RAI

RAI 361

DEVELOPMENT OF A PROTOTYPE PLASTIC SPACE ERECTABLE SATELLITE

Contract No. NAS5-3923

with the

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

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Quarterly Report
December 1965-February 1966

March 15, 1966

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1.0 INTRODUCTION

During the current reporting period, fabrication of the deliverable items from Rexwell mesh, was completed. The bonding was done at Ultrasonic Seal, Inc., Ardmore, Pennsylvania. In addition, the mechanical, electrical and photomicrographic tests have been carrired out on the mesh. Additionally, samples of Sea Space thin polyethylene film (0.15 mil) were irradiated and subsequently heat treated in air and nitrogen. Tensile and shrinkage tests were then performed on the samples to determine the effects of irradiation, heat and oxidation on the film. A 1 mil high density polyethylene film has been selected for initial tests to determine the feasibility of irradiating, extracting, heat treating, perforating, and plating thin polyethylene film. The film selected is Marlex 6002 made by Phillips Chemical Co. This has been done so as to determine the processing problems on a less costly representative polyethylene film. Initial tests indicate good platability of this film.

The setup for the extraction program has been started. Constant temperature baths and auxiliary controls have been procured as well as the requisite solvents and antioxidants.

Finally, preliminary calculations have been started in order to determine the required thickness of polyethylene film that will be able to withstand a buckling pressure of five times solar pressure.

2.0 COMPLETION OF FABRICATION - ULTRASONIC BONDING

The fabrication scheme for all the deliverable items consists of ultrasonically bonding a predetermined 1/4-inch overlap between adjacent subsegments of mesh.

At first, continuous ultrasonic bonding was attempted. The specimens to be bonded were passed between a bar operating at an ultrasonic frequency and an anvil. The operation caused tearing and buckling of the mesh at the bond.

It was then necessary to use an intermittent bar welding operation (using an Ultrasonic Seal "402" model bonder). This operation consists of placing the mesh to be bonded between the bar and the anvil, applying pressure and then oscillating the bar at ultrasonic frequency. This operation resulted in a smooth and pressed bond.

Upon close examination of the bonded material, it was observed that the bonded mesh peeled. This failure to achieve a satisfactory bond was due to the interference of the thin copper coating on the mesh surface. At first it was believed that cleaning action caused by ultrasonic frequency sufficiently removed enough copper to permit a polyethylene bond. This was not so. It was then necessary to remove selected areas of copper from the 1/4-inch overlap with nitric acid. A schematic diagram of the copper removal plan is presented in Figure 1.

With the removal of copper from selected areas of the mesh, it was found that a strong and true bond was achieved at those areas. The ultrasonic operation was applied to the whole bonding length to insure a smooth and uniform thickness between subsegments.

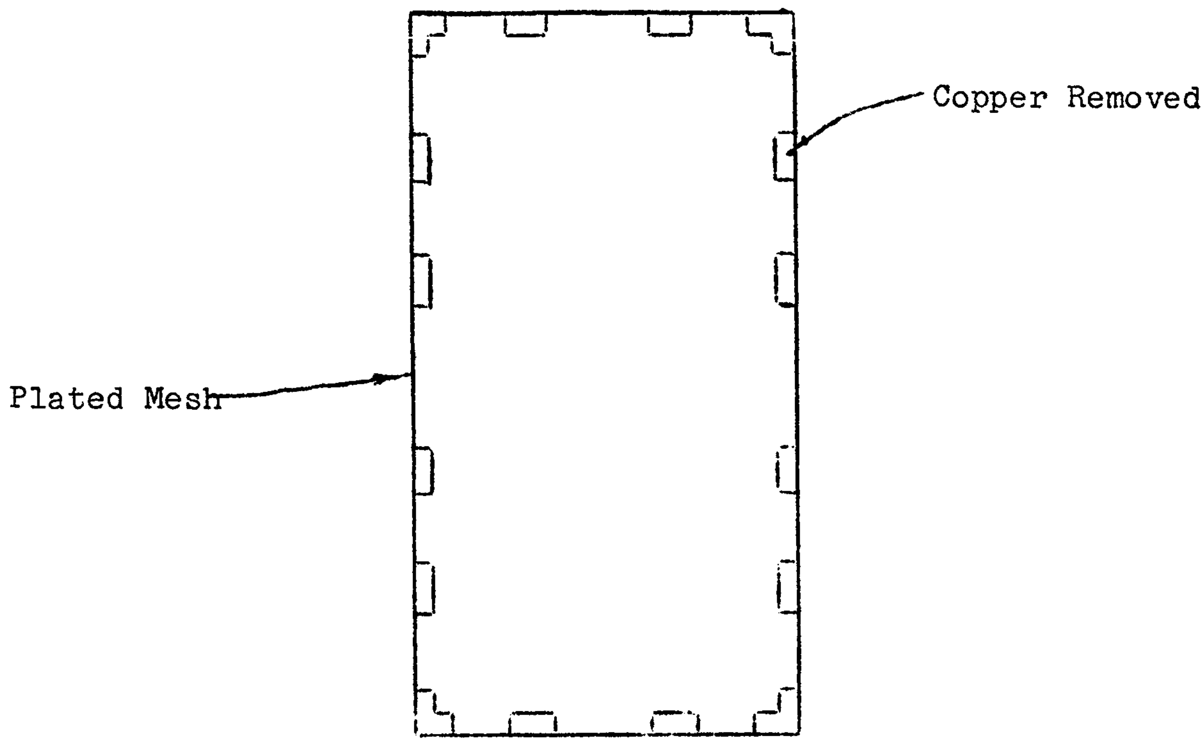


Figure 1 SELECTED AREAS OF REMOVED COPPER

2.1 Operating Conditions

With establishment of the proper mesh surface conditions and operating tool, the following operating conditions were used to bond the deliverable items:

