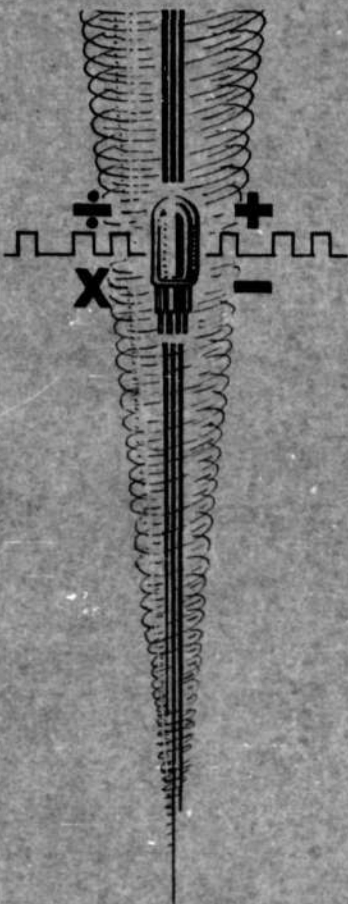


PROJECT WHIRLWIND

Contract N5ori60

SUMMARY REPORT NO. 2

VOLUME 10

STORAGE TUBES
(PART II)

SERVOMECHANISMS LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Copy 30

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH

SPECIAL DEVICES CENTER

PROJECT WHIRLWIND
Summary Report No. 2
November, 1947

STORAGE TUBES, PART II

Volume 10 of 22 Volumes

Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

CONTENTS

INTRODUCTION

Electrostatic storage tubes have been selected for the high-speed internal memory of the Whirlwind computers. The tubes are of the deflection type where a cathode ray beam writes on a dielectric surface. Both plus and minus signals are read out of the tubes representing the digits 0 and 1. Signals are stored permanently and are maintained by a holding gun.

The present tube status now lies between the research and the development phases. Large output signals of about 0.1 volts for a reading time of 3 microseconds has been obtained. Signal-to-noise ratio in most cases is excellent. The spacing between stored charges is good but should be reduced somewhat. Changes in gun current, the dielectric thickness, and the secondary emitting material should be made to reduce the writing time from the present 20 to 60 microseconds. Better independence of control on stored charges is desirable and techniques seem available for achieving independent control.

One tube has recently been tested which would store 12 data points in a three-quarter inch diameter circle. Tests on tube life and the life of secondary emitting surfaces are under way, but results have not yet been obtained.

Volume 9, M-159, summarizes the storage tube program to date. Memorandum M-130 discusses some results obtained on one of the first complete storage tubes. Better operation has been obtained with more recent models.

In R-110 is the storage tube presentation to the Harvard Computation Symposium in January 1947. The objectives outlined there still seem reasonable. The use of low energy electrons from a holding gun was discussed and this feature has been tested in trial tubes.

Volume 9, M-130, shows the division of staff time in the storage tube work. Test equipment is included in Volume 19. Much time has been devoted to vacuum tube techniques, some of which are discussed in Volume 9, M-159, M-112, and M-46. Some studies with an electrolytic plotting tank are reported in Volume 9, M-56 and R-130.

The study of aluminum oxide as a dielectric and preparation of satisfactory surfaces is discussed in the work by Macdonald, Volume 10, R-131 and R-128.

Deflection circuits for electrostatic tubes have been proven feasible. Deflection circuits and power amplifiers are reported in Volume 10, E-32, E-31 and R-120.

REFERENCE INDEX

M Series Memorandums

REF.	VOL.	REF.	VOL.	REF.	VOL.
M-32	8	M-95	8	M-133	18
M-46	9	M-96	9	M-134	7
M-56	9	M-99	15	M-135	7
M-58	15	M-100	8	M-136	7
M-61	8	M-101	11	M-137	7
M-62	4	M-103	16	M-138	15
M-63	4	M-105	19	M-140	4
M-64	4	M-106	11	M-141	7
M-65	14	M-107	19	M-142	8
M-66	4	M-109	16	M-143	9
M-68	15	M-110	15	M-144	10
M-69	4	M-111	7	M-145	11
M-71	8	M-112	9	M-146	12
M-72	16	M-113	7	M-147	13
M-74	14	M-114	19	M-148	14
M-76	4	M-116	16	M-149	15
M-77	15	M-117	7	M-150	16
M-78	8	M-118	16	M-151	17
M-80	16	M-119	16	M-152	18
M-81	16	M-121	9	M-153	19
M-82	16	M-123	7	M-154	20
M-83	16	M-124	8	M-155	21
M-85	14	M-127	7	M-156	22
M-89	11	M-128	16	M-157	11
M-91	15	M-129	7	M-158	7
M-92	15	M-130	9	M-159	9
M-94	8	M-131	16	M-160	8
		M-132	16	M-161	7

REFERENCE INDEX

E Series Memorandums

C Series Memorandum

REFERENCE INDEX

R Series Memorandums

REF.	VOL.	REF.	VOL.
R-36	14	R-115	4
R-49	14	R-116	4
R-63	14	R-117	16
R-64	3	R-118	16
R-89	19	R-120	10
R-90	4	R-121	19
R-94	14	R-122	18
R-98	14	R-123	17
R-100	14	R-124	11
R-103	14	R-125	14
R-104	16	R-126	19
R-106	15	R-127	5
R-108	15	R-127	6
R-109	19	R-128	10
R-110	9	R-129	12
R-111	15	R-130	9
R-113	15	R-131	10
R-114	8	R-132	10

Project Whirlwind
Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts.

SUBJECT: THE PHYSICAL CHARACTERISTICS OF ALUMINUM OXIDE DIELECTRIC LAYERS

Written by: J. Ross Macdonald

Date: September 23, 1947

Summary

The anodization of aluminum is an electrolytic process whereby the outer surface of an aluminum article is converted to a non-conducting aluminum oxide layer. Anodization is carried out in an acid bath.

First, measuring techniques are described for determining the following properties of anodized aluminum oxide dielectric films: thickness, resistivity, breakdown field strength, and dielectric constant.

The bulk of the report describes the application of the above-mentioned measuring techniques to dielectric films formed under a variety of anodizing conditions. Preliminary measurements of resistivity were made in an evacuated desiccator. Later measurements were made on 15 anodized samples sealed in highly evacuated glass envelopes. Silver paint and paste were used to secure electrical contact to the outside of these oxidized samples, and it was found that silver paste penetrated substantially down into the pores of the oxide layer, while the penetration of silver paint particles did not seem to be appreciable.

Measurements of thickness as a function of anodizing time and anodizing conditions are presented in 12 graphs. Variations of both temperature and acid concentration, and anodizing current and voltage were investigated separately to determine an anodizing procedure which would yield an adequately hard and thick oxide film. It was finally found that a hard layer at least five mils thick could be formed by anodizing at a bath concentration of 3% oxalic acid, at a temperature of 24°C or less, and at a constant voltage of 80 volts d-c, for eight hours.

The results of the foregoing measurements indicated that a thick dielectric film having quite adequate mechanical and electrical properties for griddle surface use could be formed by anodizing for eight hours or more at a constant voltage of 80 volts, a bath concentration of 3% oxalic acid, and a temperature of 24°C. Indications are that an even harder film can be formed at lower anodizing temperatures. It is therefore suggested that further growth curves by plotted of film formation at low temperatures for a variety of bath concentration, temperature, voltage, and (low) current density conditions in order to determine an anodizing procedure which will produce films with optimum electrical and mechanical characteristics.

It was not found possible to anodize completely through griddle structure walls (rectangular) 10 mils thick in 14 hours of anodization under the above conditions, however. It would seem that this difficulty could be overcome by employing tapering walls.

Description of Measuring Techniques

In order to properly evaluate anodized aluminum dielectric layers, it was felt desirable to measure the following characteristics of the film:

a. thickness
b. resistivity
c. breakdown strength
d. dielectric constant

Figure 1 shows a picture of the apparatus used to determine the resistivity of an anodized layer. Essentially, the method used depends upon measuring the resistance between a given area on the outer surface of the anodized layer and the inside metal. Preliminary measurements were made between a drop of mercury resting on the dielectric surface and the inner metal. The mercury was held by a containing ring so that only a surface area, A, of 0.39 centimeters^2 rested on the anodized layer. Because there was a strong force of electrostatic attraction between mercury and metal when voltage differences greater than 200 volts were applied, the mercury drop flattened out somewhat as the applied voltage was increased. This phenomenon made it impossible to determine the size of the mercury contact area very accurately. The resistivity, ρ, itself is computed from the formula: $\rho = \frac{A}{d}R$, where R is the resistance measured between the conductor of area A, through the film of thickness d, to the inner metal; therefore errors in the determination of A contribute to the inaccuracy of ρ. In addition, this formula does not account for the edge effect present under these experimental conditions. These effects both cause the computed value of ρ to be less than the actual value, but the total error in ρ, including inaccuracies in determining R, is probably less than 25 percent. This accuracy is quite adequate for general evaluation of the oxide surfaces. In some of the later measurements, the contact area was determined much more accurately by coating a known area of the anodized film with conducting silver paint or paste. Considerably larger areas were used, giving both a better average value of the resistivity and less error due to edge effect. Because the resistance to be measured was usually in the range from 10^8 to 10^{13} ohms, it was necessary to use a more refined circuit than an ordinary ohmeter for its measurements. Also, it was desired to measure the resistance as a function of voltage applied across the dielectric layer. Therefore, the circuit shown in Fig. 2 was employed. The voltage V_0 was supplied from a high-voltage rectifier, variable from 0 to 1300 volts. R_1 was usually either a 100, 1000, or 10,000 megohm resistor, depending upon the resistance being measured. The voltage across R_1 was measured with a Measurements Corporation Electronic Voltmeter, Model 62 (shown at the right of Fig. 1), having an input resistance, R_m, of approximately 10^{10} ohms. The resistance of the sample, R_s, at any given applied voltage, v_o, is then:

$$R_s = \left[\frac{V_o - V_1}{V_1}\right] \left[\frac{R_1 \times R_m}{R_1 + R_m}\right]$$

and the actual voltage applied to the sample, V_s, is $(V_o - V_1)$. For values of R_1 less than or equal to 10^9 ohms, the effect of R_m is negligible, so that the equation may be rewritten:

$$R_s = (V_o/V_s - 1)\ R_1.$$

In measuring samples of very high resistance where it was necessary to use $R_1 = 10^{10}$ ohms, the more accurate formula with $R_m = 10^{10}$ ohms was employed. This value of R_m was determined by substituting a known value of resistance for R_s. The value of R_m thus obtained was not very accurate but was still adequate to allow comparative readings to be made. Finally, because of the extremely high grid resistance path of the meter through R_1 when R_1 was equal to or greater than 10^9 ohms, it was found that the meter would block for voltage readings greater than about 50 volts. This is not an important disadvantage, however, since V_1 could be kept less than 50 volts for any values of V_o and R_s by using different values of R_1.

In order to determine both the resistivity and dielectric constant of the oxide film, it was necessary to know the film thickness, d. This quantity was found by measuring the total thickness of a flat sample in several places, both before and after the anodized layer had been removed. Since the film covered both sides of such a sample, the average value of the film thickness was one half the average of the differences between the two sets of measurements. Because the anodizing process has a very high "throwing" power, there was little reason to believe that the layers on separate sides of a given sample should differ in thickness appreciably. Nor was any significant difference in film thickness at different points on a flat sample detected with the micrometer.

With a conducting layer on top of the anodized surface secured by the same methods as employed in the resistance measurements, the capacitance between this layer and the inner metal was measured with a Boonton "Q" Meter Type 160-A (shown at the left of Fig. 1). The frequency at which most capacitance measurements were made was one megacycle. The capacitance and thickness of the film being known, the dielectric constant, K, could then be computed from the formula: $K = Cd/0.0885A$, where d and A must be expressed in centimeter units, and the capacitance, C, is in micromicrofarads. Again, this method of measurement and this formula take no account of the edge effect. In this case, however, the edge effect causes the computed value of the dielectric constant to be somewhat larger than the actual value, in contradistinction to the effect it has upon the computed value of the resistivity.

There have been shown to be several errors in the methods used to determine resistivity and dielectric constant. Although the errors render these procedures unsuited for accurate determinations of these physical quantities, their presence is not serious for the application to which the measurement techniques were applied. It was desired to obtain comparative data on samples anodized under different conditions, so that the dielectric and mechanical properties of the oxide layers could be assessed and the anodizing conditions thereby optimized. These measurements, therefore, did not require more than a fair degree of relative accuracy. Finally, although it was desired to establish the absolute ranges of the variables measured to determine the possibility of using aluminum oxide as a dielectric storage surface, great accuracy of measurement was not necessary for the adequate evaluation of this possibility.

General Characteristics of the Anodizing Process and of Aluminum Oxide Layers

The exact mechanism of the formation of an oxide coating on aluminum during anodization is not yet fully understood.* Anodization is possible only in electrolytes in which an oxygen-containing anion is present; yet the growth of the film does not satisfy Faraday's electrolytic law. This anomalous behavior is largely caused by two effects. First, not all the nascent oxygen discharged at the anode combines with the aluminum to form aluminum oxide; instead, four or five percent of the oxygen remains uncombined. Second, the oxide film is partially dissolved during anodization by the acid action of the electrolyte. These two effects cause the film to grow more slowly than indicated by Faraday's law.

The oxide layer formed is amorphous aluminum oxide, or alumina. Probably aluminum hydroxide is formed first but it dehydrates with continuing electrolysis and becomes porous aluminum oxide. The actual film formation takes place at a very thin barrier layer of oxide at the base of the pores. In this type of formation, pores are necessary to carry the oxygen ions to the metal-oxide interface, and hence presence of the pores is essential to continued growth of the film. However, the pores are usually less than 0.1 micron in diameter and there are more than a million of them in each square centimeter of surface. The common axis of orientation of the pores runs approximately perpendicular to the surface of the metal.

The appearance of oxide layers formed in oxalic acid depends primarily upon the current density employed during formation and the time of formation. At a constant current density of 46 amperes/foot^2, the layer is a straw brown after 15 minutes; as the anodization continues, the color deepens and turns gray-green. Finally, after an hour or more of anodization, the film becomes completely white. Striking changes in the physical character of the surface are also to be noted during the anodization. At first, the surface is very hard and can scarcely be scratched with a knife. However, by the time the color has become white, the surface is relatively soft and powdery. After two hours of anodization at 46 amperes/foot^2, white powder can even by rubbed off the surface with the finger.

---

* Refs. 1, 2.

This excessive softness is an undesirable characteristic for a griddle surface, since the walls of the griddle structure, if anodized all the way through, would not be mechanically rigid and might crumble. All preliminary measurements of oxide layers were made on layers formed at 46 amperes/foot^2 in order to assess the dielectric properties of the relatively thick oxide films which could be formed at this current density. However, after these properties were found to be adequate for a griddle surface, it became desirable to develop a method whereby not only thick films could be formed but also the hardness and rigidity of the oxide layer could be preserved throughout the anodizing process. Therefore, the anodizing variables, such as temperature, current density, and acid concentration, were varied in an effort to form a surface having both good dielectric characteristics and maximum hardness.

Results of Preliminary Measurements

Preliminary measurements were made on eight spade-shaped samples having a spade portion two inches long by one and a half inches wide, all cut from a single sheet of 1/16th-inch 2S aluminum. All of these samples were anodized for one hour at a current density of 46 amperes/foot^2 and a temperature of 24°C in accordance with Reference 1. In order to determine the effects of pore sealing upon the electrical characteristics of the films, two samples were sealed by boiling in distilled water, and two by the electrolytic process described in References 3 and 4 and 5.

Measurements on these samples were first begun in air with a mercury drop used to secure contact. However, it was found that because of the porous structure of the samples, moisture could not be eliminated and low resistance and erratic results were obtained. Therefore, the measurements were made in a large desiccator exhausted to a pressure of about 10^{-2} millimeters of mercury by a mechanical force pump. It was still found, however, that it was necessary both to heat the samples with an infrared heat lamp before exhausting the desiccator and to allow them to remain in a vacuum overnight to obtain reproducible results. Also, it was necessary to wait about a half-hour after voltage was applied to the samples during resistance measurements before polarization currents became negligible and the true resistance could be measured.

Figure 3 shows representative curves for the resistivity of the variously treated samples computed from resistance measurements made according to the above procedure. From these curves it can be concluded that electrolytic sealing decreases the resistivity of an anodized sample by a factor of about ten, while boiling reduces the resistivity about a thousand times. Evidently the removal of most of the air did not remove the moisture from the boiled samples, since their resistivity remained practically unchanged when they were put in a vacuum. Both pore-sealing methods seemed to increase the hardness of the samples somewhat but only at the expense of a substantial decrease in resistivity. Since the resistivity of the unsealed samples was in the range of 10^{13} to 10^{14} ohm-centimeters, this characteristic of the oxide layer seemed adequate for griddle surface use.

However, there is no justification to the assumption that the procedure which was followed removed all the moisture from the pores of the electrolytically sealed and unsealed samples. Nor does this treatment approximate that which is used to remove the occluded gas from an electronic tube preparatory to sealing off. Since an actual storage surface used in a storage tube must undergo the latter process, resistance measurements should ideally be made on samples so treated. This treatment involves heating the metal elements of the tube to a temperature of 400 to 500°C with radio-frequency current and evacuation to a pressure of 10^{-6} millimeters of mercury or better. In the succeeding resistance tests it was therefore decided to subject the samples to this treatment and to seal each one off in a small glass envelope while the inside pressure was maintained below 10^{-6} millimeters. In order to make resistance tests, contact was secured to the outside of each sample by covering a given area with a conducting paint or paste.

Breakdown tests were also made on the eight preliminary samples using the mercury-drop top contact. It was first attempted to make these tests in a vacuum, but it was found that the lead-in wires in the desiccator would flash over for applied voltages in excess of 500 volts. Since it was not possible to evacuate the container enough so that higher voltages could be applied, the breakdown tests were made in air. It was found that none of the samples would break down at 1300 volts, the limit of the power supply used. Since the thickness of all of these samples was measured to be about 0.0026 inches, the breakdown strength was thus greater than

$$\frac{1300}{0.0026}\ \text{volts/inch} = 5 \times 10^{5}\ \text{volts/inch}$$

Since this value is more than adequate for storage tube operation, the breakdown characteristics of the samples were not investigated further in these preliminary measurements.

Capacitance measurements were also made on these eight samples. It was found that ageing in a vacuum had negligible effect upon the values of capacitance measured, although such ageing produced an increase in measured "Q". This effect can probably be directly attributed to the increase in resistivity caused by such ageing. These capacitance measurements, in conjunction with thickness determinations, yielded a computed value of dielectric constant of three for films of average thickness, 0.0026 inch. However, not enough samples were measured to make this a very accurate value. The frequency dependence of the dielectric constant was determined by measuring the capacitance of several samples over the entire range from 0.2 to 20 megacycles. No appreciable variation of K with frequency could be detected in this range.

The thickness measurements on these eight samples showed very little variation. All the samples were anodized for one hour at constant temperature and current density, and the total variation from the average value of 0.0026 inch did not exceed ±0.2 mil. In addition to the thickness measurements on samples anodized for one hour, measurements were also made on several samples anodized for two hours. It was found, as expected, that the thickness was not a linear function of anodizing time but fell off as the anodization progressed. The thickness after two hours was about 0.0040 inch, rather than the 0.0052 inch which would have been measured if the growth had been linear. Also, as previously mentioned, the film formed in two hours of anodization was found to be quite soft and powdery. No actual curves of film thickness as a function of anodizing time are given at this point because the results of a more accurate and thorough investigation of film growth are presented in a later section.

Measurements on Sealed-In-Vacuum Samples

The results of the preliminary measurements indicated that resistivity determinations should be made in a high vacuum after thorough heat treatment in order to approximate the environment that a storage surface would meet under actual operating conditions in a storage tube. Figure 4a shows the first four round anodized samples that were used to make vacuum measurements of this nature, while Fig. 4b shows two experimental griddle-surface samples. The pores of samples 2 and 3 in Fig. 4a were sealed electrolytically and by boiling respectively. The other two samples were left unsealed. Like the preliminary samples, these four were anodized at a constant current density of about 46 amperes/foot^2 and a temperature of approximately 24°C.

After the anodization and sealing were completed, the front surfaces of these samples were coated with Hanovia Liquid Silver Paint No. 122-A. This coating was baked on in a furnace for three hours. The final temperature reached was 500°C. Then these samples were mounted in tubes similar to those shown in Fig. 5. The square metal plates shown on top of the anodized samples within the tubes are used to make positive contact to the silver coating. During evacuation of these tubes, the supporting elements and the inside aluminum of the samples were heated with radio-frequency current to about 500°C to drive out occluded gases. A great deal of gas was thus removed from the anodized layers. The final seal-off pressure was lower than 10^{-6} millimeters of mercury.

Before many measurements could be made on these samples, the resistance of the first sample in tube I dropped from more than 10^5 megohms to 0.22 megohms. It was not possible to determine the cause of this virtual short circuit, but it was recognized that more vacuum-tube samples would be necessary to enable meaningful measurements to be obtained. Consequently, eight more samples were prepared. The anodizing and sealing conditions for these samples (1 to 8) are summarized in Fig. 6, which also gives these conditions for the samples first constructed (II to IV). The film thickness estimated from anodizing time and current density, d, is given as 0.0024 inch for the first three samples in Fig. 6 rather than the 0.0026 inch determined from the earlier thickness measurements and used for the succeeding samples. The lower value is used to account for the fact that the actual current density employed in anodizing the first three samples was approximately 42.5 amperes/foot^2 instead of the 46 amperes/foot^2 used for the last eight samples.

It was thought to improve the technique of preparation of the second set of samples in two ways. First, all samples were heat-treated in a vacuum before anodization as well as afterwards to ensure the removal of gases in the aluminum itself, and second, Hanovia Silver Paste No. 38 (for glass) rather than silver paint was used to form a thicker, more lasting coating on the faces of the samples.

As can be seen from Fig. 6 these samples were anodized at different temperatures and for different lengths of time in an effort to find the effect of varying these parameters upon the resistivity. This effort was unsuccessful however, because of the use of the silver paste coating. It was found that the resistance from this coating, through the anodized film, to the inside metal was of the order of two ohms for all eight samples after thorough baking in air at 500°C to set the coating. Further baking in air did not increase the resistance. Because the coating of paste applied was much thicker than the silver paint layer used, there were evidently enough particles and moisture to penetrate all the way through the pores of the anodized layer and thus to short it out. There were probably not enough particles available in the silver paint layer for this to happen, or possibly the silver paste particles were smaller than those of the paint and could hence penetrate the minute pores more easily. However, even silver paint must be suspect in regard to penetration because of the failure of the sample in tube I.

It was found that after heat treatment in a vacuum, the resistance of most of these samples increased tremendously, however. As shown in Fig. 6, three of them remained effectively shorted, but the resistance of the others reached more normal values. However, capacitance measurements on the unshorted samples indicated much higher values than might have been expected had there been no penetration. Evidently the heating in vacuum removed the remanent moisture that was causing the anodized layers to appear shorted, but the silver particles remained part of the way down in the pores of the layers and decreased the effective thickness. Therefore, it was found that the capacitances computed from estimated values of film thickness based on anodizing time and from a dielectric constant of three were much smaller than those actually measured on the five unshorted samples.

Assuming a value of three for the dielectric constant, the effective thickness of each of the layers, d_1 was computed from the measured capacitance values. Then, by comparison with the thickness estimated from length of anodization, d_o, it was possible to compute a rough value of the average percentage penetration of the silver particles into the oxide layers. This approximate measure of the penetration was computed for all eleven samples and is shown in Fig. 6.

It can be seen from Fig. 6 that silver paint seems to penetrate a negligible amount into the pores. The eight percent for samples III could easily be due to cumulative experimental errors. It is not possible to tell very accurately from the small number of samples coated with silver paste which factors influence the penetration of the paste particles into the oxide layer. There is no clear-cut correlation between samples treated similarly. However, the average penetration of the four samples anodized at about 14°C is considerably lower than that of the four anodized at 25°C. This result might be expected from the fact that samples anodized at lower temperatures are harder than those formed at higher temperatures and presumably have smaller pores.

Fig. 6 also gives the resistivity of these eleven samples, computed from the resistance measured with 200 volts applied to the samples. No resistivity curves as a function of voltage are given because the resistance of most of the samples was too high to measure accurately with the available equipment. For resistance values greater than 10^{12} ohms, it was found impossible to zero the electronic voltmeter when using a shunt resistance, R_1, of 1,000 or 10,000 megohms. And, in addition, even these large values of R_1 did not produce large enough meter deflections for accurate reading. Therefore, the higher resistivities in Fig. 6 can only be specified as greater than 10^{15} ohm-centimeters.

The resistivities of the samples coated with silver paste were determined from d_1, the computed thickness of the anodized layer taking penetration into account. These values do not have very much meaning, however, because of the penetration phenomenon. Penetration of silver particles almost all of the way down through a few of the pores in an anodized layer would cause a greater change in measured resistance than it would in measured capacitance. Therefore, it is not really valid to use the value of the effective thickness of the layer here computed from capacitance measurements for resistivity calculations.

It can be seen from Fig. 6 that the resistivity of all the boiled samples not shorted is of the same order of magnitude as that of the unsealed samples. This result is very different from those of the earlier low-vacuum measurements. Evidently, thorough heat treatment in a high vacuum converts the aluminum oxide monohydrate in the boiled films back to anydrous aluminum oxide with a consequent increase in resistivity. Also, very little polarization effect was noted during measurements on any of these eleven samples. Its appearance in the earlier tests was probably caused by moisture that had not been removed from the oxide layers.

Although it was impossible to obtain accurate measurements of the resistance of most of these sealed-in-vacuum samples, the approximate values of the resistivities show that the aluminum oxide layer, when properly dried out, has a more than adequate resistivity for use as a dielectric storage material in a storage tube. In addition, the evidence of Table I indicates, though not conclusively, that electrolytic pore sealing decreases the resistance of an anodized layer.

Results of the Search for Optimum Anodizing Conditions

The results of the preceding measurements indicated that unsealed aluminum oxide layers, when measured under conditions approximating the environment of a storage tube, have a high enough resistivity for use as storage surfaces. In addition, previous measurements in air showed that the breakdown strength of the material was sufficiently high. However, these measurements also indicated that while it was possible to produce films four or five mils in thickness by anodizing at 46 amperes/foot^2, such films did not have the requisite hardness and mechanical rigidity for griddle surface use even when electrolytically sealed. Therefore, it was decided to make a systematic study of the growth of the oxide film under varying anodizing conditions in order to find a set of conditions under which a thick, hard coating of aluminum oxide could be produced.

The major parameters that it was decided to vary were bath temperature and concentration, and current density. Figures 7, 8, and 9 present most of the pertinent information available in the literature.* Figure 7 shows a small maximum of film thickness for the higher current densities at the low acid concentration of 1.43 percent oxalic acid. Figure 8 indicates that it is

*Fig.7, Fig.8, Fig.9 are from Ref. 6, pp.125, 127, 154.

possible to form layers as thick as ten mils, although there is no data given concerning the electrical and mechanical properties of such thick films. Finally, Fig. 9 gives the breakdown voltage of oxide films for thicknesses up to almost three mils. The breakdown field strength decreases somewhat with increasing thickness and at 0.07 millimeters is only 1.16 x 10^5 volts/inch. However, since no information is given about the conditions under which the films used in the breakdown measurements were formed this curve cannot be taken to apply generally.

Because of the relative paucity of information available in the literature, it was decided to begin the investigation with the current of density of 46 amperes/foot^2 which had been used to form the previously measured films. In order to secure accurate thickness data it was necessary to use flat samples of well-determined area and as constant a thickness as possible. Figure 10 shows some of the small samples used. Although the color tone values in the picture do not correspond exactly to those of the samples themselves, a lightening in color can be seen from left to right. The first sample on the left is unanodized, while the anodizing periods (and hence film thickness) of the rest increase from left to right. Smaller samples than the ones used in the preliminary investigation were chosen so that less total anodization current would be required during anodizing, and it would hence be easier to held the temperature constant. All of these samples were cut from a single sheet of 2S aluminum, 1/16-inch thick. The samples themselves were cut one-half an inch wide and were immersed in the bath to a marked line so that a current density of 46 amperes/foot^2 could be maintained with a current of one-half an ampere per sample.

Figures 11 through 13 show the growth of an oxide film over a two hour anodizing period for different bath temperatures. These curves were drawn from thickness measurements made both before and after anodization and after removal of the oxide film. The sets of two closely spaced points on these curves show the spread between two separate samples anodized for the same length of time. Where only one point is given, the measurements yielded identical results. In Fig. 14, the average of each set of points is plotted rather than the points themselves.

