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MICROWAVE REFLECTIVITY OF DEPOSITED ALUMINUM FILMS FOR PASSIVE RELAY COMMUNICATIONS

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MICROWAVE REFLECTIVITY OF DEPOSITED ALUMINUM FILMS FOR PASSIVE RELAY COMMUNICATIONS

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SUMMARY

Reflectivity measurements from 400 Mc/sec to 10 kMc/sec on 2,200 Å thick aluminum deposited on 1/2-mil-thick Mylar film show this material to be a very good reflector of radio waves. Measurements made under conditions of stress and temperature which would be encountered by a communications sphere, such as Project Echo (1960 Iota), showed very little deterioration of the high reflectivity. Construction seams and packaging effects also caused very little reflectivity change. Under conditions of severe temperature cycling, aluminum removal and decreased reflectivity occurred.

INTRODUCTION

With the concept of a communications satellite such as Project Echo (1960 Iota), the need arose to study the reflective properties of the material used to fabricate the satellite. Reference 1 is a theoretical study and also refers to experimental reflectivity measurements made on aluminum-coated Mylar. The purpose of the work reported here was to find whether the high reflectivity of this material was likely to be reduced in actual use. Therefore, reflectivity was measured in the laboratory under simulated operating conditions. Specifically, it was of concern whether the imposed conditions of temperature and stress might cause deterioration of the satellite reflectivity by cracking, stressing, or otherwise altering the thin aluminum film. Other possible causes of decreased reflectivity investigated were the seams made during construction and the folds made during packaging. In addition, reflectivity was measured for material which had been deliberately partitioned into isolated areas. Conditions for which reflectivity has not been tested are stress and temperature in vacuum and ultraviolet exposure.

SYMBOLS

j	vector operator
l	distance between 6-decibel points
l_x	distance between minimum and 6-decibel points
V_f	voltage forward wave
V_{max}	voltage maximum
V_{min}	voltage minimum
V_r	voltage reflected wave
V_θ	voltage at distance θ from minimum
Z_c	characteristic impedance
Z_r	load impedance
Z_s	space impedance
Z_w	waveguide impedance
Γ	reflectivity
θ	phase angle of forward or reflected wave
λ_c	cutoff wavelength
λ_g	waveguide wavelength
ρ	voltage standing wave ratio

TEST CONDITIONS

All reflectivity measurements were made in waveguides. Frequencies at which tests were made were 0.4, 1.5, 3.0, and 10 kMc/sec. Film samples were inserted perpendicular to the waveguide axis and were contacted on both sides by waveguide flanges. For each setup, a signal generator was coupled to the waveguide with suitable isolation and matching, a slotted line was used to measure the resulting standing wave ratio, and a terminated section was used after the sample to absorb the energy transmitted through the sample. Conditions for the various tests are discussed in subsequent sections.

Frequency

A frequency range of 0.4 to 10 kMc/sec covers the range for most communication experiments. Reflectivity was measured at 0.4, 1.5, 3.0, and 10 kMc/sec to cover this range. Tests were conducted at 0.4 kMc/sec while the samples were being subjected to heat and stress. Since the 0.4 kMc/sec reflectivity values were unaltered by this treatment, the same samples were tested at the remaining frequencies under ambient conditions.

Heat and Stress

It has been estimated (ref. 1) that under the worst conditions the maximum temperature to be expected for a Project Echo sphere is 350° F. The skin stress encountered will depend on the method of inflation but, for the most severe method proposed, peak stresses of less than 2,000 pounds per square inch are expected.

Temperature Cycling

The possibility of mechanically flaking the aluminum surface by contraction and expansion due to temperature cycling was considered. The temperature extremes for an Echo type satellite from sunlight to Earth's shadow are predicted (ref. 1) as -164° F to 350° F. Because of the equipment availability at the time of the tests, the temperature cycling was done between 0° F and 350° F. Two samples were tested; one sample was cycled 44 times and the other 60 times. These samples were temperature-cycled under unilateral spring stress which was set to 3,000 pounds per square inch at room temperature.

Seams

Large conducting films used for space communications would normally be constructed of many segments joined together in some fashion. In the case of the Project Echo sphere the present construction is 82 gores which are 46 inches wide at the "equator" and taper to 36-inch-diameter pole caps. Thus, near the poles the seams are less than 2 inches apart. The gores are joined by butt joints glued to 1-inch-wide strips. The d-c contact of such a joint is poor but at high frequencies the capacity coupling through the strip is high. The calculated capacitive reactance is 0.6 ohm per square inch at 400 Mc/sec for 1/2-mil-thick aluminum-coated Mylar films back to back. The measured d-c resistance of the film is on the order of 1 ohm per square which is a factor of 10 greater than the calculated value based on the bulk resistivity of aluminum.