1. Bar used: 1/2-inch wide, 2-1/2-inches long, monel metal, flat face.

2. Frequency: 20,000 cycles/second.

3. Pressure: 70-80 psi.

4. Clearance: 0.030-0.040 inch.

5. Power: 400 watts.

6. Contact time: 1.5 second (ultrasonic frequency applied).

7. Hold time: 0.5 second (for cooling).

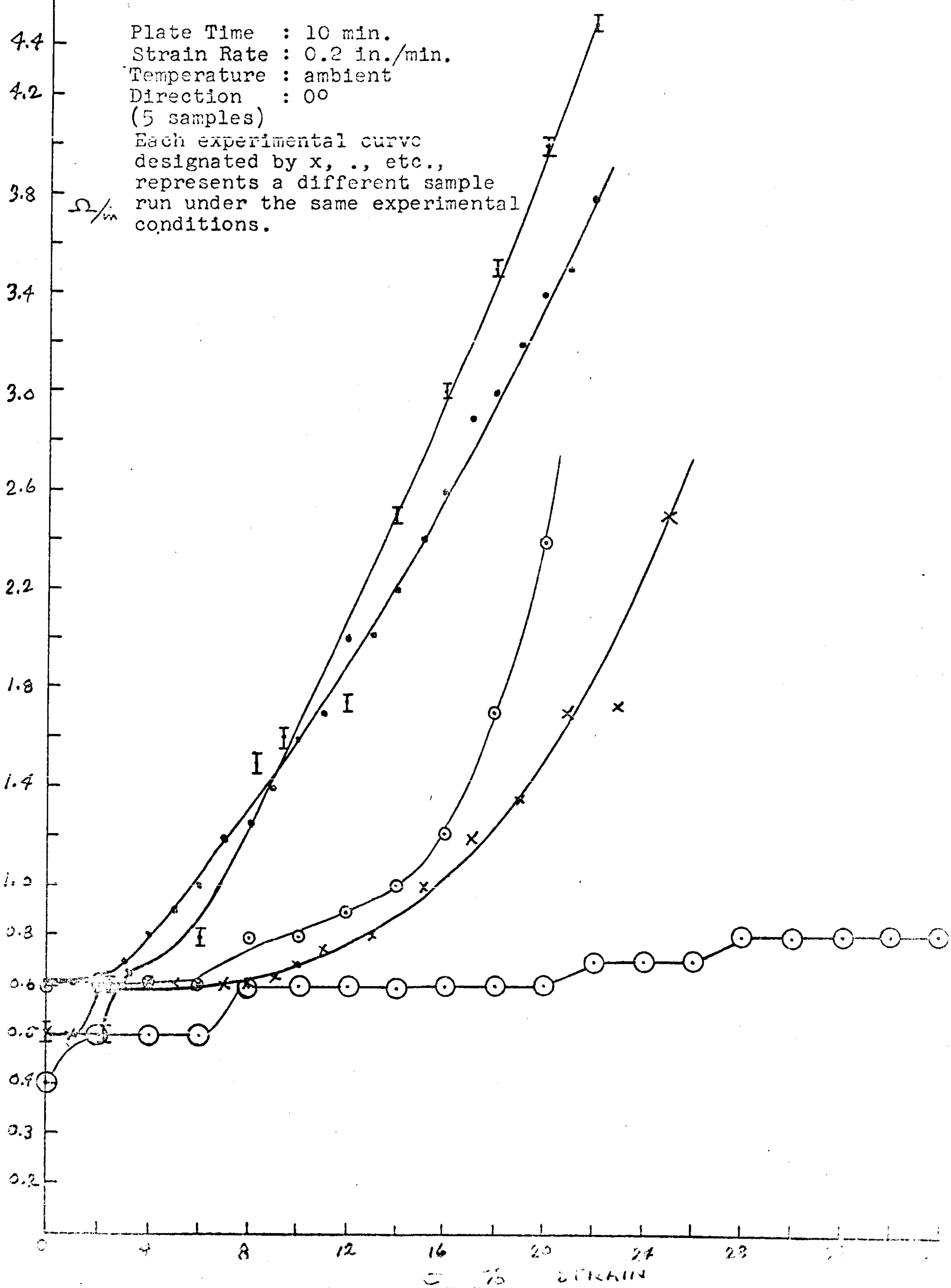
2.2 Electrical Continuity

Electrical resistance measurements were taken on 1-inch square samples of plated Rexwell MX-44 mesh during tensile tests. The actual data points are plotted vs. strain in Figures 2 and 3 for five samples. It can be seen from the graphs that the maximum specified resistance of 2 ohms/sq. occurs at approximately 20% strain; after which there is a very rapid loss in continuity (rapid increase in resistance).

Resistance measurements were also taken across the bonded mesh. Results indicate, see Figures 4 and 5, that the continuity across the bond is much less than in the plated mesh itself. Additionally, losses in continuity occur more rapidly with increasing strain for the bonded-plated mesh. In fact, after approximately 4% strain there is nearly no continuity. These results for the bonded mesh may be expected since there is not really a true bond between the plated pieces of mesh.

Resistance measurements were additionally made during a bend radius tensile test. (Samples were pulled between a glass filled epoxy resin knife edge and the jaws

