DEVELOPMENT AND EVALUATION OF A RIGIDIZED INFLATABLE MICROWAVE REFLECTOR

K.F. Gibson

Computing Devices of Canada Ltd.

G.M. Peace

Bendix Corporation Research Laboratories

INTRODUCTION

The Aerophysics Division of Computing Devices of Canada has recently completed the development of a rigidized inflatable microwave reflector for possible application in space. The reflector is prepackaged in a small container and automatically unfolds forming a rigid reflecting surface.

The parabolic reflector surface is achieved by means of a proprietary forming technique that eliminates the use of accurate jigs or patterns for the preparation of the reflecting surface.

This paper presents a discussion of the materials and the method used to produce a number of experimental reflectors. The results of a microwave evaluation test program are presented.

Figure (1) illustrates the proposed microwave reflector in its inflated and rigidized condition. A container for the rigidizing agent, mixing, storage, and flow control system is shown attached to the rim of the microwave reflector. This is only one means of providing rigidization to the reflector and in subsequent studies predistribution or storage in a premixed form will be considered. In its simplest form the reflector is made by bonding a polyester film to the top and bottom surfaces of a flexible support rim. The inner surface of one of these films is coated with a metallic reflecting material. Provision is made for feeding a rigidizing agent into the support rim and then into the space between the two membranes which form the front and back surfaces of the reflector. Low density foaming plastics have been the main rigidizing agents considered to date. Numerous other configurations are possible with this technique and some of these are mentioned later. However, the main objective of the present study has been to demonstrate the feasibility of forming the curved reflecting surface by this simple technique which would be useful as a microwave reflector.

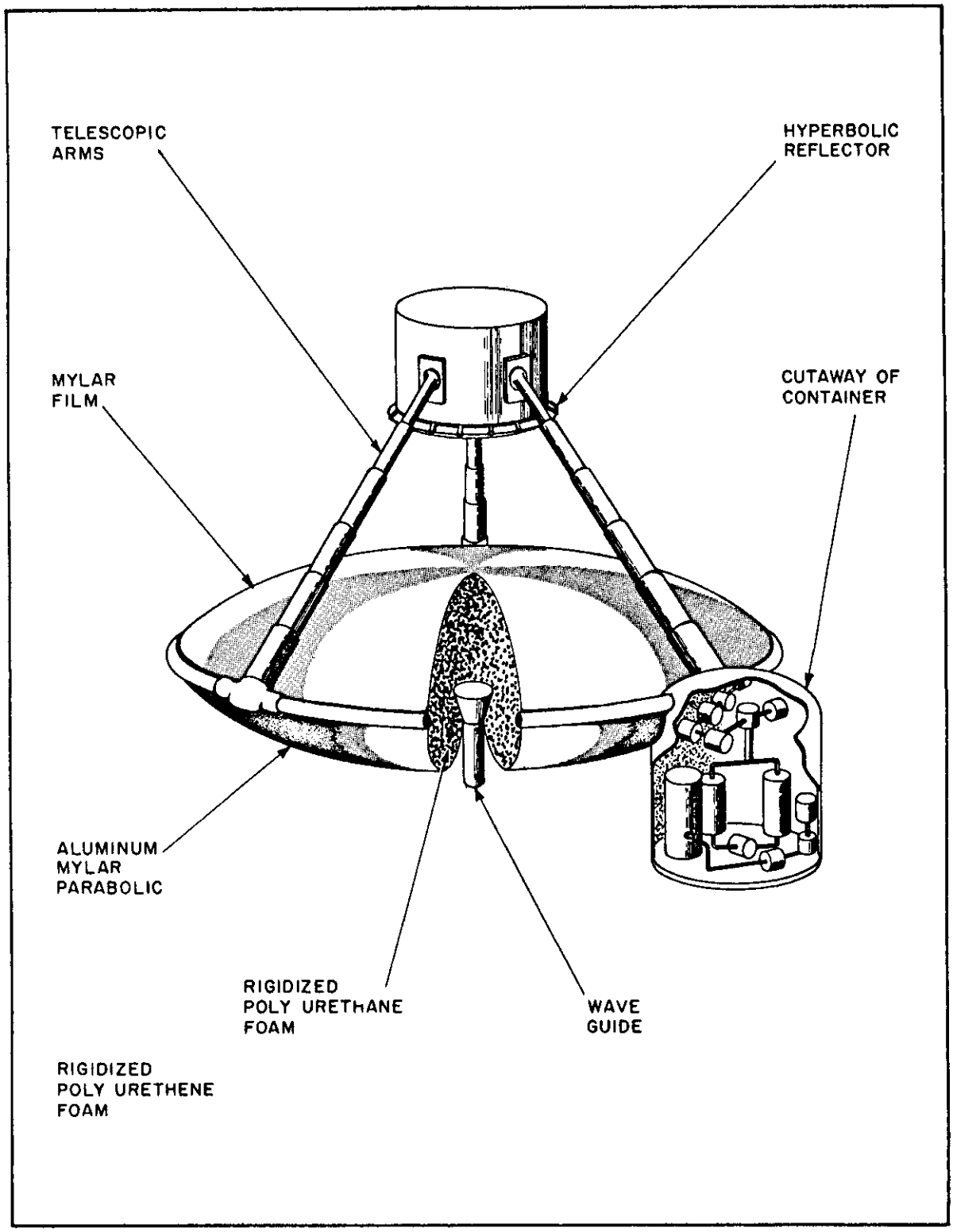

Figure 1

The Microwave Reflector in Space

THEORY

Consider a membrane of negligible weight and flectural rigidity suspended with a uniform edge tension over a closed circular boundary and dilated by a pressure P over one surface. The characteristic differential equation of the membrane surface is obtained by the equations for static equilibrium of an infinitesimal surface element. As the overall deflection is relatively small (δ/D is approximately 0.1) there is justification in assuming that the surface tension is uniform in magnitude in all positions on the surface. In this case with small deflections, the edge forces on the element are Tds and Tdy where T is the constant tensile force per unit width of the membrane.

Figure (2) illustrates the following equations -

The downward vertical component of Tdy on the left hand edge is

$$F_1 = T\,dy \sin\theta \tag{1}$$

and the upward vertical component of the Tdy on the right hand side is

$$F_2 = T\,dy \sin\gamma \tag{2}$$

now θ and γ differ by the change in slope between X and X +dx, this change may be written

$$\gamma = \theta - \left(\frac{\delta^2 z}{\delta x^2}\right) dx \tag{3}$$

In a typical reflector produced in Computing Devices' Laboratory the diameter is 3-feet and the depth is approximately 4.5-inches. Using this depth then tan (angle) = .25 and for this value there is a negligible difference between the angle and its sine. Therefore the sines in equations (1) and (2) may be replaced by the angles.

