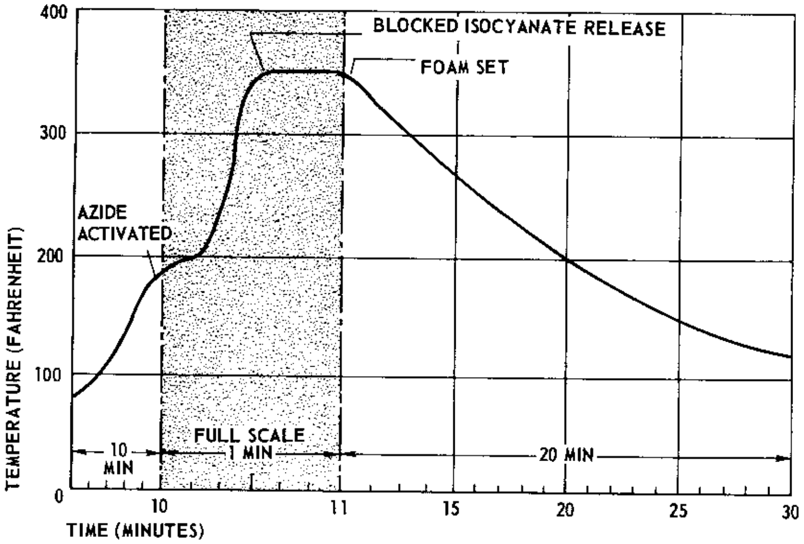

Figure 4 - Temperature History of Rigidizing Process

to have the capability of orientating the solar concentrator, so that the back side faces the sun, then a selected surface can absorb the required heat. The surface materials that were investigated are given in Table I.

TABLE I - SELECTED SURFACE MATERIALS FOR BACK SIDE OF SOLAR CONCENTRATOR

Surface	Absorptance, α	Emittance,
Aluminized Mylar	0.12	0.05
Black surface	0.9	0.9
Cr-Ni-V*	0.94	0.40
Cobalt oxide	0.93	0.24

*Chromium-nickel-vanadium.

Again, at a hypothetical orbit of 300 naut mi and a period of 100 min, the calculated surface temperatures shown in Figure 5 can be obtained by the selected surfaces. With aluminized Mylar, the temperature buildup is not rapid enough to assure a go condition. The cobalt oxide reaches 175 F in about 3 min and continues on past 220 F without leveling off. The Cr-Ni-V coating reacts in a manner similar to that of the cobalt oxide. A black surface, however, builds up to 175 F in 5 min and begins to level off at 215 F, a very desirable temperature history for this material.

As shown in Figure 4, the azide is triggered at 175 F, and the exotherm causes the material temperature to spurt to 350 F where it lingers for a minute or so and begins to cool down. Figure 6 shows the cooldown rates of those same selective surfaces, starting at 350 F. The cobalt oxide levels off at about 460 F; the Cr-Ni-V at 380 F. The aluminized Mylar with its low emittance cools down at a slow rate. The black surface, however, cools down in a highly acceptable manner.

On the basis of this brief thermal analysis, the heat requirement can probably be met by painting the surface black and orienting the solar concentrator so that the back side would face the sun for the rigidizing process.

PREPARATION OF PHYSICAL TEST SPECIMENS

The predistributed material can be applied to a membrane as either a paste or as sheets, like tile. With the latter, a ball of the material (resembling a ball of dough or clay) is placed in a hydraulic press and formed into a sheet of the desired thickness. This can then be cut and formed in patterns for almost any desired configuration.

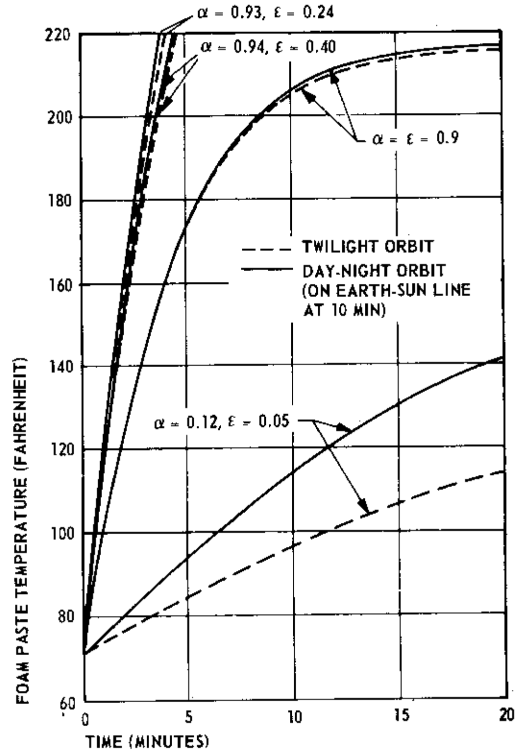

Figure 5 - Surface Temperatures versus Time (Reversed Orientation)

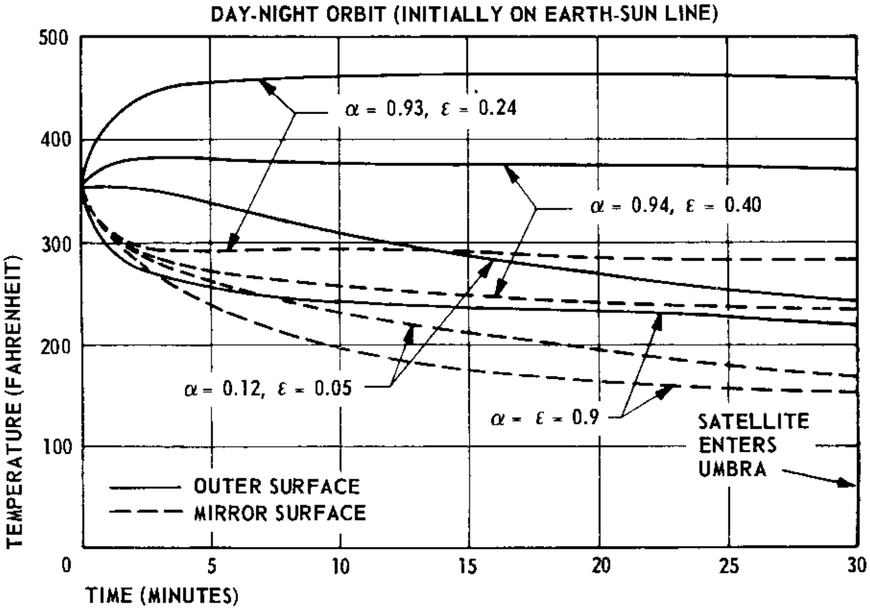

Figure 6 - Foam Temperatures versus Time (Reversed Orientation)

As a paste, the predistributed material can be troweled on, as shown in Figure 7. The membrane is then clamped to a metal ring (Figure 8), which then is inserted in a bell jar (Figure 9). The bell jar is sealed and pumped down to a pressure of 10^{-5} torr. The quartz lamps are then turned on, and heat is applied at a rate of 12.5 F per minute. Figure 10 shows a typical foam mass as removed from the bell jar. (Since the foam is of the rigid open-cell variety, it can be removed from vacuum without damage. Figure 11 shows a typical foam-mass section.) Test specimens are cut from the foam mass.

Bars of foam 1 by 1 by 4 in. have been used as test specimens for thermal expansion and stress-strain tests; 2-in. cubes have been used for density and dimensional stability measurements.

PHYSICAL PROPERTIES

Tests to determine the physical properties of the foam product were conducted in an evacuated environment of 10^{-5} torr. There is some information in the literature on the physical properties of foam material produced at atmosphere, but very little on those generated and tested in vacuum. However, the scope of this test program was to yield only sufficient physical property data to determine whether the rigidizing foam material has the basic capabilities for application to space solar concentrators.