Figure 2 RESISTANCE VS. STRAIN CURVE PLATED REXWELL MX-44 MESH



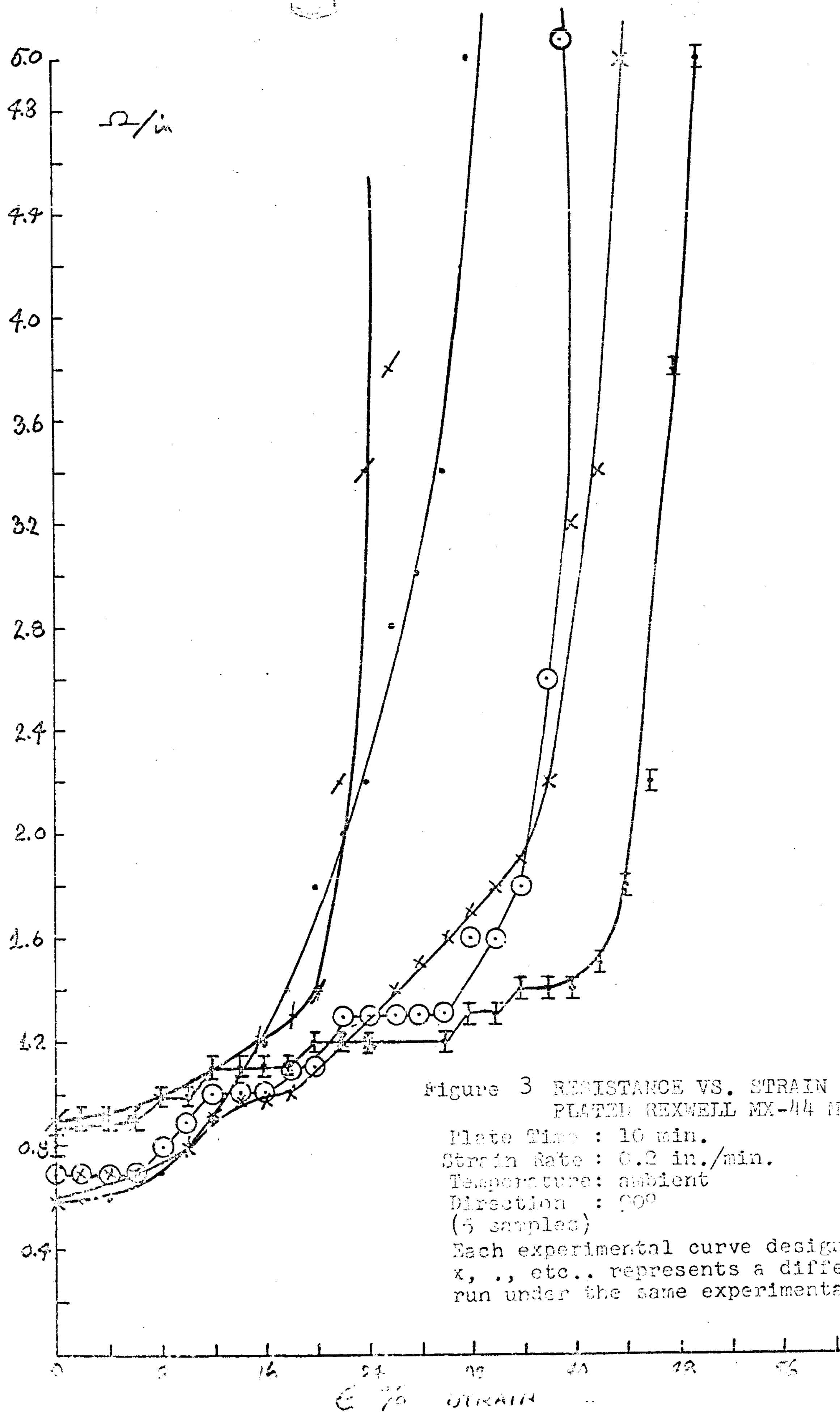


Figure 3 RESISTANCE VS. STRAIN CURVE
PLATED REXWELL MX-44 MESH

Plate Time : 10 min.
Strain Rate : 0.2 in./min.
Temperature: ambient
Direction : 90°
(5 samples)
Each experimental curve designated by
x, ., etc.. represents a different sample
run under the same experimental conditions.