Similarily the vertical components of the forces at the remaining edges are

$$F_3 = T\,dx\,\theta' \tag{4}$$

$$F_4 = T\,dx\,\gamma' \tag{5}$$

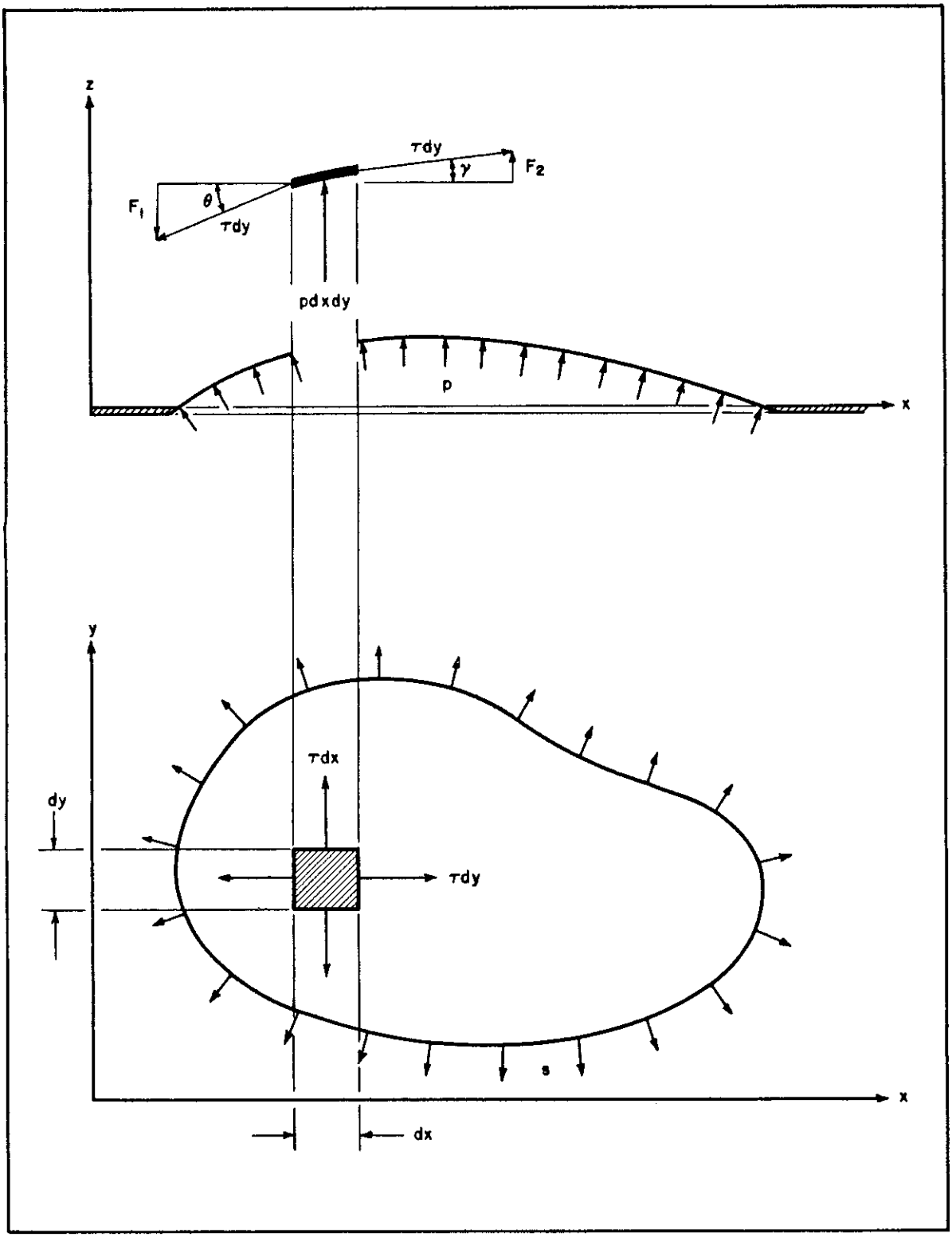

Figure 2

Dilated Membrane on a Closed Boundary

Equating the sum of these forces to the pressure force and imposing the conditions for static equilibrium

$$T dy\, \theta - T dy\left(\theta - \frac{\delta^2 z}{\delta x^2} dx\right) + T dx\, \theta' - T dx\left(\theta' - \frac{\delta^2 z}{\delta y^2} dy\right) + p\, dx\, dy = 0 \qquad (6)$$

which reduces to

$$\frac{\delta^2 z}{\delta x^2} + \frac{\delta^2 z}{\delta y^2} + \frac{p}{T} = 0 \qquad (7)$$

Transforming equation (7) to cylindrical coordinates gives

$$\frac{d^2 z}{dr^2} + \frac{1}{r}\frac{dz}{dr} + \frac{p}{T} = 0 \qquad (8)$$

The solution to equation (8) is a parabola

$$z = \frac{1}{4}\frac{p}{T}\left(r_o^2 - r^2\right) \qquad (9)$$

This theory is applicable only for very small deflections and uniform stress at all points in the membrane surface, including edges. The theory also ignores the elastic properties of the membrane and it is not surprising to find some deviation from the parabolic form in actual reflectors. Control over edge conditions and elastic properties of the membrane leads to a method of controlling the surface shape. No attempt has been made at such control in the experiments described in this paper but it is hoped these effects can be investigated in future work.

MATERIALS

The principal materials required for construction of the proposed reflector may be divided into the following categories:

(a) Rigidizing material

(b) Reflector material

Any ridigizing material for the reflector must satisfy the following requirements:

(a) Dimensional stability after cure

(b) Compatibility with space environment

(c) Sufficient rigidity and strength

(d) Small package volume and reliable deployment

(e) Low density

(f) Low microwave absorption

The following requirements are desirable but not essential:

(g) Ambient temperature cure

(h) Minimum exotherm during rigidization

(i) Non-corrosive and non-toxic

(j) Readily available

(k) Low Cost.

It was evident that one of the new foaming plastics would have to be used as a rigidizing agent. These foaming plastics have various characteristics but most of them have the property of low density.

The following foaming plastics were examined:

(a) Urethanes

(b) Polystyrenes

(c) Epoxy Foams

(d) Polyvinyl chloride foams

(e) Phenolic resin foams

(f) Silicon foams.

Indications were that the urethane foams were superior in that they had low exotherm and also the ability to be foamed in place. Alteration of foam properties within certain limits to suit various requirements is also practical by varying the formulation of the foam constituents. Although much work remains to be done on urethane foams, the state of the art of this foam relative to the others mentioned is well advanced.

There are two main methods of producing the foam; the first is called the prepolymer system in which the isocyanate and resin are mixed anhydrously and no foaming occurs. The foaming can be accomplished at some future date by the addition of a catalyst. In the other method (one shot) all the additives are mixed directly and the foam is produced immediately. A one shot system would not have been practical for this application due to the control which would have to be exercised (temperature and pressure etc) over a number of ingredients at the same time. The experiments have been restricted to the prepolymer system.[1]

The final physical properties of the foam may be varied greatly according to the mix. Rigid foams may have densities between 1.3 and 30 lbs per cu ft with corresponding changes in their compressive strengths. Urethane foams are excellent thermal insulators with exceedingly low coefficients of thermal conductivity. Difficulties have been experienced in closed molding of urethane foams, but the introduction of polyether foams aided by the development of new catalysts have alleviated most of these problems. The relatively high vapor pressure of the constituents in urethane foam rule out the possibility of curing at the ambient pressure encountered in space; therefore a relatively high pressure environment must be provided by artificial means.