In order to test experimentally the effect of seams on reflectivity, two samples were obtained with "50-percent-seams." The samples were fabricated by butting the edges of 2-inch-wide strips of film and taping, on the Mylar side, with 1-inch-wide heat-sealing aluminum-coated tape. These samples were tested while the seams were oriented both parallel and perpendicular to the electric field in the waveguide.

Handled Samples

One item of concern was deterioration of reflectivity due to the wear the balloon received during fabrication, folding, packaging, and opening. The aluminum film is noted to develop a network of fine creases as it is handled.

In order to investigate the effects of handling, one sample was subjected to average handling conditions and another sample was handled as severely as any portion of the balloon might conceivably be. These samples were prepared by the personnel who package the balloon and are identified in table I as average and severely handled samples.

Partitioned Samples

To simulate film breakup, aluminum was removed by scribing with an engraving tool to create isolated conducting squares or islands. The scribed lines were approximately 0.0005 inch wide. Samples with $1\frac{1}{2}$- inch, 3-inch, and 6-inch squares were tested at 400 Mc/sec.

EQUIPMENT

Microwave Equipment

Microwave reflectivity setups were made for 0.4, 1.5, 3.0, and 10.0 kMc/sec. Figure 1 shows a typical component arrangement. Figures 2 and 3 are photographs of the 400 Mc/sec and 10 kMc/sec equipment, respectively. A receiver was used to measure the output of the slotted line in order to increase sensitivity. The receiver also acted as a narrow band detector eliminating harmonics and spurious modes. The 400 Mc/sec waveguide equipment is further described in appendix I.

Heating Equipment

It was desired to heat the film uniformly to 350° F temperature over the cross-sectional area of the 400 Mc/sec circular waveguide (21-inch diameter) while the film was stressed and undergoing reflectivity measurements. This heating was accomplished by electrically heating the waveguide sections on both sides of the film. A 4-foot diameter by 1/4-inch aluminum "back-up plate" which contacted the film outside the guide was also heated to minimize thermal gradients at the waveguide circumference. One-half-mil Mylar diaphragms (uncoated) at either end of the heated sections blocked convective heat flow and caused no noticeable reflections.

The waveguide sections were first wrapped with glass tape and then with nichrome wire in fiber glass sleeving. A number of layers of asbestos were added for heat insulation. A maximum power input of 7,200 watts was used which could bring the film up to 350° F in $1\frac{1}{2}$ hours.

Stress Equipment

A method of simulating the skin stress of the fully inflated balloon was desired. Air pressure methods were rejected because a flat film surface was needed. A method of stretching the film uniformly in all directions in the plane of the film was approximated by cutting the samples in the form of Greek crosses and loading the outer edges uniformly in the plane of the film.

The details of the stress apparatus and film mounting are shown in figure 4. Note that the images appearing on the film are reflections of objects in the foreground.

Temperature-Cycling Equipment

Simulation of temperature-cycling conditions for the Project Echo sphere could not be duplicated with available equipment. The temperature-cycling tests which were conducted are considered to be more severe because of higher heating rates and liquid immersion even though the temperature range is lower.

The temperature-cycling equipment consisted of a 350° F glycerine bath and a 0° F alcohol bath. Film samples 7 inches by 31 inches were stretched over 1/2-inch-diameter rollers on an aluminum jig and held in tension by an adjustable spring. The samples were alternately submerged in the 350° F bath and the 0° F bath with a rinse in room temperature water between each dip. The time in each bath was approximately 20 seconds. The dimensions of the temperature-cycling baths made it impractical to obtain a sample large enough to be inserted in the 400 Mc/sec waveguide.

DISCUSSION

Methods of Measurements

The reflectivity is determined by measuring the voltage standing wave ratio ρ resulting when a sample is inserted in a waveguide. (See refs. 2 and 3.) Before the sample is inserted, the energy transmitted from the generator is absorbed at a reflectionless termination. After the sample is inserted, some energy passes through and is absorbed at the termination while some is reflected at the film; thus, a standing wave is set up between the generator and sample. The voltage standing wave ratio ρ is defined as the ratio of maximum voltage to minimum voltage (field) along the waveguide.

$$\rho = \frac{V_{max}}{V_{min}}$$

The reflected wave V_r adds to the forward wave V_f at the maximum and subtracts at the minimum. The reflectivity Γ is defined as the fraction of the forward wave reflected; that is, $V_r = \Gamma V_f$, from which it can be shown that

$$|\Gamma| = \frac{\rho - 1}{\rho + 1}$$

The reflectivity is related to the characteristic impedance of the medium Z_c in which it is measured by

$$\Gamma = \frac{Z_r - Z_c}{Z_r + Z_c}$$

where Z_r is the impedance of the material in parallel with the medium behind it. When the waveguide reflectivity is corrected to free space, Γ becomes

$$|\Gamma| = \frac{\rho - 1}{\rho + 2\frac{Z_w}{Z_s} - 1}$$

where Z_w/Z_s is the ratio of waveguide to free-space impedance and the film impedance is purely resistive.