These curves indicate that the film builds up both inwards into the metal and outwards from its initial surface. It can be seen that as the temperature is increased the acid activity increases correspondingly and the attack on both the outside of the film and on the inside metal is greatly accelerated. At a temperature of 36°C, the final thickness of an anodized article will actually become less than the initial thickness after anodization has progressed for more than about two hours. As shown in Fig. 14, the effect of increasing the temperature upon total film thickness is practically negligible during the first hour of anodization since it is only after this long a time in the bath that the eroding action of the acid begins to act more on the film than upon the base metal. It will be noted that the thickness values given in Fig. 14 differ somewhat from those obtained with the preliminary samples. The differences are probably due chiefly to the greater precision with which the actual submerged sample area was determined for the later smaller samples and to the more precise temperature control possible with these samples.

The difference shown in Fig. 14 between the curves taken at 12°C and 24°C is almost negligible and is also practically within the limits of experimental error. Therefore, it was decided to anodize most of the succeeding samples at 24°C because of the much greater ease of holding the bath temperature constant at this value rather than 12°C or below. It was found that although films formed at 12°C for two hours were substantially harder than those formed at higher temperatures, they were still much softer than films formed for only a half an hour at the higher temperatures and were still flaky and powdery. Consequently, reduction of temperature, while increasing film hardness, does not offer a complete solution to the problem of forming a thick, mechanically hard and rigid dielectric film.

Figures 15 through 17 present the results obtained using either half the previous acid concentration, half the current density, or both together during anodization. Instead of anodizing two samples for each time interval shown on these graphs, as was done to obtain the previous growth curves, it was decided that the small loss in accuracy involved in anodizing only one sample for each time interval would be more than compensated by the extra time thus gained for further study of film-growth phenomena. Therefore, the points on the succeeding curves represent only one anodized sample each. Figure 15, for full current density and half the previous acid concentration, shows that the film does not build either inwards or outwards as fast as it does at the higher concentration. This curve had to be discontinued after about an hour because of stripping of the oxide layer at the water line after this long an anodization. This effect was probably caused by the abnormally high voltage (160 volts) that was required to maintain the given current density in the low-concentration, poorly conducting bath after an hour of anodizing. During the first part of the anodizing process, the voltage necessary to maintain a current density of 46 amperes/foot^2 is below 100 volts but gradually rises as the film becomes thicker and its wet-resistance increases. Practically the entire voltage drop appears across the oxide film, and, as the resistance of the acid-filled film increases, more and more power must be dissipated in the film if the current is kept constant. With an applied voltage of 160 volts and a current per sample of one-half an ampere, each small sample must dissipate 80 watts; therefore, it is not surprising that localized heating at the water line, where the bath cannot adequately cool the sample, should result in a stripping off of the oxide layer. This difficulty was not experienced at higher acid concentrations and a current density of 46 amperes/foot^2 because even after long periods of anodization lower voltages were required to maintain the given current. Evidently, the greater conductivity of baths having higher acid concentrations keeps the wet-resistance of films formed in such baths lower during all stages of anodization.

Figures 16 and 17 show that at lower current densities also the effect of a 3 rather than a $1\frac{1}{2}$ percent acid concentration is definitely beneficial to film formation. These results are in contradiction to those of Fig. 7, taken from the literature, which show a slight maximum at the lower acid concentration. However, in that figure the maximum is very slight and the points shown do not lie very near the two curves drawn for higher current densities. Figure 18 summarizes the effect of the different current density and acid concentration conditions upon the total thickness of the film formed. Both current density and bath concentration can be seen to contribute to the growth of the film in different degrees. Curve C, at half current density and full concentration, is especially noteworthy because of its linearity. The hardness of the samples formed under the conditions of curve C greatly exceeded that of others formed at twice the current density. However, the thickness was not as great at the lower current density and the hardness was still not adequate. Nevertheless, reduction of the anodizing current density was indicated by these results to be one method of increasing the hardness of the final film. It was therefore decided to make a number of much longer anodizing runs at relatively low current densities.

The results of three long anodizing runs are summarized in Figures 19 through 22. Since the results shown in Fig. 18 indicated that increasing the acid concentration of the anodizing bath caused the film growth curve to remain linear for longer anodizing times, it was decided to increase the acid concentration and to make a long run to determine how long this linearity could be maintained. Figure 19 therefore shows the results of anodizing for six hours at a current density of 23 amperes/foot^2 and an acid concentration of six percent oxalic acid. This figure should be compared with Fig. 16 for three percent concentration and the same current density. In the two-hour region in which comparisons can be made, there is no appreciable difference between the two figures. The growth curve for the higher concentration remains linear for $3\frac{1}{2}$ or 4 hours, then begins to fall off rapidly as the acid erodes the outer surface of the film faster than it is built up. These results would seem to indicate that although increasing the acid concentration above $1\frac{1}{2}$ percent is worth while, further increase above 3 or 4 percent is unwarranted.

Although samples anodized for six hours at 23 amperes/foot^2 and six percent acid concentration had an oxidized layer of more than adequate thickness for griddle surface applications, these anodized films were still not hard enough. In order to further reduce the current density during anodizing, it was decided to carry out some anodizing runs at constant voltage rather than constant current. With constant voltage the initial current density is very high, but the current density rapidly drops off as the first thin oxide barrier-layer is formed on the metal surface. After the first large decrease in current density, the subsequent decrease is very slow. The average current density during any given period is a function of the applied voltage and the acid concentration. For an applied voltage of 100 volts, it was found to be approximately 12 amperes/foot^2 during the eight-hour anodizing period shown in Figs. 20 and 21, while for 80 volts it was about 7 amperes/foot^2.

These values are substantially lower than any used in the previous runs at constant current density; consequently, longer anodizing times are required to form films of thicknesses comparable to those formed at the higher current densities. However, this disadvantage is minor if harder films can be formed by anodizing at lower current densities.

Figures 20 and 21 show the growth of the oxide film for constant applied voltages of 100 and 80 volts. As shown explicitly in Fig. 22, a thicker film can be formed in a given length of time at the higher voltage because of the greater average current density. On the other hand, it can be seen from Fig. 22 that the 100 volt thickness curve rounds off more in the last two hours of the anodizing run than does the 80 volt curve. Therefore it is probable that as thick films can be formed at 80 volts as are possible at 100 volts by extending the anodizing period somewhat for the lower voltage. Even the film formed at 80 volts is thick enough after eight hours of anodization, however, to enable a tapered griddle-surface wall having a maximum thickness of ten mils to be anodized completely through. In addition, the film formed at 80 volts was found to be considerably harder than that formed at 100 volts, and both of these films were much harder and smoother than any of comparable thickness previously formed at 46 or 23 amperes/foot^2.

Resistance and breakdown measurements were made on eight samples of different thicknesses anodized at constant voltage. Resistance measurements were made as in the preliminary investigation in an evacuated desiccator with mercury used to make electrical contact with the samples, and no appreciable differences could be detected between the resistivities of samples formed at constant voltage and constant current. Nor was it possible to discover any variation in resistivity with oxide thickness. Breakdown measurements were made on a total of 22 of these small-size samples anodized under all the different voltage, current, and acid concentration conditions described thus far. Measurements were made in air with a variable d-c power supply having a maximum output voltage of 6,000 volts. Again no significant differences between samples anodized at constant voltage and at constant current could be found. However, the range of measured values was large: breakdown occurred at field strengths ranging from 2.6×10^5 to 1.3×10^6 volts/inch. The average value of the breakdown field strength for these 22 samples was 6.9×10^5 volts/inch.

Because the scatter in observed breakdown values was particularly large at small thicknesses (probably because inhomogeneities in the film affected the breakdown strength more for small thicknesses than for large), it was impossible to make certain of the dependence of the breakdown strength upon thickness over the entire thickness range measured. At thicknesses exceeding three mils, however, a trend toward decreasing breakdown strength with increasing thickness was quite evident. This result is in qualitative agreement with the data given in Fig. 9, but quantitatively the breakdown strengths measured here considerably exceed those which may be computed from the curve of Fig. 9. Not enough samples were measured for each of the different anodizing conditions to make it possible to establish unequivocally any correlations between breakdown strength and anodizing conditions such as current, voltage, temperature, and acid concentration.

Dielectric constant determinations were carried out for 33 of these small samples. The values obtained ranged from 2.6 to 6.2 with an average value of 4.26. The most probable error of these values, computed from the scatter assuming a gaussian error distribution, was found to be 26 percent of the average dielectric constant. This large a probable error cannot be adequately explained by attributing it exclusively to errors in the individual measurements used to compute the dielectric constant. The maximum probable error which it seems reasonable to assign to the capacitance measurements is five percent. Three or more capacitance measurements were made at different positions on each side of every sample, and these six or more values averaged to give the final capacitance used. It was hoped in this way to cancel out the effect of any difference in film thickness between the two sides of a given sample, since it is the average value of the thicknesses of the films on either side of a smaple which is determined by the thickness measuring method. The maximum probable error of the thickness measurements should also be five percent or less. Because of the edge effect and difficulty in measuring the area of contact between a mercury drop and a sample, the accuracy to which the area of contact is known is probably no better than ten percent. Since the overall probable error of the dielectric constant in percent is the rms value of the individual percentage probable errors of the quantities used to compute the dielectric constant, its value should then be approximately 12 percent.

Although it was impossible to determine any definite dependence of the dielectric constant upon film thickness or anodizing conditions, the disagreement between the probable error determined from the individual measurements used to compute the dielectric constant and the actual probable error found from the scatter in the computed values is evidence that some such dependence exists and that the scatter is not due solely to errors in measurement. The actual determination of the factors which cause such scatter would require a more carefully controlled and extensive investigation. However, it is worth noting that the average value of the dielectric constants of the eight samples anodized at constant voltage, which was found to be 4.7, differs by only nine percent from the overall average of the dielectric constants of the thirty-three samples measured, and the scatter in values of these eight samples was small.

In an effort to obtain more comparative data between samples anodized at high constant current densities and at constant voltage (low average current density), four smooth round samples similar to those shown in Fig. 24b were sealed in vacuum tubes of the type depicted in Fig. 5. In Fig. 24b, the first of the samples shown is unanodized, the second anodized five hours at 80 volts, and the third anodized one and a half hours at 46 amperes/foot^2. The constant-voltage sample is actually considerably darker than the dead-white constant-current sample, but the color values do not show up clearly in the picture.

Of the four samples mounted in vacuum tubes, one pair was anodized at 80 volts while the other pair was anodized at 46 amperes/foot^2. The bath temperature was 24°C in both cases. The anodizing times of the two pairs were adjusted with the help of Figs. 14 and 22 to make the final film thickness of all the samples approximately four mils. One of each pair of samples was electrolytically sealed. Silver paint, covering a circular area of 0.44 inches^2, was baked on the middle of each sample to secure electrical contact to the top of the anodized films. Then the samples were heated to 400°C in a vacuum before the glass tubes were closed off at a pressure of 10^{-7} millimeters of mercury.

Resistance measurements on these samples did not produce much new information. No appreciable difference in the resistivities of samples anodized at constant voltage and at constant current for either the unsealed or electrolytically sealed samples was detected. The resistivity of unsealed samples was found to be of the order of 10^{15} ohm-centimeters and that of sealed samples was about ten times less. Extensive measurements of the resistances of these samples were not undertaken because of the lack both of time and of accurate equipment for measuring resistances greater than 10^{12} ohms. In addition to large inaccuracies occurring from the necessity of measuring resistances of this magnitude with available equipment, the computed value of the resistivity is rendered even more approximate by the necessary use of film thickness values estimated from anodizing times.

The dielectric constants of these different films were determined from the estimated film thickness and from capacitance measurements. Again, no significant differences could be found between samples anodized under the two different current and voltage conditions, but pore sealing seemed to have a considerable effect. The average dielectric constant of the two unsealed layers was 4.8, while that of the sealed films was only 3.1. However, this determination, depending as it does upon estimated thickness values, neglecting any penetration of silver paint into the film, and comprising only two samples of each type, cannot be taken as conclusive evidence of a decrease in dielectric constant with sealing, especially in view of the wide scatter in dielectric constant determinations for the thirty-three small samples previously mentioned.

Finally, some experimental griddle-surface samples were anodized both at constant current and constant voltage to determine whether the griddle walls could be anodized completely through and if requisite film hardness could be obtained. The initial griddle pattern was formed by embossing flat 2S aluminum with a hardened steel die under a pressure of approximately 40,000 pounds per square inch. The circle embossed by the die was one inch in diameter The actual dimensions of the griddle structure can be most easily specified with the aid of Fig 23. Dimension "a" shown on that drawing is 10 mils; "b", 25 mils; and "c", approximately 15 mils.

In Fig. 24a, the first griddle sample shown on the left is unanodized, the second anodized for two hours at 46 amperes/foot^2, and the third anodized $5\frac{1}{2}$ hours at 80 volts. The bath temperatures during these anodizations were held at 24°C. Two griddle samples anodized for two hours at 46 amperes/foot^2 are also shown in Fig. 4. As expected, it was found that the samples anodized at the high constant current density were too soft and powdery to make an ideal griddle surface, while those anodized at 80 volts were harder, smoother, and quite acceptable for griddle surface use. It was found impossible to anodize completely through the griddle walls, however, even with 14 hours of anodization at 80 volts. After removal of the oxide film, a very fine metal fin less than a half a mil in thickness still remained at the center of each pocket wall. It was possible to anodize down into the tops of the walls so that the film thickness on the tops was greater than five mils, but the current-carrying metal fins which remained could not be completely anodized through even though a film at least seven mils in thickness ought to have been formed on each side of the 10-mil-thick wall in this anodizing time. Possibly a longer anodization at a slightly increased average current density would convert most of the center metal in the walls to oxide, but even under these conditions a considerable amount of metal might remain in the center of the oxide layer if the fins were oxidized through near their bottoms (as might well happen with walls of constant thickness) and the electrical contact between the remaining upper metal parts and the metal of the base thus destroyed. This difficulty could be easily removed by using tapered walls having a 10 to 20 degree taper as shown in Fig. 25.

Recommendded Anodizing Conditions

The results of the foregoing measurements indicated that a thick dielectric film having quite adequate mechanical and electrical properties for griddle surface use could be formed by anodizing for eight hours or more at a constant voltage of 80 volts, a bath concantration of 3% oxalic acid, and a temperature of 24°C. Indications are that an even harder film can be formed at lower anodizing temperatures. It is therefore suggested that further growth curves be plotted of film formation at low temperatures for a variety of bath concentration, temperature, voltage, and (low) current density conditions in order to determine an anodizing procedure which will produce films with optimum electrical and mechanical characteristics.

Written by D. Ross Macdonald
Approved by JF

References:

1. Edwards, J.O., "Anodic Coating of Aluminum," American Electroplaters' Society Monthly Review 26:7:513-532 (July, 1939).

2. Edwards, J.O., and Keller, K., "The Structure of Anodic Oxide Coatings," Transactions of the American Institute of Mining and Metallurgy, Institute of Metals Division 156:288-300 (1944)

3. Rankin, W.K. and Brossman, J. R., "Method of Protectively Coating Aluminum or Aluminum Alloys". U.S. Patent 2, 161, 636, Filed October 21, 1936; Granted June 6, 1939.

4. Macdonald, J. R., A Storage-Tube Dielectric Surface for Secondary Electrons Control Master's Thesis, Electrical Engineering Department, M.I.T. (September 12, 1947)

5. Macdonald, J.R., "Procedures Used in the Embossing and Anodization of Aluminum," Report No. R-128 Servomechanisms Laboratory, M.I.T.

6. Jenny, A., The Anodic Oxidation of Aluminum and Its Alloys. (Lewis, W., trans., New York: The Chemical Publishing Co., Inc., 1940)

Drawings:

Figure No.	Drawing No.
1	A-31159
2	A-30910
3	A-30922
4	A-31157
5	A-31158
6	A-30907
7)	A-30923
8)	"
9)	"
10	A-31160
11	A-30924
12	A-30925
13	A-30926
14	A-30927
15	A-30928
16	A-30929
17	A-30930
18	A-30931
19	A-30932
20	A-30933
21	A-30934
22	A-30935
23	A-31162
24	A-31161
25	A-30921

FIG. 1 RESISTANCE AND CAPACITANCE MEASUREMENT EQUIPMENT

A-31159

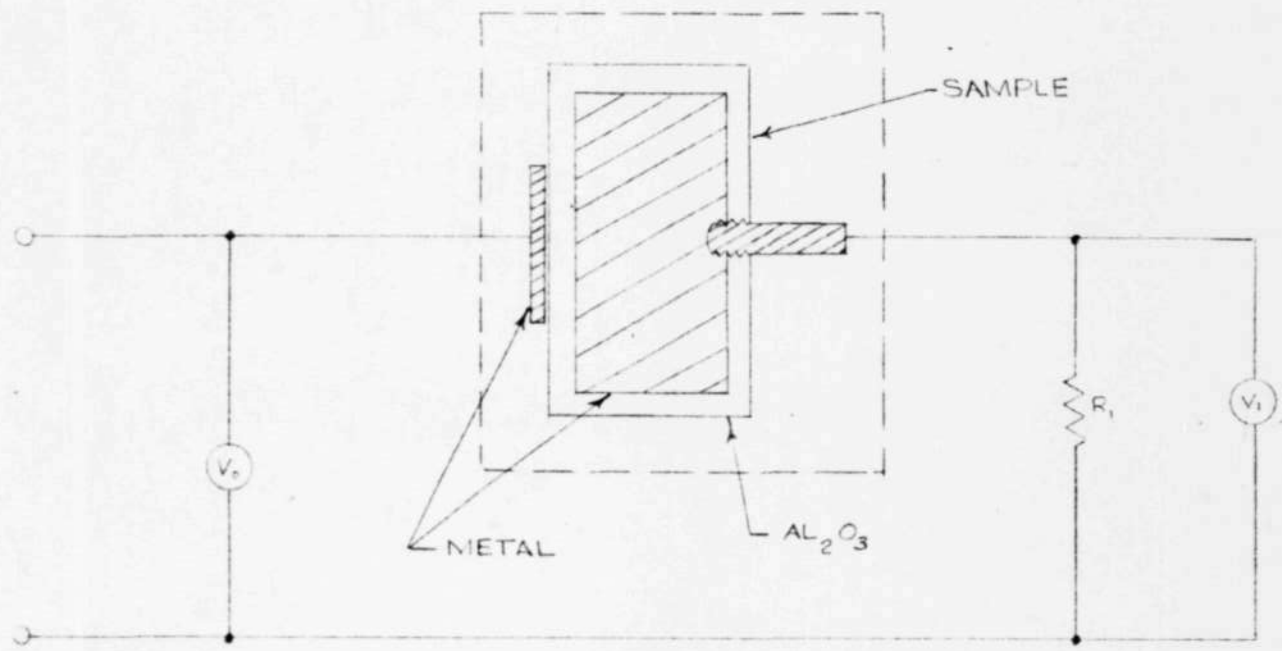


FIG. 2

CIRCUIT FOR RESISTANCE MEASUREMENTS

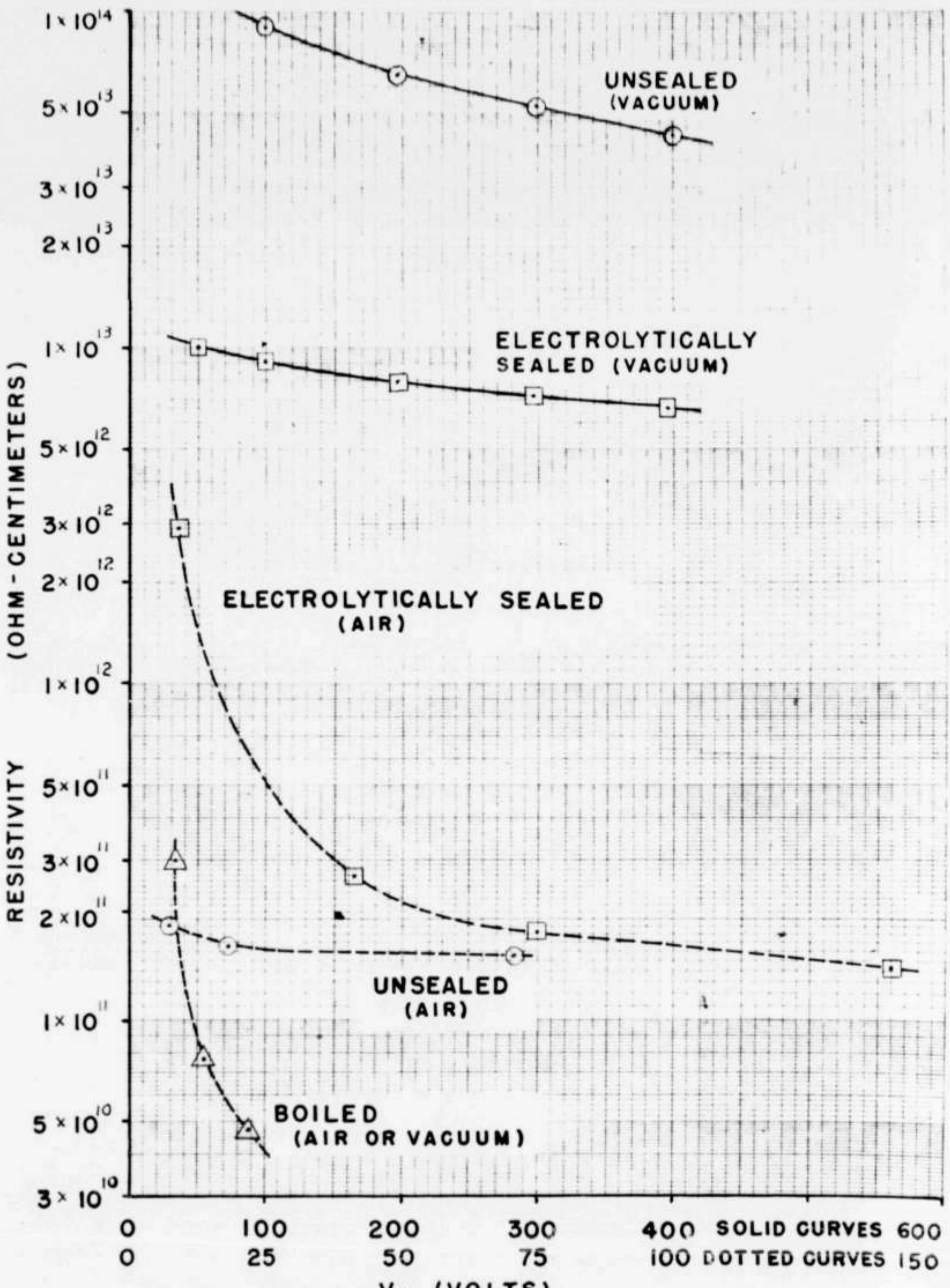
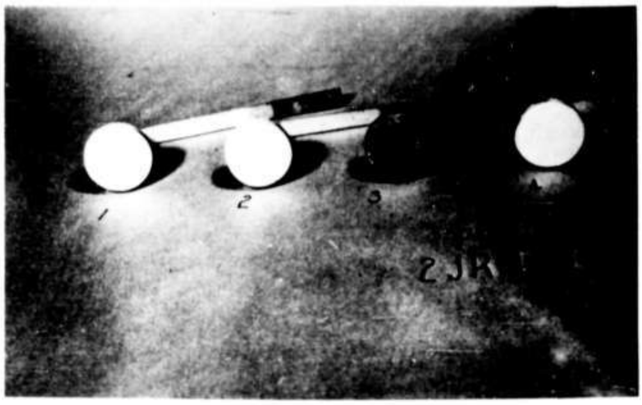


FIG. 3 - RESISTIVITY OF DIFFERENTLY SEALED SAMPLES IN VACUUM AND AIR

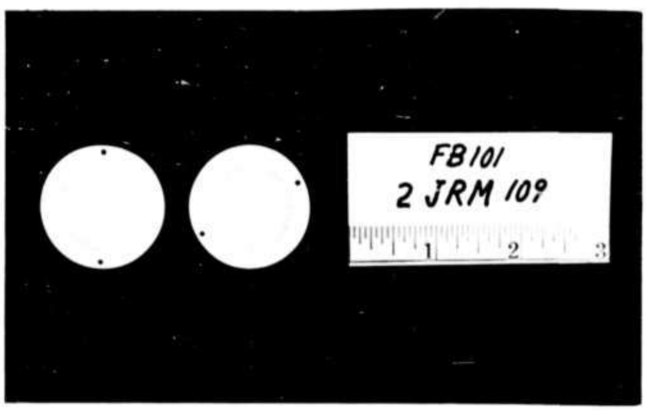
USED IN 6345 REPOR, NO. R-131

A-30922

A-31157



a



b

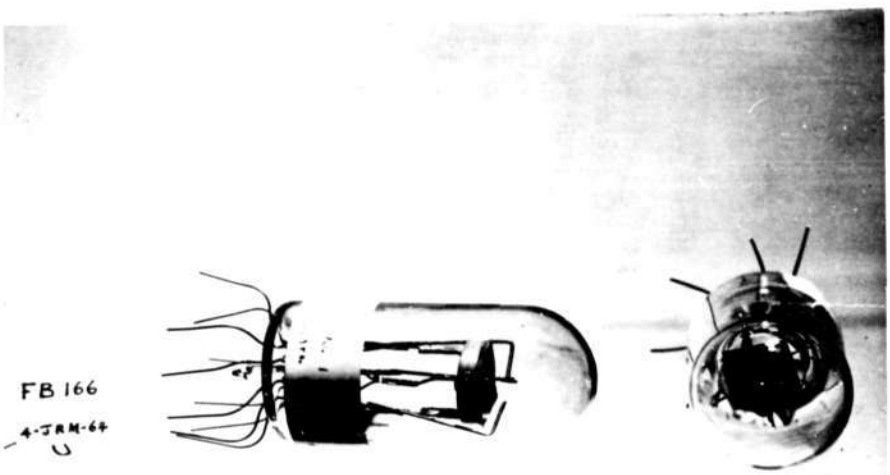
FIG. 4 ANODIZED SAMPLES

USED IN 6345 REPORT R-131

A-31157

A-31158

USED IN 6345 REPORT R-131



VACUUM – TUBE SAMPLES

FIG. 5

1-31158

VACUUM TUBE SAMPLES	ANODIZING TIME (HOURS)	ANODIZING TEMPERATURE (°C.)	SEALING METHOD	CONTACT MATERIAL	CONTACT AREA (in.^{2})	ESTIMATED THICKNESS d_0 (INCHES)	MEASURED CAPACITANCE (uuf)	COMPUTED THICKNESS d_1 (INCHES)	% PENETRATION $\frac{d_0-d_1}{d_0} \times 100$	RESISTIVITY AT 200 VOLTS (ohm-cm)
II	1	24	ELECTROLYTIC	SILVER PAINT	0.71	0.0024	196	0.00244	0	6×10^{12}
III	1	24	BOILING	SILVER PAINT	0.71	0.0024	217	0.00221	8	$>10^{15}$
IV	1	24	NONE	SILVER PAINT	0.71	0.0024	201	0.00239	0	$>10^{15}$
1	1	25	NONE	SILVER PASTE	1.00	0.0026	763	0.00089	66	$>10^{15}$
2	1	25	BOILING	SILVER PASTE	1.00	0.0026	~	~	100	SHORTED
3	1	14	NONE	SILVER PASTE	1.00	0.0026	358	0.00189	26	$>10^{15}$
4	2	14	BOILING	SILVER PASTE	1.00	0.0040	234	0.00288	28	10^{15}
5	1	25	NONE	SILVER PASTE	1.00	0.0026	468	0.00144	45	7×10^{13}
6	1	25	ELECTROLYTIC	SILVER PASTE	1.00	0.0026	~	~	100	SHORTED
7	1	14	NONE	SILVER PASTE	1.00	0.0026	~	~	100	SHORTED
8	2	14	ELECTROLYTIC	SILVER PASTE	1.00	0.0040	450	0.00150	63	8×10^{13}

FIG. 6
COMPARISON OF VACUUM-SEALED SAMPLES

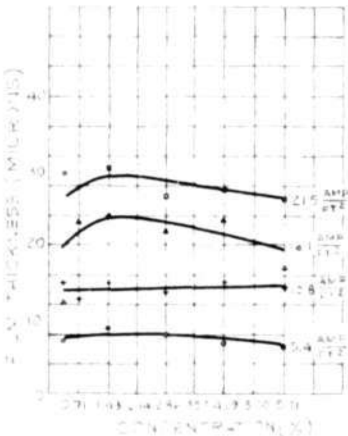


FIG. 7 - GROWTH IN THICKNESS OF THE FILM AT CONSTANT C.D.'S IN RELATION TO THE CONCENTRATION OF THE OXALIC ACID, D.C.

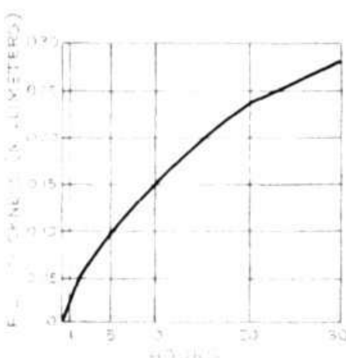


FIG. 8 - GROWTH IN THICKNESS OF FILM WITH TIME DURING A 30 HOURS' TEST PERIOD, 5% OXALIC ACID, 60 VOLTS, D.C.