A polyether urethane foam which was blown with a halohydrocarbon was chosen. According to the manufacturer this foam was very stable after rigidization and had a 90 to 95% closed cell structure. It is self-bonding to most surfaces and the bond exceeds the tensile strength of the foam. Its chemical resistance is excellent and it will withstand a temperature variation of -200°F to+250°F with little effect on dimensional stability. The foam has good elongation and is capable of moving with the surface to which they are bonded without affecting the cell structure or cell properties. The densities of these foams in an unrestricted mold is 2 lbs per cu ft. Tensile strengths are from 50-55 psi, compressive strengths at yield of 30-35 psi.

The foam proved to be suitable as far as rigidity is concerned, although problems were encountered in its dimensional stability with variations of temperatures. The density of the foams proved to be in the region of 2 lbs per cu ft and the cell structure was acceptable at the end of the series of experiments.

To keep the weight of the reflector as low as possible it is desirable that the metallic reflecting surface be a thin film. This is readily available in the form of polyester films with a metallic coating of very high reflectivity. The main consideration is that if the reflector material surface has irregularities then they must be smaller than the wave length of the incident radiation.

The particular film chosen to contain the foaming urethane was polyethylene terphthalate, commercially known as Mylar. This film is readily obtainable in an aluminum coated condition of various thicknesses. The aluminized Mylar proved to be an excellent microwave reflector, although a wrinkling problem was encountered and is mentioned later.

SPACE ENVIRONMENT

The space environment is characterized by:

(a) Zero gravity

(b) Vacuum-thermal effect

(c) Solar energy flux

(d) Meteorite Hazard

ZERO GRAVITY

The absence of gravity is, generally speaking, an asset to the construction of a space device due to the elimination of the major source of mounting loads and stresses. This lack of gravity introduces a minor problem in the storage and transfer of liquid rigidizing materials but should be readily solved.

VACUUM THERMAL EFFECTS

It is estimated that at an altitude of 600 miles (the start of the Van Allen Belt) the pressure would be about 10^{-10} torr, and rates of volatization and sublimation become appreciable at these low pressures for materials of relatively high vapor pressure such as organic compounds. In general, the vapor pressure of the basic molecular polymer constituting a plastic is not likely to be high enough to cause a significant loss of material, except for the short terminal molecules found at the surface. However plasticizers found in many plastics have relatively high vapor pressures which may cause the loss of large amounts of material. The rate of diffusion of the plasticizer within the plastic thus plays an important part in the overall loss. Improperly compounded or incorrectly cured composites will experience critical losses. This emphasizes that the utmost care and the best techniques must be used when adopting plastics for use in space.

The classic equations used for quantitative studies on the evaporation rate of materials in space are generally not applicable to plastics due to their complex molecular structures. Recently much experimental work has been done in this field and the results would indicate that the decomposition rates are radically altered by the addition of small amounts of impurities, In general, loss rates tend to decrease exponentially with time when surface temperature is constant. The mass loss rate for plastics is controlled by temperature and is primarily a surface phenomena - weight losses increase significantly with decreasing material thickness.

In summarizing, it may be said that the effects of high vacuum on structural plastics are not as serious as was previously supposed and may be minimized by careful compounding of the plastic constituents.[2]

SOLAR ENERGY FLUX

Deterioration may be produced in polymers by ultra-violet radiation in the 0.2 - 0.4 micron band acting under a high vacuum. Other degrading sources are ionization induced by gamma rays up to .001 microns in wave length and bombardment by heavy

ions. The effects of high level radiation on plastics have been thoroughly investigated. Polymers are subject to damage depending on temperature and pressure, and the presence of any reinforcing fillers. Plastics are damaged by scission of bonds and subsequent reorientation of molecular structure. This reorientation consists of the formation of new bonds between chains, breaking of chains, evolution of gases and reaction with the ambient environment.[3]

Test data on polyethylene terphthalate (Mylar) when exposed to a combination of radiation in the range 2000 - 6000 Angstroms and pressures in the neighborhood of 10^{-6} torr for periods of up to 500 hours produced weight losses of approximately 1%. The polyester shows a significant increase in flexural rigidity up to 200 hours exposure which is attributed to cross linking. After 500 hours, ultimate flexural strength decreases but is slightly greater than the original strength.[3]

Significant quantities of heat may be absorbed by the reflecting structure and the attendant thermal stresses and structural deterioration may cause the reflector to warp and become useless. It is therefore desirable that a low absorptivity be accompanied by a reasonably high emissivity.

METEORITE HAZARD

Vehicles operating in space will collide with meteoroids and other celestial matter of varying size, mass and velocity, with resultant damage varying from minor surface pitting to total destruction. The probability of meteoroid puncture is far less than the probability of erosion from dust. The reflecting surface would be well protected against meteoroid dust by the urethane foam.

LABORATORY EXPERIMENTS

The major emphasis in these tests was to demonstrate that a surface suitable for microwave reflection could be developed by simply forming a thin diaphragm with a foaming plastic. Less emphasis was placed on operational aspects and the system design considerations. However the following problem areas were recognized:

(a) Rigidizing material assessment and selection -

(i) rigidity

(ii) dimensional stability

(iii) density

(iv) elevated temperature resistance tests.

(b) Support structure materials assessment -

(i) flexibility

(ii) dimensional stability

(iii) density

(iv) elevated temperature resistance tests.

(c) Reflector assessment -

(i) microwave reflectivity

(ii) temperature control characteristics.

(d) Structure developments -

(i) bonding techniques

(ii) fabrication techniques

(iii) method of inflation

(iv) methods of rigidization

(e) Rigidizing agent handling systems -

(i) storage

(ii) mixing

(iii) flow control

(iv) injection

(v) predistribution methods

(f) Packaging -

(i) collapsing technique

(ii) folding methods

(iii) storage container

It is not proposed here to tabulate all our laboratory experiments, but more to discuss the results and the paths which were indicated by successful experiments.

It was obvious from the beginning of the foam handling that great care had to be taken when the constituents were mixed. The constituents had to be held at closely defined temperatures, e.g. the blowing agent between 65 and 75 deg. F. and the mixing had to

be closely controlled as far as time, temperature, and the efficiency of mixing were concerned. Various sophisticated mixing methods were tried but in the end the simplest possible mixing device was used, that is an electric motor driving a mixing paddle. Experiments were carried out with various mixing paddles and mixing techniques and it was found that the resultant foam structure depended upon:

(a) the shape of the paddle

(b) the mixing speed

(c) the mixing technique

These parameters dictated the flow pattern of the fluids during the excitation period.

When it was thought that a reasonable foam could be produced, an apparatus was set up which clamped two sheets of mylar along the circumference of an 8-inch diameter ring. The two sheets of mylar were separated by a nominal distance of .5-inch. The foam was injected into this mold using a hand operated piston device and the resulting deformation of the Mylar indicated that there was a reasonable hope of duplicating this experiment on a larger scale. Numerous experiments were carried out on this 8-inch jig and the reflectors were sectioned and foam structures examined. It was found that the foam, when injected into the circumference of the mold, seemed to travel in a front across the mold. This front was generally of a larger cell structure and higher density than the remaining foam.