Figure 4 RESISTANCE VS. STRAIN CURVE PLATED AND ULTRASONICALLY BONDED REXWELL MX-44 MESH

Plate Time : 10 min.
Strain Rate : 0.2 in./min.
Temperature: ambient
Direction : 0°
(4 samples)
Each experimental curve designated by x, ., etc., represents a different sample run under the same experimental conditions.

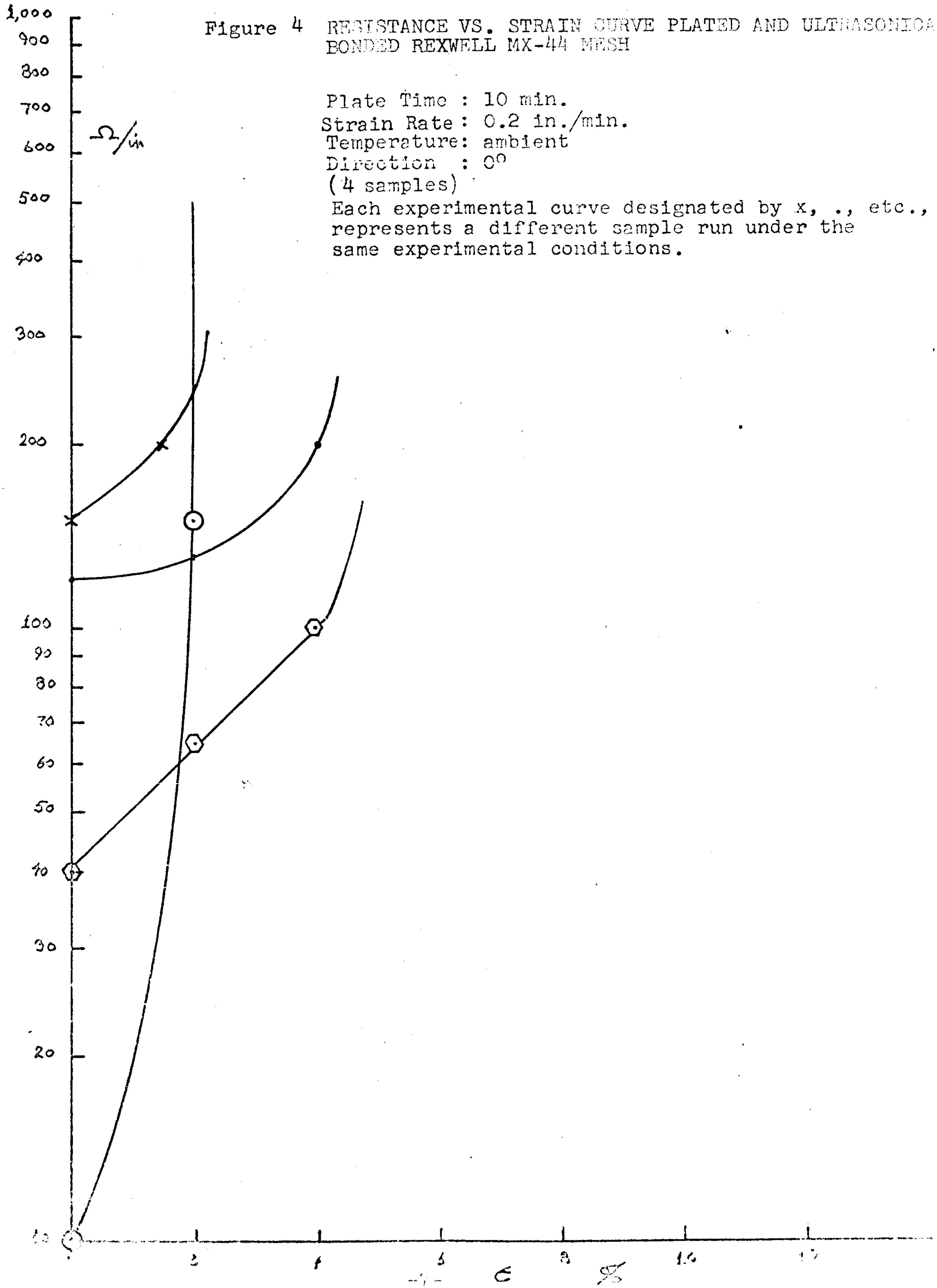
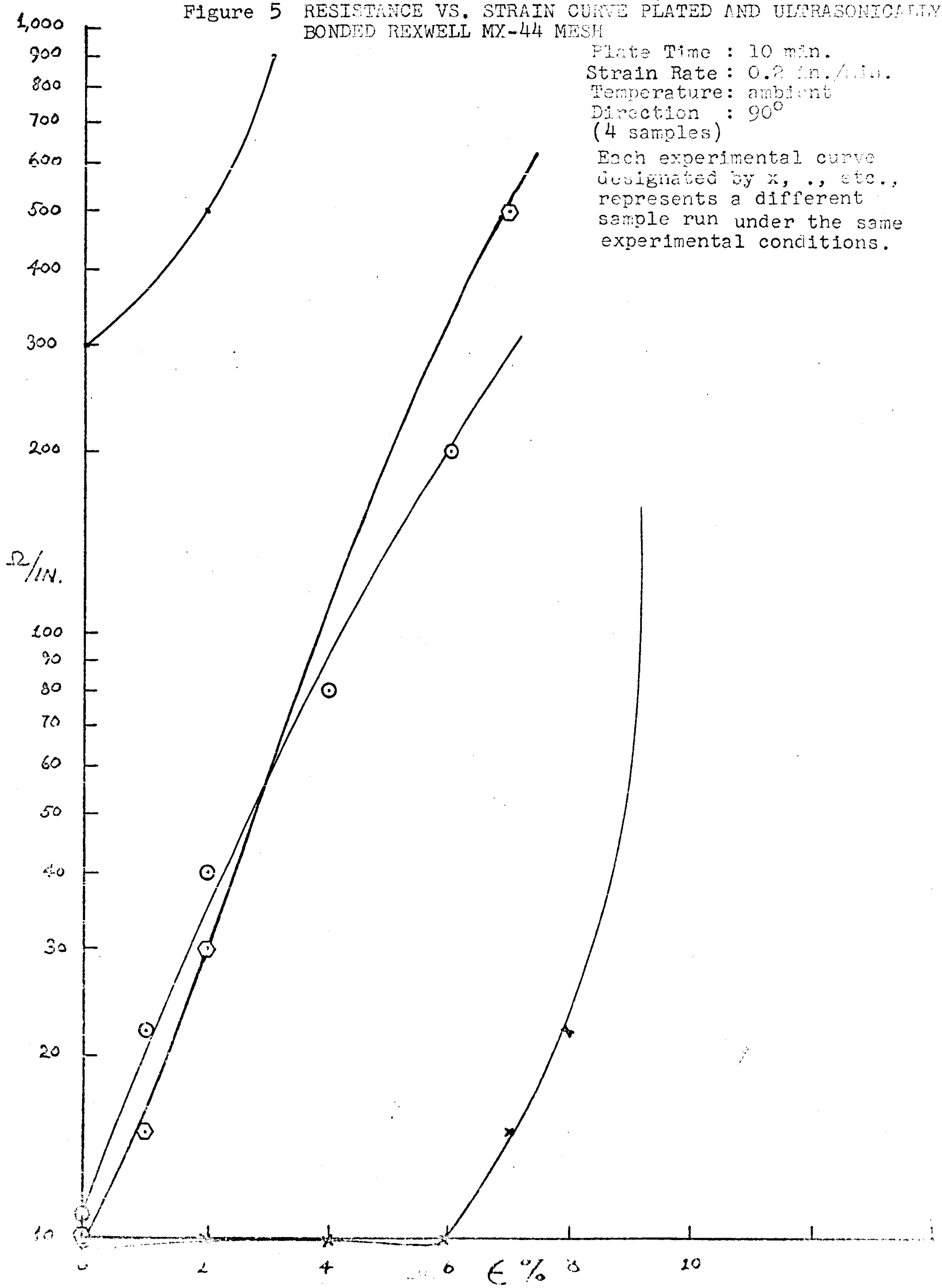