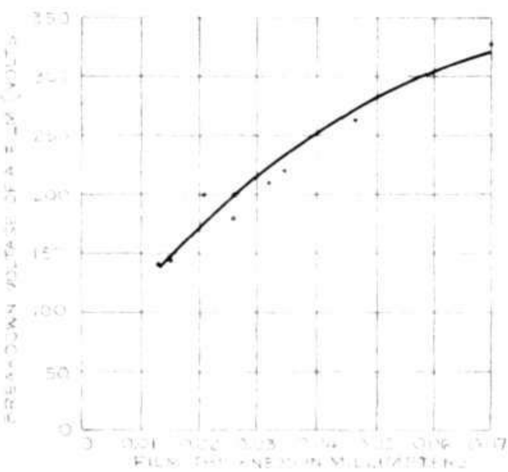
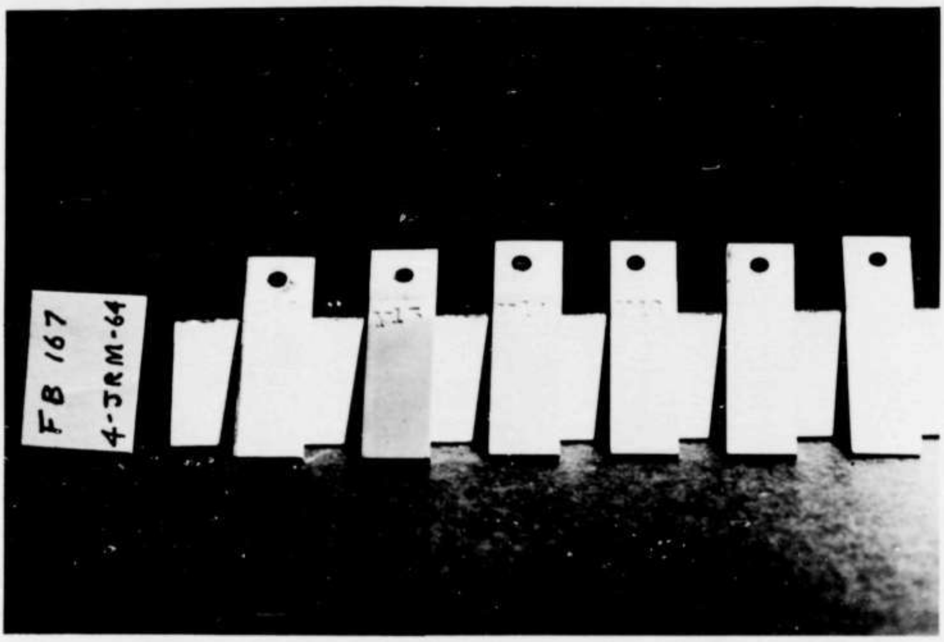


FIG. 9 - BREAKDOWN VOLTAGE OF OXIDIZED ALUMINUM WIRES 1.3 MILLIMETERS IN DIA. IN RELATION TO THE FILM THICKNESS.

4-31160



SMALL TEST SAMPLES

FIG. 10

USED IN 6345 REPORT R-131

-31160

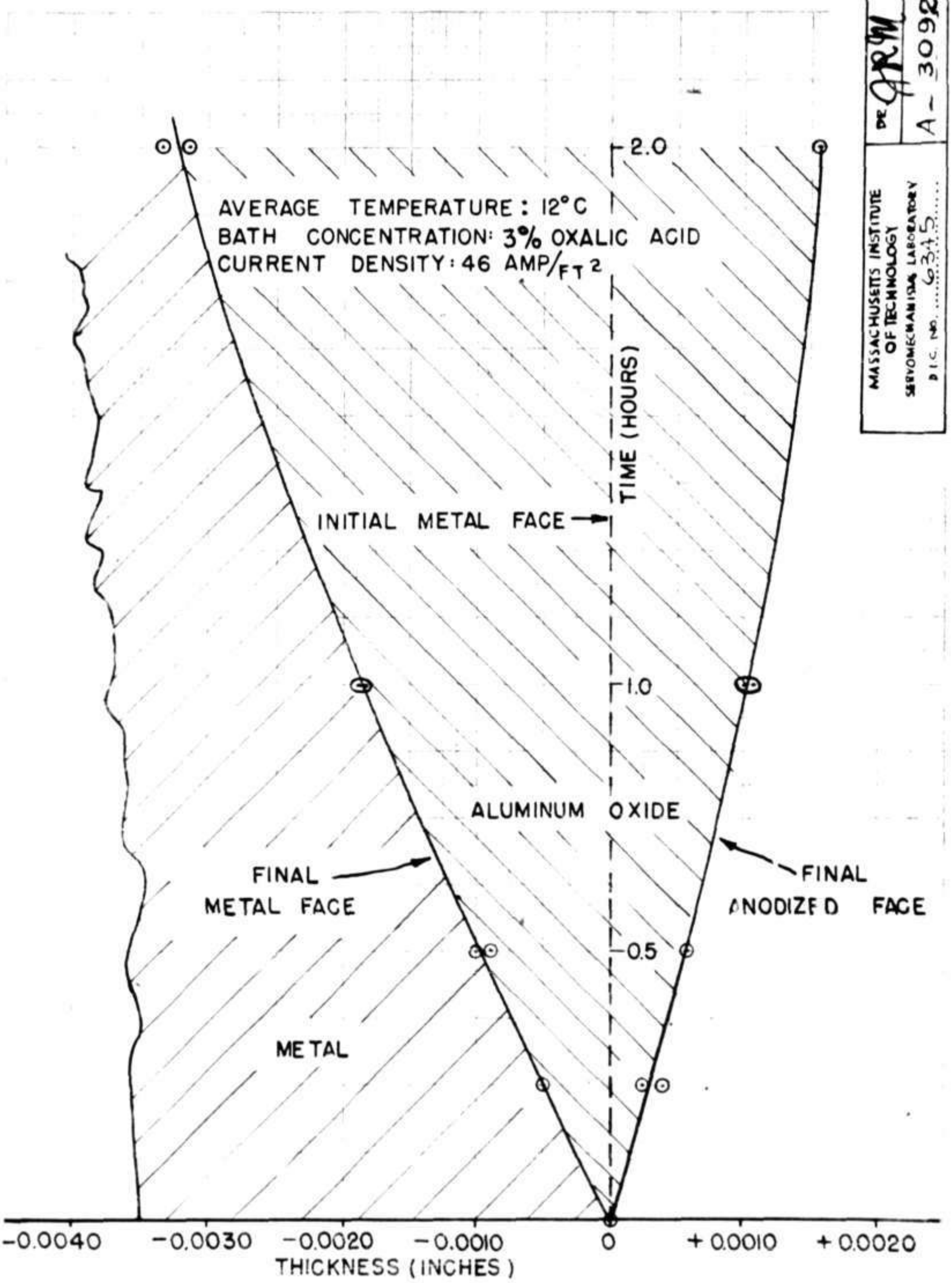


FIG. 11. GROWTH OF ANODIZED LAYER

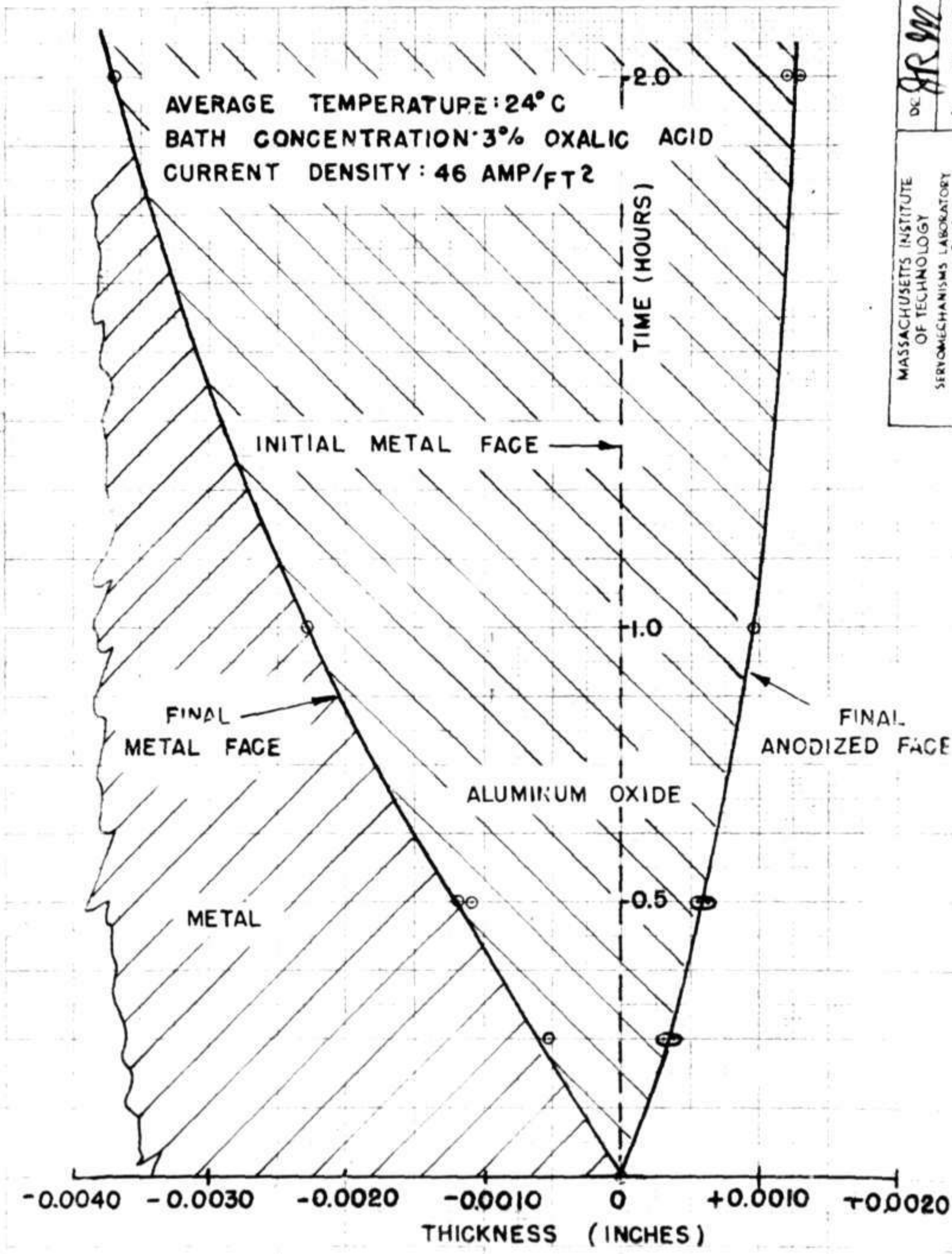


FIG. 12 GROWTH OF ANODIZED LAYER

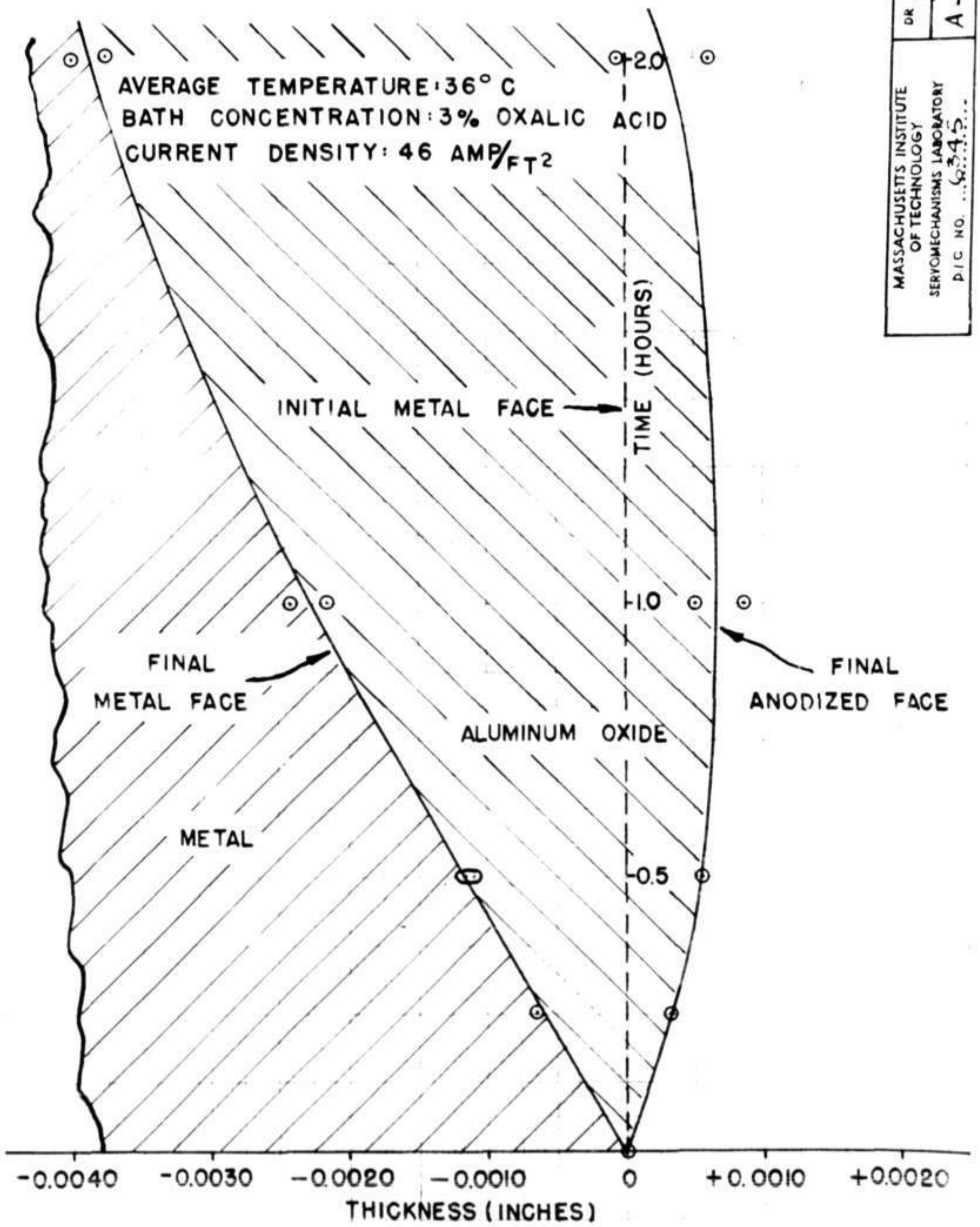


FIG. 13 GROWTH OF ANODIZED LAYER

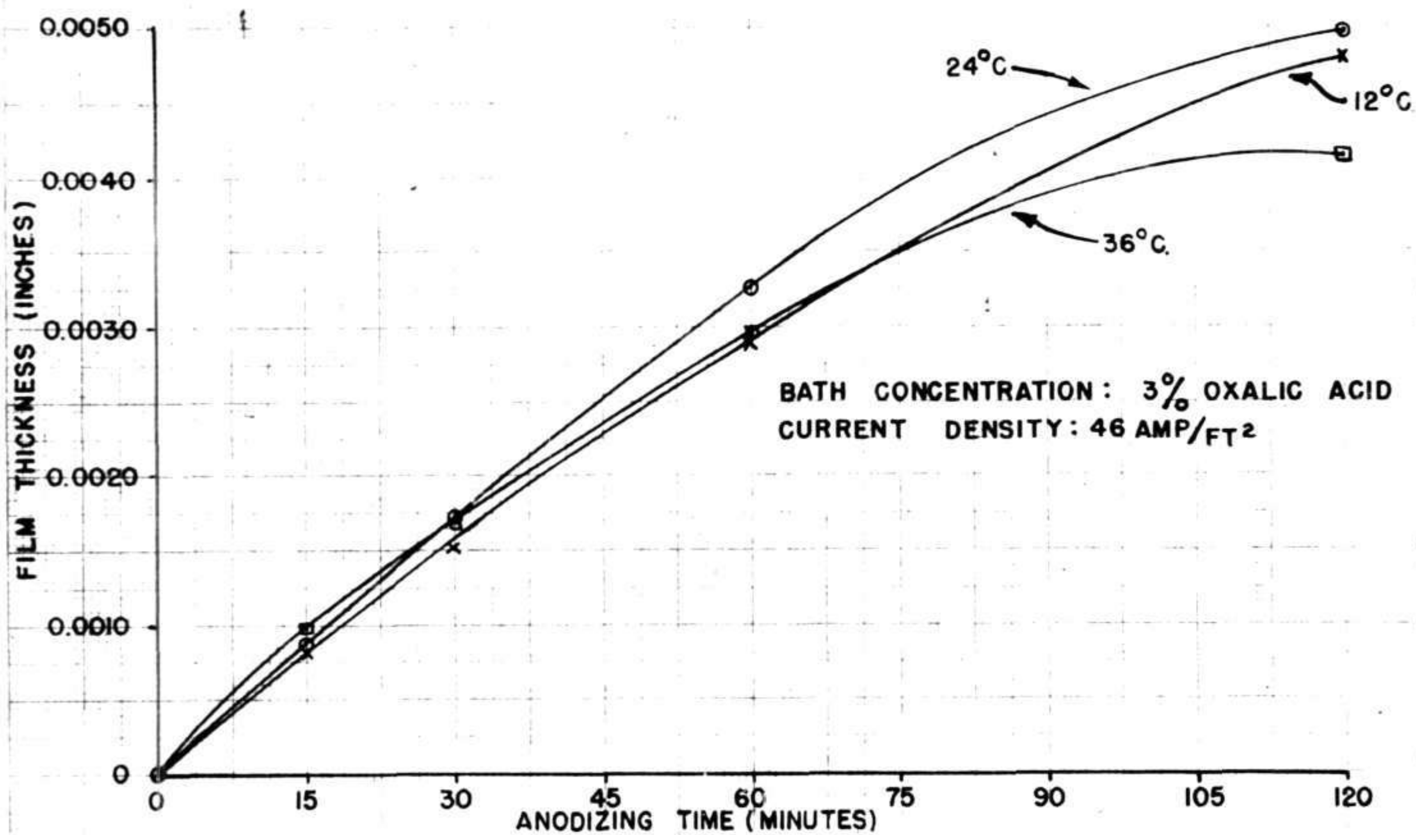


FIG. 14 VARIATION OF ANODIZED FILM THICKNESS WITH TEMPERATURE OF BATH.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY SERVOMECHANISMS LABORATORY D.I.C. NO. 6345	DR JRM
	A – 30927

AVERAGE TEMPERATURE: 24°C
BATH CONCENTRATION $1\frac{1}{2}$% OXALIC ACID
CURRENT DENSITY: 46 $AMP/_{FT^2}$

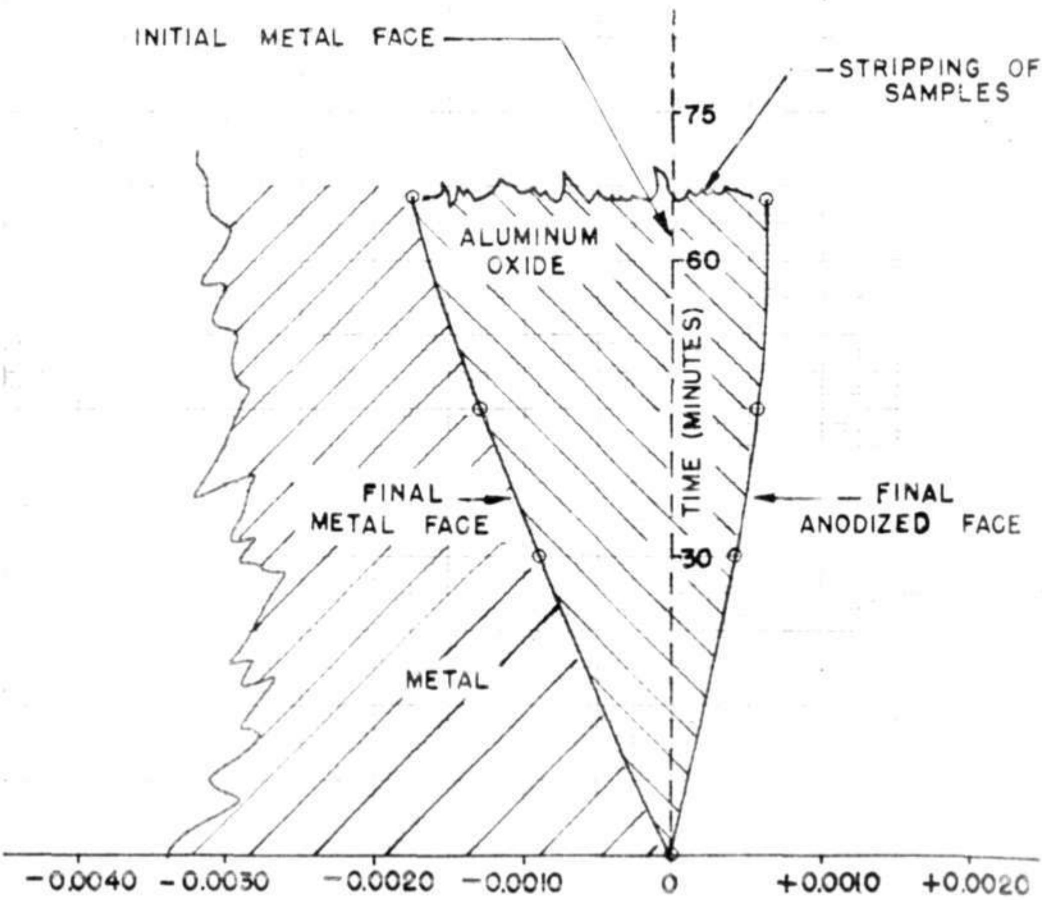


FIG. 15 GROWTH OF ANODIZED LAYER.