Identical experiments were carried out on a 3-foot diameter clamping ring, the foam being manually injected at the circumference. A reflector produced using this rig is shown in Figure (3). In some of these experiments the foam was injected at three separate parts of the circumference, but this resulted in the wave fronts meeting at the center of the reflector causing a bad foam structure at this point. All the experiments were carried out in a laboratory where fine temperature control was not possible, and it was noticed that after the foam had fully rigidized the temperature changes during the few days after rigidization caused crinkling of the Mylar surface. The program continued with the rigidizing of an outer plastic tube. Various materials were tried but the most suitable of them seemed to be a cloth reinforced polyvinyl tube. Eventually a technique was perfected so that the ring could be unfolded to a circular configuration by the injection of air and then foam rigidized.

The next step in the program was to bond the Mylar to the ring and to rigidize both the outer ring and the reflector in one operation. Figure (4) shows a section of one of these reflectors. A rough dimensional check was made on the reflector surface and it was found that the inner area of approximately two feet diameter was close to parabolic while the outer edges had a lower focal length. The support ring imposed edge conditions on the Mylar which further distorted the final shape of the reflector.

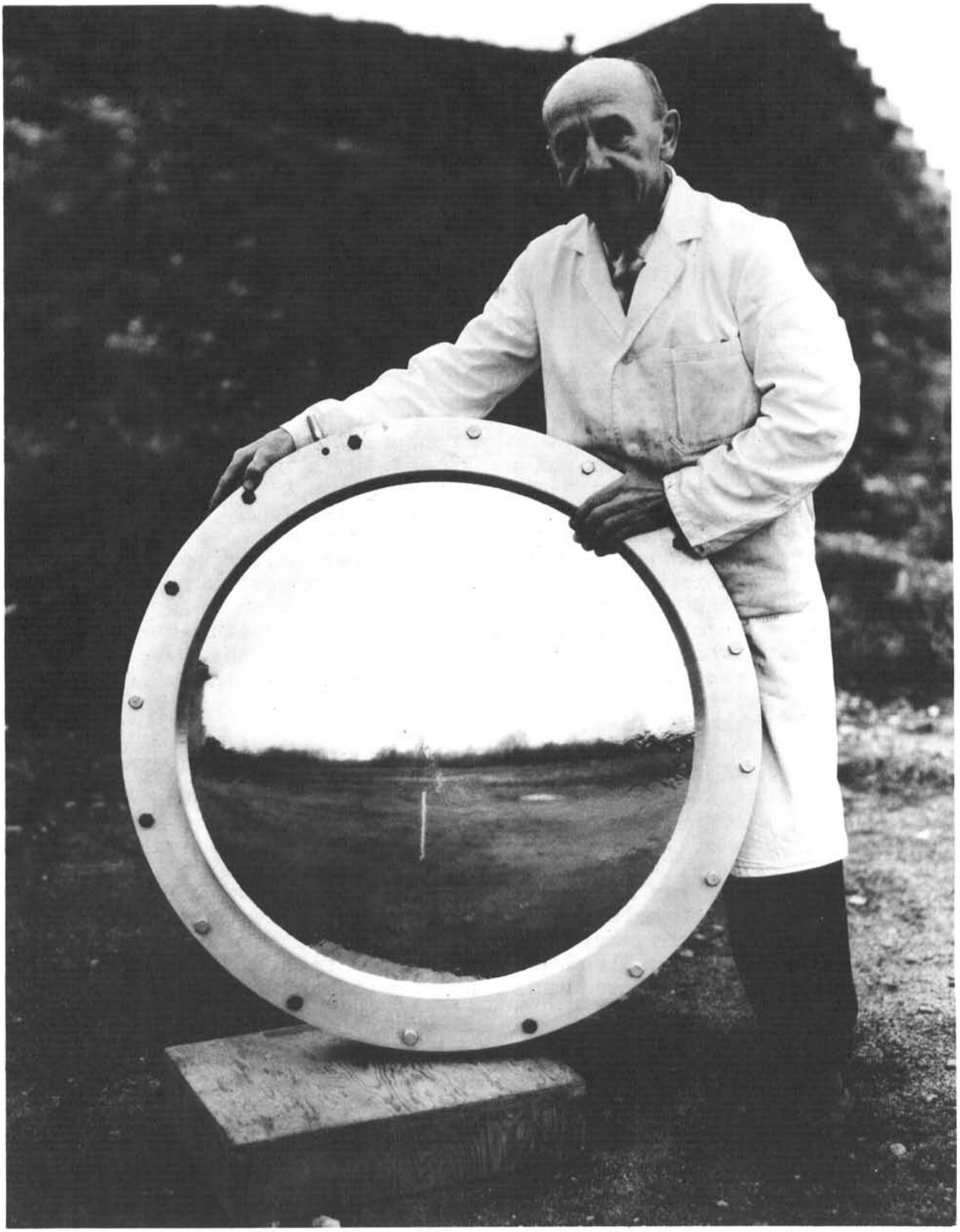

FIGURE 3

THREE FOOT DIAMETER REFLECTOR WITH ALUMINUM RIM

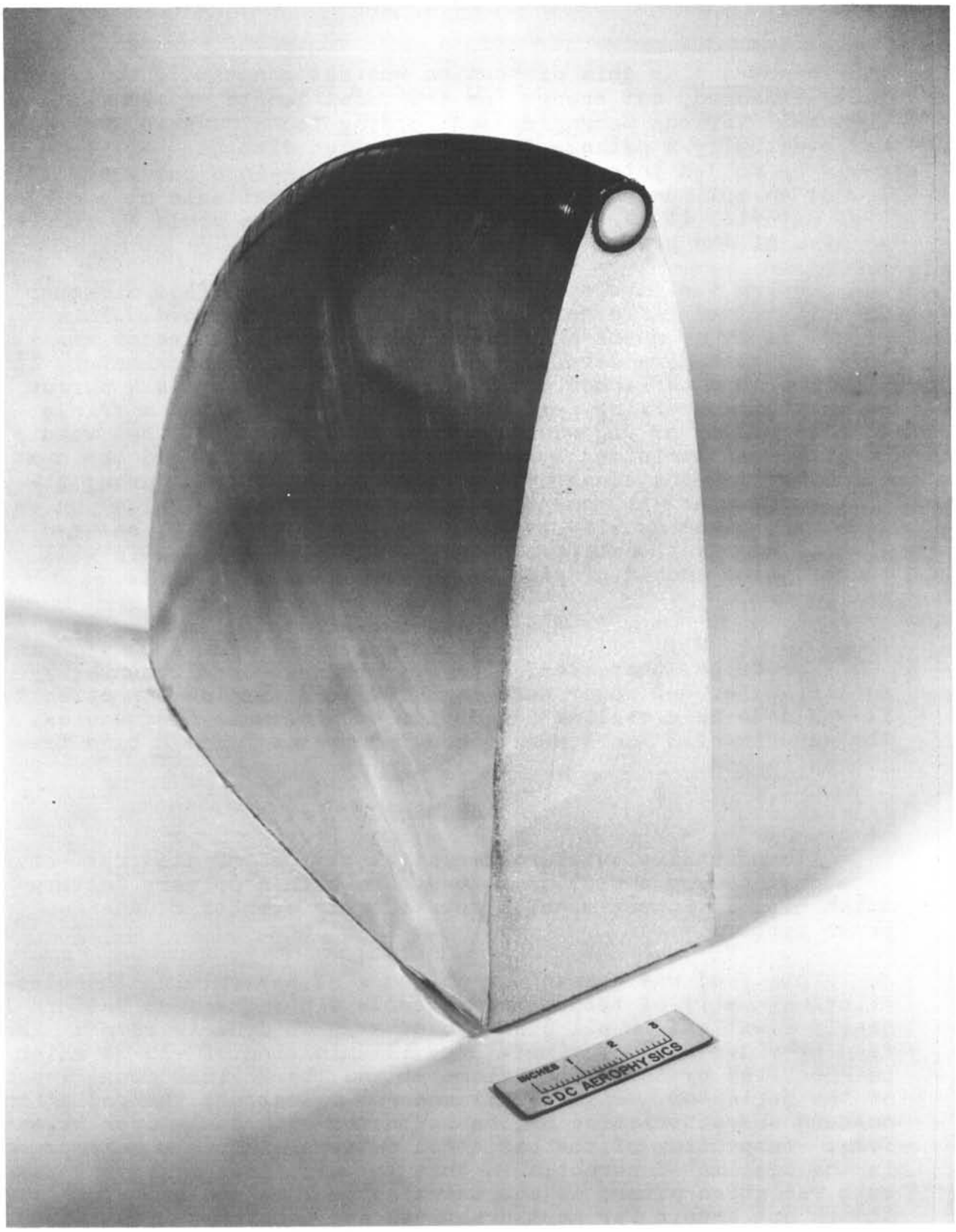

FIGURE 4
SECTION OF THREE FOOT DIAMETER
RIGIDIZED RIM REFLECTOR

It was noted that this distortion was not constant on all surfaces produced, but changed as the focal length of the reflector changed. Various packaging and folding techniques were studied and eventually a package for a three foot diameter reflector could be folded into a 3-inch x 5-inch x $1\frac{1}{2}$-inch package. This is not an optimum and with the use of more suitable circumferential material it is estimated that this volume could be reduced to 1/ 4 of the present package volume.