Figure 5 RESISTANCE VS. STRAIN CURVE PLATED AND ULTRASONICALLY BONDED REXWELL MX-44 MESH



of the tensile tester. See Figure 6.)

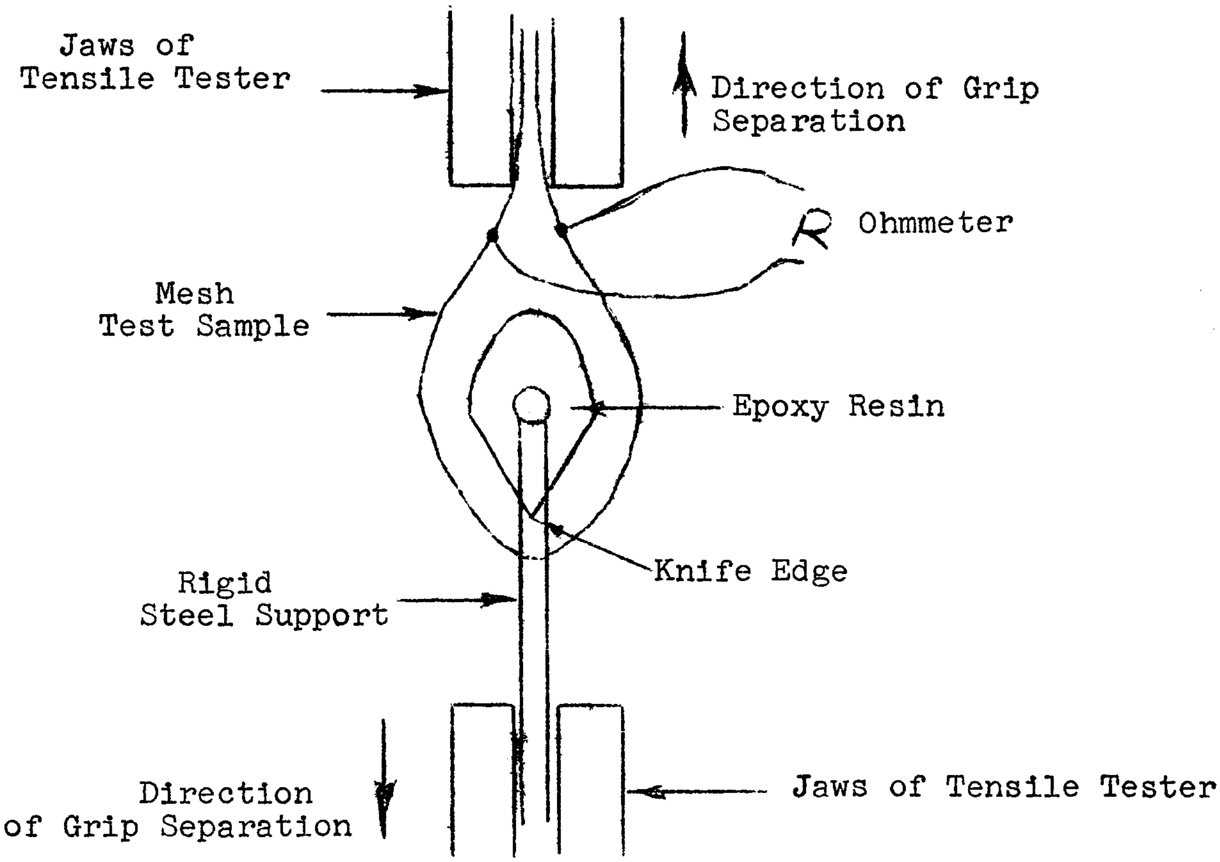
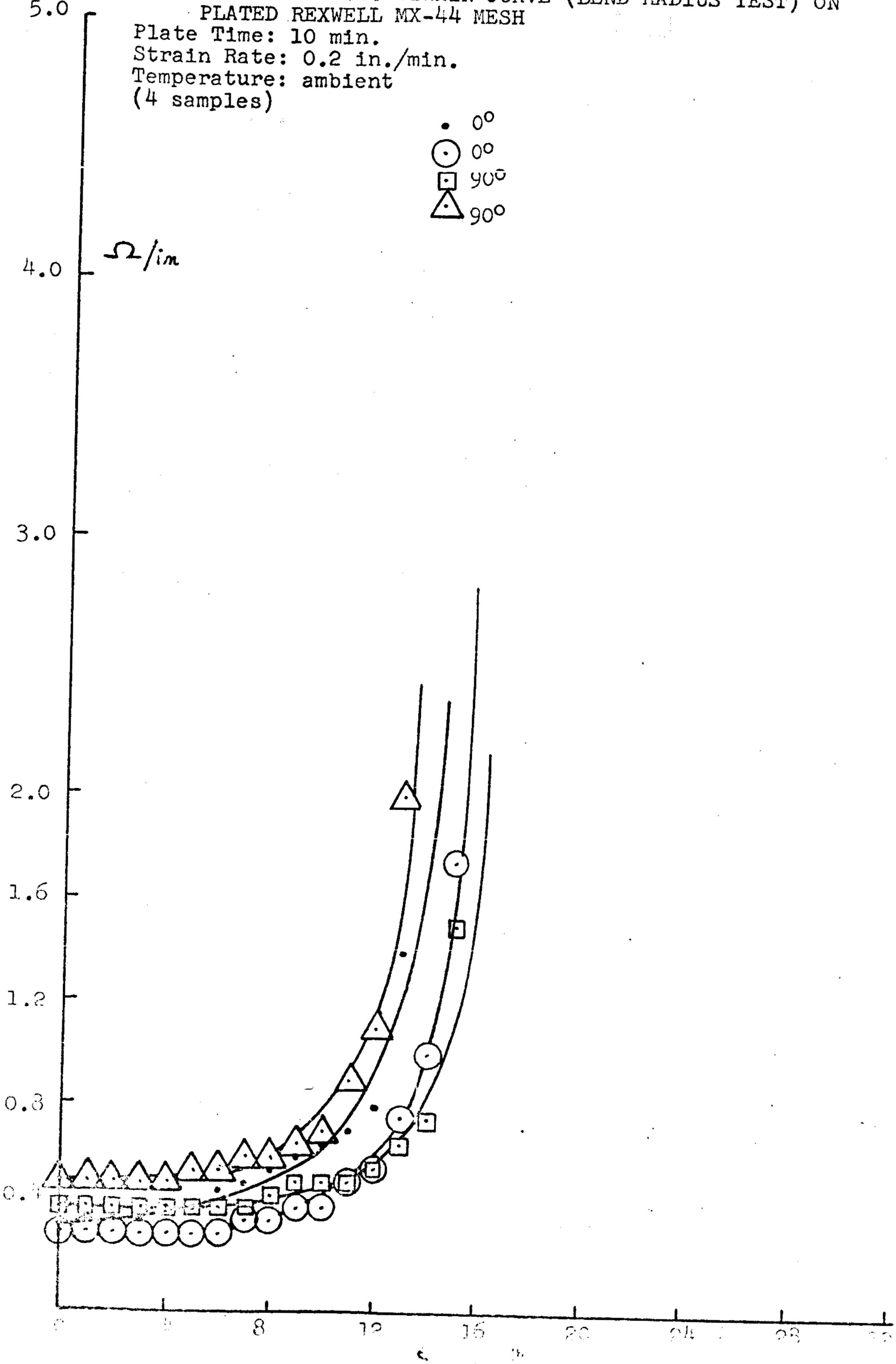


Figure 6 BEND RADIUS TENSILE SCHEMATIC

The results of this test (see Figure 7) indicate that loss of continuity with strain comes faster under these more stringent test conditions.

Figure 7 RESISTANCE VS. STRAIN CURVE (BEND RADIUS TEST) ON PLATED REXWELL MX-44 MESH



3.0 MECHANICAL TESTING

Tensile tests were performed on the Rexwell mesh through its various stages of processing. The tests were performed on 1-inch wide samples using an Instron tensile tester, Grip separation on the jaws of the tensile tester was 1-inch. Tensile tests were pulled in the 0^{o}, 45^{o} and 90^{o} directions.

In addition, flexural rigidity tests were performed on the irradiated heat treated and plated mesh in the 0^{o}, 45^{o} and 90^{o} directions. Table 1 summarizes the testing results.

The tests indicate that there is a general increase in strength and rigidity (and stiffness) of the material with processing. This can be seen from the increasing values of yield force, F_y, modulus of elasticity, E, and flexural rigidity, G, with processing. On the other hand, there is less of a decrease in strength. This is due to the fact that induced coosslinkage and the copper plate nullify the degrading effects of radiation and chemical attack, This can especially be seen from the near consistency of F_y in Table 1, going from irradiated-heat treated material to plated material.

The mechanical properties of the bonded mesh are also included in Table 1. It can be seen that there is a large decrease in strength at the bond. This loss in strength is the same for both bonds with coated copper and without. The loss in strength is caused by stress concentrations at the edge of the bond. In all tensile tests failure occurred at this location.

Table 1

Results of Mechanical Tests

Direction Degrees	F_y (lbs./in.)	F_u (lbs./in.)	ϵ_y (%)	ϵ_u (%)	ϵ_m (%)	E (psi x 10^{+5})	G (lb.ft. x 10^{-5})
UNPROCESSED MESH							
0	10.9±0.5	18.3±1.3	7 ±0.8	807±67	827±63	0.72±.08	83.0±10.9
45	12.0±0.4	13.7±0.9	27.7±3.8	591±75	723±60	-	104.1±26.4
90	14.0±0.8	16.4±1.4	8.4±1.0	778±69	798±120	0.59±.07	193.0±55.5
IRRADIATED MESH							
0	11.7±0.6	13.7±0.9	7.2±1.2	353±15	411±23	0.66±0.9	122.1±16.6
45	11.9±0.3	13.8±0.8	25.0±1.5	306±36	469±53	-	129.0±17.0
90	15.6±1.4	15.6±1.4	7.2±1.8	7.2±1.8	253±71	0.70±1.4	221.7±67.3
IRRADIATED-HEAT TREATED MESH							
0	12.9±1.2	14.5±1.2	7.5±1.7	303±29	345±30	0.80±.20	134.0±11.1
45	13.1±2.0	14.8±4.0	42.0±2.0	228±28	385±20	-	144.0±10.5
90	18.8±1.7	21.5±2.7	9.2±3.0	167±66	263±30	0.69±.25	311.7±36.0
IRRADIATED-HEAT TREATED-PLATED MESH							
0	15.7±0.7	14.6±0.9	5.0±0.0	163±31	217±31	1.23±.06	157.6±32.9
45	13.0±0.3	13.6±0.3	40.0±0.0	75±19	108±38	-	201.6±27.4
90	19.4±0.9	17.1±0.4	7.5±1.7	20±3	85±7	0.81±.18	414.4±72.5
IRRADIATED-HEAT TREATED-PLATED-BONDED* MESH							
0	8.6±1.0	-	4.6±0.5	-	31±30	0.75±0.17	-
90	15.9±0.6	-	7.0±2.0	-	35±12	0.77±0.22	-
IRRADIATED-HEAT TREATED-PLATED BONDED** MESH							
0	8.8±2.9	-	4.0±0.3	-	33±25	0.95±0.19	-
90	15.3±2.3	-	5.0±1.0	-	27±3	0.86±0.13	-