For large values of $\rho(\rho > 10)$, the "twice minimum power" method is often used to determine Γ. This method involves measuring the distance on either side of the minimum at which the power is twice that at the minimum. Because of the very small distances at the high voltage standing wave ratio encountered, a method has been devised to determine ρ for the distance at four times the minimum power. This measurement is called the "six-decibel method." A derivation is given in appendix II which shows that, for small displacements,

$$\rho = \frac{\sqrt{3}\lambda_g}{\pi l}$$

where λ_g is twice the distance between adjacent minima and l is the distance between 6-decibel points above the minimum.

Accuracy of Measurements

The accuracy of measurement depends on the accuracy with which the probe movement and signal level change are measured and on the inherent limitations of the method. The signal level change is measured within 0.2 decibel which gives less than a 0.1-percent change in reflectivity above 98 percent. The probe displacement is measured within 0.02 centimeter. The resulting accuracy depends on frequency, being less than 0.1 percent at 400 Mc/sec and within 0.7 percent up to 3 kMc/sec. At 10 kMc/sec, however, the required probe displacement for measuring 97-percent reflectivity is on the same order as the vernier accuracy. Where this limitation applies, the values are given as greater than 97 percent.

The real limit to the accuracy of the measurements below 10 kMc/sec is the inherent limitations of the method, that is, probe penetration variation, probe perturbation of field, waveguide nonuniformity, and so forth. It is estimated that the absolute values are good to 1 percent and comparative values are accurate to within 0.2 percent at 400 Mc/sec, 0.4 percent at 1.5 kMc/sec, and 0.7 percent at 3 kMc/sec.

RESULTS

Reflectivity of the samples as a function of frequency is given in table I. The measurements at 10 kMc/sec, as previously discussed, are given as greater than 97 percent without comparison between samples except for the temperature-cycled samples. The 400 Mc/sec tests were conducted while stress and temperature were being imposed.

Stress

Reflectivity at 400 Mc/sec was measured as a function of stress up to stress values of 4,000 pounds per square inch. The variation found (99.1-percent to 99.2-percent reflectivity) was within the experimental error. From a number of tests a slight trend was noticed for higher reflectivity values under stress but it was felt that even this small change was due to removal of wrinkles and better waveguide contact rather than to a material reflectivity change.

Heating With Stress

Film samples were cycled several times at temperatures up to 365° F without altering the reflectivity at 400 Mc/sec. The skin stress was also varied up to 1,600 pounds per square inch with the film at elevated temperatures without causing a change.

Temperature Cycling

Figure 5 shows a back-lighted photograph of a sample temperature cycled 60 times. It is seen that, for the conditions under which these tests were made, considerable aluminum removal occurred. Reflectivity values between 82 percent and 94 percent were found for areas with average aluminum removal.

For areas of the film as small as the cross-sectional area of the 10 kMc/sec waveguide, wide variations in the amount of aluminum removed could be found; therefore, the 10 kMc/sec measurements were influenced by the area of the film chosen. The 10 kMc/sec values given in table I were for areas which were judged to be average. These films were also checked at the best and worst spots and these results are given in table II. The average and best conditions were reasonably high but areas could be found that gave low reflectivity.

The results of these tests indicate that random removal of aluminum such as shown in figure 5 does not severely decrease the reflectivity. This type of reflection is analagous to that obtained by using a wire mesh for a ground plane and is in contrast to partitioned sample results where a small amount of aluminum removal resulted in nonconnected areas and low reflectivity. These results also show that micrometeoroid damage should not greatly reduce the reflectivity.

It should be emphasized that the heat-cycling tests reported here are not representative of actual space conditions and do not imply that the aluminum film will deteriorate in the same manner when temperature cycled in space.

Seams

The conducting backup strip used in seam fabrication is capacity coupled through the Mylar film to both gores forming the seam. Thus, even if the gores do not touch, good electrical contact should prevail at radio frequencies. If the seams are oriented so that current is not required to flow across them, their presence should not be felt.

Two samples, made with seams as described previously, were each tested with the seams parallel and perpendicular to the electric field. These results are given in table I which shows the reflectivity to be greater than 97 percent. A small but consistent difference was noted between parallel and perpendicular orientation, the reflectivity for the perpendicular orientation being lower as would be expected because of current flow patterns.