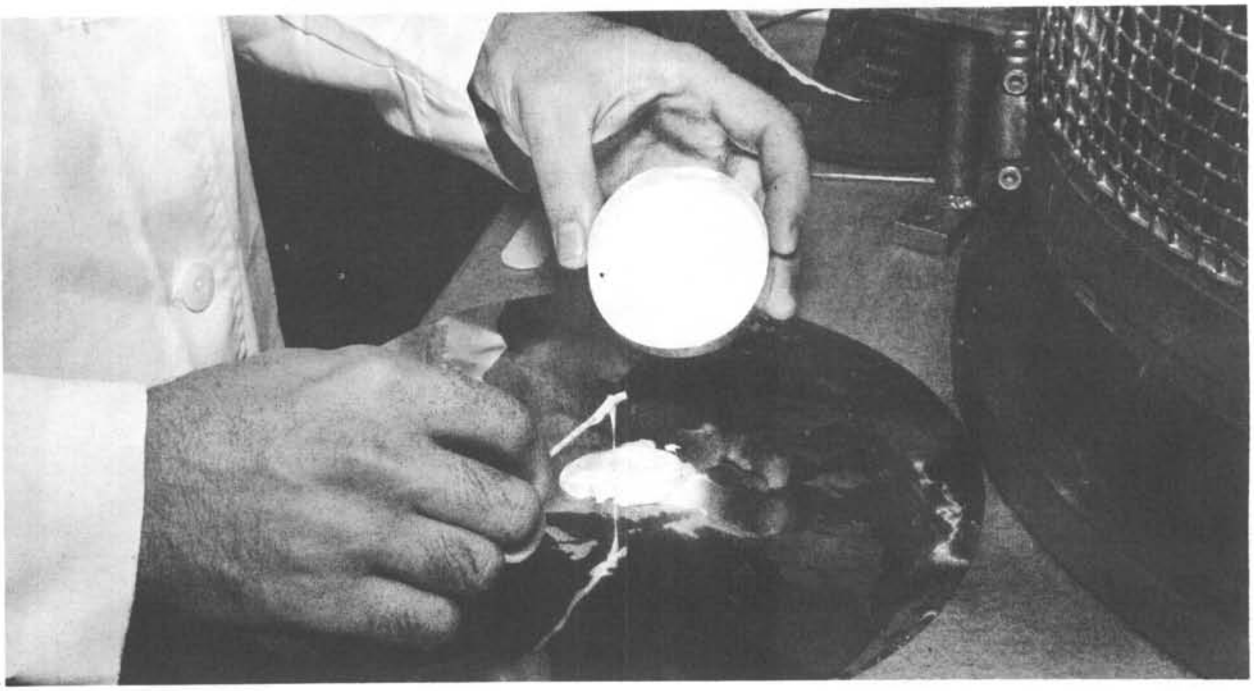

Figure 7 - Preparation of Test Sample

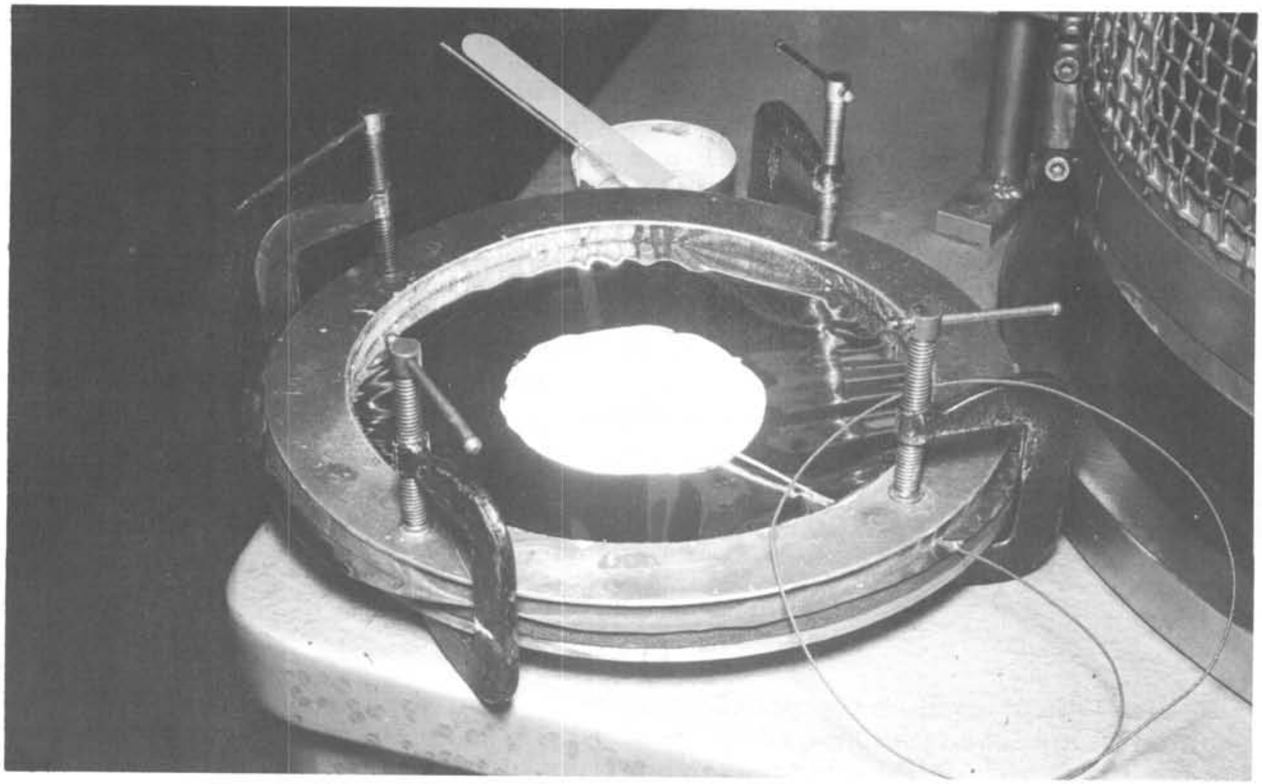

Figure 8 - Test Sample in Ring Fixture

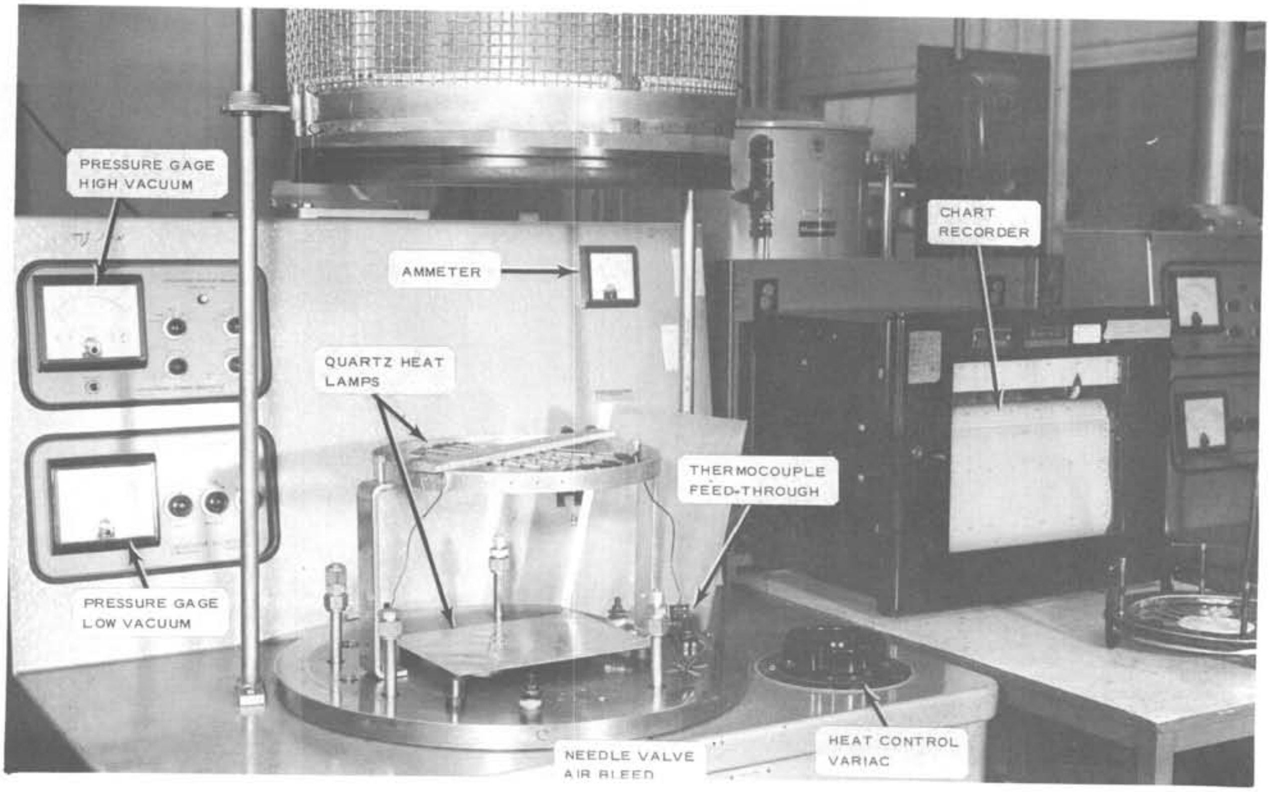

Figure 9 - Bell-Jar Test Facility

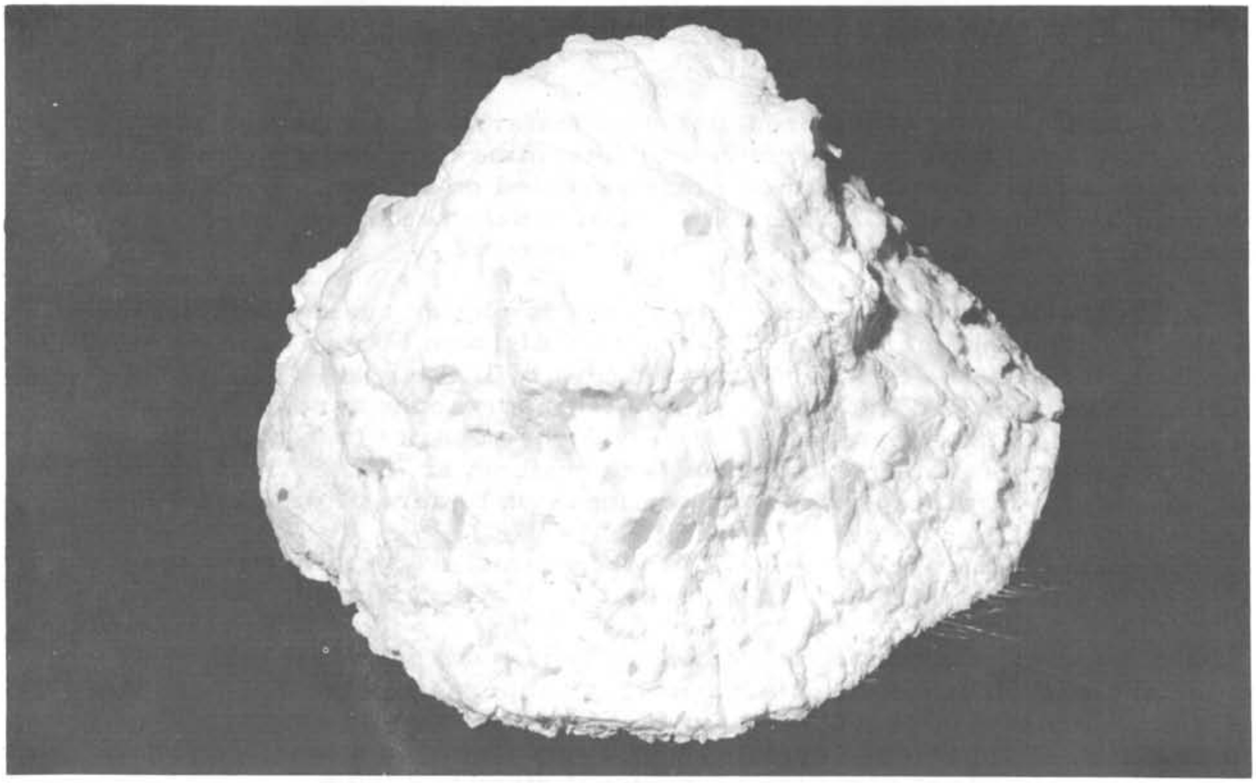

Figure 10 - Typical Foam Mass

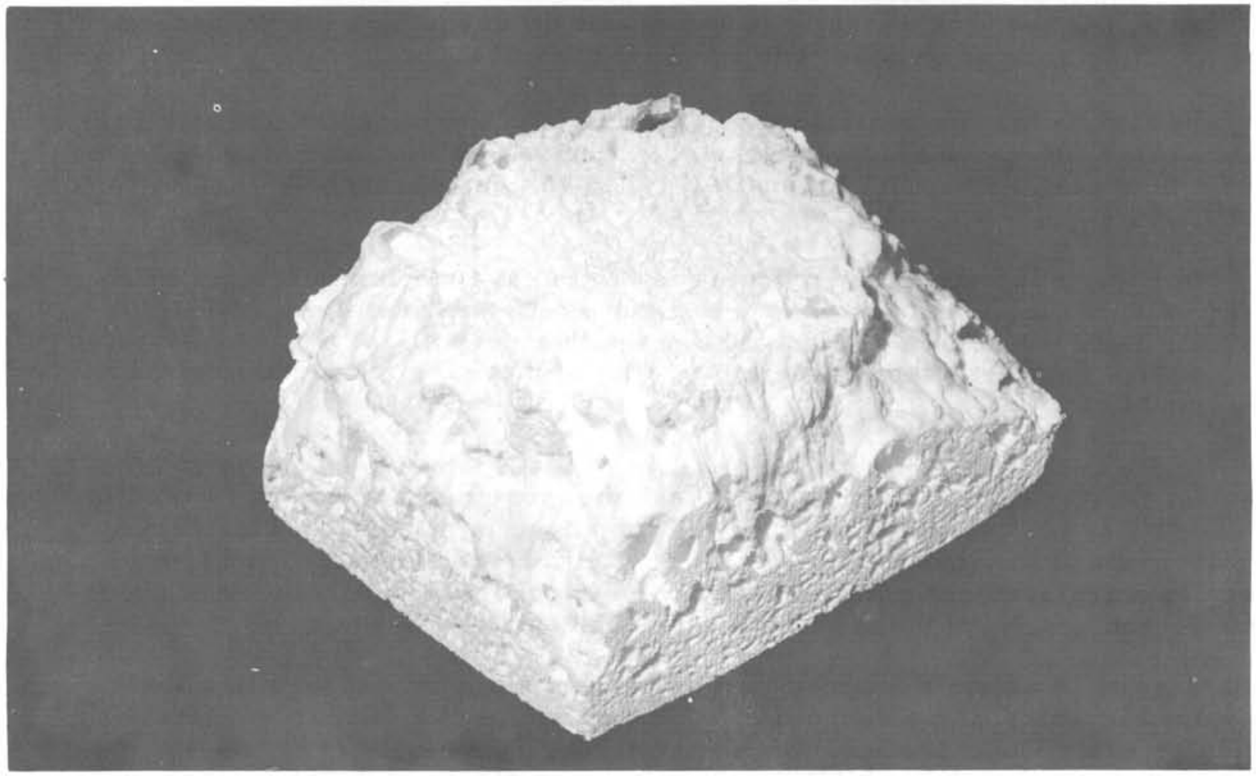

Figure 11 - Typical Foam-Mass Section

The foam product of the predistributed material with densities ranging from 3 to 4.5 pcf were vacuum tested to determine their basic physical properties within the temperature range expected on an orbiting solar concentrator (-200 to +240 F). The following test data are obtained from a formulation having a microquartz filler of 2 percent.

In Figure 12, the tensile ultimate stress is plotted against temperature for the density range of the material tested. At room temperature, a 3-pcf-density material has a tensile ultimate stress of 3.5 psi; at -200 F, it increases to about 4. At the other extreme, it approaches zero at approximately 235 F. With a material of slightly higher density (4.6 pcf), the tensile ultimate stress is 22 psi at room temperature; at -200 F, it is up to 27 psi. At 250 F, it falls to 14 psi and continues on to zero at or about 300 F.

When the tensile yield stress is plotted against temperature for the various densities of the foam, the curves follow a very similar pattern.

In Figure 13, the tensile modulus stress is plotted against temperature for the various densities of foam. At room temperature, the 3.2-pcf foam has a tensile modulus of 300 psi; at -200 F, it increases to almost 600 psi; and at 240 F, it approaches zero. The 4.6-pcf foam has a tensile modulus of just over 1000 psi at room temperature; it rises to 1700 psi at -200 F and falls to less than 500 psi at 250 F.

In Figure 14, the compression yield stress is plotted against temperature for foam at the various densities. The general trend is for the values to rise at the lower temperatures and to fall off at the high temperatures, approaching zero at or about 300 F.