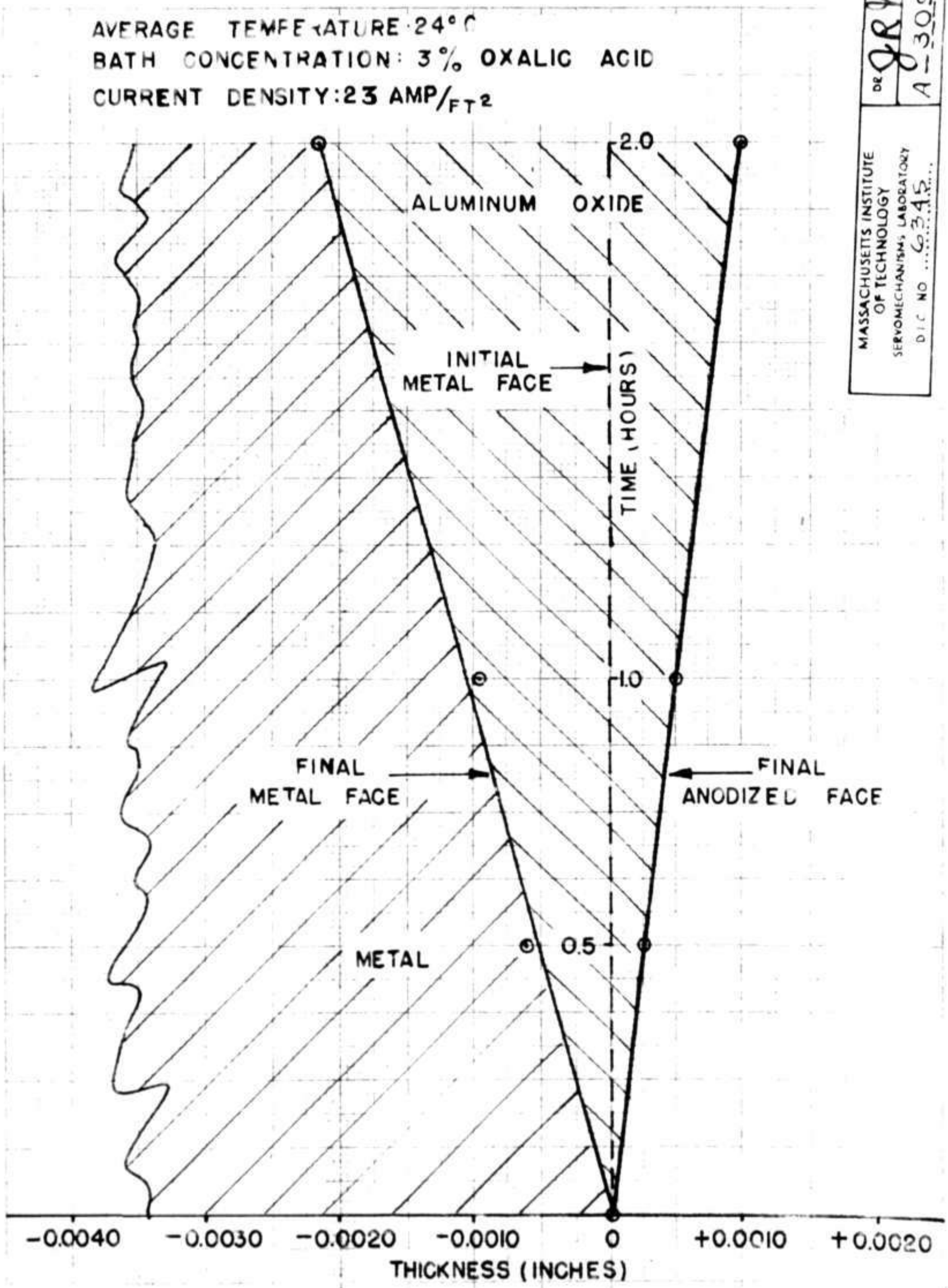


FIG. 16 GROWTH OF ANODIZED LAYER

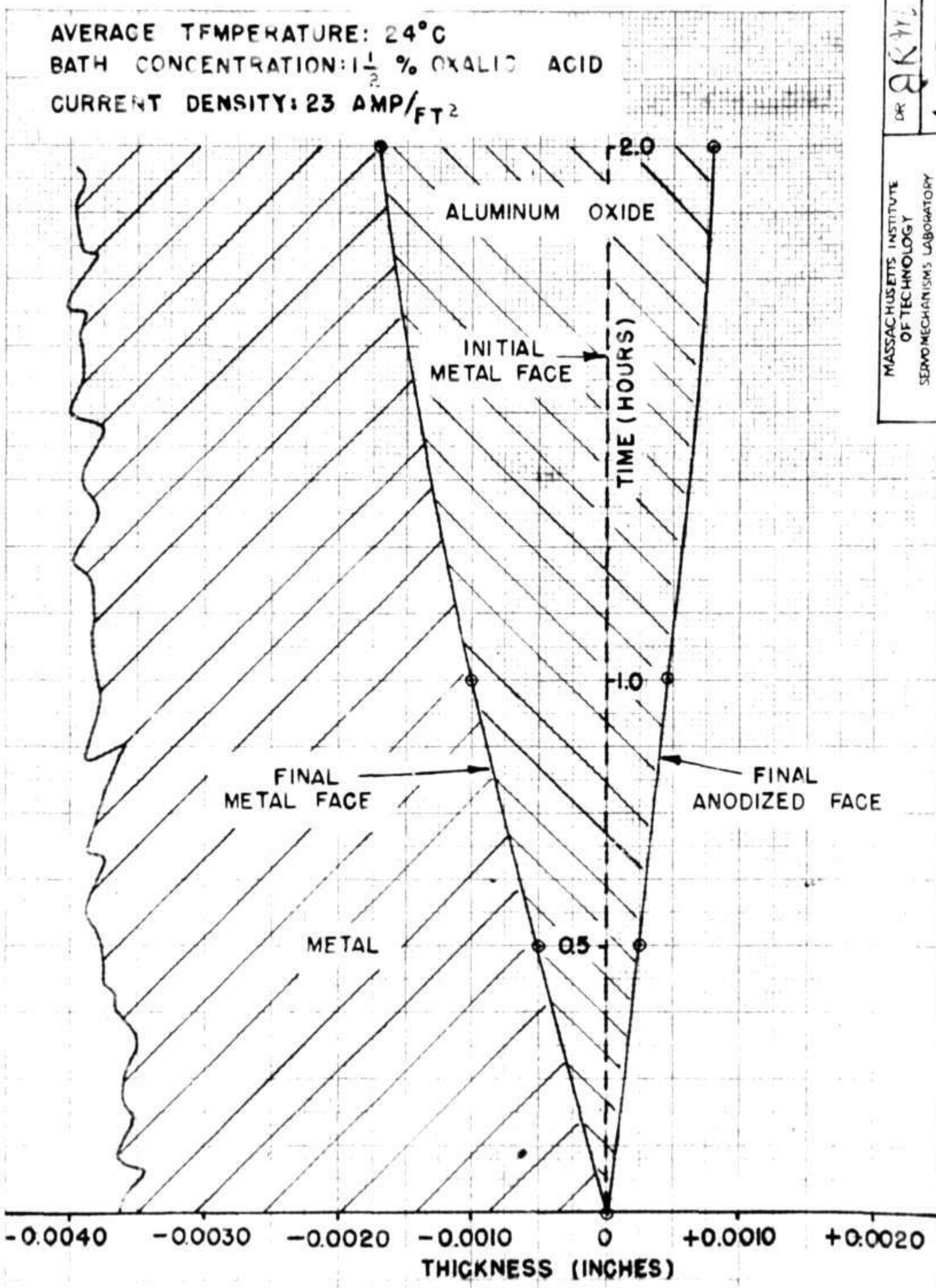
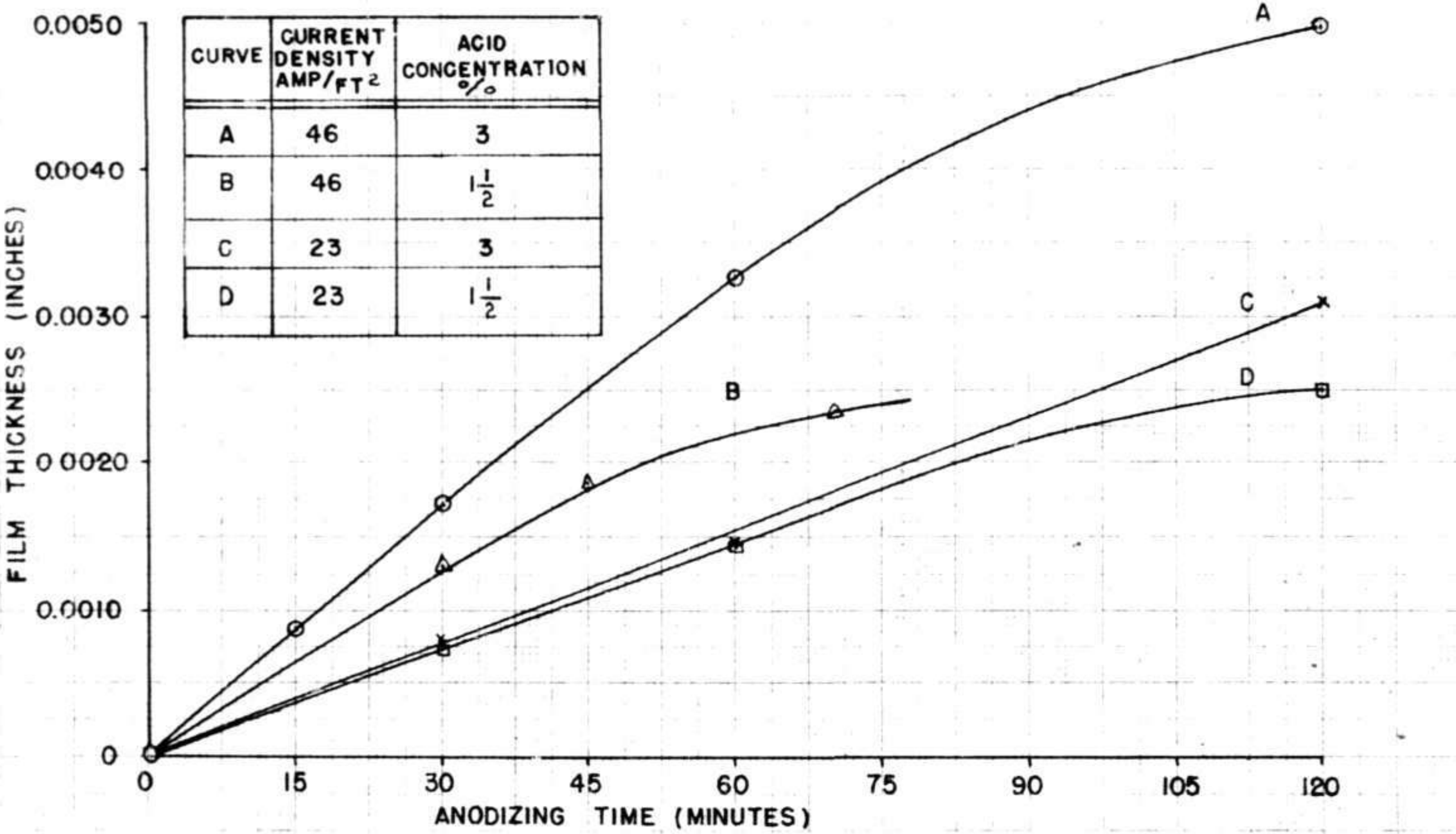


FIG. 17 GROWTH OF ANODIZED LAYER

AVERAGE ANODIZING TEMPERATURE: 24° C



CURVE	CURRENT DENSITY AMP/FT²	ACID CONCENTRATION %
A	46	3
B	46	1 1/2
C	23	3
D	23	1 1/2

FIG. 18 EFFECT UPON FILM THICKNESS OF VARIOUS ANODIZING CONDITIONS AT CONSTANT TEMPERATURE.

A-3093

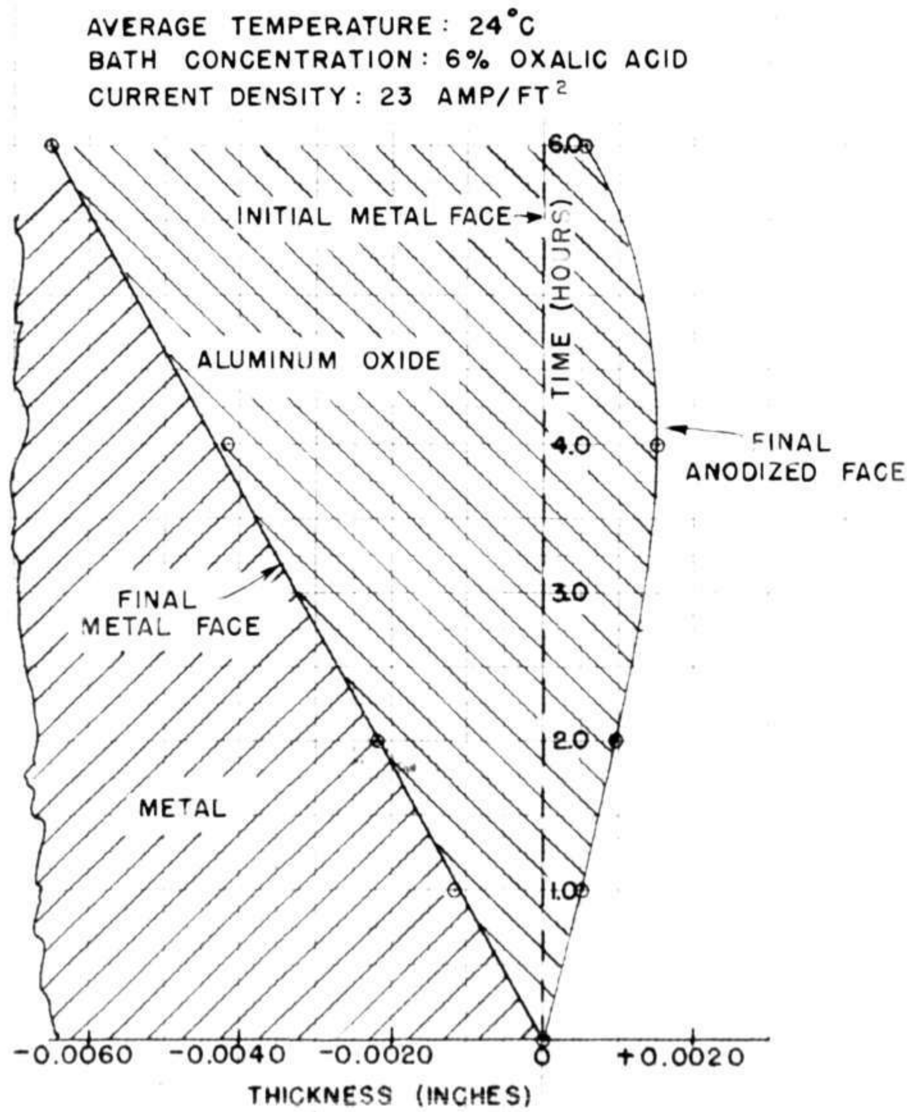


FIG. 19 GROWTH OF ANODIZED LAYER

USED IN G345 REPORT NO R-131

A-30937

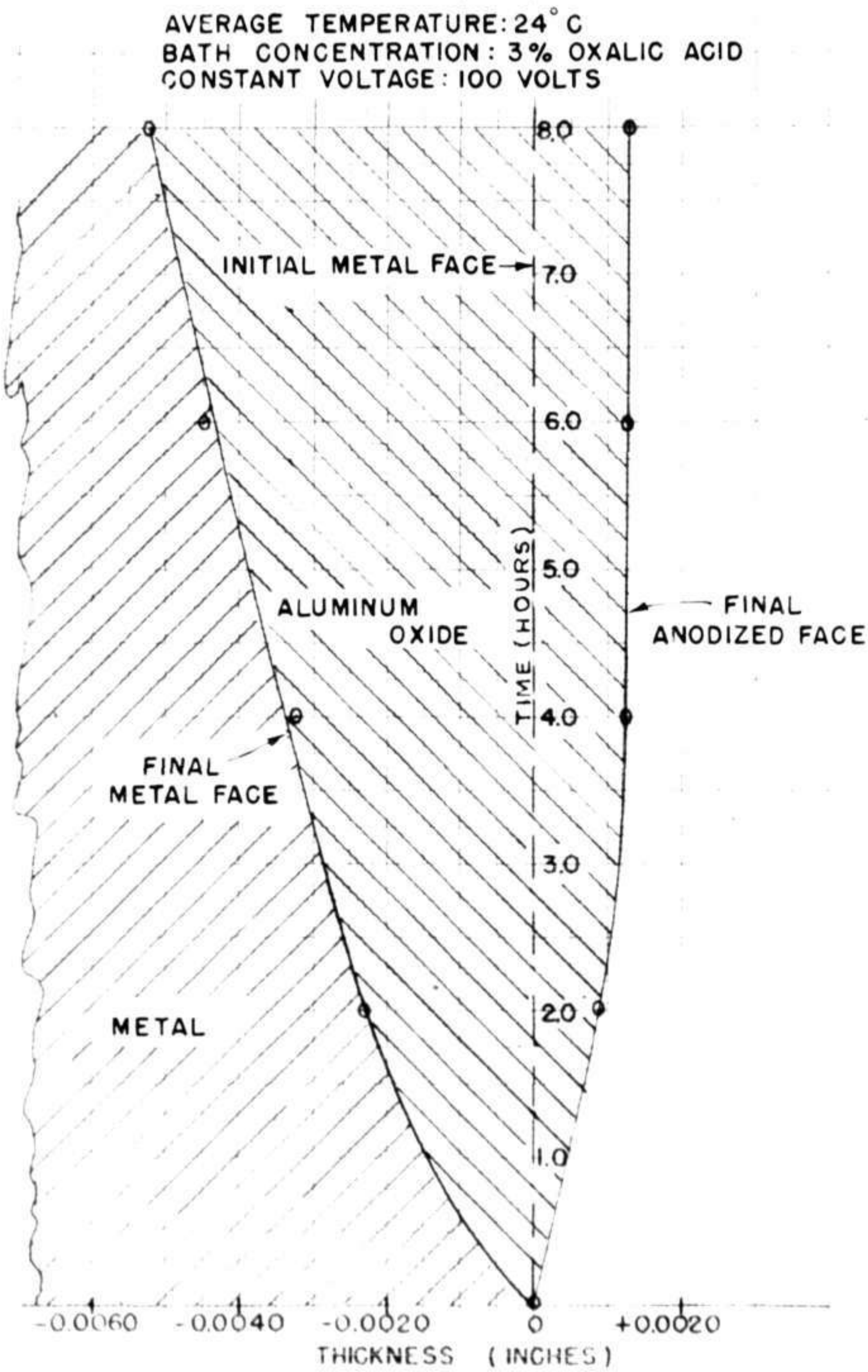


FIG. 20 GROWTH OF ANODIZED LAYER

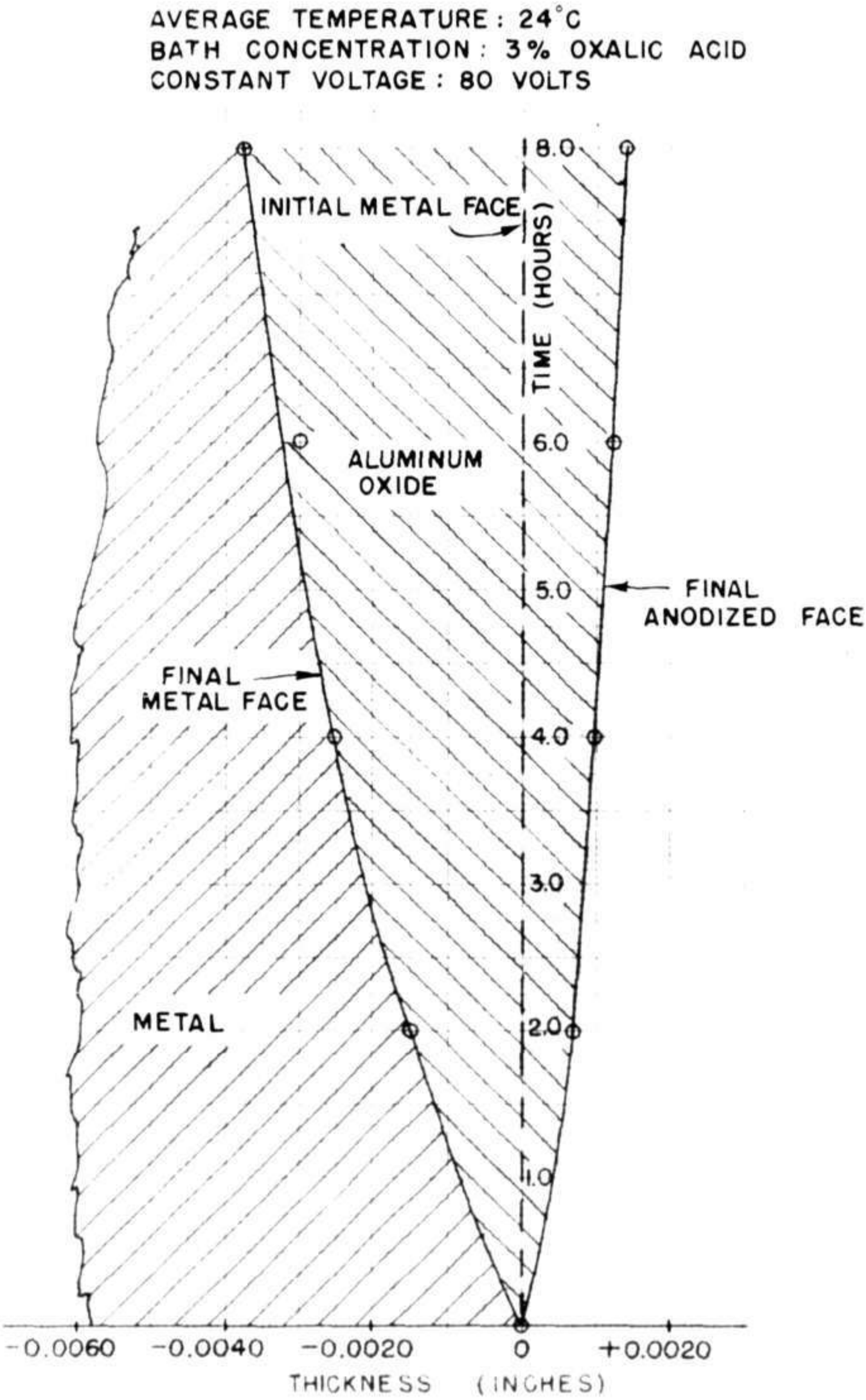
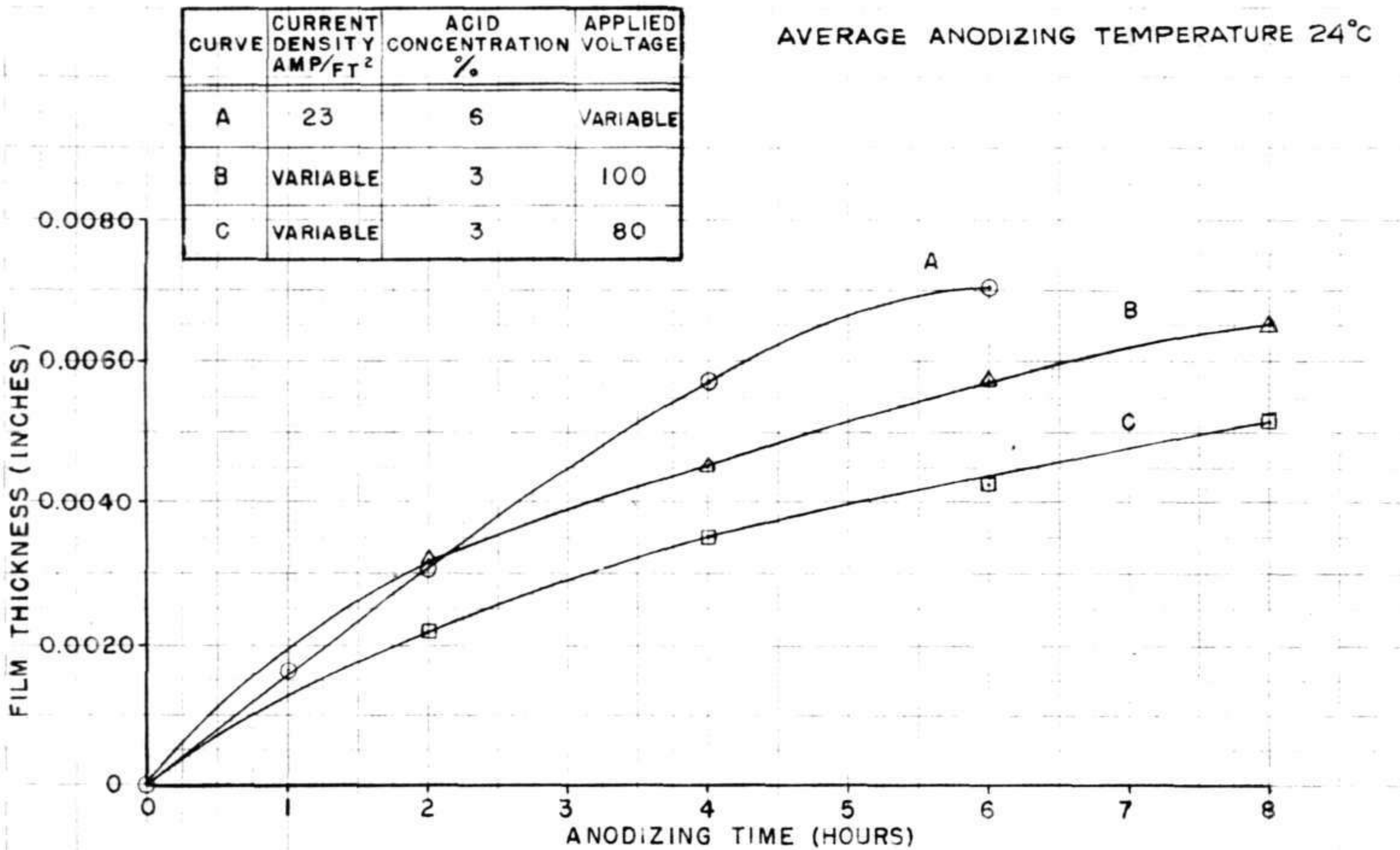


FIG. 21 GROWTH OF ANODIZED LAYER



CURVE	CURRENT DENSITY AMP/FT²	ACID CONCENTRATION %	APPLIED VOLTAGE
A	23	6	VARIABLE
B	VARIABLE	3	100
C	VARIABLE	3	80

FIG. 22 EFFECT UPON FILM THICKNESS OF VARIOUS ANODIZING CONDITIONS AT CONSTANT TEMPERATURE

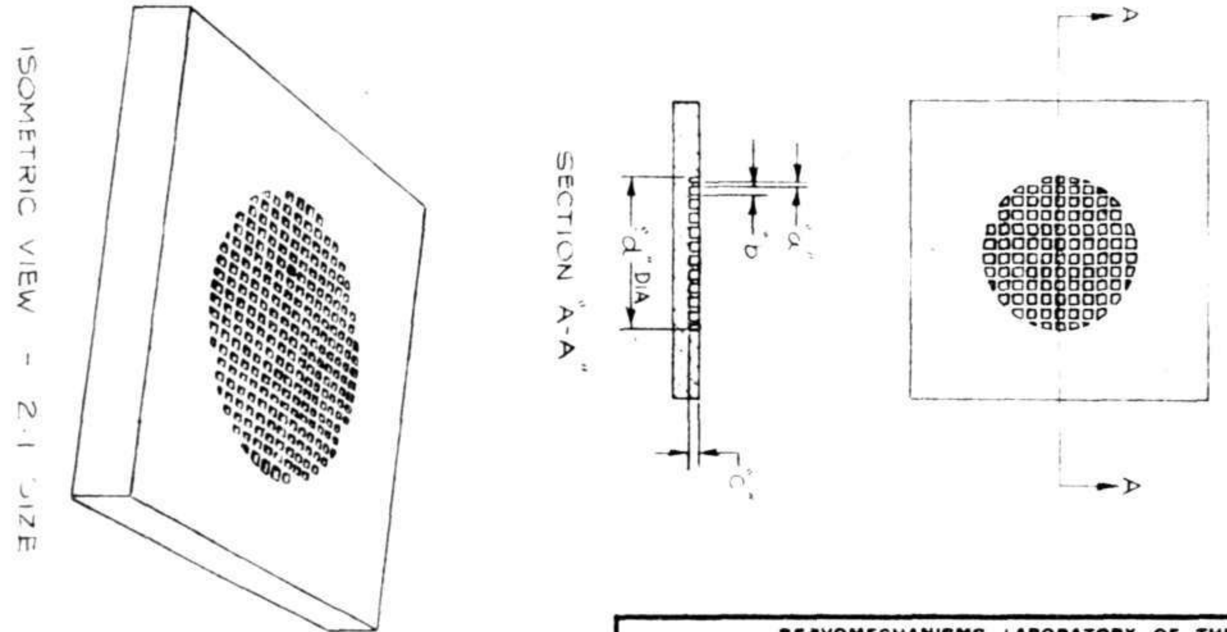


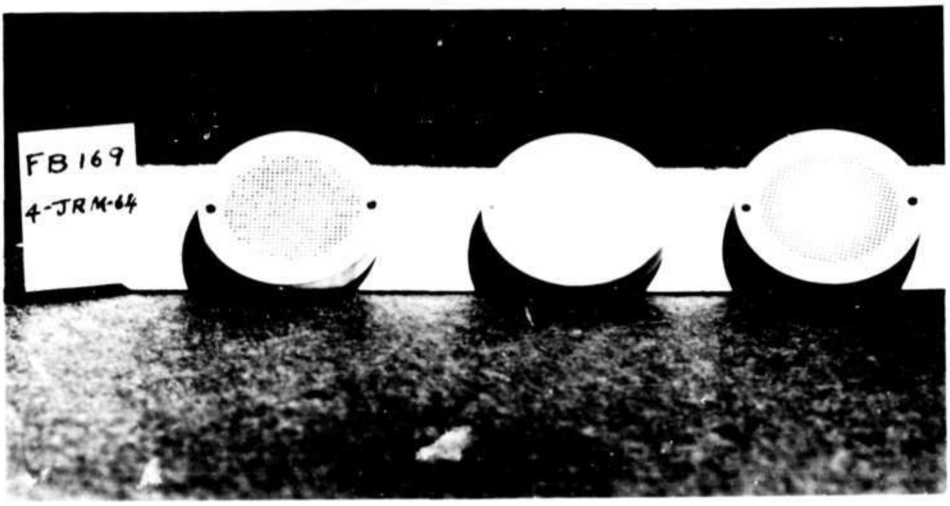
FIGURE 23

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

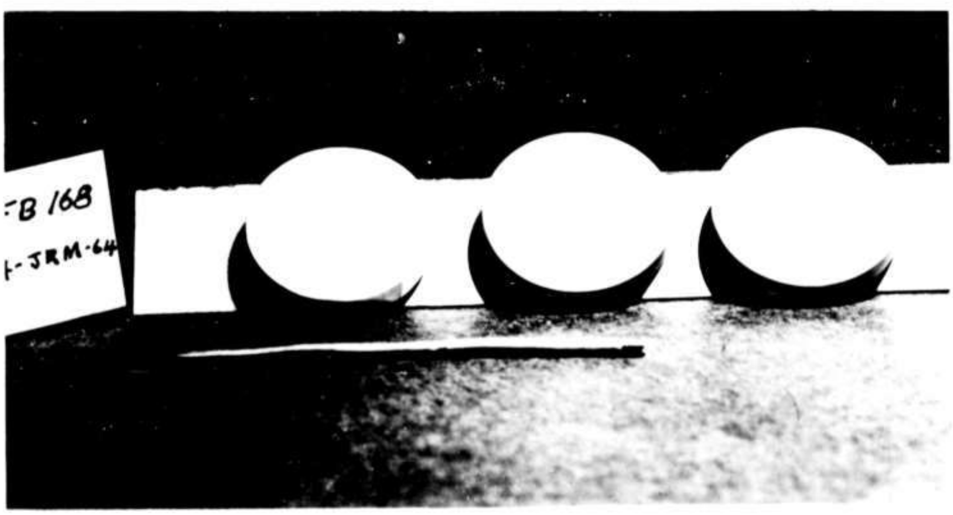
"GRIDDLE" STORAGE SURFACE

SCALE:	DR. F. B. 5-12-47		A-31162
ENG. J.K.M.	CK	APP.	

A-31161



a.



b.

SMOOTH AND GRIDDLE SAMPLES

FIG. 24

USED IN 6345 REPORT R-131

A-31161

A-30921

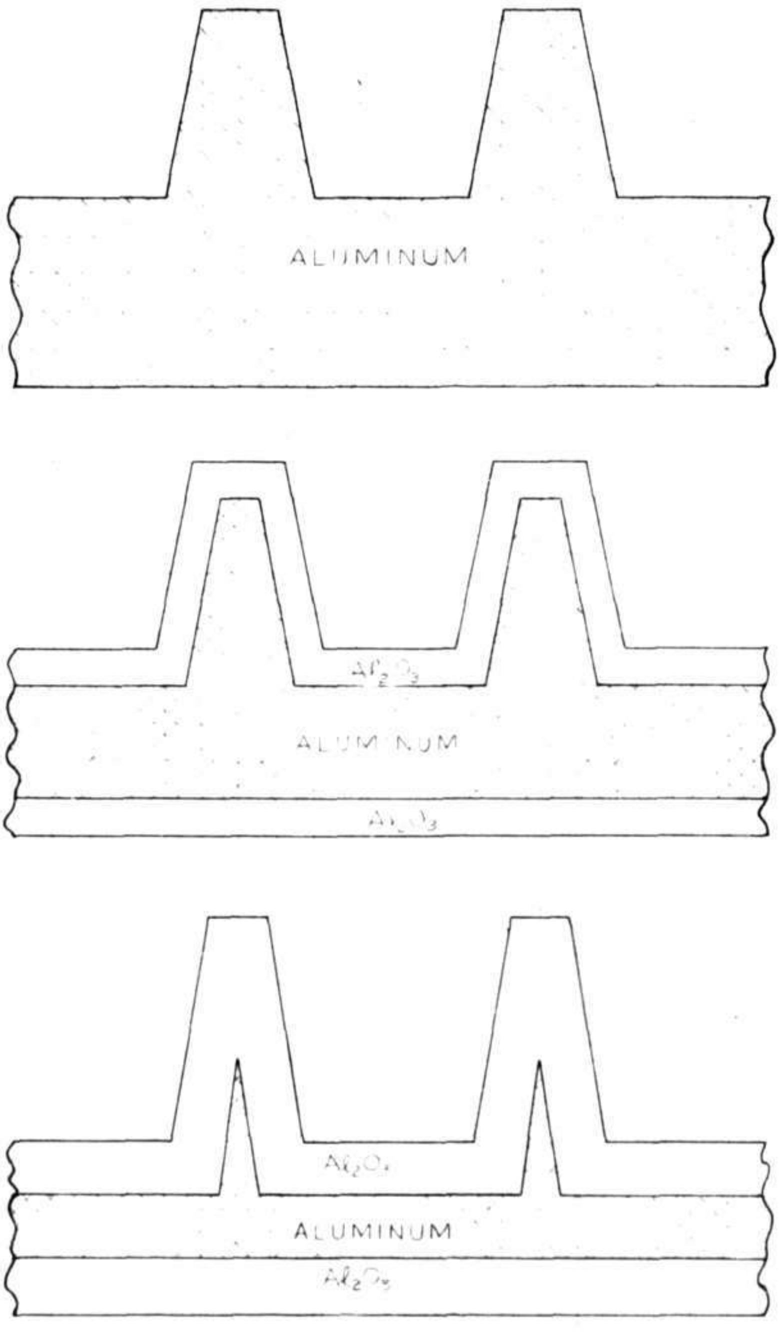


FIG. 25 STAGES IN THE ANODIZATION OF A CRINKLE SURFACE WITH SLOPING SIDES

Project Whirlwind
Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts.