Handled Samples

The handled-sample measurements are certainly subjective tests but the values of greater than 97 percent found for even the severely handled samples indicate that the handling received during packaging of the Echo balloons should cause no serious reflectivity decrease.

Partitioned Samples

The consistent high reflectivity values of all samples except those temperature cycled led to an experiment to test the idea that partitioning or breaking up the conducting film into islands would decrease the reflectivity. Such was found to be the case as shown in table III.

These results indicated that breaking up the film into nonconnected areas separated by approximately 0.0005-inch gaps does cause reflectivity deterioration and that the reflectivity decreases as the island size decreases.

CONCLUDING REMARKS

Reflectivity measurements were made from 400 Mc/sec to 10 kMc/sec on 2,200 Å thick aluminum deposited on 1/2-mil-thick Mylar film. High reflectivity values were found for all simulated-use conditions tested. Stress up to 4,000 pounds per square inch, temperatures up to 365° F, handling of the material in a manner judged to simulate the most severe packaging conditions, and tests of samples containing a large number of seams gave reflectivity readings above 97 percent. Temperature cycling in liquid baths caused lower reflectivity but the average values were still above 82 percent.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., November 23, 1960.

APPENDIX I

400 Mc/sec EQUIPMENT

The 400 Mc/sec waveguide components were designed for this specific project and are briefly discussed here. Figure 1 shows the component arrangement.

Waveguide

Circular waveguide was chosen for ease of fabrication. A diameter of 21 inches was chosen to propagate only the fundamental mode $TE_{1,1}$. (See ref. 4.) The waveguide was rolled from 0.032-inch aluminum and resistance welded. Each section was 4 feet long with an inside diameter of 21 ± 1/16 inches. Cover flanges were made from 1/4-inch aluminum plate. Mating sections were bolted together and the inside joints ground to match.

Slotted Line

The slotted-line section was rolled from 1/4-inch-thick aluminum and was also 4 feet long. One-half-inch-square aluminum bars were fastened on either side of a 1/4-inch-wide slot running to within $1\frac{1}{2}$ inches of either end of the section. This construction provided a very rigid base for the probe carriage.

Probe Carriage

The probe carriage was machined from a block of brass $2\frac{1}{4}$ inches by 4 inches by $1\frac{1}{2}$ inches. This rather massive type of construction of probe carriage (and slotted-line section) gave smooth reliable readings and was found to be superior to an early model of lighter construction. Crystal detector and radio frequency output connectors were provided. The probe depth adjustment and electrical output design of the carriage borrow very liberally from the design of the General Radio type 874-LBA slotted line.

Termination

The termination was a cone of microwave absorbent material attached to a plexiglass frame. This cone was 54 inches long with a base diameter (21 inches) to fit the waveguide. The base was attached to an aluminum plate which closed the end of the waveguide. The standing wave ratio for this termination was 1.06.

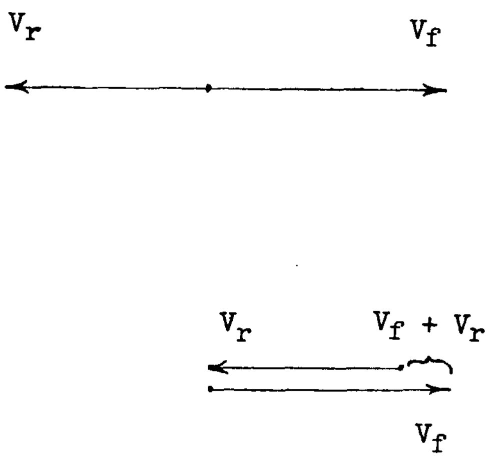
Coaxial Cable to Waveguide Adaptor

A transverse electric $\left(TE_{1,1}\right)$ mode excitation was made by extending an antenna across the diameter of a waveguide section. The signal was introduced at one end of the antenna and a shorting stub was used on the other end to balance out the reactive component. A sliding end plate was provided to adjust the radiation resistance.

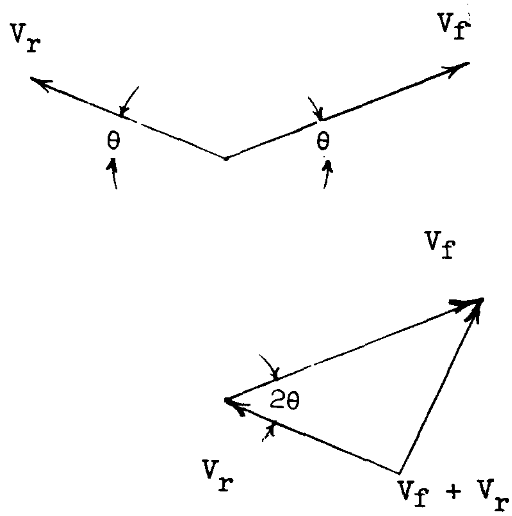
APPENDIX II

SIX-DECIBEL METHOD OF VOLTAGE STANDING WAVE RATIO MEASUREMENT

It is desired to determine the probe displacement from the minimum at which the voltage is twice that at the minimum (double voltage gives four times the power or 6 decibels). The vector sketch illustrates the relation between forward (V_f) and reflected (V_r) waves and their vector sums.