In Figure 15, the compression modulus is plotted against temperature for foam of the various densities noted. The values increase slightly from room temperature to -200 F, and fall off to values approaching zero at or about 250 F.

In Figure 16, the shear modulus is plotted against temperature for the various densities noted. The values given are from room temperature to 240 F. Note the series of straight lines with a very slight negative slope. The values vary less than 10 percent with the increase from room temperature to 240 F.

In Figure 17, the elongation of a bar of foam 1 by 1 by 4 in. is plotted against temperature. Once again, these measurements were performed in a vacuum of 10^{-5} torr. The "knee" of the curve is at 250 F. This curve was for one of the lower-density foams. With higher-density foams, the knee appears at slightly higher values. A 3-pcf foam has the knee at about 260 F, and a 3.5-pcf foam has the knee at about 280 F.

Figure 18 shows the creep curves for two samples exposed to a temperature of 185 F and a vacuum of 10^{-5} torr while at a 50-percent tensile yield stress. The creep becomes somewhat negligible after 75 hr. However, one of the samples did exhibit a primary creep strain of 0.011 in. per inch during the first 75 hr as compared to an elastic strain of 0.007 in. per inch.

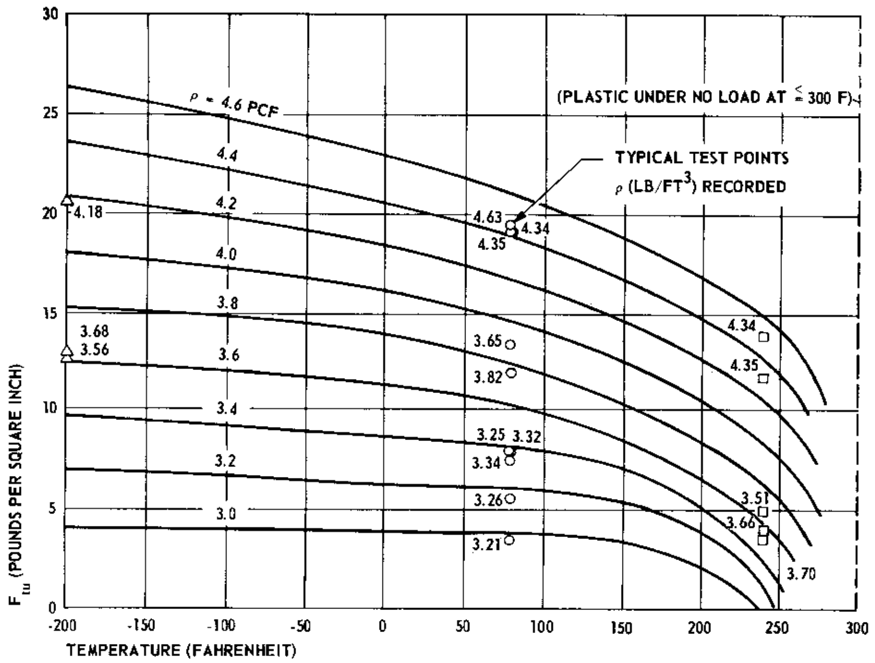

Figure 12 - Tensile Ultimate Stress versus Temperature

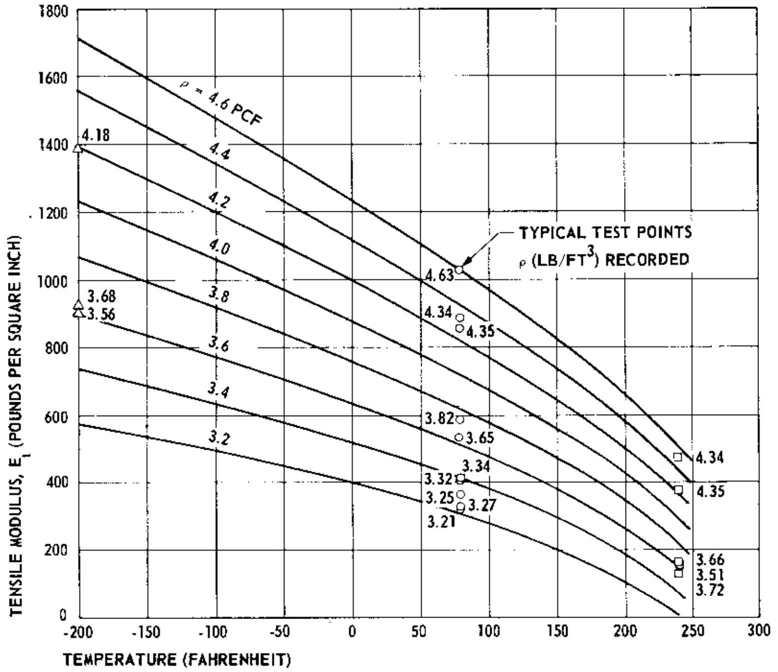

Figure 13 - Tensile Modulus Stress versus Temperature

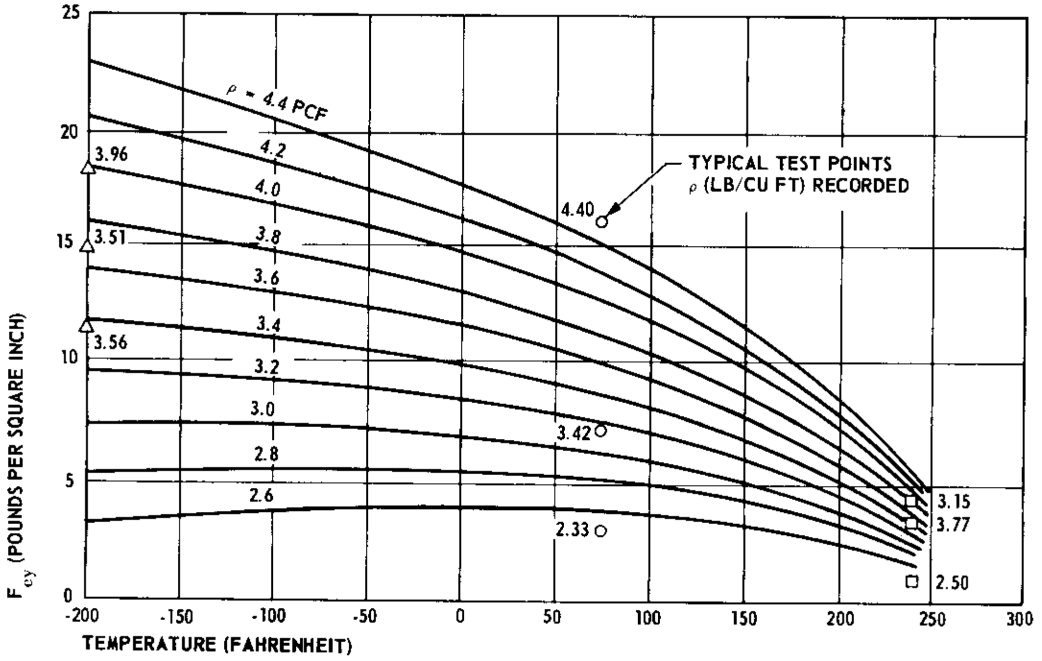

Figure 14 - Compression Yield Stress versus Temperature

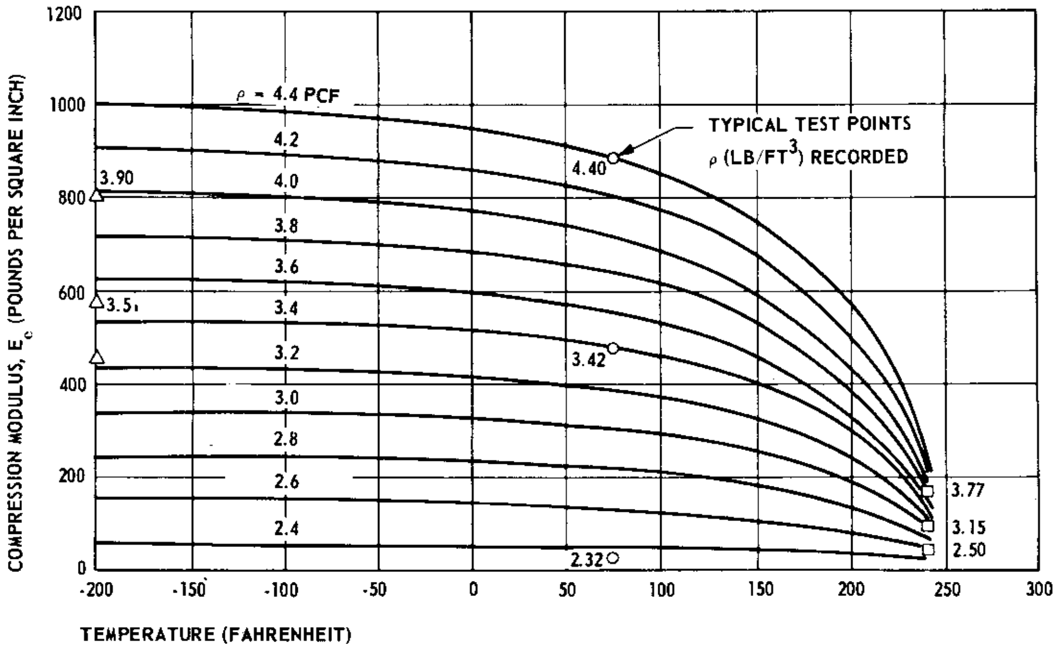

Figure 15 - Compression Modulus versus Temperature

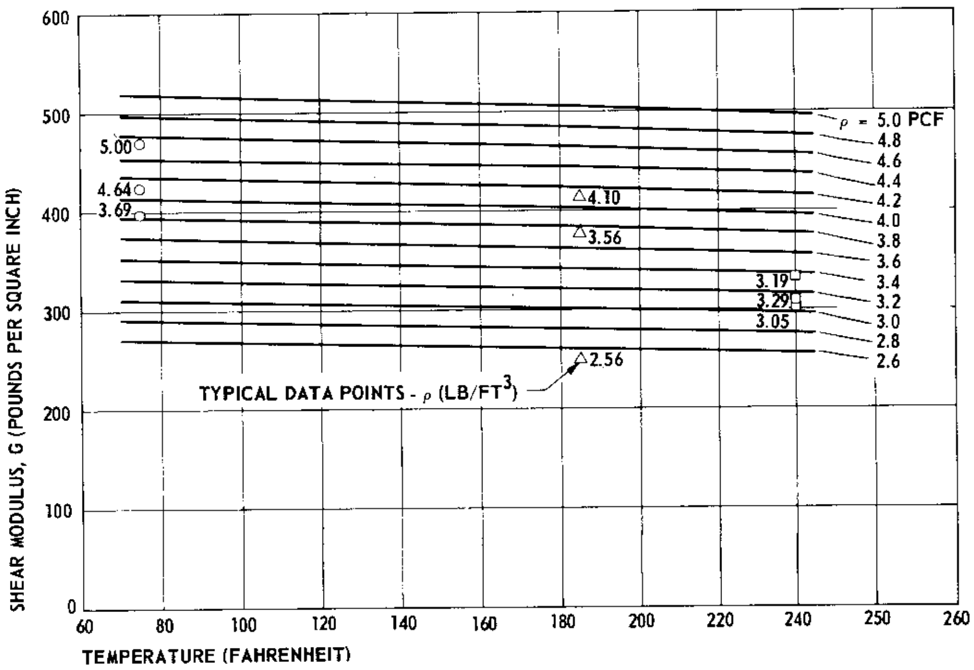

Figure 16 - Shear Modulus versus Temperature

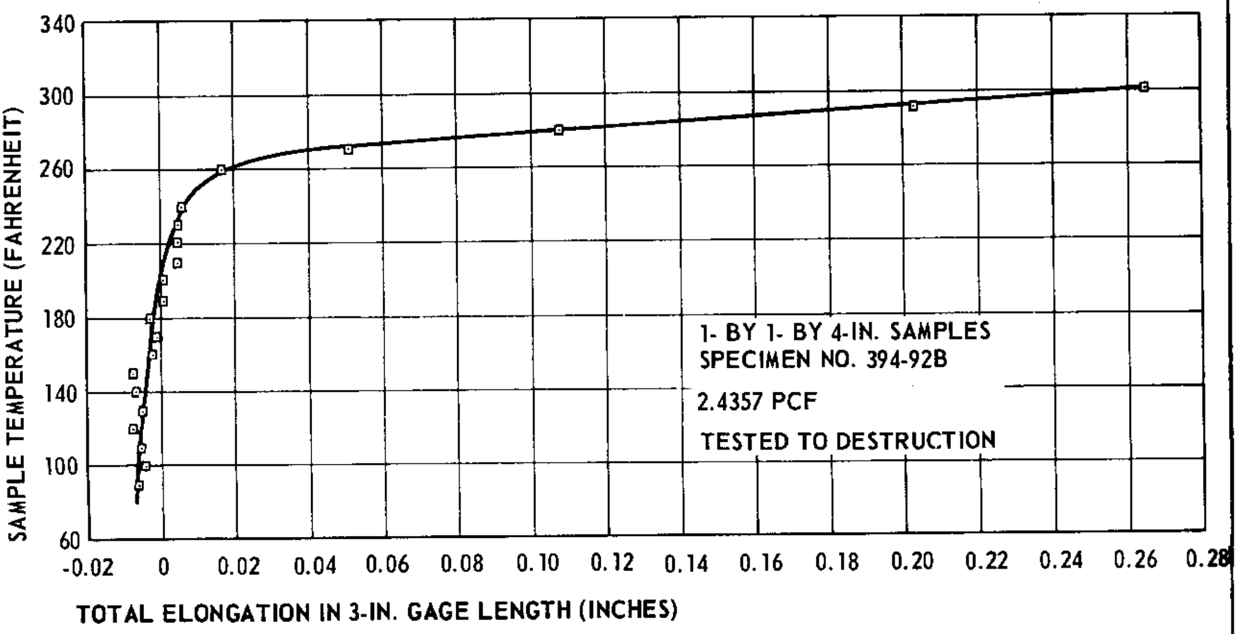

Figure 17 - Linear Thermal Expansion

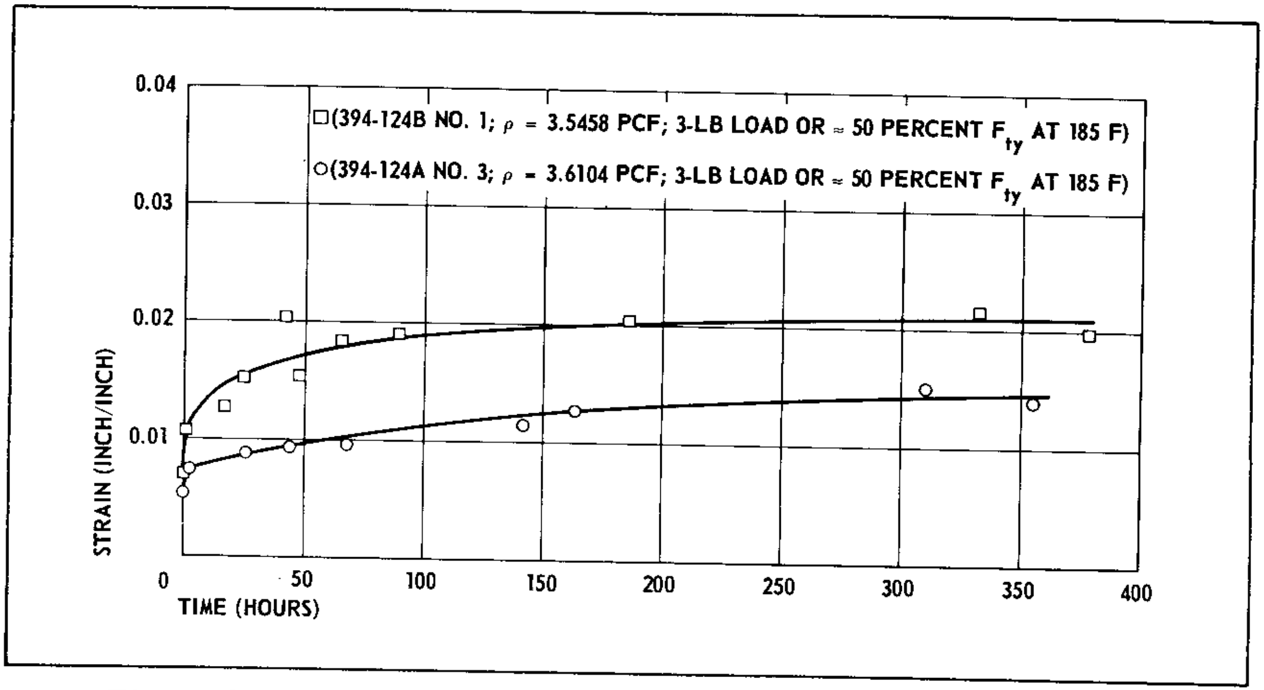

Figure 18 - Predistributed Foam Creep Curves for Two Samples

Dimensional stability measurements were made on 2-in-cube samples that were exposed to vacuum at room temperature. Dimensional changes over approximately 1000-hr periods amounted to less than one percent.