During the laboratory experiments, a three foot diameter foam rigidized reflector weighing 4 lbs was produced. This weight is by no means an optimum and a 3-foot reflector was foreseen with more development work, weighing approximately $1\frac{1}{2}$ lbs. In this reflector the Mylar surface would have a narrow urethane foam backing. To produce such a reflector a triple diaphragm type of rig would have to be used. The first void between the aluminized Mylar would be foam filled and the next void, backing the clear Mylar, would be gas filled during rigidization. At the moment, polyurethane foams of 2 lbs per cu ft of rigidized density have volume expansion ratios between 30-35. But as the state of the art improves this ratio will increase and should provide for lower mass reflectors.

MICROWAVE EVALUATION

Electrical characteristics of the first developmental 3-foot diameter reflector were measured to determine how effective it would be as a collimating device at microwave frequencies. The experimental tests were conducted in the X and C band frequency ranges.

X-BAND PROPERTIES

X-band radiation characteristics of the inflated reflector were obtained by employing a feed horn with a primary pattern which closely approximated a rotationally symmetric Gaussian power pattern.[4]

This feed was chosen for purposes of determining the electrical symmetry of the foamed parabola since the feed pattern is nearly identical in all planes over a 25 db dynamic range. The feed provided an approximate edge illumination of -10 db which is specified by the 3-foot diameter and the 28-inch focal length of the reflector. Figures (6) and (7) illustrate the radiation pattern characteristics of the reflector with the aforementioned feed. Inspection of the radiation patterns indicate non-symmetry in the collimated parabola in that the side lobe structure for both radiation planes is not identical. This non-symmetry, although not severe for most practical applications, is related to phase errors produced by mechanical non-uniformities and properties of the foamed dielectric. The side lobe level indicated in Figures (6) and (7) is approximately 10 db higher than that obtainable with an ideal parabolic reflector with the same aperture illumination and is an indication of the presence of phase error.