(a) At minimum condition



(b) At an electrical distance θ

At the minimum,

$$V_{min} = V_f + V_r = V_f - \Gamma V_f = V_f(1 - \Gamma)$$

At a distance θ radians,

$$V_\theta = V_f(\cos\theta + j\sin\theta) + \Gamma V_f(-\cos\theta + j\sin\theta)$$

$$V_\theta = V_f\left[(1 - \Gamma)\cos\theta + j(1 + \Gamma)\sin\theta\right]$$

For the magnitude of V_θ to be twice the magnitude of V_{min}.

$$|2V_{min}| = |V_\theta|$$

Substituting V_{min} and V_θ from these equations and simplifying yields the following relations:

$$\left|2V_f(1 - \Gamma)\right| = \left|V_f\left[(1 - \Gamma)\cos\theta + j(1 + \Gamma)\sin\theta\right]\right|$$

$$|2| = \left|\cos\theta + j\,\frac{1 + \Gamma}{1 - \Gamma}\sin\theta\right|$$

$$|2| = |\cos\theta + j\rho\sin\theta|$$

$$2 = \sqrt{\cos^2\theta + \rho^2\sin^2\theta}$$

$$4 = 1 - \sin^2\theta + \rho^2\sin^2\theta$$

$$3 = \left(\rho^2 - 1\right)\sin^2\theta$$

Solving for ρ^2 yields

$$\rho^2 = \frac{3 + \sin^2\theta}{\sin^2\theta}$$

Expressing in terms of distance rather than radians,

$$\theta = \frac{2\pi l_x}{\lambda_g}$$

where

λ_g guide wavelength

l_x distance from minimum to 6-decibel points

$$\rho = \sqrt{\frac{3 + \sin^2\dfrac{2\pi l_x}{\lambda_g}}{\sin^2\dfrac{2\pi l_x}{\lambda_g}}}$$

This expression can be simplified for the case of small displacements since

$$3 + \sin^2 \frac{2\pi l_x}{\lambda_g} \approx 3$$

and

$$\sin^2 \frac{2\pi l_x}{\lambda_g} \approx \left(\frac{2\pi l_x}{\lambda_g}\right)^2$$

from which

$$\rho \approx \frac{\sqrt{3}\lambda_g}{2\pi l_x}$$

Since the distance l is measured between the 6-decibel points,

$$l = 2l_x$$

and

$$\rho \approx \frac{\sqrt{3}\lambda_g}{\pi l}$$

REFERENCES

1. Wood, George P., and Carter, Arlen F.: Predicted Characteristics of an Inflatable Aluminized-Plastic Spherical Earth Satellite With Regard to Temperature, Visibility, Reflection of Radar Waves, and Protection From Ultraviolet Radiation. NASA TN D-115, 1959.

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3. Purcell, E. M.: Measurements of Standing Waves. Technique of Microwave Measurements, Carol G. Montgomery, ed., McGraw-Hill Book Co., Inc., 1947, pp. 473-512.

4. Anon.: Reference Data for Radio Engineers. Fourth ed., International Telephone and Telegraph Corp., c.1956.

TABLE I.- REFLECTIVITY MEASUREMENTS

Sample	Reflectivity, percent			
	0.4 kMc/sec	1.5 kMc/sec	3.0 kMc/sec	10 kMc/sec
Plain film	*99.2	99.0	99.0	>97
Seams:				
Seams perpendicular to electric field	98.8	98.2	97.8	>97
Seams parallel to electric field	99.2	98.2	98.5	>97
Controlled handling:				
Severe	98.6	98.2	98.2	>97
Average	99.2	98.6	98.5	>97
Temperature cycled:				
Sample 1 (44 cycles)	----	89	90	94
Sample 2 (60 cycles)	----	87	82	94

*Under various conditions of stress and temperature.