The foam is self-bonding to the film substrate. Peel tests have been run at room temperature and up to 240 F. Also, after exposure to vacuum and ultraviolet radiation for periods of up to 1000 hr, there was some reduction of peel strength with increased temperature and ultraviolet exposure; however, even the minimum values obtained are considered more than adequate for solar concentrator applications.

This foam should be tested immediately after its production in vacuum, but this is impossible. However, since the material is open-celled, its removal from the production vacuum chamber for shaping into test samples and its reinstallation in a vacuum chamber for test are believed to have had little effect on its physical properties. Under these circumstances, this procedure was about the best that could be done. It could not be accomplished with closed-cell material.

TWO-FOOT MODELS

Several two-foot models of solar concentrators have been fabricated. These concentrators were rigidized in a vacuum chamber, where the predistributed foam was activated by heat.

Figure 19 shows a hemispherical assembly of an inflated solar concentrator. The paraboloidal portion is aluminized Mylar; the remaining portion, transparent Mylar. The rim of the hemisphere is attached to a plexiglass plate. The internal pressure is maintained at 7 in. of water. A back flap on the back of the mirror serves as a separator when the concentrator is packaged.

Figure 20 shows the model with the back flap taken up and the predistributed material applied to one-half the mirror area, which runs to the line. The hub area shown will have twice the thickness of foam over the rim area. The purpose of the aluminum-foil heat shield was to keep as much heat as possible off the plexiglass baseplate. After rigidization, a nichrome hot wire burns off the pressure envelope.

Figure 21 shows the membrane mirror with the double and single thickness of predistributed material applied to the mirror area.

Figure 22 shows the back flap spread in position over the predistributed material.

Figure 23 shows the mirror assembly placed in the vacuum chamber. The plexiglass plate is balanced on three screw jacks. The spiral above the mirror is an infrared heating element.

Figure 24 shows the chamber door closed and the heating unit in position.

Figure 25 shows a view of the surface in the vacuum chamber with the heating initiated.

Figure 26 shows the foaming action just beginning.

Figure 27 shows the foaming action progressing.

Figure 28 shows the foaming action completed.

Figure 29 shows the hot-wire burn-off.

Figure 30 shows the chamber door open and the rigidized mirror portion with the balloon limp.

Figure 31 shows the face of the rigidized mirror (not trimmed) and the plexiglass plate. The instrument in the foreground is a contour-measuring apparatus that is attached at the hub. The instrument makes a 360-deg sweep. Its fingers are set at different radii and are calibrated with a template to the contour of a perfect parabola.

Figure 32 shows the temperature and pressure curves during the rigidizing process. There were 14 thermocouples embedded in the predistributed material in 14 locations. They all traced out a temperature curve that was very much the same. The internal pressure of the balloon was retained at 7.5 in. of water ± 0.5 in. The pressure was released just before burn-off. The chamber pressure seemed to follow the temperature pattern. It rose slightly with the increase in temperature; as the azide activated and gave off some nitrogen, there was a sudden rise in chamber pressure. After the