SUBJECT: THE EMBOSSING AND ANODIZATION OF ALUMINUM FOR STORAGE TUBE DIELECTRIC SURFACES.

Written by: J. Ross Macdonald

Date: October 20th, 1947

Introduction

In the electrostatic storage tube being developed for the Whirlwind computers, a griddle storage surface represents one approach to the solution of the problem of secondary electron control. The general characteristics of a griddle surface are shown in Drawing A-31163, and Drawing A-31116 shows two actual griddle surfaces. Instead of being flat, the surface consists of a large number of small square pockets separated by narrow ridges. In order to form a dielectric into this relatively complicated structure it was decided first to press the pattern into soft aluminum, then to oxidize the surface of the aluminum (anodization) to form a thin dielectric layer. The griddle part of the surface of the experimental samples shown in the picture is a circle of one inch diameter, while the outside diameter of the samples is 1-3/8 inch.

Procedure Employed to Emboss Aluminum to Form a Griddle Structure

The first step in the process is the preparation of the aluminum to be embossed. In order to make a sample of the size shown in Drawing A-31116, a square 4-by-4-inch piece of aluminum is cut from 1/4-inch-thick 2S aluminum sheet. This is commercially pure aluminum, having only 0.8 percent impurities, and is used because desirable physical characteristics of the anodized aluminum layer can be obtained only through using as pure aluminum as possible. Next, a serial number for identification is stamped slightly off-center on one side of the square of aluminum. Then the other side is polished on a buffing wheel to remove scratches.

The actual embossing has been accomplished with a die made according to the specification of Drawing A-30908. A piece of 1/8-inch-thick neoprene with a 1½-inch-diameter hole in its center is placed around the outside of the die to equalize the pressure and facilitate stripping of the embossed sample from the die. The actual thickness of this neoprene sheet is determined by the height which the die face projects above the surface of the base. The neoprene should be slightly thicker than this height so that the pressure is properly equalized. Pressure for the embossing has been provided by a manual Olsen testing machine, number 201 in Room 1-210 at M. I. T. This machine provides a maximum force of compression of 50,000 pounds.

Before being placed in the machine, both the die and the aluminum sample are well lubricated with kerosene to prevent excessive sticking. Then the sample is placed in the machine on top of a heavy steel anvil. It is covered by the neoprene, and finally the die is placed on the neoprene with die face projecting downwards through the hole in the neoprene.

The pressure is then slowly applied in steps to allow the aluminum to flow adequately. The final compression applied depends both upon the height of projection of the die face above the body of the die and upon the desired depth of penetration of the die into the aluminum, i.e., upon the desired griddle pocket depth. Using the first die constructed, whose face projects 0.187 inches above the base as shown in Drawing A-30908, it was found that pocket depths of 0.0014 to 0.0018 inch could be obtained with a final compression force of 40 to 45 thousand pounds. At least five minutes should be allowed to bring the force up from zero to this value. Then the pressure should be maintained at the final value for another five minutes to allow all flow to cease (as evidenced by the pressure's finally reaching a constant equilibrium value). The pressure is then quickly reduced to zero and the sample and die removed. During most of the embossing, it was found that the thickness of the neoprene was not properly adjusted to strip the sample from the die by itself. Therefore, samples were forced free of the die with a cold chisel and hammer when necessary. As the final step in the forming of the surface, the center 1-3/8-inch diameter circular area containing the section embossed by the die is cut out on a lathe, and the sample is ready for the first step in the anodizing process.

Recommended Procedure for Embossing a 3½-inch-Square Griddle Surface

Present plans indicate that the final storage surface used may be a square having a side of 3½ inches. Numerous difficulties are anticipated if it becomes necessary to emboss a griddle surface of this size. This area is approximately 15.5 times larger than that of the sample griddle surfaces pressed thus far. Simple proportion shows that if the same pressure is required for the embossing of the larger size surface as has been used for the smaller surfaces, a force of compression of approximately 620,000 pounds will be necessary.

The largest testing machine now available at M. I. T. has a capacity of 400,000 pounds. This machine would therefore probably be inadequate for pressing 3½-inch griddle surfaces. However, Professor Cowdrey, of the Testing Materials Section of the M. I. T. Department of Mechanical Engineering, has suggested that the problem of embossing these large samples be referred to one of the silver companies in North Attleboro, Massachusetts, which normally do a large amount of such embossing. Therefore, if the need does arise to emboss samples of this size, this suggestion should be seriously considered.

The Anodization of Aluminum

Before anodizing is begun, each sample must be carefully cleaned to remove dirt and grease. After washing with soap and water and rinsing and drying with compressed air, the sample is immersed in a hot aqueous solution of sodium hydroxide (4.7 by weight) for about two minutes. This time should be rather closely controlled since longer immersions tend to form a dull film on the aluminum. After thorough rinsing in distilled water, the sample is dipped in a cold solution of nitric acid (10% by weight) for about four minutes to remove any remaining metallic impurities. Finally, the sample is removed and rinsed in distilled water again. This cycle should be repeated several times until the sample is completely clean.

Anodizing itself is carried out in a bath consisting of three parts by weight of oxalic acid to 97 parts of distilled water. Both the cleaning and anodizing baths are fully described in Reference 1. Drawings A-31115 and A-31117 show a picture of the apparatus used for anodizing. The anodizing bath is contained in a 10-inch glass jar surrounded by a 12-inch jar. The space between the jars is kept filled with water or ice for temperature control. A 3/8-inch-diameter aluminum rod is used as a cathode during the process, and the sample itself forms the anode. A filtered d-c voltage source variable between zero and 150 volts with a maximum current capacity of 8 amperes has been used for anodizing. Drawing A-30909 shows the circuit used in anodizing. Provision is made to anodize four samples simultaneously. The four wire-wound rheostats, shown also in Drawing A-31164, are used to adjust the voltage and current for the four samples individually, while larger variations can be effected by adjusting the output voltage of the power supply.

Griddle samples must be suspended in the anodizing bath so that their entire surface is immersed. And, for proper anodizing, it is necessary that the material which suspends them in the solution also be 2S aluminum. This can be accomplished by screwing a length of 0.10-inch-diameter 2S aluminum rod into a threaded hole drilled partially through the back of the sample. The rod must be screwed into the hole very tightly so that no liquid can penetrate between rod and sample during anodization.

Two separate heat treatments should be given the griddle samples to be used in an evacuated storage tube. First, the unanodized sample should be heated by radio frequency induction while in a high vacuum to remove occluded gases from the aluminum itself. Then, after anodization, the process should be repeated to drive out gases held in the anodized layer. The temperature of the sample should never exceed 400 to 500°C during this process, to avoid crazing caused by the different coefficients of expansion of aluminum and aluminum oxide.

Pore Sealing Methods

Two different methods have been used to close the infinitesimal pores in an aluminum oxide surface. In the first of these methods the anodized sample is simply boiled in distilled water for an hour. This process partially converts the amorphous aluminum oxide to aluminum oxide monohydrate ($Al_2O_3 \cdot H_2O$). The addition of the water causes the pore walls to swell, and thereby the pores themselves are closed or at least reduced in size. A signal disadvantage of this type of sealing is that heat treatment in a vacuum to remove occluded gases also removes the added water. Therefore, the sealing is destroyed by such heat treatment.

The electrolytic sealing method described in Reference 1 does not suffer from this disadvantage. The electrolytic bath used is 15% (by weight) sodium silicate in which the ratio of silica to soda lies in the range from 2.8:1 to 3.9:1. The anodized sample is made the anode and an iron rod used as the cathode. The applied voltage is increased from zero to fifty volts in the first thirty seconds. The exact procedure whereby the voltage is further increased is not critical. The following technique is recommended for its simplicity. The voltage is increased, in steps of about twenty-five volts, so that the current density immediately before an increase is 10 milliamperes/in.^{2} or less. The initial current density upon any increase may be five or ten times greater than this, but it rapidly diminishes. This series of increases should be discontinued upon reaching 375 volts, since appreciably greater voltages cause destructive sparking in the bath. This voltage should be maintained until the current density has dropped to about 1 milliampere/in.^{2} Beyond this point the current density diminishes very slowly and the sample may be removed. The entire procedure usually takes from one to two hours.

In the electrolytic method, the pores are partially filled up. The current causes negative silica ions to migrate to the anode and enter the pores of the aluminum oxide surface. Some of the silica ions form aluminum silicate while others probably are deposited as silica in the pores. This process results in a harder finished surface which is more resistant to acids and abrasion than an unsealed surface; and the fact that the pores are partially filled makes the surface much less liquid absorbent.

Removal of the Anodized Layer

In order to make measurements of the thickness of anodized layers, it is necessary to remove the layer without affecting the aluminum beneath. The following solution may be used for this purpose: 35 cc of 85% phosphoric acid and 20 grams of chromic acid are mixed with enough distilled water to make a liter. During removal of the film, the sample is immersed in the bath, which should be kept between 80 and 100°C for best results. The time necessary for the film to be dissolved is roughly proportional to the thickness of the film and is also increased by electrolytic sealing. For unsealed film thicknesses of two or three mils, the time required is of the order of half an hour. During the process, the sample should be frequently removed, rinsed, dried, and measured with an ohm-meter to determine the point at which removal is complete. At this point the resistance between two points on the surface of the sample will be negligible, whereas there will be appreciable resistance as long as any film remains.

Actually, the point at which the sample is taken out of the bath after all the film is removed is not critical, since the bath does not attack the aluminum to any extent. This was determined by measuring the initial thickness of an unanodized aluminum sample with a micrometer, than boiling it in the removal bath for thirty minutes. No change in thickness could be detected with the micrometer.

Since the chromic acid used in the removal bath is poisonous, extreme care should be used in handling the solution when hot, so that none of the fumes are breathed and none of the liquid touches the person.

Recommended Procedure for Anodizing a 3-1/2-Inch-Square Griddle Surface

The present experimental anodizing equipment might be used to anodize 3-1/2-inch-square storage surfaces, but such use would be very inefficiant. Only one such sample could be anodized at once and temperature control would be very difficult. Therefore, if more than a few such samples were required, it would be advisable to procure a larger bath container and an electric refrigerating unit. Provision should be made to anodize several samples simultaneously in the bath to save time.

It has been found that maximum film thickness consistent with film hardness can be obtained by anodizing at a constant voltage of 80 volts in a 3% oxalic acid bath. The anodizing current required at constant voltage drops off as the anodizing progresses, yet even the average current necessary for a single large griddle sample over a ten-hour anodizing period would be of the order of five amperes. Therefore, an average of 1600 watts would be dissipated in a bath in which four samples were being anodized, and a d-c power supply having a maximum capacity of 40 amperes or more would be required.

Written by J. R. Macdonald

Approved by JWF

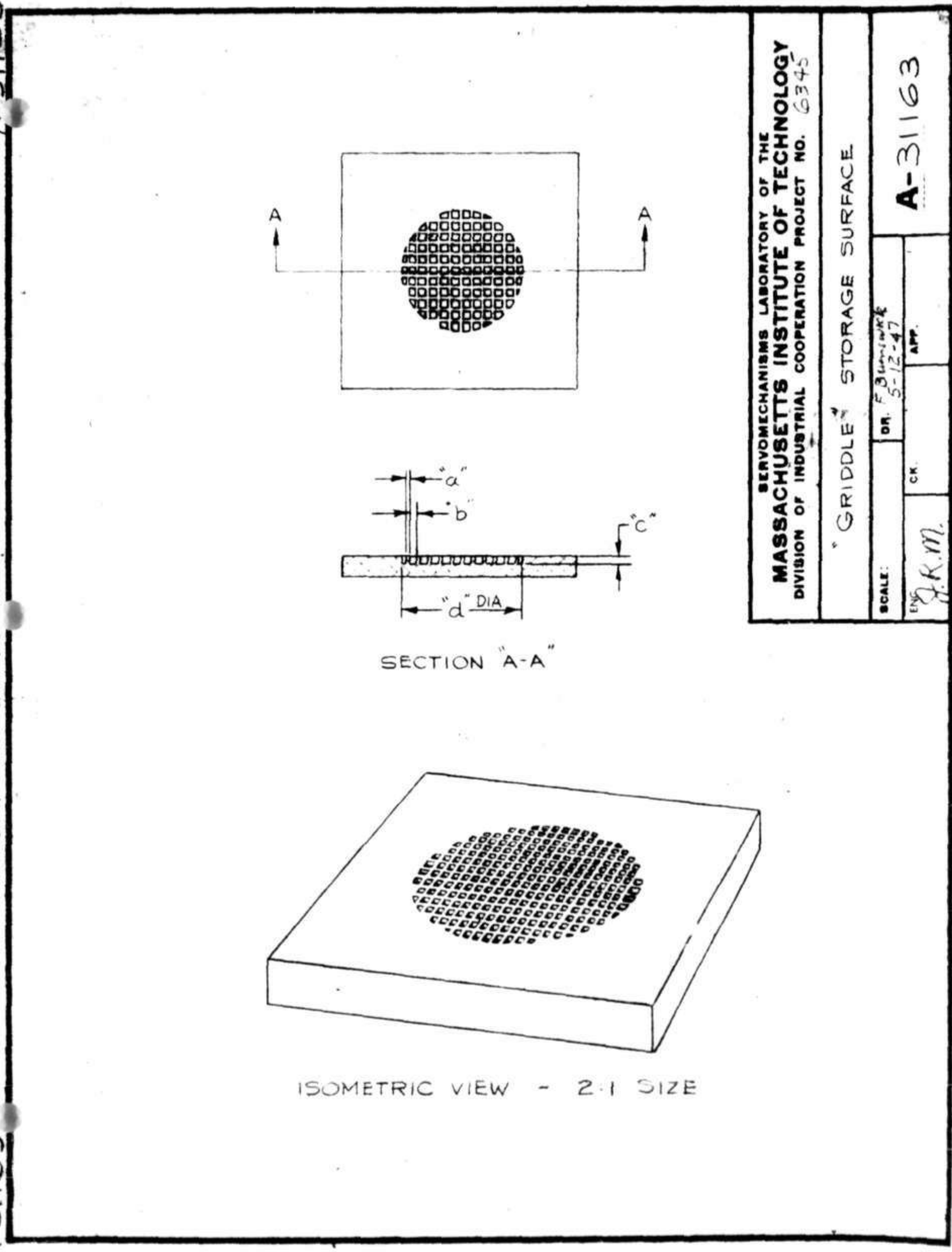
References: 1. Method of Protectively Coating Aluminum or Aluminum Alloys. Rankin, W. K. Brossman, J.R., U.S.Patent. No. 2,161,636; Issued June 6, 1939.

2. The Preparation and Testing of Anodized Aluminum Dielectric Surfaces. Macdonald, J.R., M. I. T. Servomechanisms Laboratory Memorandum No. M-67.

Drawings: A-31163
A-31164
A-30908
A-30909
A-31115
A-31116
A-31117

jrm:ohg

A-31163

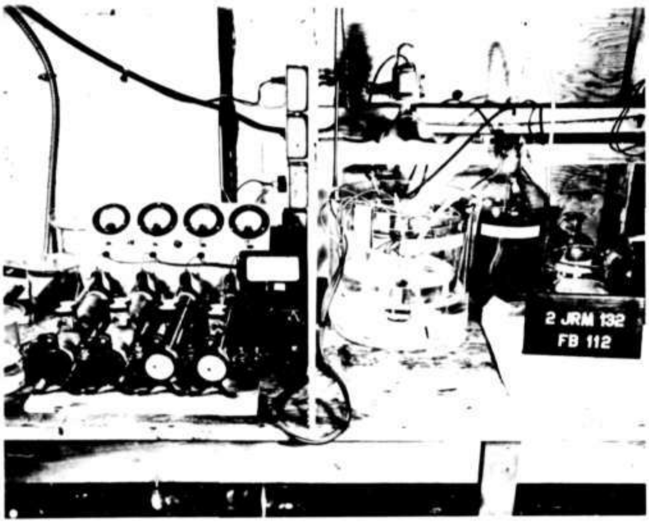


USED IN 6345 REPORT NO. R-128

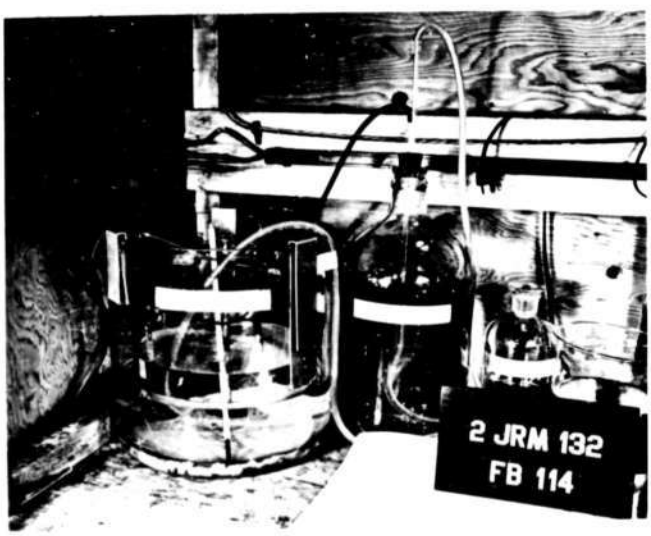
A-31163

A-31164

A-31164



a



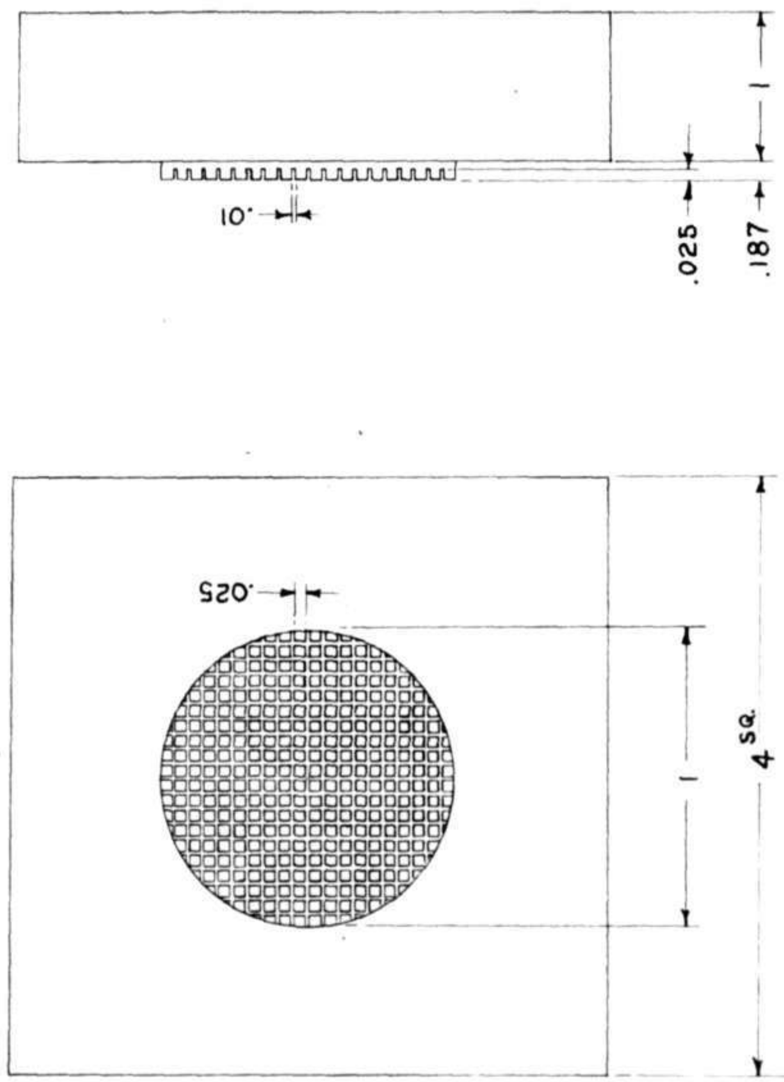
b

ANODIZING APPARATUS

USED IN 6345 REPORT R-128

A-31164

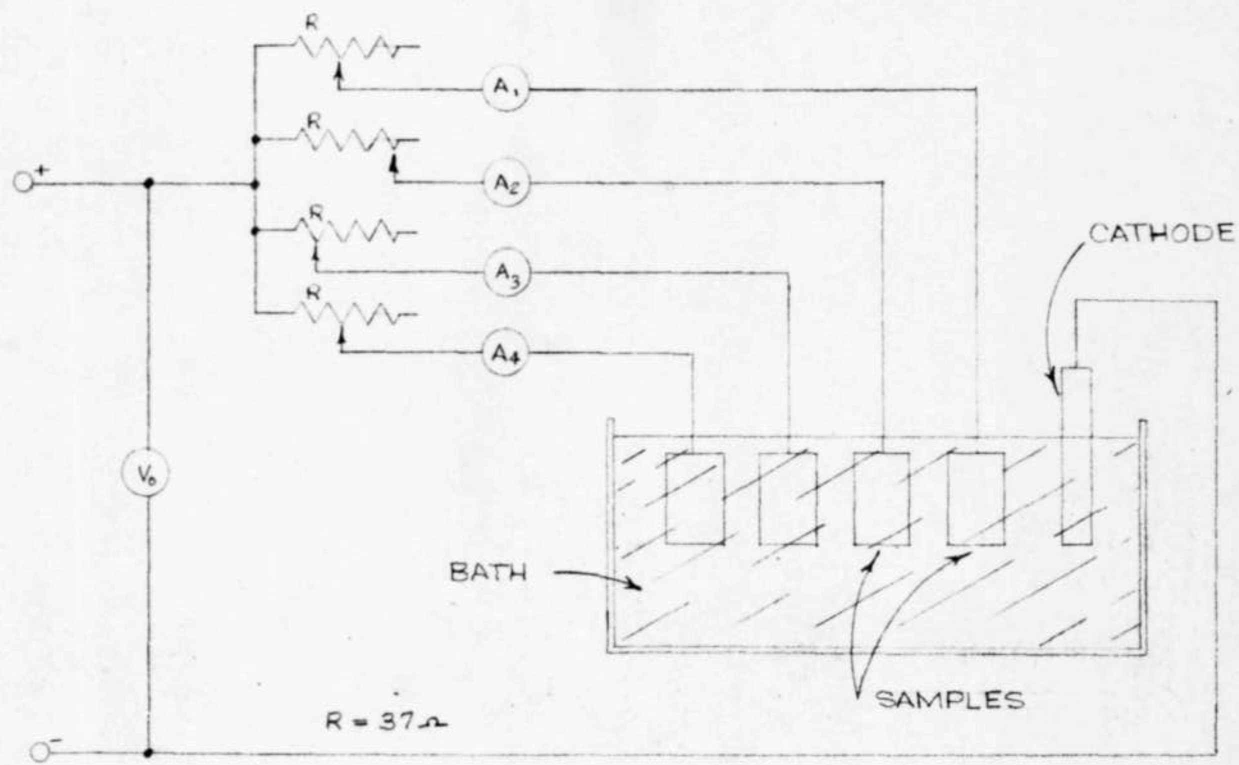
4-30908



GRIDDLE SURFACE
EMBOSSING DIE

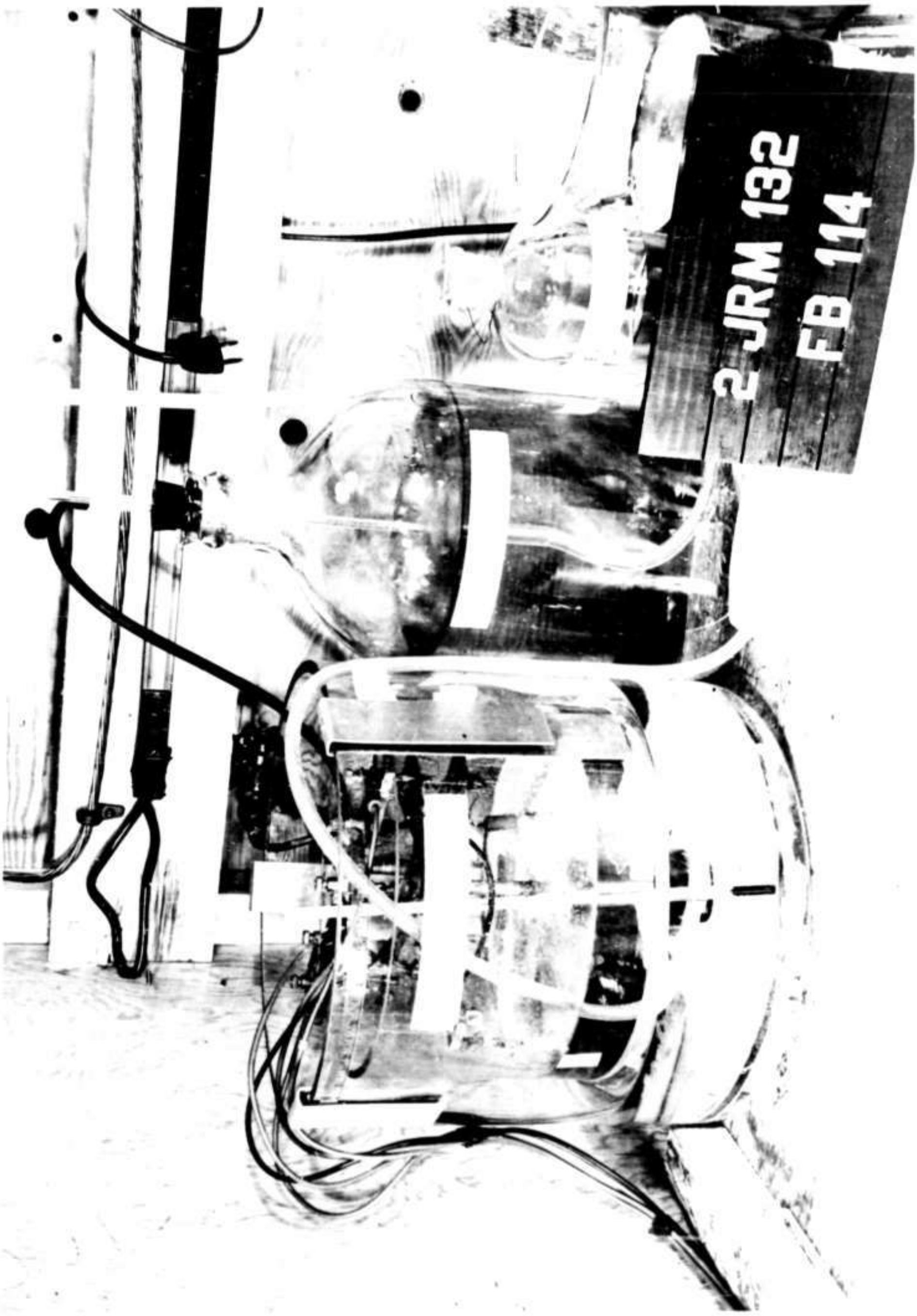
USED IN J345 REPORT NO R-128

4-30908



ANODIZING CIRCUIT

A—3111?