TABLE II.- REFLECTIVITY OF TEMPERATURE-CYCLED FILM AT 10 kMc/sec

Condition of film section tested	Reflectivity, percent	
	Sample 1	Sample 2
Greatest aluminum removal	77	33
Average aluminum removal	94	94
Least aluminum removal	95	95

TABLE III.- REFLECTIVITY OF PARTITIONED FILM AT 400 Mc/sec

Sample	Reflectivity, percent
$1\frac{1}{2}$- inch squares	61
3-inch squares	64
6-inch squares	89

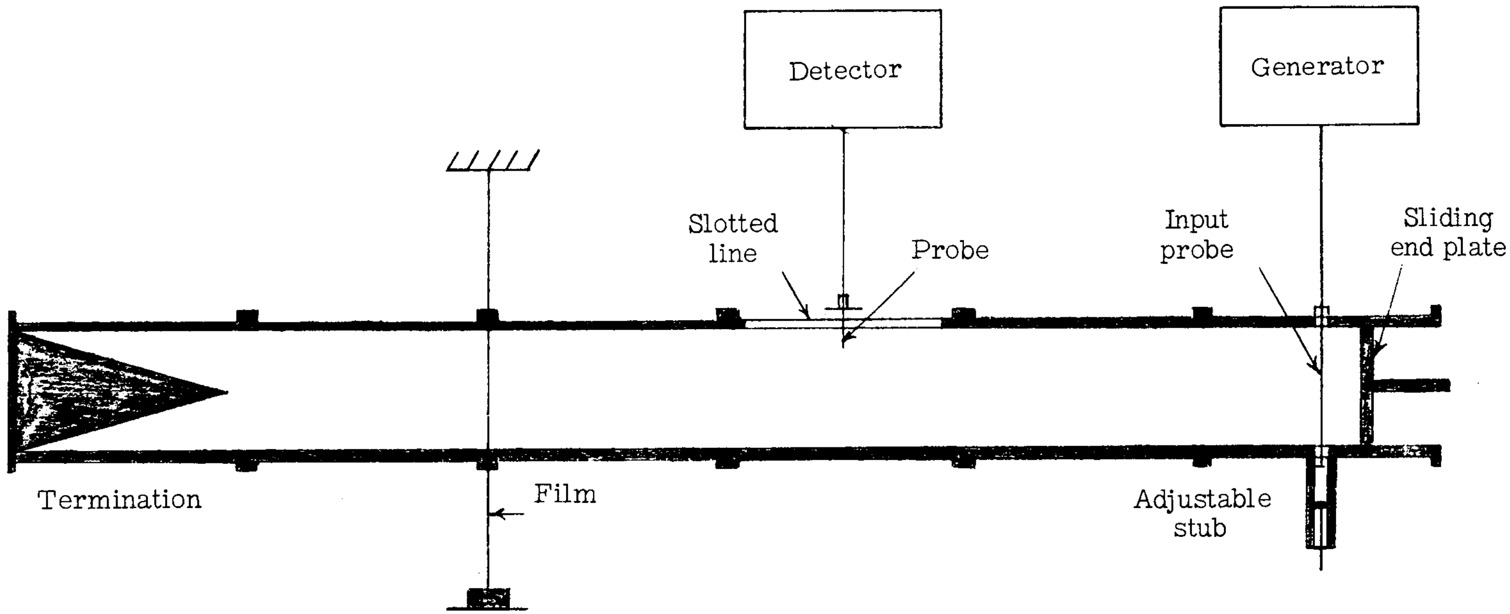

Figure 1.- Diagram of 400 Mc setup.