Figure 19 - Hemispherical Assembly of Inflated Solar Concentrator

Figure 20 - Predistributed Foam Applied to One-Half of Mirror Area

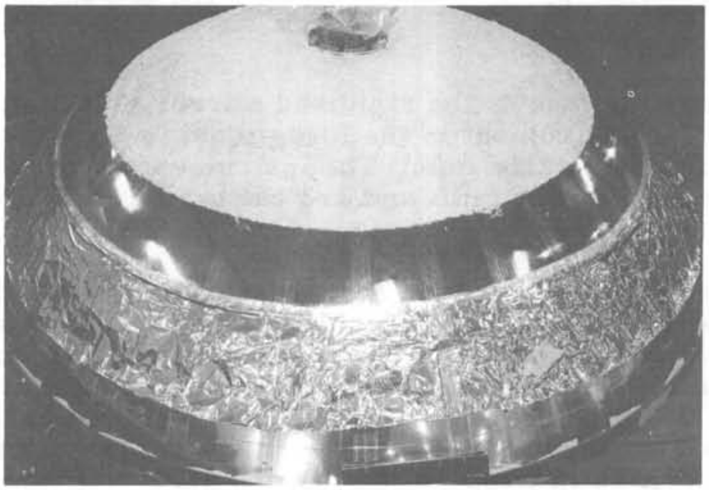

Figure 21 - Mirror with Double- and Single- Thickness Predistributed Foam

Figure 22 - Mirror with Back Flap

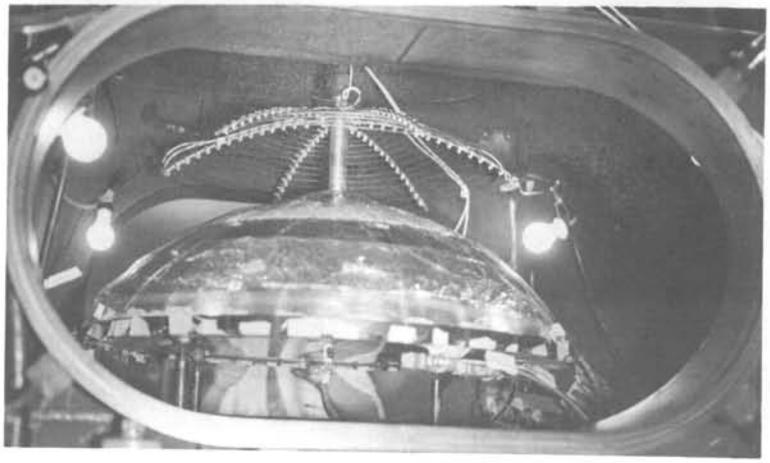

Figure 23 - Mirror in Vacuum Chamber

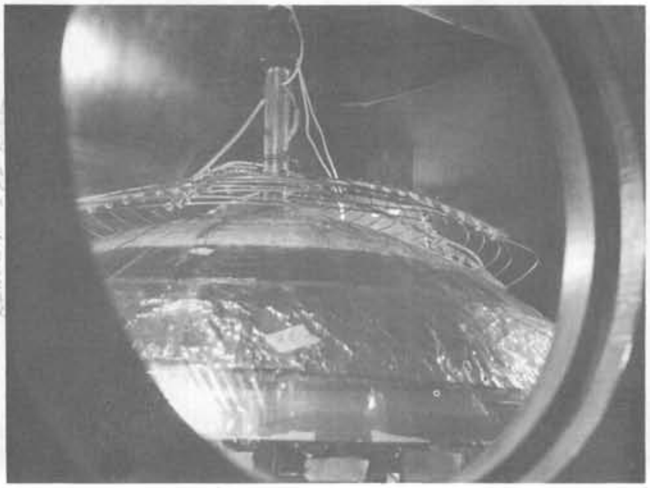

Figure 24 - Heating Unit in Vacuum Chamber

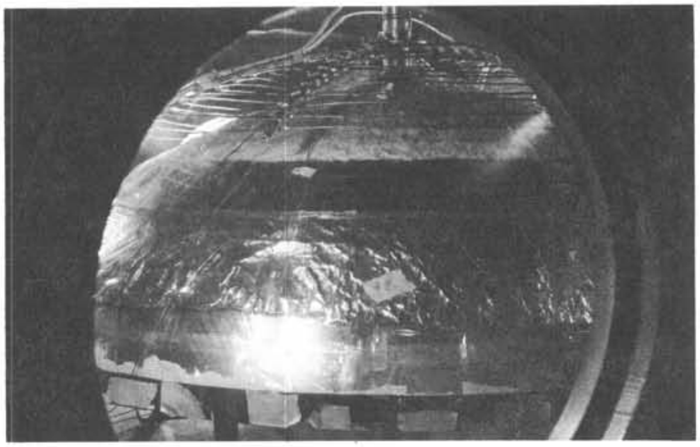

Figure 25 - Heating Started

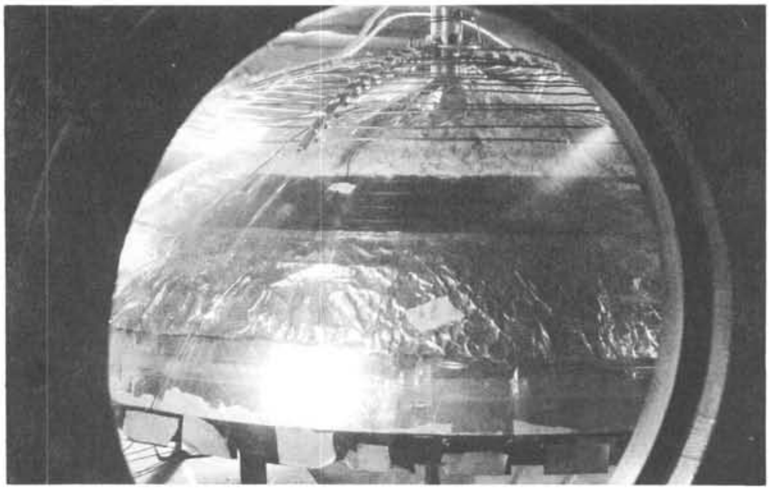

Figure 26 - Foaming Action Started

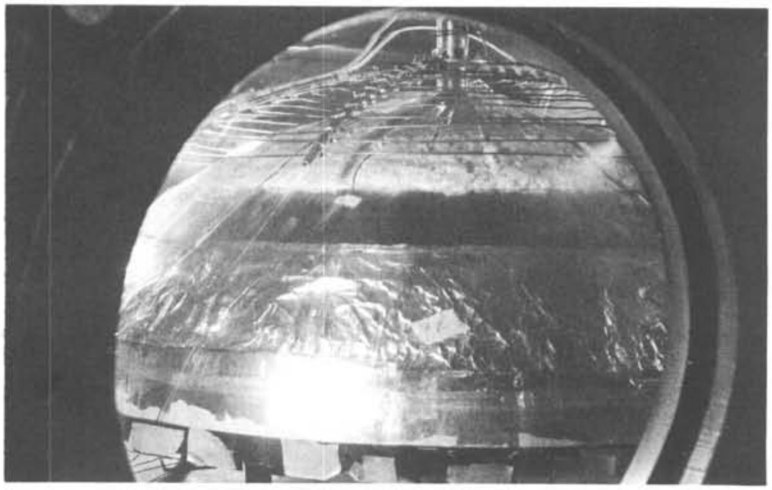

Figure 27 - Foaming Action Progressing

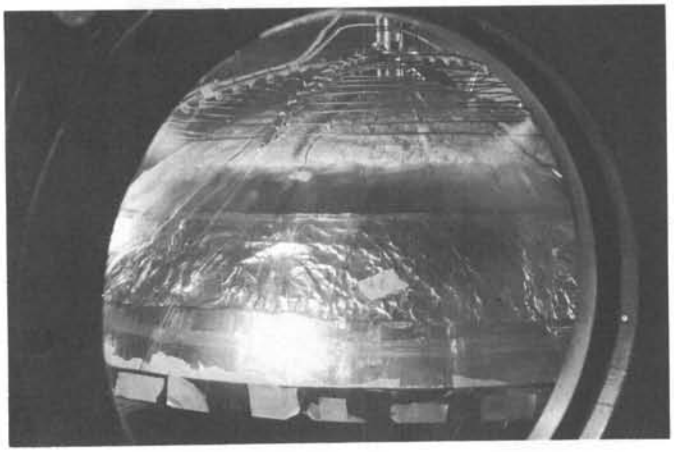

Figure 28 - Foaming Action Completed

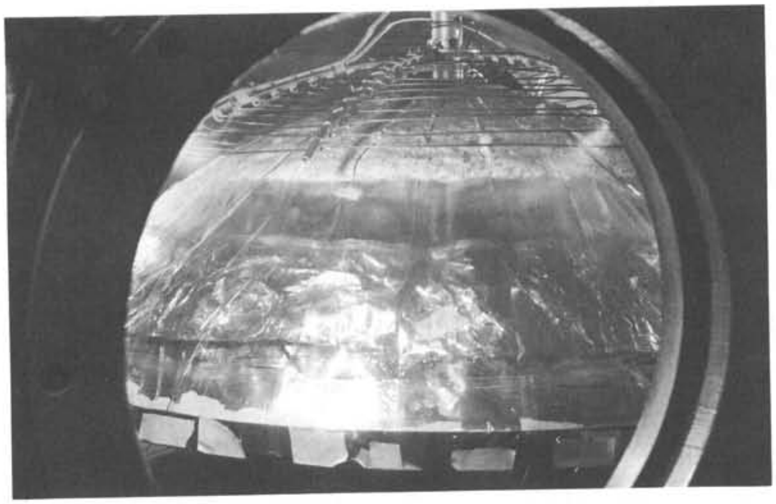

Figure 29 - Hot-Wire Burn-Off Completed

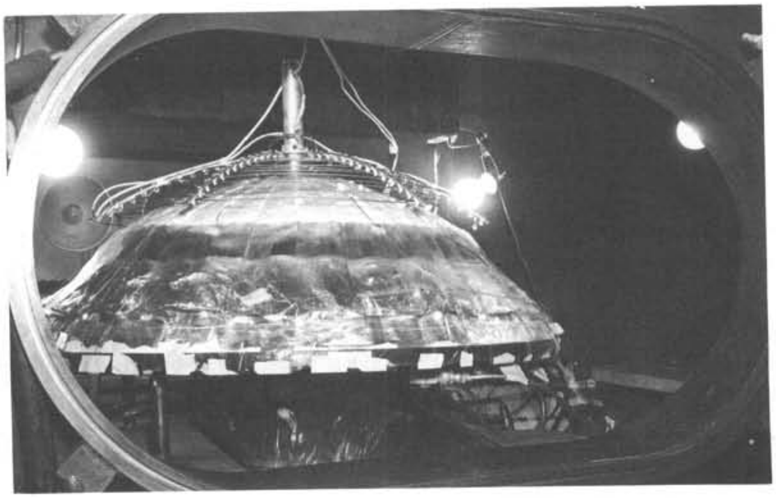

Figure 30 - Vacuum Released - Chamber Open

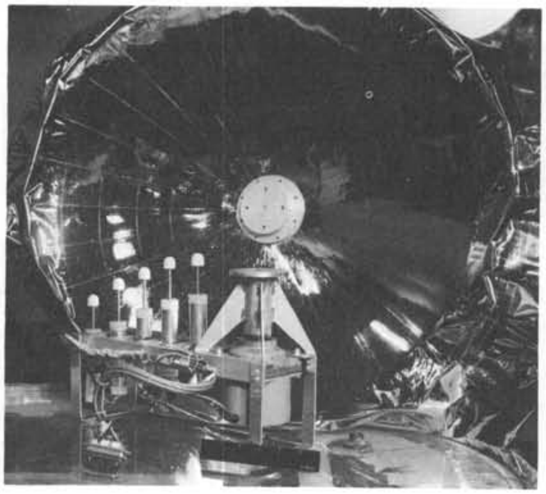

Figure 31 - Rigidized Mirror (Untrimmed) and Plexiglass Plate

foaming was completed, the pumping system caught up and again began evacuating the chamber. A slight rise in pressure occurred during the balloon burn-off, when some gas was generated and some internal pressure was released.

Figure 33 is a polar plot of the mirror contour. The fingers on the contour measuring apparatus are spaced at radii of 4, 6, 8, 10, and 12 in., respectively. The solid line represents the contour of a geometrically perfect parabola. The dotted line is the contour deviation of the pressurized membrane in the evacuated environment, and the dot-dash line represents the contour deviation after rigidization and after burn-off of the balloon, but still in vacuum.