* Copper removed from bonded area with nitric acid

**Copper not removed from bonded area.

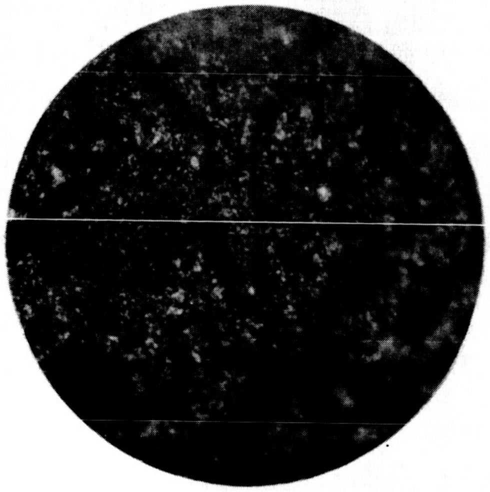
Instron tensile test; strain rate 2 in./min., ambient temperature

4.0 PHOTOMICROGRAPHS

Photomicrographs of plated Rexwell MX-44 mesh were taken at 200X magnification on a Unitron U-11 metallurgical microscope. The results are shown in Figure 8. Photograph (A) shows the plated material. It can be seen that there is a continuous grain-like coating on the sample. Photographs (B) and (C) are photomicrographs of the surface of the plated mesh at loss of continuity initiated by a normal tensile test and a bend radius test. The surfaces photographed for both of these samples were chosen at the point of maximum copper separation. It is seen by comparison with photograph (A), that after stretching the copper separates into discontinuous islands of copper at the point where continuity is lost.

Photographs (D) and (E) are photomicrographs of plated bonded mesh and plated bonded mesh at loss of continuity respectively. It can be seen from these photographs that there is less copper on the surface of the mesh because less reflective polyethylene shows up as a darker surface. The loss of copper in both photographs (D) and (E) is attributed to the cleaning action of the ultrasonic bonding operation at the bond. Additionally, in photograph (E) further copper is removed during the tensile test. The dark areas surrounding the bright line in the center of photograph (E) specifically show the cleaning and copper separation effects.

Figure 8 PHOTOMICROGRAPHS OF REXWELL MX-44 PLATED MESH (200X)



A
PLATED-UNTOUCHED

B
PLATED-PULLED TO LOSS OF CONTINUITY

C
BEND RADIUS-PULLED TO LOSS OF CONTINUITY

D
PLATED-BONDED (AT BOND)

E
PLATED-BONDED AT LOSS OF CONTINUITY
(AT BOND)

5.0 INITIAL SELECTION OF THIN POLYETHYLENE FILM

A selection of thin polyethylene film for the initial program has been made. The film is Marlex 6002 manufactured by the Phillips Johanna Co. Fifty (50) lbs. of 24-inch wide, 1-mil thick film has been ordered. The significant properties of the film are listed in Table 2.

Table 2

Properties of Marlex 6002 Polyethylene Film

Density gm/cm3	No. Average Molecular Weight (M_n)	Wt. Average Molecular Weight (M_w)	Crystalline Melting Point T_m (°C.)	Modulus of Elasticity (E psi)
0.960	~10500	~ 122000	135	11823±4135 (0°)
				8180±643 (90°)

The ratio of M_w/M_n indicates that there is a wide distribution of molecular weights in these films. This situation is quite favorable for extraction. It indicates the possibility of extracting a large amount of low molecular weight material from the film leaving a matrix of crosslinked high molecular weight fractions.

Additionally the Marlex 6002 was checked for platability. The standard copper plating cycle was used with the following exception... a five minute plate was used instead of the ten minute one. A well adhering bond was achieved with a resistance of 1 ohm/square.

6.0 EXTRACTION STUDIES

The extraction study has been expanded so as to encompass methods of increasing the modulus of elasticity of the polyethylene as well as to lower its weight. Of primary consideration in this study is the E/ρ ratio, where E is the modulus of elasticity of the material and ρ is its density. The aim of this study will be to maximize this quantity. The quantity E will be evaluated using a standard tensile test. The quantity ρ will be evaluated using a polymer density gradient apparatus which will be procured and assembled in the near future. The solvent used for all of the preliminary extractions will be xylene. It has been chosen since it is a standard extraction solvent for polyethylene.

The experimental program will tentatively consist of five parts. These are as follows:

1. Dose Variation Study. The polyethylene film will be given doses from 5 to 75 Mrads. The resultant crosslinked material will then be extracted. E and ρ will then be measured.

2. Extraction Variation Study. Polyethylene film will be irradiated at one representative dose. The degree of extraction will then be varied. A check for variations in E will be made.

3. Chemically Induced Crosslinking (swelling) Study.

Polyethylene will be swollen in allyl methacrylate (AMA) and divinyl benzene (DVB), two excellent crosslinking agents (see RAI 339, Final Report dated October 15, 1964, "Upgrading of Polymeric Materials for Electrical Applications"). Polyethylene with crosslinking agents incorporated will subsequently be irradiated to various doses of irradiation. E and ρ will be measured.

4. Solvent Optimization. It is planned to test extraction at a given dose using various solvents at temperatures below their boiling points. Silicone oil heating baths and temperature controls have been set up in preparation for the extraction studies on irradiated polyethylene. Additionally, the antioxidant n-β-phenylnaphthylamine will be added to each solvent to retard oxidation during extraction. The amount added will be 0.1% antioxidant. The solvents chosen are listed in Table 3. They have been selected because of their availability, high boiling points and superior solvent properties. Additionally, they have been selected for their specific solvent character, i.e., polar, saturated or unsaturated, see Table 3. After extraction E and ρ will be determined.