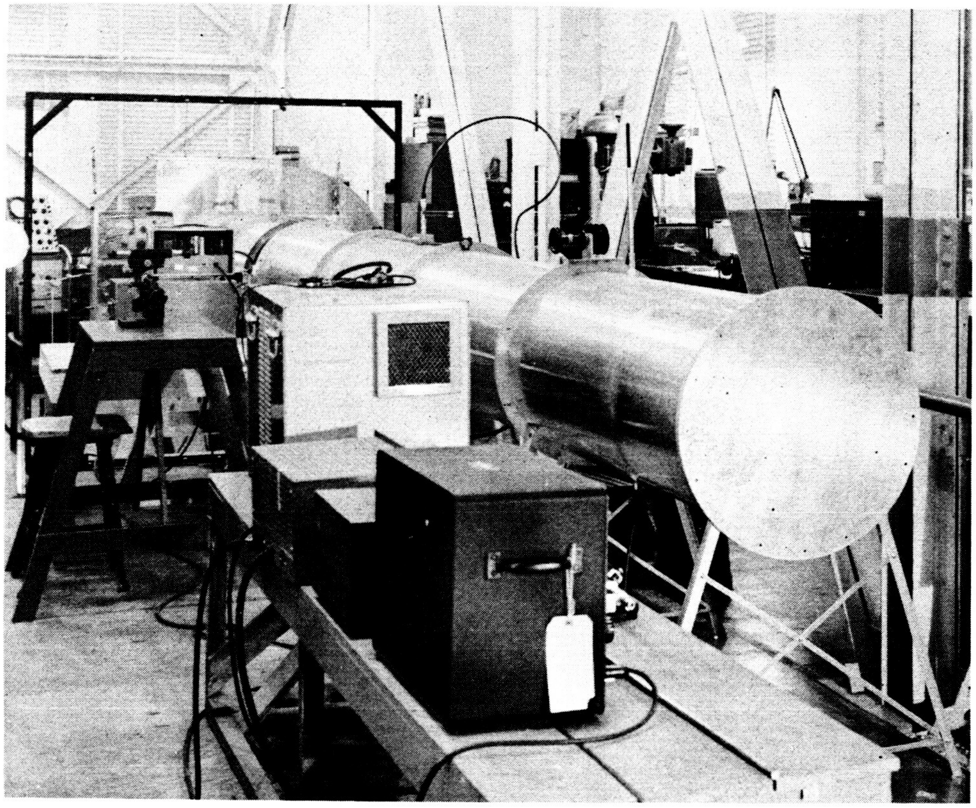

Figure 2.- Photograph of 400 Mc setup. L-60-42

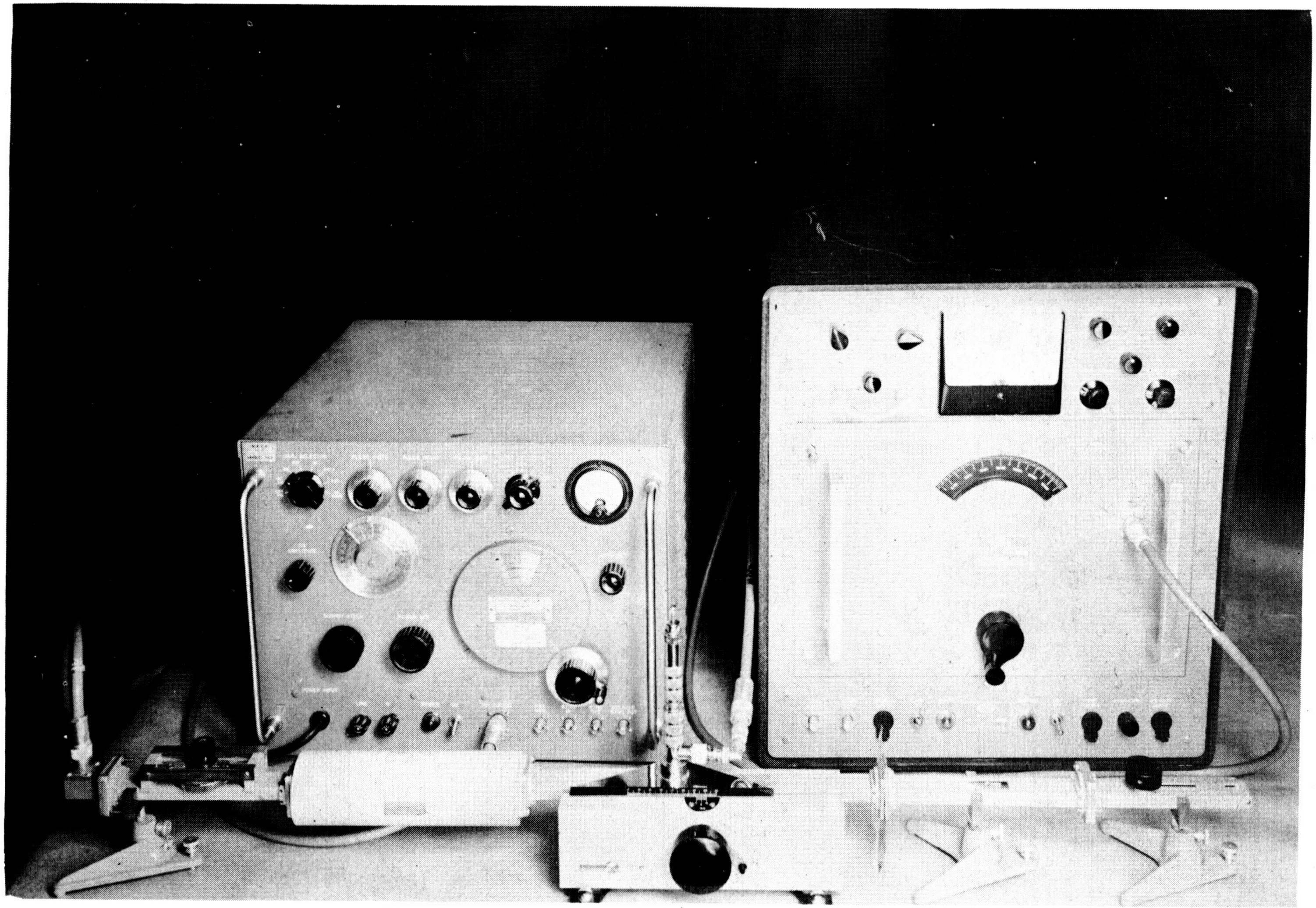

Figure 3.- Photograph of 10 kMc setup. L-60-7284