Figure 34 shows a quarter view of the front surface of this solar-concentrator model. This photo was taken in a small photographic studio with a spotlight projecting on the mirror surface from a distance of 10 ft. The diverging rays of the spotlight caused the hyperbolic pattern at the focal point. Smoke was generated to capture the concentrating rays.

CONCLUSIONS

On the basis of the work accomplished in this program, the following conclusions were reached:

1. A workable predistributed foam material capable of rigidizing solar concentrators and other membrane structures in space has been developed.
2. The predistributed foam can be heated to initiate the foaming action in space with selective surfaces to control the absorption of sunlight.
3. The foam product has useful structural strength and

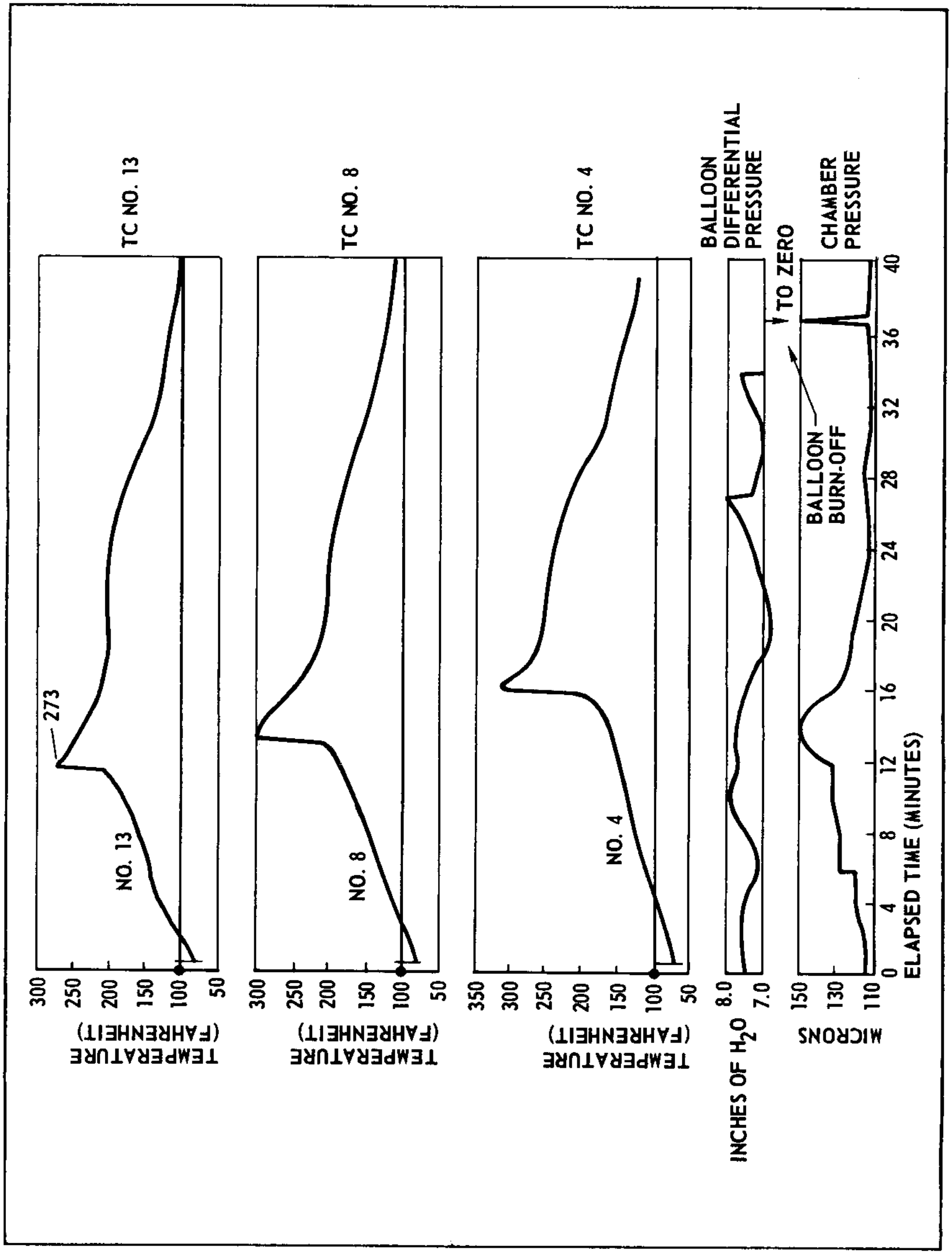

Figure 32 - Temperature and Pressure versus Time during Rigidization

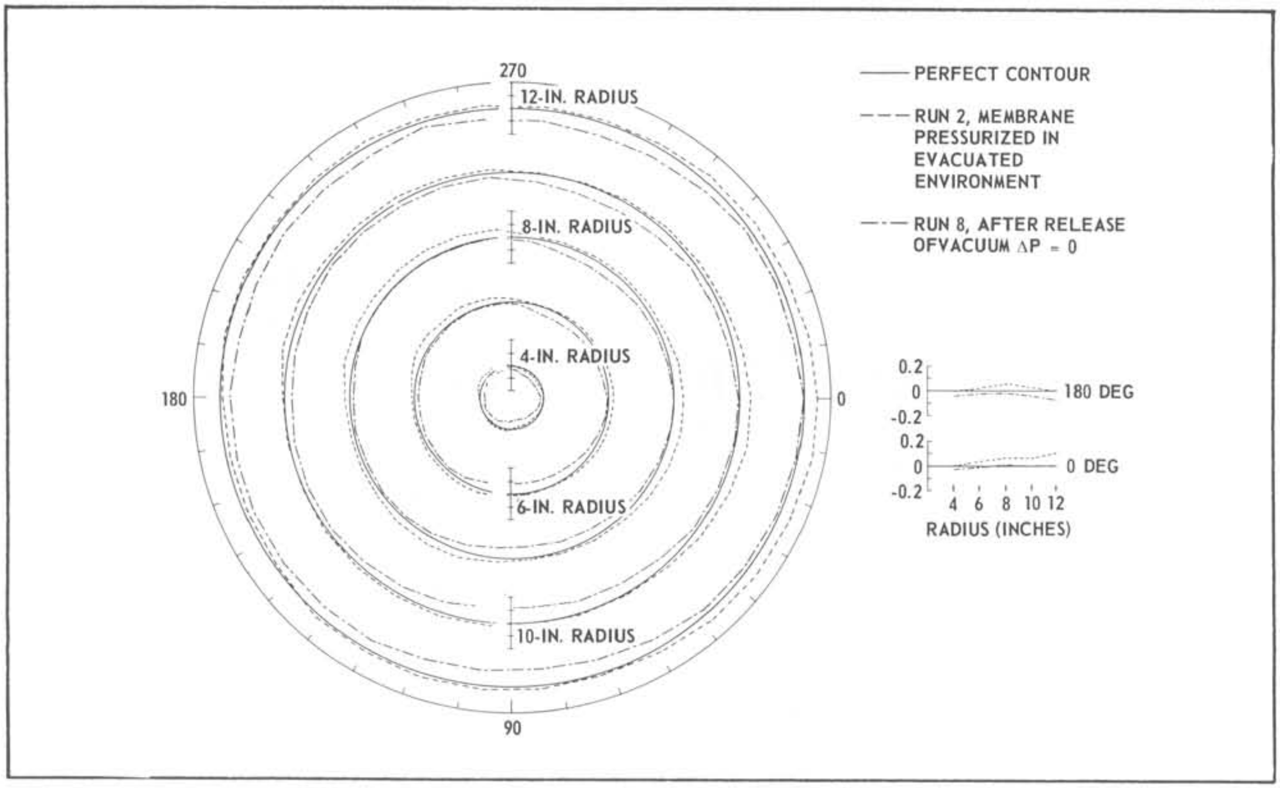

Figure 33 - Polar Plot of Mirror Contour

Figure 34 - Quarter view of Front Surface of Concentrator

stiffness in a vacuum up to temperatures approaching 240 F for densities greater than 3 lb per cubic foot. This material is primarily brittle, but a small amount of ductility is present at temperatures in excess of 100 F.

4. The limited amount of test data indicates that the tensile, compression, and shear properties increase with increasing density and decrease with increasing temperature, as is typical for urethane foams.

5. The thermal-coefficient-of-expansion tests of the foam indicate a small value, and thermal expansion decreases with an increase in density.