Table 3

Solvents Chosen for Extraction Program

Solvent	Boiling Point (°C.)	Type*
Xylene	140	US
Butyric acid	163.5	S-P
Dimethyl sulfoxide	189	P
Dimethyl formamide	153	P
Decalin (decahydronaphthalene)	194.6	US
Tetralin (1-2-3-4 tetrahydro-naphthalene)	207.2	S
Dichloro benzene (ortho)	180 - 183	US-P

*
US - unsaturated
S - saturated
P - polar

5. E/ρ Optimization. An attempt will be made to obtain the highest E/ρ using a combination of extraction and swelling techniques. The procedure will depend on the above-listed studies (1. to 4.).

At first the material will be given a mild dose of irradiation, it then will be extracted to a low density. It will consequently be swollen to a density less than its original value and then finally irradiated. This second irradiation should increase E both above its initial and intermediate value. Since E has been increased overall and ρ decreased overall there should be a net gain in E/ρ.

7.0 FILM THICKNESS

7.1 Theoretical Equation

A literature search and calculations have been undertaken to determine the thickness of film necessary to construct a 425-foot diameter sphere able to withstand a buckling pressure of five-times the solar pressure ($P_s = 1.3 \times 10^{-9}$ psi). Equations have been formed relating critical buckling pressure (P_{cr}) with shell thickness (t).[a]

$$P_{cr} = \frac{2Et}{R(1-\nu^2)} \left(\sqrt{\frac{1-\nu^2}{3}}\, \frac{t}{R} - \frac{\nu t^2}{2R^2} \right)$$

where E = Young's modulus
ν = Poisson's ratio

$$\frac{t^2}{R^2} \longrightarrow 0$$

$$\text{so, } P_{cr} = \frac{2Et^2}{R^2 \left[3(1-\nu^2)\right]^{1/2}}$$

$$\text{or} \quad t = \left[3(1-\nu^2)\right]^{\frac{1}{4}} R \sqrt{\frac{P_{cr}}{2E}} \sqrt{1-\theta}$$

where $E = 10 \times 10^3$
$P_{cr} = 5(1.3 \times 10^{-9})$
$R = 2550$ in.
$\nu = 0.5$
$1-\theta = 0.10$ where θ is the fraction of open area
$t = 0.35$ mil

[a] Formulas for Stress and Strain, 3rd Ed., Raymond J. Rourk, p. 318.

Theory of Elastic Stability, 2nd Ed., Timoshenko and Gere, pp. 512-519, Buckling of Uniformly Compressed Spherical Shells.

But they yield low values when the thickness (t) to radius (R) ratio is less than 10^{-3}. Summaries of the inaccuracy of using theoretical buckling pressure equations for large thin shelled spheres are given in Theory of Elastic Stability and Formulas for Stress and Strain. They are, respectively, as follows:

> "Experiments with thin spherical shells subjected to uniform external pressure show that buckling occurs at pressures much smaller than that given by (the equation above)...[see Footnote (a)]."[b]

> "Because of the greater likelihood of serious geometrical irregularities, and their greater relative effect, the critical stresses actually developed by such members usually fall short of the theoretical values by a wider margin than in the case of bars...... The critical stresses or loads indicated by any one of the theoretical formulas should, therefore, be regarded as an upper limit, approached more or less closely according to the closeness with which the actual shape of the member approximates the geometrical form assumed....."

Rourk additionally states that this discrepancy continues to increase with the thinness of the material.[c]

7.2 Empirical Equation

An empirical approach based on derivations in Engineering Dynamics[d] and a paper by Reiss, Greenberg and Keller[e] and stated (with an empirical form factor) in the final report of Development of an Inflatable Rigidizing Satellite[f] by the G.T. Schjeldahl Co. is presented below:

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[b] Theory of Elastic Stability, 2nd Ed. Timoshenko and Gere, p.518.

[c] Formulas for Stress and Strain, 3rd Ed. Raymond J. Rourk, p.303.

[d] Engineering Dynamics, Vol. II, Elastic Problems of Single Machine Elements, C.B. Brezeno and R. Grammel, pp. 484-496.

[e] Non-Linear Deflections of Shallow Spherical Shells, E.L. Reiss, H.L. Greenberg and H.B. Keller, Journal of the Aeronautical Sciences, Vol. 24, #7, pp.533-543, July 1957.

[f] Final Report, NAS-51190, p. 4.25.

(1) $$P_{cr} = \frac{E\,\mu t^3}{r^2 R 33(1-\theta)}$$

where 33 = empirical form factor for thin perforated films
t = film thickness
R = radius of sphere
E = modulus of Elasticity
θ = fraction of open area

$$\mu = \sqrt{0.093(\lambda + 11.5)} - 0.94$$

$$\lambda = \frac{r^4}{R^2 t^2}$$

$$r = \left(\frac{K^{\frac{1}{2}} \rho\, t}{2R}\right)^{\frac{1}{2}} \qquad K^{\frac{1}{2}} = 0.943$$

$$\rho = 25.8$$

Substituting into equation (1) and solving for t:

(2) $$t = \sqrt{\frac{33\pi R^2 K^{\frac{1}{2}} \rho\, P_{cr}(1-\theta)}{2\,\mu E}}$$

where $$\mu = \sqrt{0.093\left(\frac{K\rho^2}{4} + 11.5\right)} - 0.94$$

Further substituting the numerical values given below into equation (2)

R = 2550 in.
E = 10×10^3
0 = 0.90
$P_{cr} = 5(1.3 \times 10^{-9}$ psi)
$K^{\frac{1}{2}} = 0.93$ (given in the Reiss Article)
$\rho = 25.8$ (given in the Reiss Article)

The result obtained for t is 0.0136 in. or 13.6 mils. This method of attack is only meant to find an approximate value for the film thickness. The result is based on a centrally loaded supported spherical cap section compared to a uniformly compressed unsupported sphere. Additionally, the constant 33 is based on an aluminum polypropylene system rather than a copper polyethylene system.

7.3 Proposed Experimental Procedure

In light of the uncertainties of the above two approaches, it is proposed that an experimental method be used. The flexural rigidity

$$G = EI$$

is proportional to Et^3.

A correction factor for equation (1) is then suggested:

$$K(t,\theta) = \frac{(EI)_{\text{completed material}}}{(EI)_{\text{base material}}}$$

If $(EI)_{\text{completed material}}$ is found experimentally as a function of thickness and open area, the thickness of film required to withstand a buckling pressure of five-times solar pressure for a given open area would be found by solving the following equation by trial and error:

$$(3) \qquad 5 \times 1.3 \times 10^{-9} = \frac{K(t,\theta)}{1-\theta} \frac{E\,\mu t^3}{\pi R r^2}$$

8.0 IRRADIATED SEA SPACE POLYETHYLENE FILM

The effects of irradiation and heat treatment on ultra thin (0.15 mil) Sea Space polyethylene film were established. Samples of 0.15 mil polyethylene film were machine irradiated to 15 Mrads. The material was then heat treated at 105°C. for 16.3 hrs. To determine the effects of oxidation some samples were heat treated in air and some in nitrogen. After heat treatment tensile and shrinkage tests were performed.