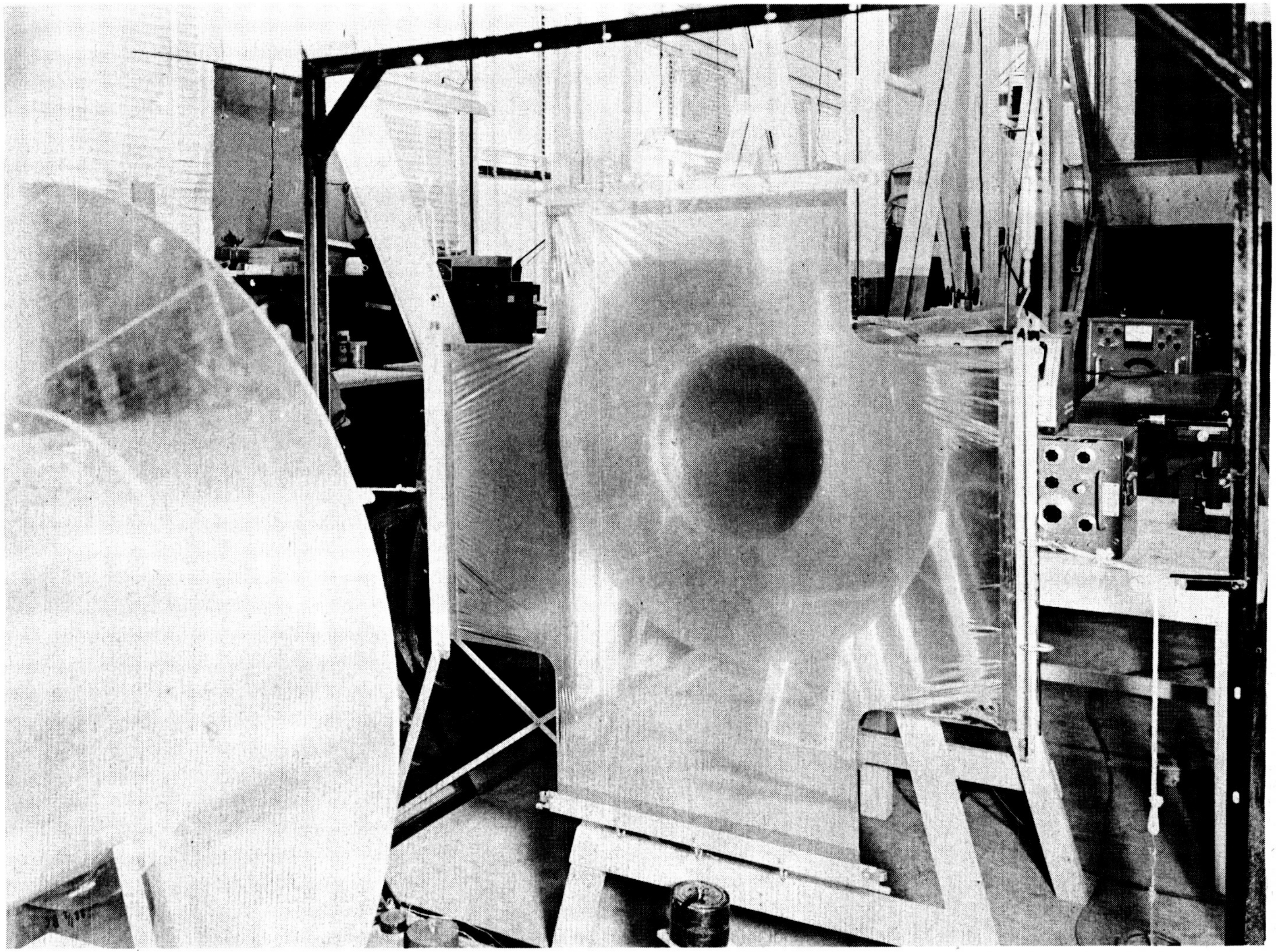

Figure 4.- Photograph of stress rack. L-60-45.1

L-60-6951

Figure 5.- Back-lighted photograph of temperature-cycled film. Full scale.