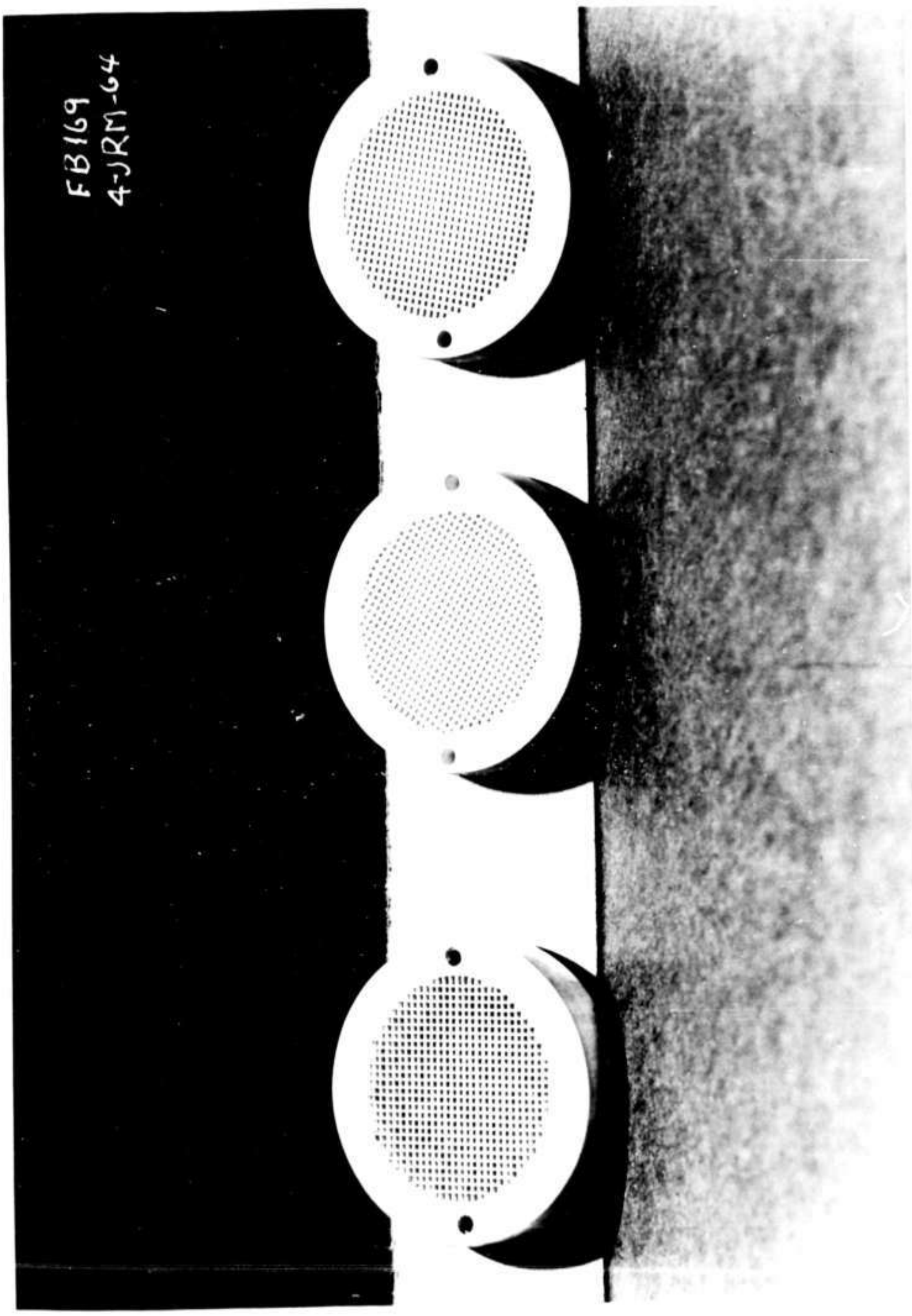


CLOSE-UP OF ANODIZING BATH

USED IN 6345 REPORT NO. R-128

A-31115

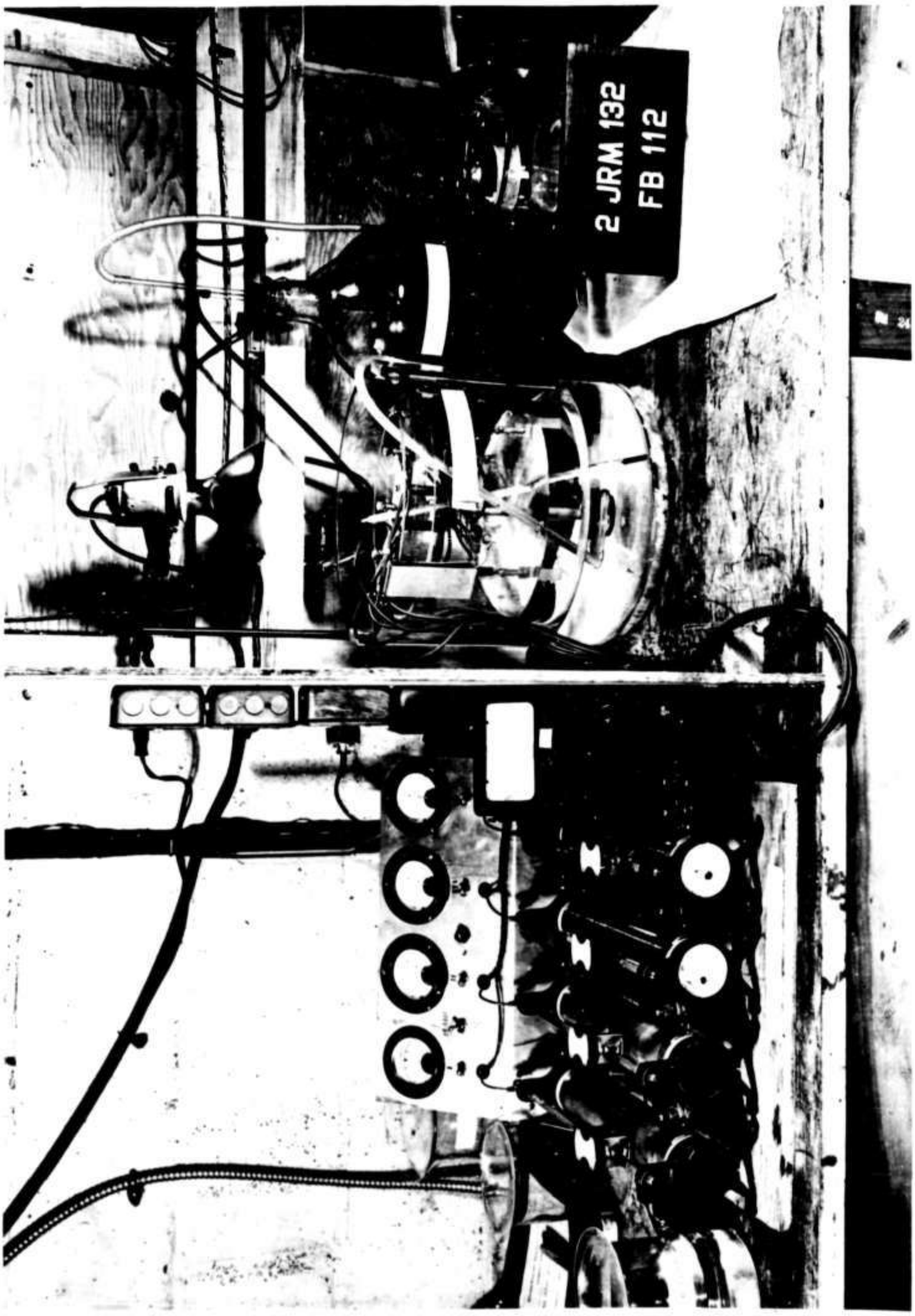
A—31116



A-31116 USED IN G345 REPORT NO. R-128

GRIDDLE SAMPLES

A-31117 USED IN 6345 REPORT NO. R-128



ANODIZING APPARATUS

6345
Report R-132

Project Whirlwind
Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

SUBJECT: STORAGE TUBE SECONDARY ELECTRON CONTROL WITH A MAGNETIC FIELD

Written by: J. Ross Macdonald

Date: October 16th, 1947

Summary

In an electrostatic storage tube, some control over the redistribution of secondary electrons created at both the signal grid wires and at the surface of the dielectric storage layer may be obtained through the use of a strong magnetic field oriented perpendicular to the storage surface.* Although this type of control has been investigated theoretically and found unsuited for final use in a storage tube, it may be of some value in experimental applications where partial control of secondary electrons is necessary.

Discussion

The case of most interest is that of negative charging of the storage surface; during such charging the signal grid is negative with respect to the surface, and secondary redistribution is greatest.** Because of the combined magnetic and electric fields, secondary electrons emitted by the incident electron beam follow helical paths of decreasing pitch as they travel away from the surface against the opposing electric field of the signal grid (see Drawing A-30913). When the initial kinetic energy of the secondaries has been entirely converted into potential energy, the electrons start back towards the surface, again following helical paths. Since the helix followed by each electron is tangent to the normal to the surface at the point of origin, the maximum distance between the point at which a returning electron may strike the surface

---

* Ref. 1, pp 62 - 64

** Ref. 2, pp 17 - 18

and its point of origin is given by the diameter of the helix which is followed (neglecting the effect of nearby charged areas on the surface), or:***

$r_{max} = 2\ (m/e)\dfrac{v_o \sin \phi}{B_z}$ where e and m are the charge and mass, respectively, of the electron; B_z is the magnetic flux density; v_o, the initial speed of the electron under consideration; and ϕ, the angle which the initial velocity vector makes with the normal to the surface at the point of origin. From this formula it can be seen that increasing the magnitude of B_z decreases the maximum redistribution distance, r_{max}.

Actually, however, for those cases in which a secondary electron completes less than one-half a helical revolution before returning to the surface, a redistribution distance less than the above maximum distance would apply. The ratio of the redistribution distance, r_H, (which applies for any number of revolutions or fractions of a revolution) to the distance an electron would travel before striking the surface in the absence of a magnetic field, r_o, is, as shown in the appendix: $\dfrac{r_H}{r_o} = R_1 \sin\left(\dfrac{1}{R_1}\right)$ where $R_1 = \dfrac{E_z}{v_{oz}B_z}$ and E_z and v_{oz} are as shown in the drawing. As shown in the appendix, this ratio reduces correctly to one in the limits of infinite electric field, or zero magnetic field, or angles of electron emission of 0 and 90 degrees from the normal to the surface. On the other hand, this ratio reduces to R_1 alone for those cases where the secondary electron completes more than a half revolution before being forced back to the surface. It is desired to make the ratio r_H/r_o as small as practical in order to reduce the redistribution distance to a minimum. However, the ratio cannot be held less than one for all angles of secondary emission since it approaches one as ϕ goes to 90 degrees. Since most electrons are emitted at angles close to the normal, the redistribution distance may be decreased for the majority of the secondary electrons by using

*** Ref. 3, pp 42, 44.

such a value of magnetic field strength that the ratio r_H/r_o is considerably less than one in the range $0<\phi<70°$. For the electric field conditions in an electrostatic storage tube, however, the value of magnetic field strength required to effect a worthwhile reduction in redistribution distance is inordinately high. As shown in the appendix, a magnetic flux density of 8000 gauss would be required to reduce the redistribution distance by a factor of ten at a value of ϕ of 30 degrees and at normal storage tube electric field conditions. So great a magnetic flux density is entirely out of the question for storage tube use. However, in cases where the electric field, E_z, at the emission surface was much lower than it is in a storage tube, the ratio r_H/r_o could be maintained less than one over the range $0<\phi<70°$ with a much smaller magnetic flux density. In such cases, magnetic control of secondary electrons might be a practical method of control.

APPENDIX

MAGNETIC FIELD CALCULATIONS

It is desired to compare the maximum secondary electron redistribution distance with an applied magnetic field to the redistribution distance without a magnetic field. A diagram showing the motion of a secondary electron liberated at the storage surface under the influence of the magnetic field, B_z, is given in Drawing A-30913. The magnetic and electric field vectors and the initial electron velocity, v_o, can be written as follows:

$$\bar{B}_z = 0 \cdot i_x + 0 \cdot i_y + B_z i_z$$

$$\bar{E}_z = 0 \cdot i_x + 0 \cdot i_y + E_z i_z$$

$$\bar{v}_o = 0 \cdot i_x + v_{oy} i_y + v_{oz} i_z$$

The parametric equations of the helical path followed by a secondary electron emitted at the point 0 with initial velocity v_o are easily calculated from $F = ma = -e\left\{\bar{E}_z + (\bar{v} \times \bar{B}_z)\right\}$ where e is the (numerical) charge on the electron, m its mass, and v its velocity. These equations are:

$$x = \frac{v_{oy}}{K_1}(1 - \cos K_1 t)$$

$$y = \frac{v_{oy}}{K_1}(\sin K_1 t) \qquad K_1 = \frac{eB_z}{m}$$

$$z = \frac{K_2}{2} t^2 + v_{oz} t \qquad K_2 = \frac{-eE_z}{m}$$

After leaving the surface at 0 and traveling outward until $\frac{dz}{dt} = 0$, the electron starts back toward the surface, which it reaches when $z = 0$. Let the total time necessary for the journey be t_o, then:

$$z = 0 = \frac{K_2}{2} t_o^2 + v_{oz} t_o \qquad t_o \neq 0$$

$$\therefore \quad t_o = -\frac{2v_{oz}}{K_2} = \frac{(2m)}{e} \frac{v_{oz}}{E_z}$$

Now, let the time necessary for an electron to complete a half revolution of the helix be t_1. A half revolution will be completed when $x = x_{maximum}$. Therefore: $x = x_{max} = \frac{v_{oy}}{K_1}(1-\cos K_1 t_1) = \frac{2v_{oy}}{K_1}$ and, $\cos K_1 t_1 = -1$.

$K_1 t_1 = (2n-1)\pi$, where n = 1, 2, 3.....

For the first half revolution, n = 1;

Therefore: $$t_1 = \frac{\pi}{K_1} = \frac{\pi m}{eB_z}$$

then: $\frac{t_o}{t_1} = \left(\frac{2}{\pi}\right)\left(\frac{v_{oz}B_z}{E_z}\right)$. Now, define the ratio $\frac{E_z}{v_{oz}B_z}$ as R_1

Finally, $$\frac{t_o}{t_1} = \frac{2}{R_1}.$$

Now, if no magnetic field had been applied, the parametric equations of the path of a secondary electron with its initial velocity in the yz plane would be:

$$x = 0$$

$$y = v_{oy}t$$

$$z = \frac{K_2}{2}t^2 - v_{oz}t$$

And the maximum excursion of the electron upon striking the surface, r_o, would be: $r_o = y_{max} = v_{oy}t_o = \left(\frac{2m}{e}\right)\left(\frac{v_{oz}\,v_{oy}}{E_z}\right)$.

In order to compare the maximum excursions with and without the applied magnetic field, two cases must be distinguished, depending upon the angle of secondary emission, ϕ, and the number of revolutions made under the influence of the magnetic field. A returning electron under the influence of magnetic field can strike the surface at a maximum distance r_H from its point of origin; which equals: $\left[x^2+y^2\right]^{\frac{1}{2}}$ at $t = t_o$.

Therefore, $$r_H = \frac{v_{oy}}{K_1}\left[2(1-\cos K_1 t_o)\right]^{\frac{1}{2}} = \frac{2v_{oy}}{K_1}\sin\frac{(K_1 t_o)}{2}$$

Since $t_o = \frac{2t_1}{\pi R_1}$ and $t_1 = \frac{\pi}{K_1}$, $t_o = \frac{2}{R_1 K_1}$

Hence,
$$r_H = \frac{2v_{oy}}{K_1} \sin\left(\frac{K_1}{2} \cdot \frac{2}{R_1K_1}\right)$$

$$r_H = \frac{2v_{oy}}{K_1} \sin\left(\frac{1}{R_1}\right)$$

The maximum excursions of a secondary electron with and without a magnetic field can be compared by taking the ratio of r_H to r_o.

$$\frac{r_H}{r_o} = \frac{\frac{2v_{oy}}{K_1}\sin\frac{1}{R_1}}{v_{oy}t_o} = \frac{2\sin\frac{1}{R_1}}{\frac{2}{R_1K_1}\cdot K_1} = R_1 \sin\left(\frac{1}{R_1}\right).$$

where $R_1 = \frac{E_z}{v_{oy}B_z} = \frac{E_z}{v_oB_z \cos\phi}$

It can now be seen that the ratio R_1 alone serves to determine under what conditions the application of a magnetic field will reduce the ratio r_H/r_o below one. The meaning of the formula for r_H/r_o can be best understood by considering two limiting cases:

<u>Case I</u>: $\frac{1}{R_1} << 1.$

Since $\frac{1}{R_1} << 1$, $\frac{\pi t_o}{2t_1} = \frac{1}{R_1} << 1$ and $t_o << t_1$

Therefore, the electron completes much less than a half revolution before returning to the surface. Because $\frac{1}{R_1} << 1$, $\sin\frac{1}{R_1}$ can be approximated by $\frac{1}{R_1}$. Then $\frac{r_H}{r_o} = R_1 \sin\frac{1}{R_1} \cong R_1 \cdot \frac{1}{R_1} = 1.$ Therefore, in this limiting case, the application of a magnetic field does not decrease the excursion of a secondary electron at all. This case is satisfied when $\frac{1}{R_1} = v_o\frac{\cos\phi}{E_z}B_z << 1$. It can thus be seen that the magnetic field makes no difference if E_z is large, and/or v_o, $\cos\phi$, and B_z are small. No matter how strong a magnetic field is applied, there is an emission angle, ϕ, sufficiently close to 90 degrees that electrons emitted at this angle will be unaffected by the field. From the form of r_H and r_o, both of which contain $v_{oy} = v_o \sin \phi$ in the denominator, it can be seen that the maximum redistribution distance is zero with or without a magnetic field when $\phi = 0$ and the electron leaves the surface normally.

Case II $\quad \frac{1}{R_1} \geq \frac{\pi}{2}$

In this case $t_o \geq t_1$ and an electron completes a half revolution or more before striking the surface. Now electrons which complete more than a half revolution can strike the surface anywhere within circles of radius $X_{max} = \frac{2v_{oy}}{K_1}$ around their points of origin, depending upon the value of the sine function $\sin\left(\frac{K_1 t_o}{2}\right)$ in r_H. Therefore, in order to compare the maximum distance which any electrons can travel under the influence of the magnetic field, the sine function must be discarded.

Then: $\frac{r_H}{r_o} = \frac{X_{max}}{r_o} = R_1 \qquad R_1 \leq \frac{\pi}{2}$

Since R_1 is less than one in this limiting case, the application of a magnetic field does decrease the maximum redistribution distance.

It is of interest to compute the value of B_z necessary to effect a decrease in the redistribution distance of 10 times at an emission angle of 30°. R_1 is then 1/10.

$$\text{Therefore, } 10 = \frac{v_o \cos \phi}{E_z} B_z$$

$B_z = \frac{10E_z}{v_o \cos \phi}$ Now if E_z is in volts/cm and v_o in cm/sec, B_z must be expressed in units of weber/cm^2. But 1 weber/cm^2 equals 10^8 gauss

Hence;

$$B_z = \frac{E_z}{V_o \cos \phi} \times 10^9 \text{ gauss}$$

Now $V_o = 5.93 \times 10^7 \sqrt{W}$ cm/sec, where W is the initial kinetic energy of a secondary electron in electron volts. W = 9 electron volts will be selected as a representative value of the initial emission energy. Now, $E_z = \frac{V_1}{d}$, and values of V_1 = 100 volts and d = 0.1 cm will be chosen to approximate storage tube conditions.

Then:

$$B_z = \frac{100 \times 10^9 \sqrt{2}}{5.93 \times 10^7 \cdot 3.01} = 8000 \text{ gauss}$$

Written by______________

Approved by______________

Reference: 1. McConnell, R.A., The Storage of Video Signals on Simple Mosaic Report 743, M.I.T. Radiation Laboratory (Feb.18, 1946)

2. Macdonald, J.R. A Storage Tube Dielectric Surface for Secondary Electron Control Masters Thesis, Electrical Engineerings Department, M. I. T., (September 12, 1947)

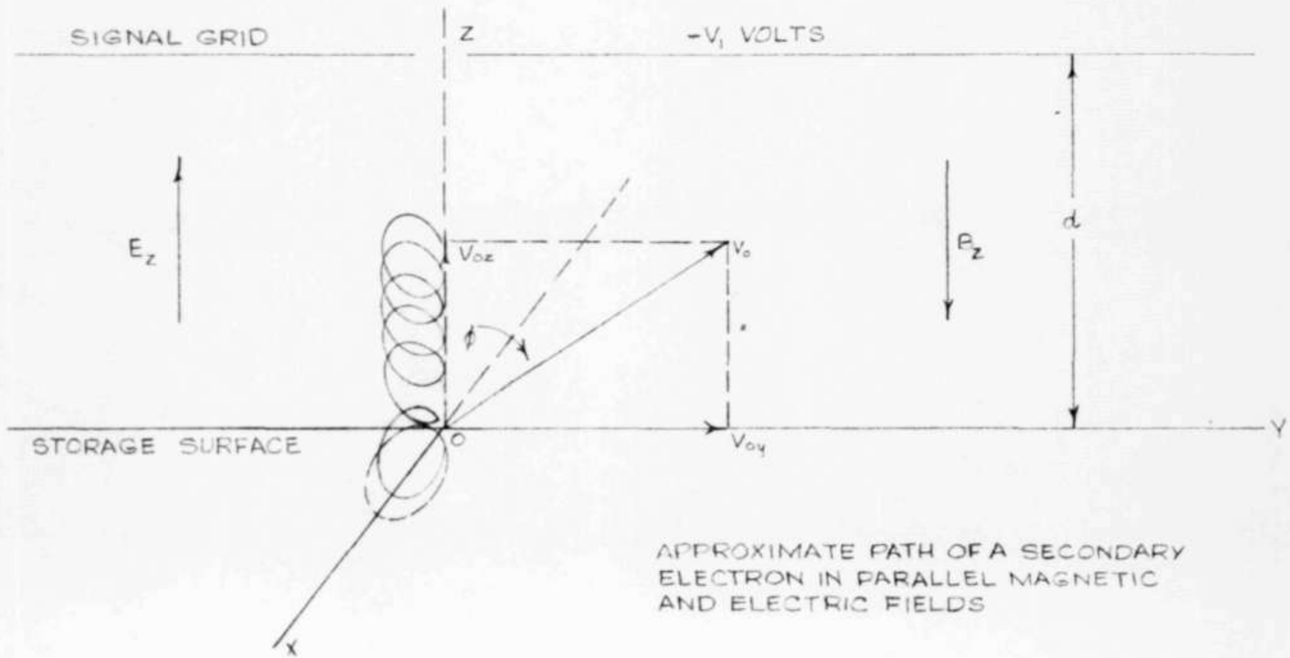
3. Members of the Electrical Engineering Staff, M. I. T. Applied Electronics (New York; John Wiley & Sons, Inc.

Drawings.

A-30913

jrm:ohg

A-30913 USED IN 6345 REPORT NO R-132



APPROXIMATE PATH OF A SECONDARY ELECTRON IN PARALLEL MAGNETIC AND ELECTRIC FIELDS

ENGINEERING NOTES NO. E-32

TO: 6345 Engineers — 6345

FROM: John C. Ely —

SUBJECT: Amplifier for Storage Tube Deflection Circuits — Drawing: B-30329

REFERENCE: Engineering Notes Nos. 31 and 33

DATE: February 20, 1947

Certain circuits under consideration for generating deflection voltages for electrostatic storage tubes are basically low-voltage, low-power decoders. These circuits, therefore, must be followed by highly stabilized amplifiers which have a high input impedance, low output impedance, gain in the range of 10 to 100, peak output of about 300 volts balanced to ground, and frequency response substantially flat from 0 to 2 megacycles per second when loaded.

One amplifier has been built and tested in the laboratory with the object of investigating the suitability of type 4D32 tubes for the output stage and, incidentally, of testing a particular type of circuit for the output and driver stage.

Drawing No. B-30329 is a schematic of the circuit used. Design was carried out on the basis of a number of estimates, particularly concerning the performance of 6Y6 tubes with feedback to the screens. With a load of 150 micromicrofarads from each plate to ground and 20 micromicrofarads from plate-to-plate, the estimated response to a step function is 2-1/2 microsecond rise time from zero to 99.9% of the output amplitude. Useable peak output was estimated to be 200 volts plate-to-plate.

Tests with a dummy load of approximately 180 micromicrofarads from each plate to ground and approximately 40 micromicrofarads from plate-to-plate showed that the actual rise time of the output was not more than 3 microseconds from 0 to as near 100% as could be measured on a DuMont Type 208 Oscilloscope when an approximately square wave with a rise time of less than 0.2 microsecond (derived from the circuit described in Engineering Notes No. E33) was applied to the input.

Gain at zero frequency measured approximately 6.5 for small input voltages. At 20 kc the gain measured about 6.5 when the output voltage was approximately 150 volts, peak-to-peak. Gain, measured on a 100 kc square wave was also approximately 6.5 when the output voltage was approximately 150 volts peak-to-peak. Feedback factor could not be measured directly, but indirect measurements indicated that the circuit had between ten and eleven db of negative feedback.

Linearity on d-c deflections was poor--apparently much worse than on a 20 kc sine-wave. This is probably due to change of resistance with load of the plate load resistors in the driving stage, since, with a d-c difference of 120 volts plate-to-plate at the output, the difference in heating of the two resistors was noticeable. Approximately 250 volts output (peak-to-peak) was obtained at 20 kc without serious departure from linear operation. It is believed that most of the non-linearity arises in the driving stage, since the plate characteristics of the output tubes (4D32) indicate that at least 300 volts peak-to-peak output should be obtainable across the load resistance used in this amplifier with no serious departure from linear operation.

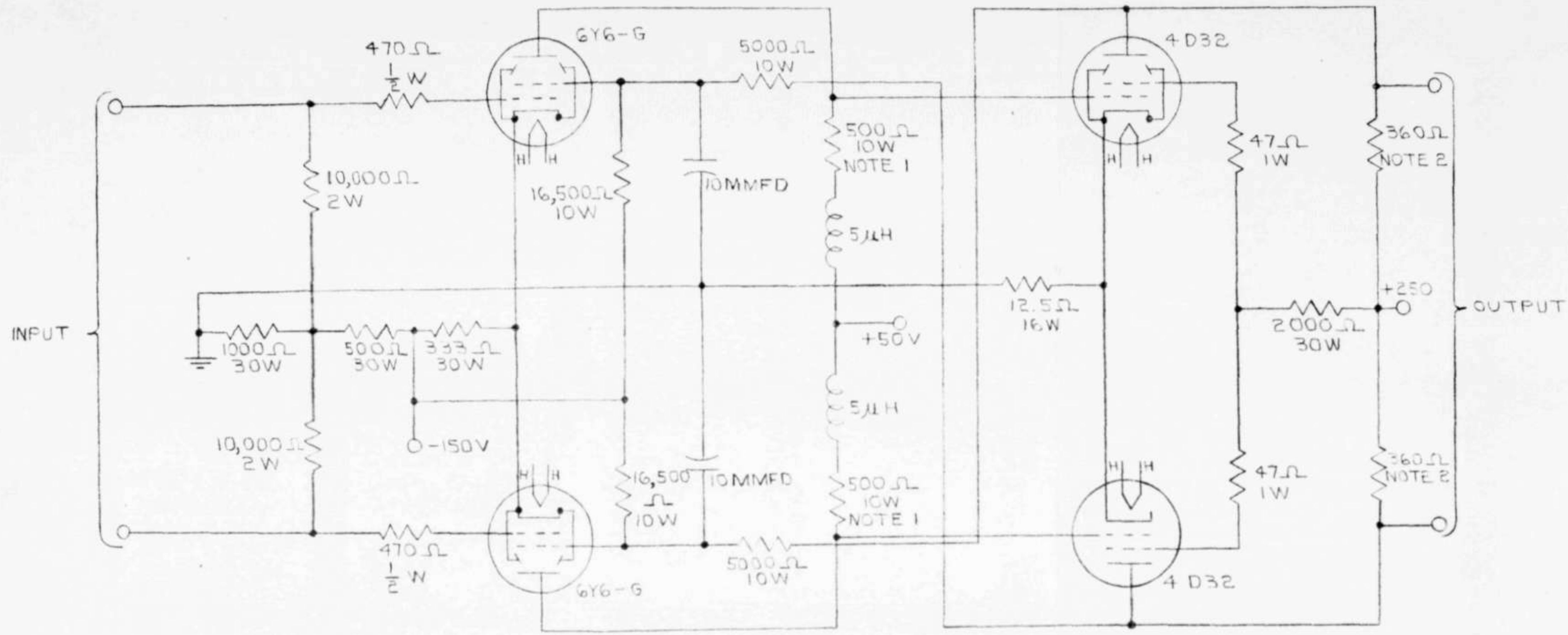
As was expected, some difficulty was experienced with oscillations in the amplifier. The first type encountered was a parasitic of very high frequency which appeared when a driving source was connected to the input. This oscillation was swamped out by addition of 470-ohm resistors in series with each grid of the 6Y6 input stages. A modification which increased the negative feedback also introduced a phase-shift oscillation involving the feedback circuit. An attempt was made to correct the phase-shift around the loop by use of shunt peaking in the 6Y6 plates and capacitive compensation of the feedback voltage divider. It was found, however, that the oscillation could not be reduced below about 15 volts amplitude in this way. It was then decided to reduce the high frequency response of the feedback divider by adding enough capacitance from the screen of each 6Y6 to ground to give stable amplifier operation. This attempt was successful. The capacitance was set at the lowest value which gave stable amplification. This value gives the best rise time available from the amplifier as now built, but there is some tendency for the amplifier to put overshoots on fast-rising or falling wave-fronts.

Wire-wound resistors were used throughout the amplifier except for the grid-leak resistors on the input and the cathode resistor on the output stage. No wire-wound resistor dissipated more than 1/2 rated power, but the heating was still excessive. It appears that wire-wound resistors for an application such as this must be run below about 1/5 of their nominal rated dissipation if change of resistance due to heating is to be avoided. The resistors used for the plate load of the 4D32 output stage were non-inductive meter-testing resistors manufactured by the States Company. Each load consisted of a 1/2 ampere resistor in series with a one ampere resistor so that the limiting rating of the combination was one-half ampere. No appreciable heating was observed in these resistors at any time.