8.1 Tensile Test Results

The results of the tensile tests are presented in Table 4.

Table 4

Tensile Properties of Sea Space 0.15 Mil Irradiated Polyethylene Film

Irradiation Dose: 15 Mrads
Heat Treatment Temperature: 105°C.
Time: 16.3 hrs.

Atmosphere	$\sigma_{y\parallel}$ (psi)	$\sigma_{u\parallel}$ (psi)	$\epsilon_{y\parallel}$ (%)	$\epsilon_{m\parallel}$ (%)	$\sigma_{y\perp}$ (psi)	$\sigma_{u\perp}$ (psi)	$\epsilon_{y\perp}$ (%)	$\epsilon_{m\perp}$ (%)
Nitrogen	2320±8	2766±32	29±2	130±0	1720±90	1720±90*	22±2	43±9
Air	2310±164	2526±364	32±5	97±10	1384±70	1384±70*	21±1	30±0

* Ultimate strength coincident with yield strength

Comparing these results with the results of Table IV of the June-August 1965 Quarterly Report, RAI 356, it can be seen that 15 Mrads of irradiation lowers the strength a slight amount and decreases the percent elongation. It can also be seen that the effect of an air atmosphere in heat treating degrades the polyethylene slightly.

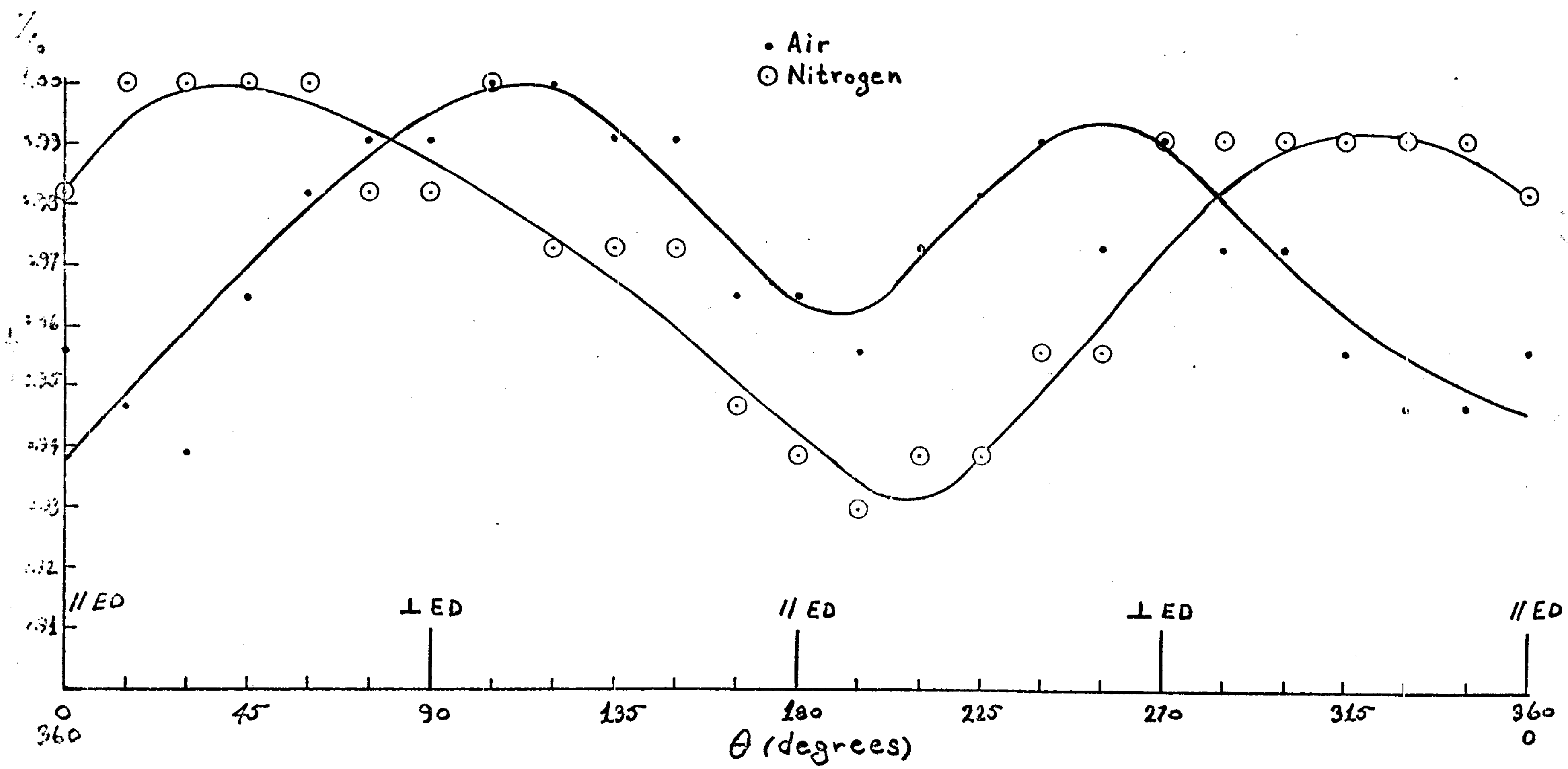
8.2 Shrinkage Test Results

A circle of irradiated thin film having a radius of 5.8 cm. was heat treated at 105°C. for 16.3 hrs. in an unrestrained condition. The test was performed in both air and nitrogen. The distance from the center of the circle to the perimeter of the circle was measured after heat treating at different included angles between direction of measurement and the extrusion direction. The ratio of new dimension to the initial radius $r/_{ro}$ was then plotted as a function of the included angle between measured radius and the extrusion direction. The results are presented in Figure 9. It can be seen that the maximum radial shrinkage, $1-r/_{ro}$, occurs at 0 and 180 degrees, i.e., the direction of extrusion, where $r/_{ro}$ is a minimum. The maximum radial shrinkage observed is only about 7%. In general, the shrinkage of the irradiated film is less than that of the unirradiated film as can be seen by comparing Figure 9 with Figure 10 in the June-August 1965 Quarterly Report, RAI 356.

9 RADIAL SHRINKAGE OF UNRESTRAINED IRRADIATED SUA SPACE FILM UPON ANNEALING

Film thickness: 0.15 mil
Initial radius: 5.8 cm.

Annealing Temperature: 105±2°C.
Annealing Time : 16.3 hrs.
Irradiation : 15 Mrads



Included Angle Between Measured Radius and Extrusion Direction, ∅ (degrees)

APPENDIX

Errata to Quarterly Report, RAI 356, June-August, 1965.

All stress values listed in Tables II, III and IV and Figures 1, 2, 7 and 8 should be twice the listed values.