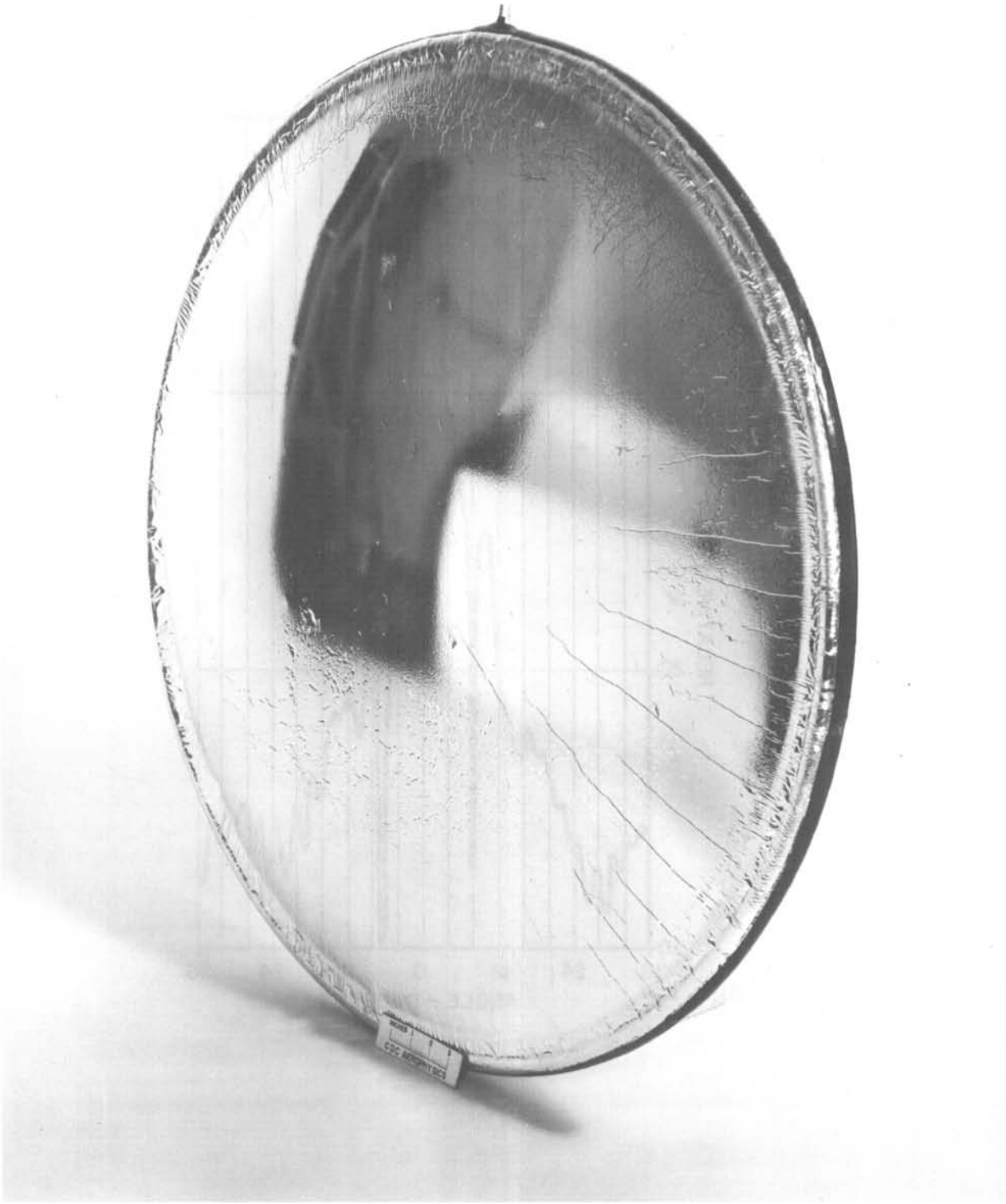

FIGURE 5

A THREE FOOT DIAMETER RIGIDIZED RIM REFLECTOR

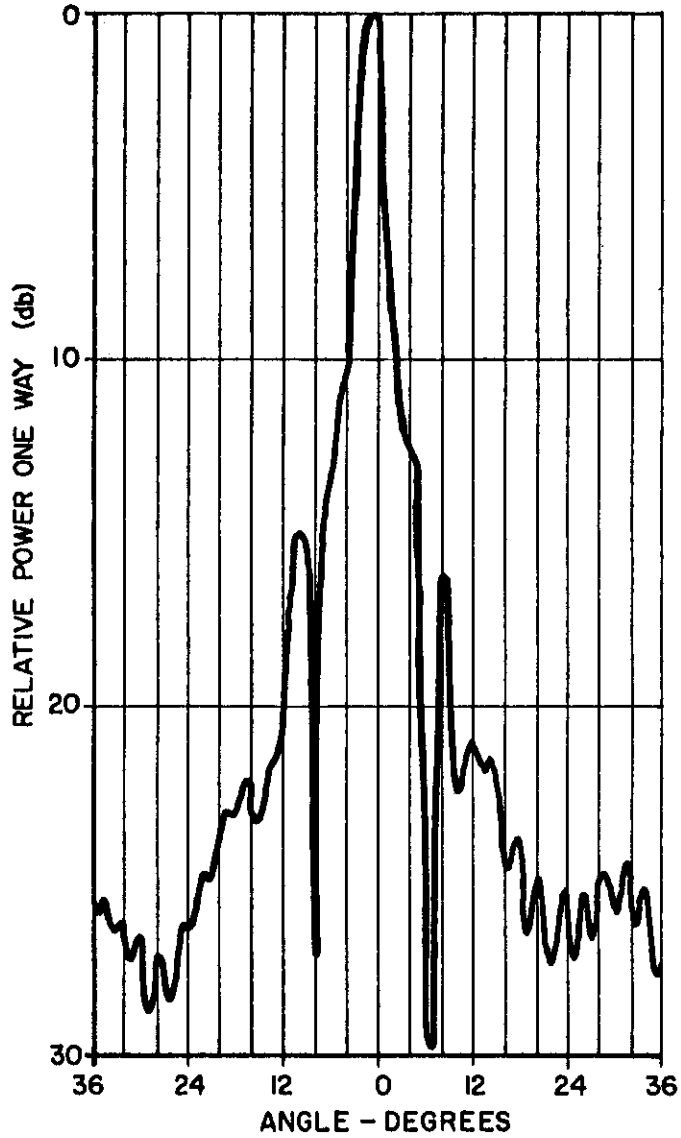

Figure 6

X-Band, Parabolic Antenna Pattern, H Plane,

at 0 Degrees

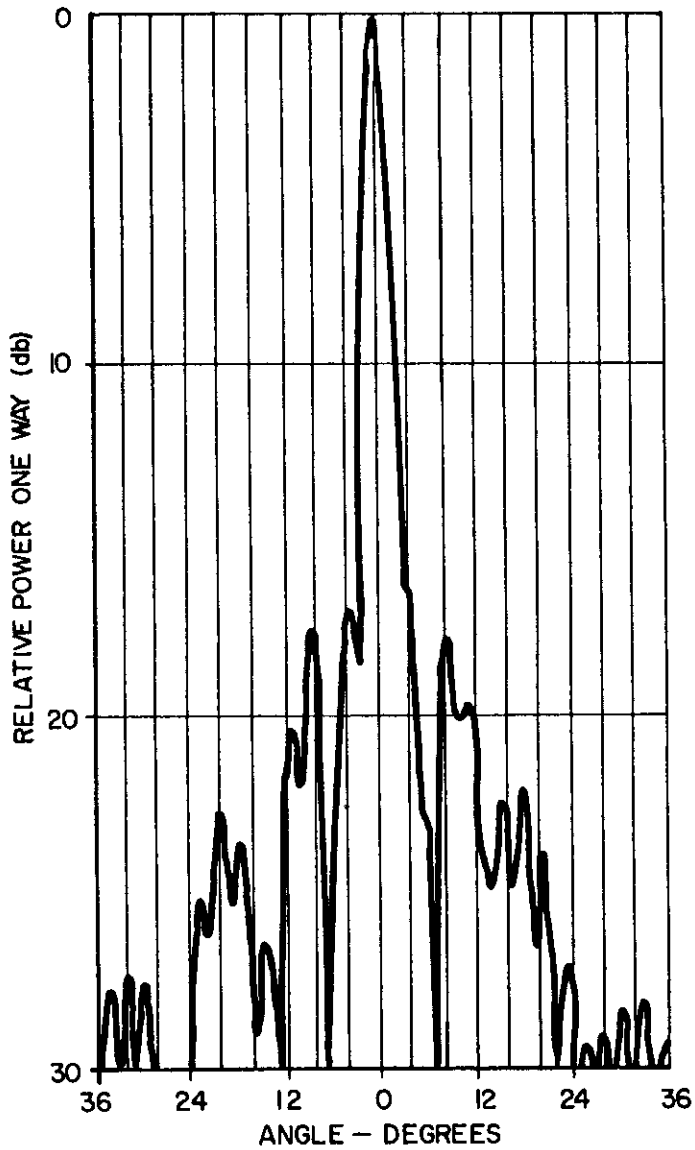

Figure 7

X-Band, Parabolic Antenna Pattern, E Plane

Measured values of gain obtained with the experimental reflector are indicated in Figure (8).

PHASE ERROR EFFECTS

Phase errors produced over a collimating aperture normally increase the side lobe level of the secondary radiation pattern and cause a reduction in gain.

In order to accurately predict the effect of phase error for parabolic reflectors one must consider the two dimensional phase distribution over the perturbed aperture. Given the resulting phase distribution and assuming a Gaussian shaped pattern one can calculate the secondary pattern characteristics and compare the result to that obtained from an ideal parabolic surface and thus predict any increase in side lobes and reduction in gain. No attempt has been made at present to accurately correlate the phase errors of the inflated parabola with its radiation characteristics. However a brief investigation has been conducted to determine first order effects of the mechanical properties of the reflector. Several sources of phase error observed from mechanical properties of the experimental reflector are discussed below.

(1) Surface wrinkle of the reflector was measured and found to be less than 10 mils from the average surface. The total phase error produced from this perturbation is less than 6° in the X-band frequency range.

(2) The surface error of the reflector was measured with a depth micrometer. The measured results are shown in Figure (9) as a function of displacement from the focal axis. The x-dimension was measured along either side of each orthogonal plane (0°, 90°, 180°, 270°) with the focal axis as the origin.

A theoretical parabolic curve fitted through the coordinate values $x = 1.25$ and $y = 12$, was used as a reference. The average error obtained was 40 mils with a maximum to minimum variation of 80 to 0 mils. This mechanical error produces a phase variation from 0° to 40° at X-band frequency. One would anticipate a 10-15 db increase in side lobe level, with respect to an ideal parabolic surface for such a phase error. A side lobe of this magnitude (approximately 17 db below the main beam) was obtained experimentally as previously discussed.