Results obtained with this amplifier indicate that a design suitable for driving at least ten electrostatic storage tubes in parallel can be developed using type 4D32 output tubes. A design using a tube such as the 6AG7 in the input stage and a cathode-follower intermediate stage to drive the 4D32 grids probably can reach a gain of five for the amplifier with good linearity and as much as ten db of negative feedback.

John O. Ely
John O. Ely

JOE:has



NOTE: 1. SPRAGUE KOOLOHM NON-INDUCTIVE WIRE-WOUND
2. STATES CO. WR200A IN SERIES WITH STATES CO. WR201A

TEST CIRCUIT-DEFLECTION DRIVER AMPLIFIER

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SERVOMECHANISMS LABORATORY

W.I.C. NO. 6345	DR. DLO 2/19/49	CK. TL 2/19/49
ENG. [illegible]	APP.	B-30329

ENGINEERING NOTES NO. E-31

TO:	6345 Engineers	6345
FROM:	John O. Ely	Page 1 of 7 pages
SUBJECT:	Deflection Circuits for Storage Tubes-Present Status of Work	Drawings: B-30330 B-30331 B-30332 B-30333
REF:	Engineering Notes Nos. E-32 and E-33	
DATE:	February 20, 1947	

I. Purpose of Notes

Work is proceeding on certain aspects of the problem of producing deflection voltage circuits for electrostatic storage tubes. This Memorandum is intended only informally to present ideas which are now being followed. Work should be far enough along to permit a formal report to be issued by March 31st. Progress in the interim will be covered by further Memoranda or Engineering Notes. Comments and suggestions are invited.

II. Basic Assumptions

In order to carry out the design, analysis, and evaluation of circuits, it is necessary either to know or to assume characteristics of input stimuli to be supplied to the circuits and output voltages required to be produced as well as impedance levels at input and output terminals. The following specifications have been assumed for the work now in progress.

A. Input

1) Parallel digit transmission will be used.

2) Only the a-c component of voltage on bus is significant.

3) Signal will consist of five co-incident approximately rectangular pulses whose amplitude is between ten and twenty volts and whose duration may be from 0.1 to 0.35 microsecond.

4) Input impedance of deflection circuit decoder must be high in order to avoid loading signal bus.

B. Output

1) The load will consist of approximately 640 cathode-ray tubes using electrostatic deflection.

2) Balanced deflection voltages will be required.

3) Each deflection plate pair will have a maximum direct capacity of two micromicrofarads from plate-to-plate and seven micromicrofarads from

each plate to ground. Methods of connecting tubes together are discussed below.

4) Deflection factor will be from 50 to 100 volts/inch. Maximum deflection of about 3-1/2 inches is expected. Computations have been based on a figure of 3.2 inches maximum deflection with a deflection sensitivity of 100 volts/inch.

5) Circuits are assumed to be required to produce 32 distinct values of deflection voltage in each coordinate (corresponding to 1024 positions of beam on target) from plate-to-plate. Zero volts plate-to-plate may or may not be included as one value.

6) It is assumed that satisfactory storage operation will result if the extreme long-time variation in the position of any particular spot from its nominal position does not exceed 1/2% of the length of a line on the storage surface and if the successive deflections of the spot to any storage location each fall within 1/4% of the length of a line. A ± 5% variation in length of a line is assumed to be tolerable.

7) An interval of 3 microseconds from the time a storage order appears on the computer bus is allowed for the establishment of the deflection potentials. This means that the time constant of any transients involved must be about 0.3 microsecond or less if 1 microsecond is allowed for operation of the switch associated with the decoder. Actually, if the switch is incorporated in the decoder, only 1/2 microsecond or less will be needed for switch operation.

8) No consideration has been given to the change in deflection factor which may result from changing potentials in the storage assembly for reading and writing. It has been assumed further that shielding adequate to reduce the deflection of the beam by stray electric and magnetic fields to negligible proportions will be employed.

9) Deflection potentials established by one storage order will be maintained until the next storage order is received by the decoder.

10) Storage tubes will be mounted on 6 inch centers. Storage tube bank will be about 20 feet long by

8 feet high.

III. Connection of Deflection Plates

It would be highly desirable to have corresponding deflection plates of all tubes in the bank connected in parallel and driven from one source. This may be done in two ways. If tube connections are grouped so that the tubes are connected together by many short lengths of cable fed in parallel, the propogation time in the cable can be neglected and the load treated as a pure lumped capacitance. If, however, the tubes are tied in at uniform intervals on a single length of cable, the resulting time of propogation from one end to the other may not be neglected. The cable can then be terminated in its characteristic impedance and the load treated as an approximately pure resistance. Because of the large amount of connecting conductor required, it will probably be necessary to use shielded cable for connections. Shielded, balanced, two-wire line might appear desirable; however, the available types of such cable are low-impedance high-capacity lines. The use of two separate co-axial cables for each group of pairs of plates seems indicated.

If RG62/U cable (93 Ω, 13.5 μμf/ft) is used, the characteristic impedance of the loaded cable will be about 57 Ω and the delay in the cable connecting 640 tubes will be about .64 microsecond. If RG63/U cable (125 Ω, 10 μμf/ft) is used, the characteristic impedance of the loaded cable will be about 70 Ω and the delay will be about <u>0.71</u> microsecond. Using connections such that the line is unterminated and the load is a pure capacitance, connection with RG62/U will give a total capacity for both tube and cable about .012 to .013 microfarad from each input terminal to ground. Connection with RG63/U would result in a slightly smaller total capacity, possibly a total figure of .011 to .012 microfarad. This indicates that in order to get the time constant of 0.3 microsecond or less which we require, the driving source must have a resistance of about 20 ohms.

It has been suggested that the line may be terminated by a resistance equal to the characteristic impedance of the line in series with a capacitor large enough to give a time-constant for the combination several times as long as the delay in the line. The capacitor may be shunted by a resistor several times as large as the characteristic impedance of the line. Such a termination would allow the use of large peak currents to charge the line and lower steady currents to maintain the potential once it is established, allowing somewhat smaller tubes to be used in the driving amplifier.

Practicability of designing circuits to produce the required voltages across a resistance as low as 20 ohms is open to question. Even the figure of 70 ohms (terminated line) is low, since, if a voltage of 150 volts each side of ground must be developed, this will require control tubes which can supply a current of over 2 amperes continuously. It may, therefore, be advantageous to split the storage bank into sections, using one decoder to set up potentials to drive a number of amplifiers, each of which in turn drives a section of the storage bank.

IV. Decoder Circuits Under Consideration

The following decoding schemes, listed in order of probable merit, are now under consideration:

A. Binary Weighted Voltage Divider

This type of circuit is represented in a simple form on Drawing No. B-30333. Immediately after the receipt of a reset pulse on the reset line, all the flip-flops are conducting on the 1 side and cutoff on the 0 side. The grids of switch triodes V1, V2, V3, V4, and V5, are each tied to the 0 side of their corresponding flip-flops. Plate-supply voltages of the flip-flops and switch triodes are so arranged that the cathodes of all triodes will be at or slightly above ground. This puts the cathode of each crystal diode at or slightly above its anode so that negligible current flows through the diodes. The voltage at the output terminal is then zero. When pulses representing a storage position are received on the input lines, the flip-flops which get a positive pulse will switch so that the 1 side is cutoff and the 0 side conducts. This lowers the grids of the corresponding switch triodes, allowing their associated diodes to conduct and turning off plate current in the triodes. Resistances R2, R3, R4, R5, and R6, are arranged so that, for equal voltages across each resistance and its associated crystal diode, they draw currents whose ratios are 1:2:4:8:16. If R1 is very small compared to the combined resistance of R2, R3, R4, R5, and R6, in parallel, the voltage at the output will be proportional to the binary number input within a fraction of one per cent.

As shown, the circuit is capable of producing a peak output of about 1-1/2 volts. This figure probably can be increased considerably, perhaps by a factor of ten, by using a cathode follower whose grid is tied to the output line to adjust the voltage across the current-determining resistors. Amplification will still be required to get sufficient peak voltage and to match the high impedance decoder to the low impedance load. Drift in value among the various resistors may introduce serious difficulties. Balanced output can be secured by simply adding another set of switch triodes, diodes, and resistors, controlling the triodes in the second set from the opposite side of the same set of flip-flops.

B. Voltage-Regulator Type Decoder

A schematic of this circuit is shown on Drawing B-30330. The name is chosen because of the similarity between the circuit and a conventional series dropping tube type of regulator. On the diagram the beam power to triode V1 is the series dropping tube. V2 is connected as a variable shunt conductance across the output so that the fall time of the output voltage will be more nearly equal to the rise time. V3 is an amplifier inverter tube to drive the grid of V1. The signal at the grid of V3 is a fraction of the voltage between the cathode of V1, which is the output terminal, and a precisely regulated constant negative voltage $-E_{cc_1}$.

R5 and one of the resistances R6 through R37 determine the size of the fraction. If a large fraction of the voltage across the divider is fed back to the grid of V3, the output voltage will be low, while a smaller feedback fraction causes V1 to conduct more so that the output voltage is higher. Choice between the various upper legs of the voltage divider is obtained through diode switches composed of V4, V36, and V68, or V5, V37, and V69, etc.

Potentials are arranged so that when the triode of any switch is turned on and all other triodes are turned off the lower diode (on the schematic) associated with the triode will be biased off while the upper conducts. If the sum of the drops across R5 and the resistor (R6 - R37) associated with the conducting diode are large compared to the drop across the diode, the output will then be almost completely independent of tube characteristics.

As shown on Drawing No. B-30330, the circuit has only one stage of amplification in the feedback loop. A three-stage amplifier may be required to secure sufficient gain, but will greatly increase the difficulty in eliminating oscillations due to phase-shift around the loop. Adaptation of the circuit for balanced operation requires the addition of another complete set of control and switch tubes only, the same flip-flops and 32-position input switch serving for both sets. Balanced operation will materially lessen the difficulty of achieving sufficient regulation on the positive and negative power supplies for the system.

Difficulties expected to arise in this type of circuit are chiefly the phase-shift oscillations mentioned above and change of resistance values with age and temperature.

C. Carrier Type Decoder

Drawing B-30331 is a schematic for the elementary form of this circuit. A high-frequency (10-30 mc) carrier of constant amplitude is generated by the R.F. generator. The carrier is fed through an amplifier whose gain is a known function of a d-c control voltage and then through a linear power amplifier whose gain is stabilized by an r-f negative feedback loop. Oppositely polarized diodes rectify the output and develop a balanced d-c voltage across the load. The output of the power amplifier is also applied to the upper end of a voltage divider whose ratio may be switched to any one of 32 values by means of a diode-triode switching arrangement. A diode-rectifier and r-c filter change the output of the divider to a negative d-c bias which is then applied to the control input of the variable gain amplifier.

Advantages of this system would be that the control stages work at a low power level, the control signal is derived from the actual output voltage, and the power amplification required is done in a-c circuits operating at optimum impedance levels. Considerable difficulty may be experienced in arranging time constants throughout the system so that the required rise time can be secured without running into oscillations at high frequencies.

D. Ladder-Network Type Decoder

Schematic diagram is shown on Drawing B-30332.

In operation digits representing one co-ordinate of the storage position are applied to the input of the 32-position switch. As soon as the switch is set, a pulse is supplied through the switch to the selected flip-flop, which then switches on the corresponding pentode.(V3 through V33). Plate current of the pentode flows through R5 and the ladder-network attenuator in series, causing a voltage at the output. The drop across R5 is fed through an amplifier back to the screens of the switch pentodes in such a way that an increase in pentode plate current causes a decrease in screen voltage. If the gain around the feedback loop is high enough, the drop at the plate of any pentode when its control grid is at a given potential will be substantially independent of tube characteristics. Since the voltage at the output is the sum of the drop across R5 and the drop across the ladder network multiplied by the attenuation factor of the sections of the network between the conducting tube and the output terminal, the output also will be substantially independent of tube characteristics.

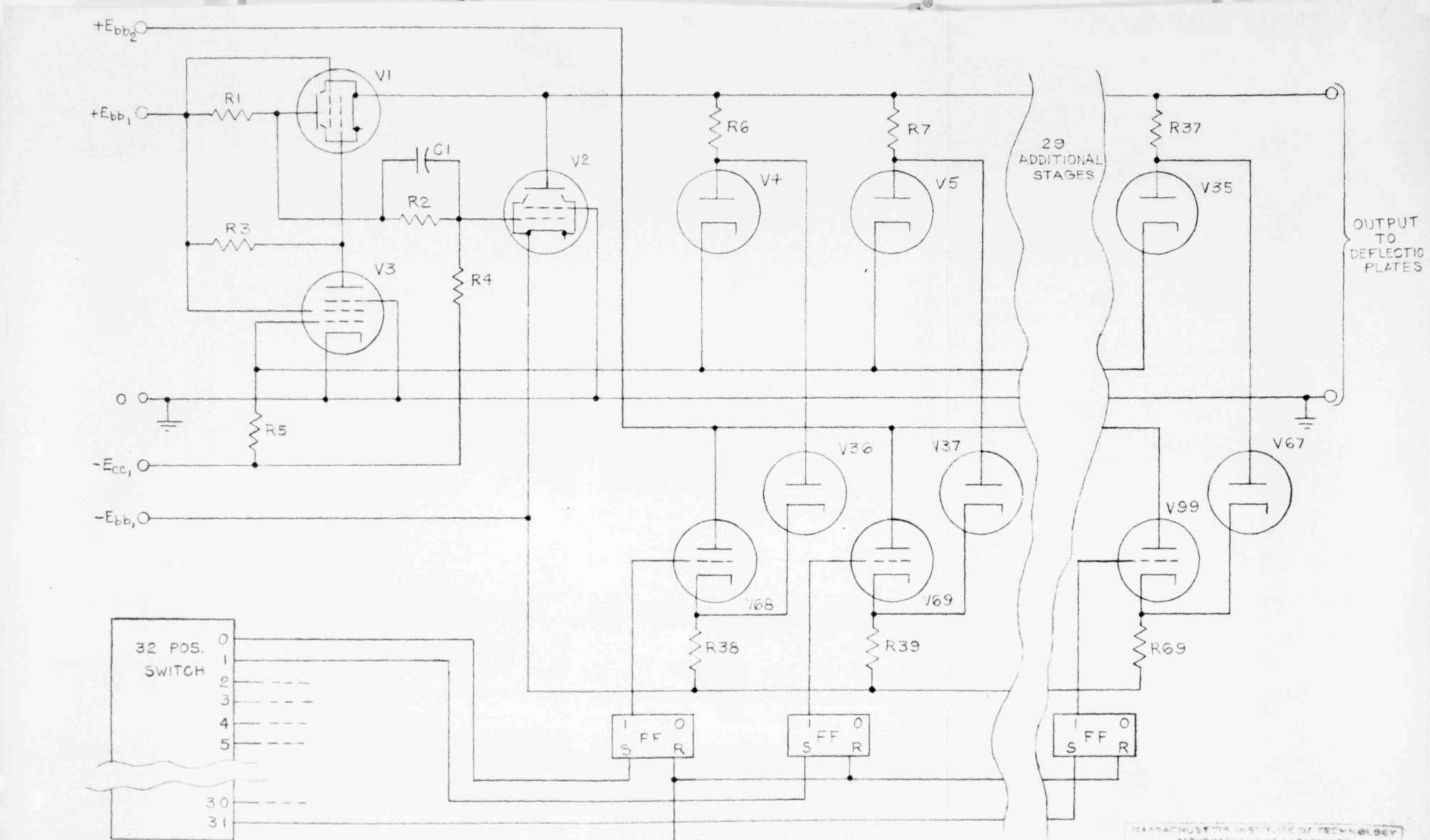
Chief advantage claimed for this circuit is that all switch pentodes operate under identical conditions and it is expected that a number of identical tubes can be caused to draw equal currents through equal load resistances more easily than the same number of identical or different tubes can be made each to draw a different assigned value of current through a different value of resistance. Successful operation, however, depends on securing a very high gain around the feedback loop, and this does not appear to be very feasible at the present time. The resistances in the ladder network are all of odd values and must be cut to rather close tolerances, while very high stability is required in all resistance values in the circuit with regard to aging, temperature variation, and voltage and current variation.

V. Driver Amplifiers

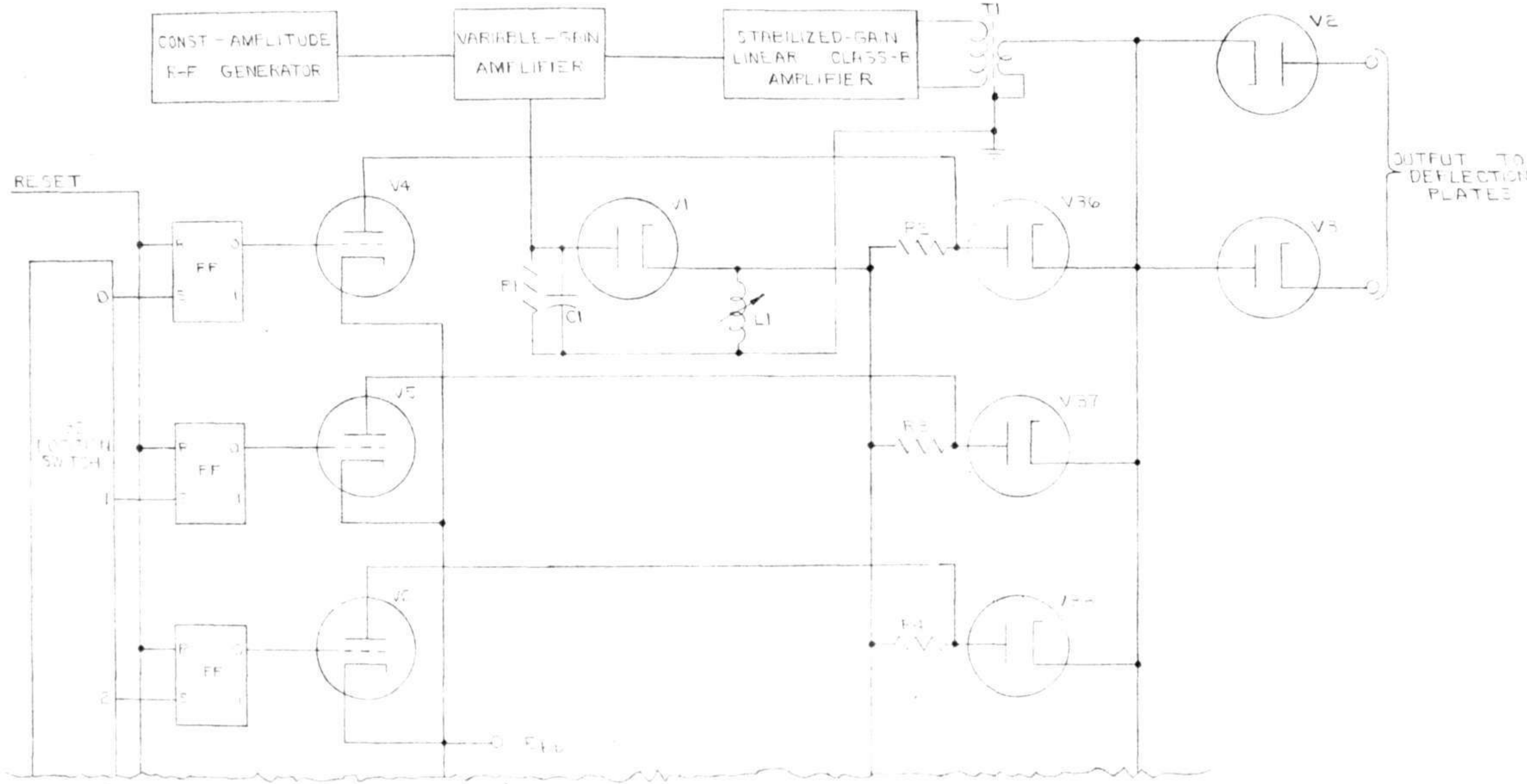
Since two of the decoding circuits under consideration do not produce sufficient output to drive the deflection plates directly, some consideration has been given to amplifiers for driving low resistance and high capacitance loads. The need for gain stability requires use of a large amount of negative feedback, while the requirement that any given deflection voltage shall be maintained for an indefinitely long time (until a new storage order is received) leads to d-c coupling throughout the amplifier. One amplifier has been built and tested driving a load equivalent to about ten pairs of cathode-ray tube deflection plates connected in parallel with RG62/U cable, unterminated. Results of the tests are reported in Engineering Notes No. E-32.

John O. Ely

JOE:has



VOLTAGE-REGULATOR TYPE DEFLECTION-VOLTAGE GENERATOR



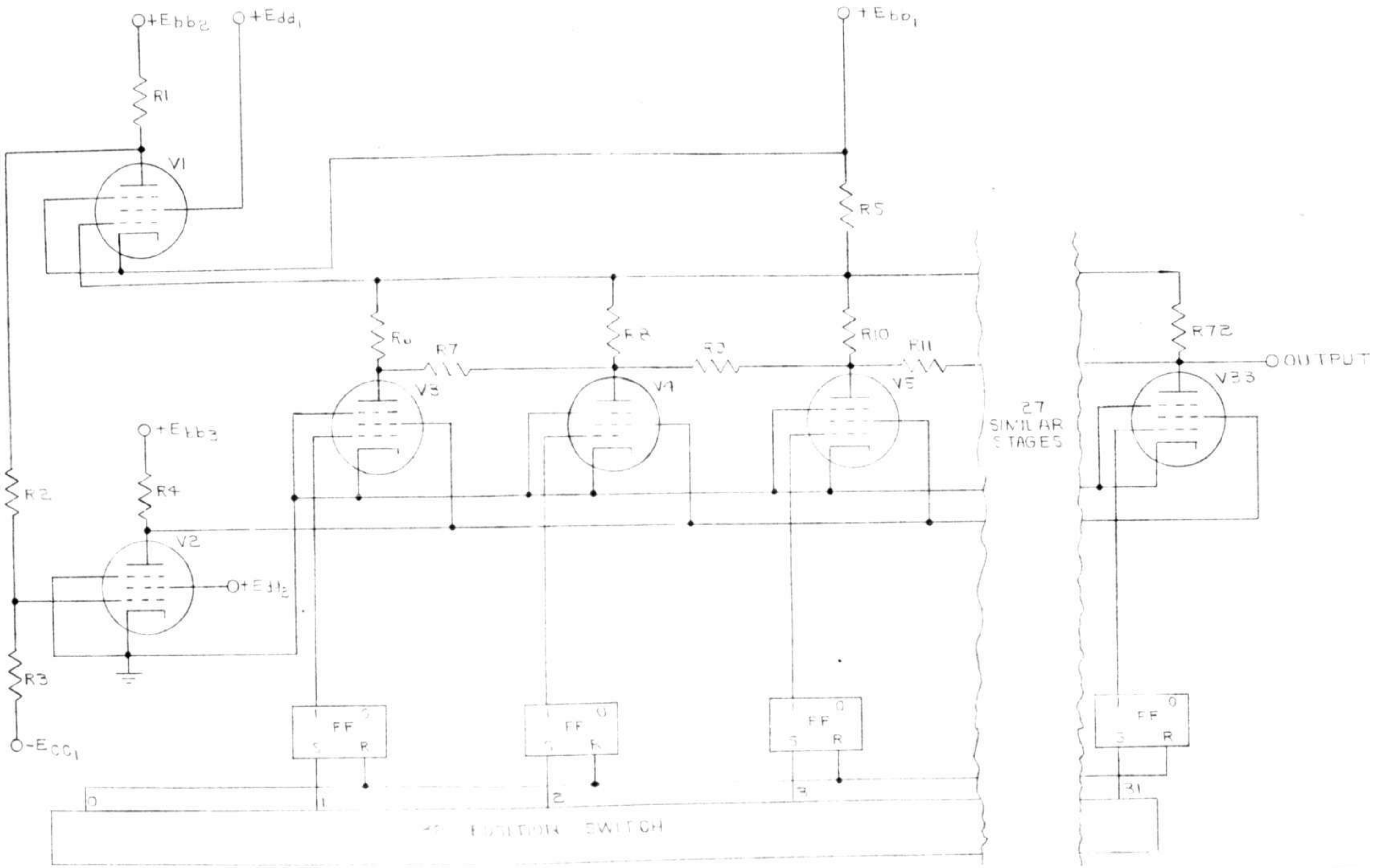
NOTE: 23 ADDITIONAL STAGES (NO ...) NOT SHOWN

CARRIER - TYPE DEFLECTION - VOLTAGE GENERATOR

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SERVOMECHANISMS LABORATORY

6345 | DR D.. | CK TL

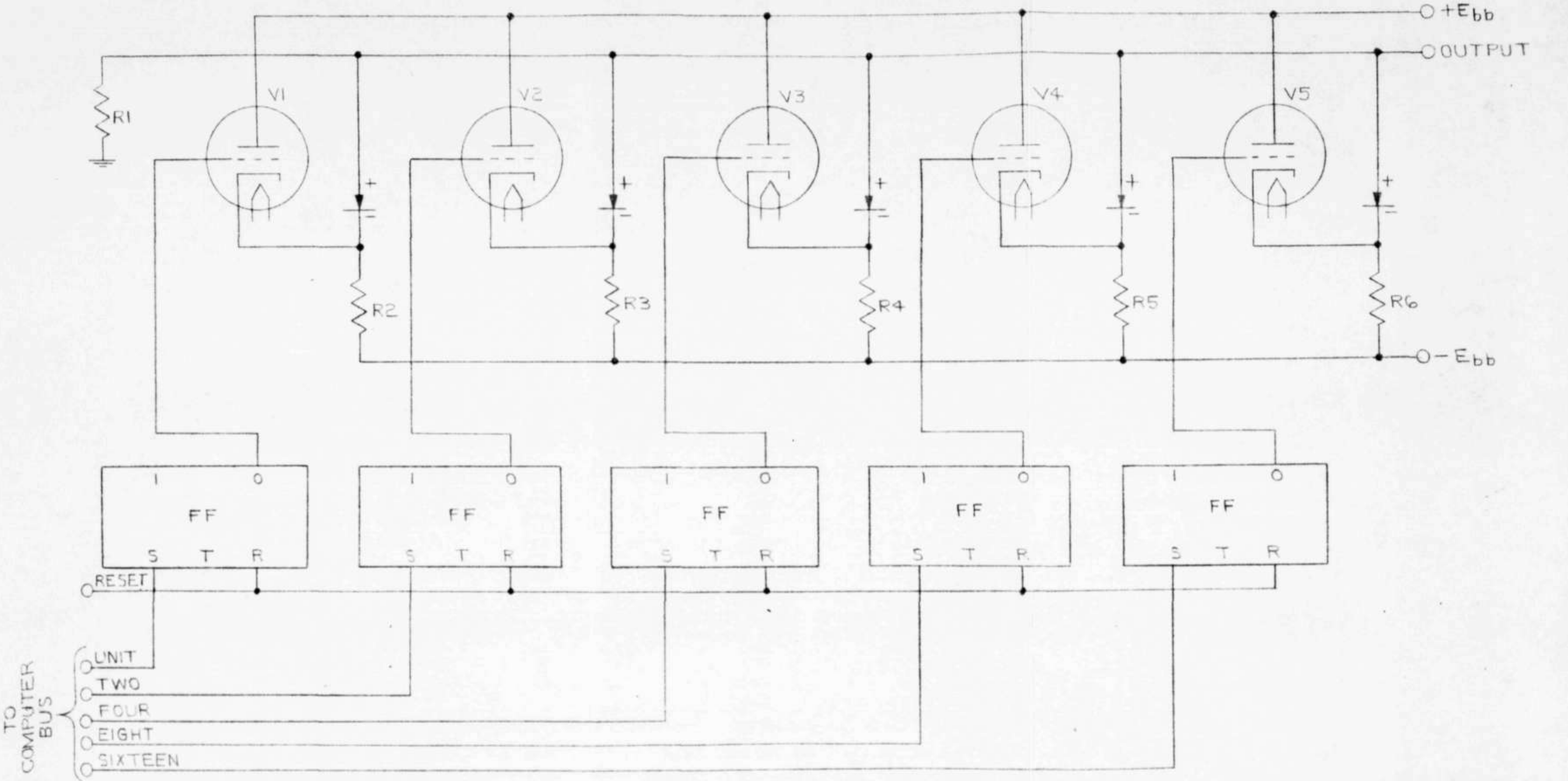
B-30331



LADDER-NETWORK TYPE DEFLECTION-VOLTAGE GENERATOR

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SERVOMECHANISMS LABORATORY
6343
B-30332

USE. IN 6345 REPORT R-120



BINARY-WEIGHTED VOLTAGE-DIVIDER DECODER FOR STORAGE TUBE DEFLECTION CIRCUIT.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SERVOMECHANISMS LABORATORY
D.I.C. NO. 6345 | DR DLO 2/18/47 | CK TL 2/18/47
ENG. JE. | APP. | B-30333

Project Whirlwind
Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

SUBJECT: DEFLECTION CIRCUITS FOR ELECTROSTATIC STORAGE TUBES

Written by: John O. Ely

Date: November 7, 1947

TABLE OF CONTENTS

I. SUMMARY

Among the circuits required for the control of electrostatic storage tubes are circuits which furnish voltages to deflect the primary-electron beam in accordance with orders received from the computer. Preliminary design studies have led to the conclusions expressed and discussed in this report.