(3) The dielectric foam also effects the phase property of the radiating system to some degree. The aperture phase differential as produced by the presence of the foamed dielectric is also dependent on aperture illumination. For a highly tapered illumination the phase error produced by the foamed dielectric is minimum. The insertion phase of the foamed material used in these experiments is approximately 3.7° per inch at X-band frequency.

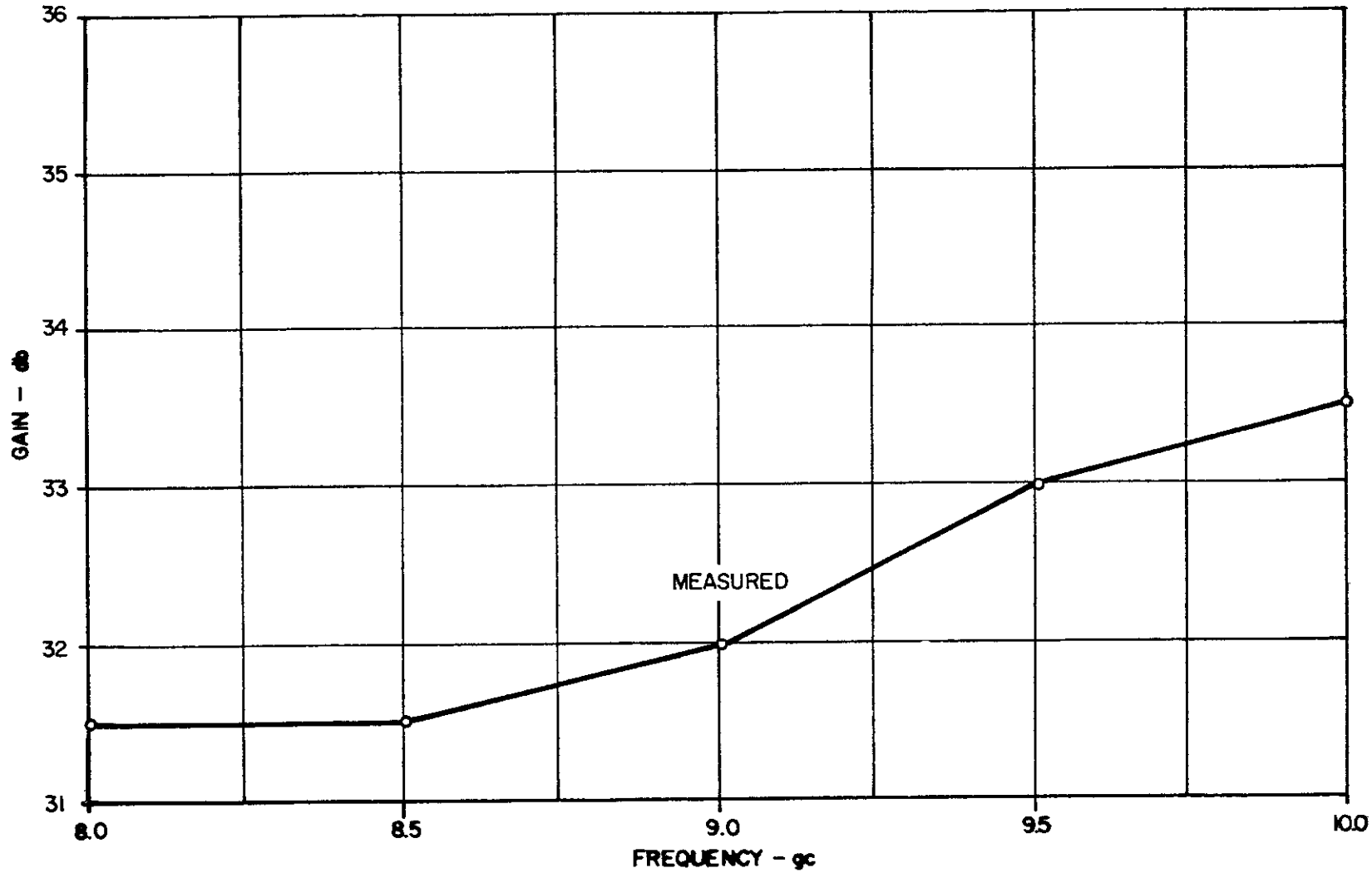

Figure 8. X-Band Gain Measurement as a Function of Frequency.

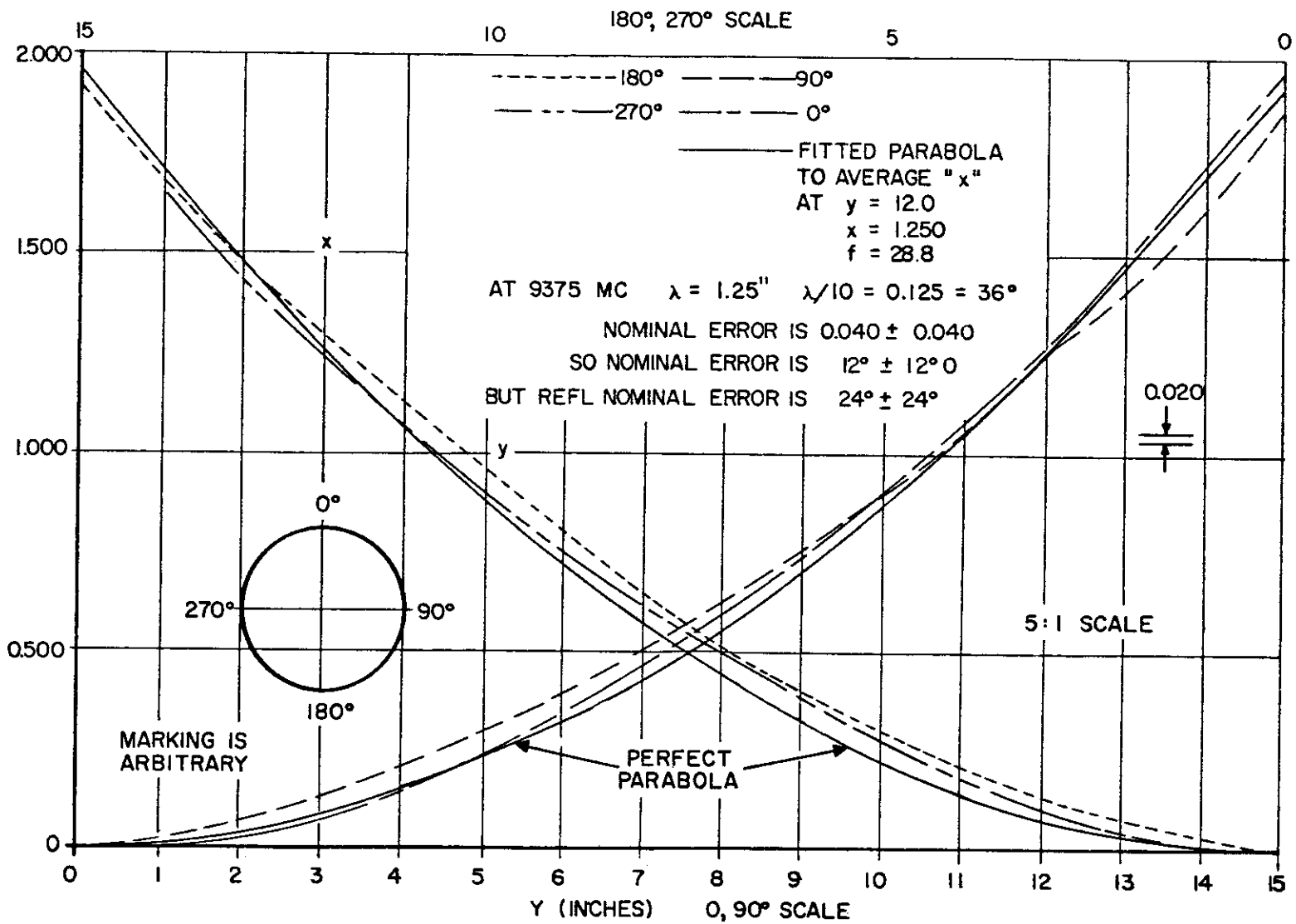

Figure 9. Measured Parabolic Reflector Dimensions.

C-BAND PROPERTIES

A C-band sectoral horn that produced a parabolic aperture edge illumination of -2.5 db and -7.5 db for H and E planes respectively, was used to observe the effect of a lower frequency. The measured patterns were as predicted. The -2.5 db aperture gave -12 db side lobes with a 4.5 degree main beam. The -7.5 db aperture had -15 db side lobes and had a 5 degree beamwidth.

Figure (10) shows the antenna as tested on the outdoor range.

CONCLUSIONS

The application of the proprietary forming technique in the development of a Rigidized Inflatable Microwave Reflector and the subsequent microwave tests performed, indicate that the present surface characteristics, resulting from the fabrication process used, permit the reflector to be used satisfactorily at X-band microwave frequencies or lower. Further refinements in the process, or smaller dish dimensions, could permit the useful extension of the method to K-band frequencies.

The investigation of the described techniques as applied to the manufacture of a much larger reflector and the application of predistibuted rigidizing agents are also foreseen as being necessary in future development activities.

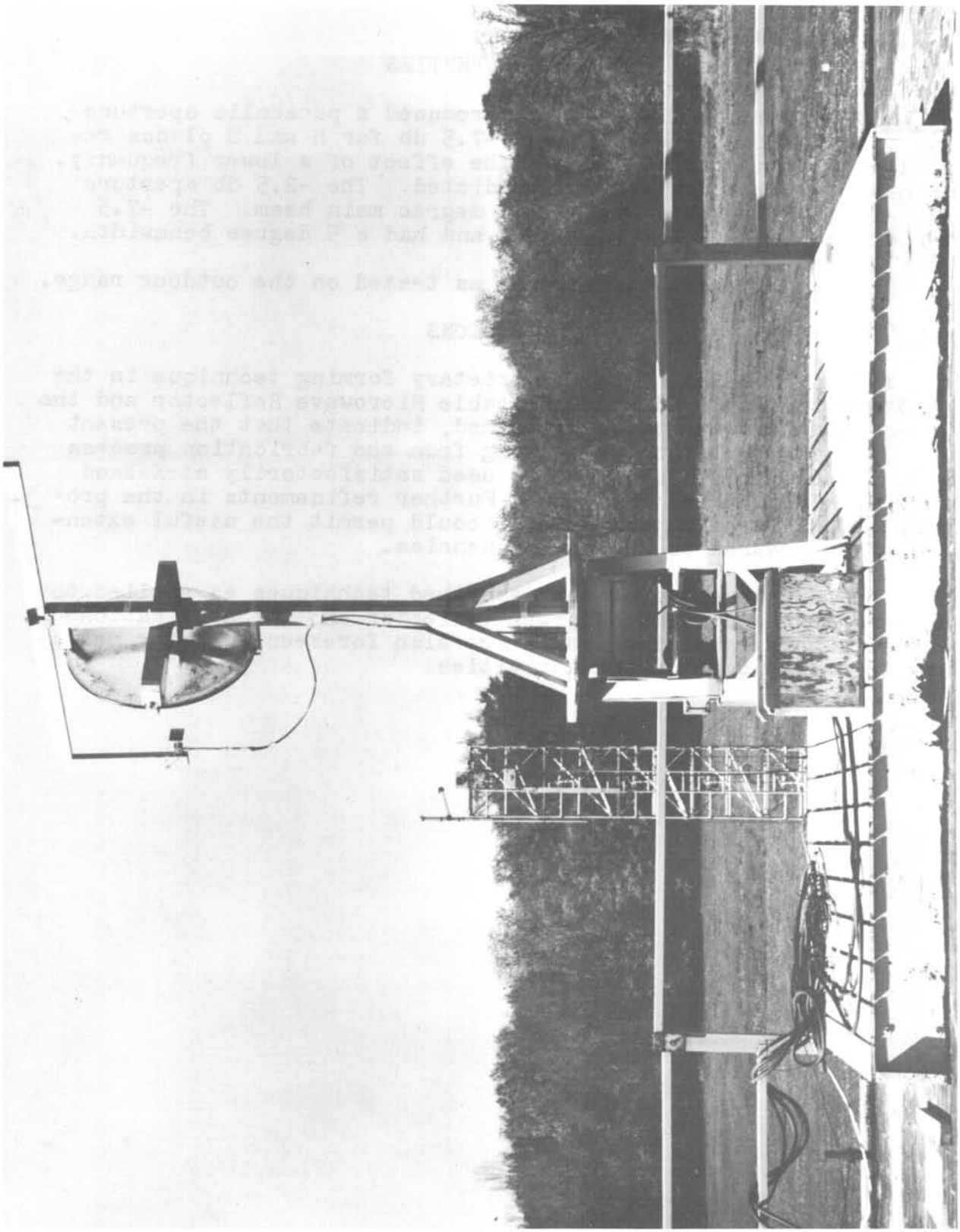

FIGURE 10

185 Foot Antenna Range Test Equipment

REFERENCES AND BIBLIOGRAPHY

1	Ferrigno, T.H.	Rigid Plastic Foams. Reinhold Press.
2	Gatzek, L.G., Isenberg, L.	The Space Environment as related to Materials Engineering for Space Power Systems Materials and Processes for Space Power and Primary Propulsion Symposium. January 2-5, 1963, Philadelphia.
3	Mauri, R.E., Fugger, J.	Structural Materials-Organic Space Materials Handbook, Lockheed Missiles & Space Company.
4	Peace, G.M., Swartz, E.E.	Amplitude Compensated Horn Antenna. Microwave Journal March 1964.

BIBLIOGRAPHY

Saylor, W.P. et al	Space Radiation Guide - Aerospace Medical Division USAF.
Houck, O.K.	Effects of Fabrication Materials and Processes on Solar Energy Collection Performance - Wright Patterson A.F.B. 1963.
Clark, D.R.	Solar Reflector Testing in Combined Vacuum and Ultra Violet-Boeing Co. 1963
Hildreth Press Inc	Modern Plastics Encyclopedia 1964.
Computing Devices of Canada	Solar Energy Concentrator - Proposal No. 4048/TP1, May 1963.
Gibson, K.F.	A Report on a Preliminary Study of a Rigidized Inflatable Space Reflector, Computing Devices of Canada, April 1964.