In order to make numerical computations possible when any particular subject was under study, a considerable amount of data was assumed relating to the physical form and the operating characteristics of the storage tube. The assumptions made are listed in the report.

The general problem of supplying common deflection voltages to many storage tubes used in a single bank is discussed under two main topics. First, the effects of manufacturing tolerances are considered and possible means of compensating for the effects are suggested. Second, the input impedance, transmission delay, and attenuation in the transmission line are considered; the conclusion is drawn that a special type of line should be designed and constructed.

Two types of circuits capable of translating orders from the computer into deflection voltages are discussed; a binary-weighted decoder with an amplifier, and an equal-increment decoder which needs no amplifier. Designs for experimental models of each type circuit are incorporated in the appendix.

Major problems, together with recommendations for their solutions are:

1. Compensation for effects of manufacturing tolerences.
   Recommendation withheld pending accumulation of actual data on storage tubes.

2. Design of transmission line.
   Recommend use of large-diameter, air-spaced, balanced, two-wire line terminated at the end remote from the deflection-voltage generator. Actual design constants will depend on electrical characteristics of the storage-tube prototype model.

3. Deflection-voltage generator.
   Choice between the two proposed types should be deferred until data on the storage-tube prototype is available. Work in the interim should be concentrated on the binary-weighted decoder and associated amplifier.

II. INTRODUCTION

A. Brief Description of Storage Method

This report deals with electronic switching circuits designed to establish specified potentials at the beam-deflection plates of cathode-ray tubes used as electrostatic storage devices. Knowledge of the form of the proposed storage tube and its mode of operation is necessary to understand clearly the elements of the design problem, and it is suggested that references A and B will supply detailed information on this subject.

Briefly, the electrostatic storage tube will consist of two electron gun structures and a storage assembly enclosed in an evacuated glass envelope. The first electron gun will supply a sharply-focused beam of high-velocity electrons which may be deflected by means of potential differences established between the plates of two pairs of deflection electrodes, the axes of the deflection-plate pairs being mutually perpendicular and also perpendicular to the axis of the undeflected beam. This beam of electrons will strike a storage surface within the storage assembly and will cause the area under the beam to assume one of two potentials, choice between the two being made in response to the potential established on a control electrode within the storage assembly.

For reading of the stored information, the electron beam is again directed to the storage surface while a neutral potential is held on the control electrode within the storage assembly; electronic circuits detect the flow of displacement currents as the area under the beam on the storage surface is charged or discharged to a neutral potential. The second electron gun within the storage tube will supply a very broadly focussed beam of low-velocity electrons which may be thought of as a uniform spray over the entire storage surface. This beam of low-velocity electrons will render a given pattern of charge stable by means of secondary emission phenomena.

In the Whirlwind series of computers, the electrostatic storage tube will be used in such a manner that one digit of each of approximately 1,000 words will be stored in a rectangular array on the storage surface. The operation of the computer makes it necessary that each storage area on the surface be instantly and independently available for reading, writing, or erasing purposes. The computer will designate any given storage location by supplying to the storage system eleven or fourteen binary digits. The storage-tube deflection circuits will interpret part of these binary digits as composing two binary numbers which may be thought of as X and Y coordinates of the storage location on a rectangular coordinate system. Since each binary word of storage will be located in sixteen separate storage tubes for Whirlwind I and forty storage tubes for Whirlwind II, and since two or sixteen banks of storage tubes will be employed, it will be necessary to use one or four digits of the storage order to designate the bank of storage tubes in which the stored number will be found, this set of digits corresponding to a Z coordinate of the storage space.

B. Basic Assumptions

In order to carry out the design, analysis, and evaluation of a circuit, it is necessary either to know or to assume characteristics of input stimuli to be supplied to the circuit and output voltages required to be produced, as well as impedance levels at input and output terminals. The following data have been assumed in the storage tube deflection circuit work so far.

1. Input

a. Parallel digit transmission will be used for the deflection circuit order.

b. Only the a-c component of voltage on the digit-transfer bus or any signal input line is significant.

c. The signal for each coordinate will consist of a five-digit number composed of coincident pulses whose amplitude is between 10 and 20 volts and whose duration may be from 0.05 to 0.25 microseconds.

d. Input impedance of the deflection circuit decoder must be high in order to avoid loading the digit-transfer bus.

e. Additional pulses will be supplied to the deflection circuit on individual lines for the purpose of resetting the deflection circuit decoder, reading back the storage order for checking purposes, etc.

2. Output

a. The load will consist of 32 storage tubes for Whirlwind I or 640 storage tubes for Whirlwind II. Electrostatic deflection will be used.

b. Balanced deflection voltages will be required.

c. Each deflection plate pair will have a maximum direct capacity of 2 $\mu\mu f$ from plate to plate and 7 $\mu\mu f$ from each plate to ground. Methods of connecting tubes together are discussed below.

d. The deflection factor will be from 50 to 100 volts per inch. Maximum deflection of about $3\frac{1}{2}$ inches, peak to peak is expected. Computations have been based on a figure of 3 inches maximum deflection with a deflection factor of 67 volts per inch.

e. Circuits are assumed to be required to produce 32 distinct values of deflection voltage in each coordinate, corresponding to 1,024 positions of the beam on the target. Zero volts plate-to-plate may or may not be included as one value.

f. It is assumed that satisfactory storage operation will result if the extreme long-time variation in the position of any particular spot from its nominal position does not exceed 1/2% of the width of the array on the storage surface and if the successive deflections of the spot to any storage location each fall within 1/4% of the width of the array. A ±5% variation in the width of the array is assumed to be tolerable.

g. An interval of 3 microseconds from the time the storage order appears on the digit transfer bus is allowed for the establishment of the deflection potentials.

h. No consideration has been given to the change in deflection factor which may result from the change of potentials in the storage assembly for reading and writing. It has been assumed further that shielding adequate to reduce to negligible proportions the deflection of the beam by stray electrostatic and magnetic fields will be employed.

i. Deflection potentials established by one storage order will be maintained until a reset pulse is received by the decoder.

j. Storage tubes in Whirlwind I will be mounted on 12" centers. The storage tube bank for Whirlwind I will require 32 square feet of front area. Storage tubes in Whirlwind II will be mounted on approximately 6" centers, and the storage tube bank will be about 20' long by 8' high.

III. CONNECTIONS TO DEFLECTING PLATES

A. General Considerations

In order to reduce the amount of equipment required and to facilitate testing and checking operations it would be desirable to have a single decoder and driver unit. This indicates that corresponding deflection plates of all storage tubes in the storage bank should be connected in parallel. Two factors must be kept in mind when designing the connecting circuits. First, mechanical tolerances allowed in the manufacture of the tubes will result in variation from tube to tube of deflection sensitivity and position of the undeflected spot. Second, the large amount of capacitance associated with the deflection plates and their connecting cables, the large peak voltage required to be produced, and the short time allotted for the establishment of the voltage are three factors which, in combination, require that very high currents be supplied by the driving source. The connection scheme must be designed to minimize the current requirements.

B. Compensation of Tube Variations

1. Types of variation encountered

Commercially manufactured five-inch cathode-ray tubes intended for general oscillographic use are held to tolerances such that the deflection sensitivity of any one tube may deviate from the nominal value for the type by not more than ±20%. Tolerances on alignment of the electron-gun structure are such that the undeflected spot will fall within a 1-inch square whose diagonals intersect at the center of the tube face and whose sides are parallel to the axes of deflection. It is expected that these tolerances can be reduced by careful mechanical construction and close quality control to a figure of ±5% deviation of deflection sensitivity from the average value and 1/4 inch for the side of the square within which the undeflected spot will fall.

2. Compensation of deflection sensitivity

One of the assumptions listed under topic II-B above is that the allowable variation of the width of the array on the storage surface from its nominal width will be ±5%. If no provision is made for compensating the difference between the deflection sensitivities of individual tubes, even the smaller tolerance on deflection sensitivity will not allow the attainment of the assumed limits on the variation of the width of the array since it will not be possible to maintain the maximum deflection voltages at an exact nominal value.

The simplest method of compensating for variations in deflection sensitivity would be to use a pair of R-C attenuator sections at each of the more sensitive deflection-plate pairs, the attenuation of any pair of sections being chosen to reduce the effective sensitivity of their associated deflection-plate pair to the same sensitivity as the least sensitive pair acceptable under the tolerances set up for the tubes. By this means the effective deflection sensitivity of any pair of plates may be brought to within ±1% of the lowest uncompensated sensitivity accepted. If a π configuration is adopted for the attenuator, it will be possible to adjust the elements so that the effective shunt capacitance and resistance at the input to all deflection-plate pairs is the same.

Other schemes of compensation, such as adjustment of accelerating potential in the electron-gun, separate amplifiers for each pair of plates, etc., do not appear to be practical.

3. Compensation of Undeflected Position

If it is found that the tube-to-tube variation of the undeflected position of the beam causes too great a reduction of the useful storage area, compensation may be applied in any of a number of ways.

Since the deflection voltage probably will be maintained for a fixed, short length of time each time it is established, capacitive coupling to the deflection plates may be used. Such coupling will allow insertion of a positioning voltage at each pair of deflection plates. Some form of clamping must be used to restore the d-c component of the deflection voltage at the plates. One of the high-voltage germanium crystal diodes should prove adequate for this application. Care must be taken to make the impedance of the positioning-voltage source low enough to prevent appreciable changes in bias with changing duty factor.

A better method which has been suggested for adjusting the spot position is to insert two additional pairs of deflection plates on the electron-gun structure. These auxiliary plates would carry a steady difference of potential which could be adjusted so that the point of impact of the electron beam would lie exactly at the center of the storage surface when the main deflection plates were all held at second-anode potential. Since these auxiliary plates would only carry d-c voltage they need have only a low deflection sensitivity and could, consequently, be made considerably shorter along axis of the tube than the main plates. An additional function which might be served by the auxiliaries would be shielding between the two main deflection-plate pairs. This shielding would be useful in reducing undesired coupling between the two axes of deflection.

Other schemes of compensation, such as an external permanent magnet whose direction and distance from the axis of the tube are adjustable, a separate amplifier for each pair of plates in the group, etc., are possible but are not so attractive from the standpoint of ease and stability of adjustment and amount of equipment required.

C. Control of Input Impedance

1. Types of Connection

Because of the large physical size of the storage-tube bank and the large number of storage tubes in the bank, a large amount of cable is required to make connection to all deflection plates. In order to reduce stray coupling to a minimum, some form of shielded transmission line will be used. When considering the question of which type of line should be used and what the resulting performance of the system will be, a number of factors must be investigated. Before discussing these factors, however, it is necessary to outline two possible connection schemes and to see what effect the choice of one scheme or the other will have on the rest of the deflection circuit problem.

One way of feeding the deflection plates would be to use short lengths of cable to connect up small groups of tubes with the input ends of the cables all fed in parallel from the deflection-voltage source. In the case of WWII, for example, the deflection-voltage generating circuits might be located in the center of the storage-tube bank with sixteen rows of tubes having twenty tubes per row on each side. Each row of twenty tubes might be fed by one cable with the input ends of the thirty-two cables coming together at the output terminal of the generator. The end of the cable remote from the generator would not be terminated. In such a system as this if the time required for electromagnetic waves to be propagated from the input end to the most remote point in the system is small compared to the time constant of any transient voltage which may be applied to the input, the effect of the series inductance of the transmission line may be neglected and the input impedance of the system can be considered as that corresponding to a lumped capacity. The time required to establish a voltage at the most remote point in the system is very nearly the same as that required to establish the same voltage at the input.

A second way of feeding the deflection plates would be to use a single length of cable to feed all corresponding electrodes with the taps for individual tubes taken off at uniform intervals. If the spacing between taps is small enough that the time required for electromagnetic waves to be propagated from any tap to the next succeeding tap is small compared to the time constant of any transient voltage which may be applied to the line, the loading may be considered as if it were distributed uniformly along the line. Since this condition exists in the present application, and since the characteristics of transmission lines with uniformly distributed parameters are described by relatively simple mathematical relations, it is possible to calculate the pertinent constants of the loaded line. A considerable simplification in the calculations results from the fact that the losses in the line and at the deflection plates are very small and can be neglected in most of the calculations. It is particularly important to note that the characteristic impedance of the loaded line under the conditions which exist in this application is very nearly a pure resistance. The end of the line farthest from the deflection-voltage generator will be terminated with this characteristic resistance, and the load presented to the generator will be the same resistance. The time required to establish a given voltage at the end of the line farthest removed from the input and is equal to the time required to establish the voltage at the input plus a fixed transmission delay which is characteristic of the loaded line and may be calculated.

Both of the connection schemes outlined above would result in approximately the same total capacitance for the deflection plate system if the same tube spacing and type of connecting cable were used. The first type of connection, which results in a capacitance load being presented to the deflection-voltage generator, must be driven by a constant-voltage source having low internal resistance. A maximum allowable value for this internal resistance may be calculated from the fact that the product of (a) the resistance and (b) the total capacitance of the deflection system plus the output capacitance of the generator must not exceed approximately one seventh of the difference between (a) the time required for the decoder to set up the deflection voltage called for and (b) the three microseconds alloted for the over-all operation of the deflection circuits. With the second type of connection, which presents a resistive load to the deflection voltage generator, either a constant-voltage source or a constant-current source may be used. A major part of the delay in this case will be the transmission delay in the line; but the over-all operation time of the deflection circuit will include not only the delay but also at least seven times the produce of the characteristic resistance of the loaded line (in parallel with the output impedance of the driving source) multiplied by the output capacitance of the driving source, in addition to the time required for decoder operation.

2. Factors Affecting Choice of Transmission Line

It is desirable, in order to reduce power dissipation in the deflection circuits, to choose a type of transmission line which, when loaded by the deflection plates, will result in a high impedance at the input to the deflection-plate network; at the same time the velocity of propagation in the loaded line must be high enough to satisfy the transmission-time restrictions of the connection scheme in which it is used. Because of the fixed capacitance shunted across the line at each deflection plate connection, if the same dielectric is used in all types of line considered it is possible to increase the input impedance only at the expense of decreased velocity of propagation; however, both the input impedance and the velocity of propagation increase as the specific inductive capacity of the dielectric is decreased. For this reason an air-insulated transmission line is preferable to a line having solid dielectric.

Attenuation of the deflection voltage as it travels along the transmission line is undesirable in either of the two connection schemes proposed. In the case of unterminated lines treated as a lumped capacitance attenuation has an effect which may be considered as equivalent to a small resistance in series with the capacitance. No inequality of the equilibrium voltage at the various deflection plates results from attenuation if this type of connection is used; but for systems of the same total capacitance and the same voltage build-up time, the system with large attenuation will require a source having lower impedance than will the system with small attenuation. This difference is small, however, and the improvement in input impedance due to reduced attenuation does not alone justify the use of an expensive or physically inconvenient type of transmission line.

Attenuation in the transmission line has a somewhat different effect in the case of a single, uniformly loaded line. Under these conditions the driving-source impedance required to establish a given equilibrium voltage at the input to the line is not materially altered; the difficulty is that, with a constant voltage at the input, the equilibrium voltage at each successive pair of deflection plates is slightly smaller as the distance from the input end of the line increases. If, as suggested above, it is necessary to utilize compensating circuits to equalize the deflection sensitivities of individual tubes, then these same circuits can be used also to compensate for attenuation in the transmission line. If however, it is found possible to maintain tolerances on deflection sensitivity such that the variations need not be compensated as long as a given value of transmission line attenuation is not exceeded, then is becomes highly desirable to keep the attenuation in line below this value.

Consideration of the above points shows that the most desirable type of transmission line for connection of the deflection plates to the deflection voltage generator is an air-insulated line whose geometry is arranged so that the transmission delay in the loaded line is the longest which is tolerable in the connection scheme chosen; furthermore, the attenuation in the line should be small. An air-insulated line will be a rigid or semi-rigid type. The requirement of longest tolerable delay means that the ratio of the diameter of the shield or outer conductor to the diameter of the inner conductor or conductors will be large. Small attenuation means large-diameter inner conductor. These points, taken together, indicate that the physical size of the transmission line may limit achievement of the desired electrical characteristics.

Appendix A contains calculation of the properties of RG-62/U co-axial cable loaded as it would be for use in both WWI and WWII storage tube banks, and also properties of an air-insulated, rigid, shielded, balanced, two-wire line which is suggested.

IV. DECODING CIRCUITS

A. Function of the Decoder

It will be recalled that the principal input to the deflection circuits comes from the digit transfer bus of the computer and consists of a group of pulses which represent, according to a logically chosen code, the location of a point on the storage surface to which the reading and writing electron beam of the storage tube must be deflected. On the other hand, the actual deflection of the beam is accomplished by means of potential differences established between the plates of each deflection-plate pair. Any complete set of deflection circuits must, therefore, include a device which serves to convert the coded input into two voltage magnitudes. The device which makes this conversion has been called the "decoder" in discussion of the deflection problem, and is so designated in this report.

In considering the operation of the decoder and the requirements to be met, it is convenient to think of the coded input as representing two integers written in binary notation. Ten lines of the digit-transfer bus are connected to the decoder input through gated amplifiers; five consecutive lines carry pulses representing the binary digits of one integer while the other five lines carry the second number. To insert numbers into the decoder it is necessary to open the gates at the input of the decoder and then feed voltage pulses representing the desired numbers onto the digit-transfer bus. As soon as the pulses have had time to pass through the decoder input gates, these gates must be closed so that subsequent pulses appearing on the bus will not affect decoder operation. According to the code chosen for WWI, occurrence of a positive pulse at any input terminal of the decoder while the input gates are open represents appearance of the digit <u>1</u> in a corresponding position in the number as written in binary notation; non-occurrence of a positive pulse at an input terminal during the same time interval indicates that the digit <u>0</u> appears at a corresponding position in the number. Since a five-digit binary number can represent 2^5 integers, each of the input numbers may have, independently, any integral value from <u>0</u> to <u>31</u> inclusive.

Decoders for WWI and WWII will be designed so that the magnitudes of the two output voltages are as nearly as possible a linear function of the input integers. An expression for this desired function is:

$$E_n = E_o + \frac{E_{31} - E_o}{31} N$$

where E_n is the voltage output for input number N, E_o is the voltage output for input number 0, E_{31} is the voltage output for input number 31, and N is any integer from 0 to 31, inclusive. Because each input number is operated on in exactly the same fashion, the decoder will consist of two identical sections. In the following discussion, only one section of the decoder will be considered, it being understood that the second section will be the same in all respects.

B. Types of Decoders

A number of circuit arrangements have been proposed as being capable of producing the required relation between digital input and voltage output. Only two of the schemes, proposed as alternatives, are discussed below. The first is characterized by economy of space and equipment, large power dissipations in certain rather critical components, necessity for maintenance of extremely close tolerances on a number of resistors, and, in general, necessity for very close design and adjustment of the circuit. The second is characterized by ability to operate with rather broad tolerances on components, a more desirable situation with regard to power dissipation, and the possibility of extensive control of the shape of the output-vs-input function.

The first system of decoding derives its operation directly from the character of the binary code. To review briefly, an integer to which the decoder must respond is represented by the occurrence or non-occurrence of a positive voltage pulse at each of five input terminals during a specific interval of time.

The value of the integer represented is obtained by assigning an integral value or "weight" to the occurrence or non-occurrence of a pulse at each input terminal, and summing up these weights. With the input terminals numbered in order of increasing weight, the assigned values are (using decimal notation with Arabic symbols) as follows:

Terminal Number	Value Assigned: Occurrence	Value Assigned: Non-Occurrence
1	$2^0 = 1$	0
2	$2^1 = 2$	0
3	$2^2 = 4$	0
4	$2^3 = 8$	0
5	$2^4 = 16$	0

This method of assigning values is called "binary weighting" because the assigned weights form a geometric progression with ratio two.

A decoding circuit which uses binary weighting to decode the input pulses is shown in an elementary form on drawing B-30333. In operation, the circuit approximates a linear summation of current from five separate current sources which are weighted in accordance with the binary code. Referring to the drawing, immediately after the receipt of a pulse on the reset line all flip-flops are conducting on the 1 side and cut off on the 0 side. The grids of switch triodes V1, V2, V3, V4, and V5 are tied to the zero side of their corresponding flip-flops. Plate supply voltages of the flip-flops and switch triodes are so arranged that the cathodes of all triodes will be at or slightly above ground. This puts the cathode of each crystal diode at or slightly above its anode, so that negligible current flows through the diode. The voltage at the output terminal is then zero. When a set of pulses representing a storage position are received on the input line, the flip-flops which get a positive pulse will switch so that the 1 side is cut off and the 0 side conducts. This lowers the grid of the corresponding switch triodes, allowing their associated diodes to conduct and turning off plate current in the triode. Resistances R2, R3, R4, R5, and R6 are arranged so that for equal voltage across each resistance and its associated crystal diode, they draw currents whose ratios are as 1:2:4:8:16.

If R1 were very small compared to the combined resistances of R2, R3, R4, R5, and R6 in parallel, the current flowing through R1 (and hence the output voltage) would be very nearly proportional to the binary number input. The output voltage for this case would, however, also be very small compared to the voltage supplied to the divider. An increase of output voltage may be secured, at the expense of a departure from linearity, by decreasing the ratio of R2 (and hence R3, R4, R5, and R6) to R1. The ratio of output voltage to voltage supplied the divider is given by the expression:

$$\frac{e_o}{E} = \frac{N}{\frac{R_2}{R_1} + N},$$

where N is the input binary number. This equation is plotted on Drawing A-38251-G as a function of N with R_2/R_1 as a parameter. Drawing A-38252-G is a plot of the slope of the output curve as a function of N, again using R_2/R_1 as a parameter. The equation of these curves is:

$$\frac{1}{E}\,\frac{e_o}{N} = \frac{\frac{R_2}{R_1}}{(N + \frac{R_2}{R_1})^2}$$

It is readily apparent from these curves that a compromise must be made between large output with poor linearity and small output with good linearity.

As drawn, the circuit suffers from the disadvantage that for reasonable values of supply voltage and power consumption the output is small and at high impedance level. Some difficulty also may arise from the use of triode switching, since it may be impracticable to supply a grid swing on the triodes large enough to reduce cathode current to a negligible value. Furthermore, the circuit, as drawn, furnishes only a single-ended, or unbalanced, output. Appendix B of this report contains an evolved design which uses amplification and negative feedback to overcome the objections of small output at high impedance level. This circuit is arranged to produce a balanced output which may be applied to both plates of a deflection plate pair simultaneously.

A rudimentary four-position form of a second type of decoder is shown in drawing B-30751. The principle of operation of this circuit is a linear summation of unit current sources, one unit current source being supplied for each increment of deflection required. In the drawing, the double tetrodes V1A, V1B, V2A, V2B etc. represent the unit current sources. Dual tetrodes are provided in order that balanced deflection voltages may be secured, that is, the A side of each unit current source is connected to one side of the load while the B half of each current source is connected to the other side of the load. The two control grids of the unit current source tube are connected to the two plates of a flip-flop which has its plate load so arranged that the plate of the non-conducting tube will be approximately at ground potential while the plate of the conducting tube is approximately 50 volts below ground potential. This assures that one tube of the current source will be conducting strongly while the other half is cut off. The cathode resistance of the current source is provided in order to increase the plate resistance of the two tubes by degenerative action and thereby to reduce to some extent the effects of unbalance between the two sides of the tube and the change of current through the tube with age.

The circuit is so arranged that immediately after the receipt of a pulse on the "reset" grid of the flip-flop, the B half of the unit current source will be conducting while the A half is cut off. The "set" grid of each flip-flop is connected to the plate of the corresponding amplifier tube in the group of circuits designated as a "one-way line". The purpose of the one-way line is to take a signal which arrives at the grid of any one of the tubes and cause this signal to be propagated only to the right; thus, it can be seen that a signal which is introduced at the grid of the right-hand amplifier tube of the one-way line will cause a change of state only in the flip-flop labeled 1. Similarly a pulse introduced to the grid of the second tube from the right in the one-way line will affect only the flip-flops labeled 1 and 2. The pulse introduced tothe grid of the third tube from the right in the one way line will affect flip-flops 1, 2, and 3. In this way it is possible to cause a switching of current in a number of increments equal to the numerical value of the point at which the signal is introduced.

The signal is inserted into the one-way line at the proper point by means of the four-position electronic switch. This switch receives its stimulus from the digit transfer bus in the form of a two-digit binary number and opens one of the gate tubes on its output in accordance with the input number. A "set-up" pulse is then passed through the gate tube into the one-way line, setting up the corresponding flip-flops, and causing a switch in current from the B half to the A half of the proper number of unit current sources.

Inspection of the mode of operation of this circuit makes it apparent that the output voltage will certainly vary monotonically with the input number, and that, if the dynamic plate resistance of the unit current source tubes is high compared to the resistance of the load, the output voltage will vary approximately linearly with input number. Further advantages of this type of circuit are that the output impedance is quite low so that the load may be driven without any extra amplification being needed. Furthermore, the system can be a-c coupled throughout except for the coupling between the grid of the unit current source and the plate of the associated flip-flop; therefore, a minimum number of voltage supply levels are required for operation. The design of a 32-position circuit of this type is given in Appendix C of this report.

V. RECOMMENDATIONS

A. Connections to Plates

It is not possible at the present time to say whether or not special coupling circuits will be needed at each storage tube to compensate for manufacturing tolerances; accordingly, no recommendation is made concerning the actual line-to-tube coupling.

Although an unterminated connection using type RG-62/U coaxial cable is practicable for use in the small storage-tube bank of WWI, choice of such a connection is not recommended because the design of circuits to drive the connected load could not be applied directly to WWII with its large bank of storage tubes. It is recommended, rather, that design for WWI be carried out on the basis of a terminated connection using a specially constructed transmission line whose performance will be satisfactory for use in WWII also.

B. Deflection-Voltage Generator

On the basis of present information it is felt that satisfactory performance can be obtained from either of the two types of deflection voltage generators described in section IV above. Although the binary-weighted decoder with a power amplifier requires less space and equipment for its operation than the "equal-increment" type of decoder (which can, however, drive the load directly), the latter type possesses considerable advantages in its freedom from high-wattage, close-tolerance resistors and its ability to provide individual control of the increment magnitudes. It is recommended, therefore, that choice between the systems be deferred until definite information on the storage tube is available to replace the assumed data used up to the present time.

Any further work done on deflection circuits before a storage tube prototype is available should be directed mainly toward development of the binary-weighted decoder and its associated amplifier, since the design of the equal-increment system is less critical and will require less experimental adjustment and verification than is required for the binary-weighted system.

As soon as a prototype storage tube is available, work should be started on the determination of the constants of the tube which affect deflection circuit design. It is especially important that any lack of linearity in the deflection of the beam over the entire storage surface be measured, as well as any change in deflection factor which results from the different potential used in the storage assembly for writing a 1, writing a 0, or reading out of the tube. When these factors are known it will be possible to determine whether or not dynamic compensations must be used on the deflection circuits and if compensations are required work may be started on the design of the compensating circuits.

Written by: John D. Ely

Approved: JWF

APPENDIX A

CHARACTERISTICS OF LOADED TRANSMISSION LINES

1. Assumptions made in Calculations

Although neither the electrical characteristics nor the physical size and shape of the electrostatic storage tubes to be used in WWI and WWII have been determined at the present time, the assumptions made in section II of this report allow computation of the electrical characteristics of any transmission line used to connect together the deflection plates of storage tubes having the assumed characteristics. In addition to illustrating a method which may be used to calculate the transmission line data needed for a final deflection circuit design, which may be done only after the final form of the storage tube has been fixed and its electrical characteristics measured, calculations made on the basis of the assumed storage-tube data furnish sample transmission line data which may be used in investigating designs for other parts of the deflection circuit. Transmission line data calculated on the basis of the assumed loading will certainly be of the same order of magnitude as the constants which will exist in the final design, and probably will be within a range of ± 20% of the final values.

Storage tube data needed and values assumed are:

Plate-to-plate capacitance of each deflection plate pair	2	μμf
Plate-to-ground capacitance of each deflection plate	7	μμf
Distance between adjacent storage tubes: for WWI	12	inches
for WWII	6	inches

Equations which neglect transmission line and load losses will be used to compute capacitance, inductance, characteristic resistance, and delay in both the original unloaded line and the loaded line. The equations needed are:

$$\text{Characteristic resistance } (R_o) = \sqrt{\frac{\text{Series inductance per unit length}}{\text{Shunt capacitance per unit length}}} = \sqrt{\frac{L}{C}}$$

$$\text{Delay per unit length,} \quad T = \sqrt{LC}$$

Direct-current attenuation only will be calculated, this value being the one which determines the variation of the final amplitude of the deflection voltage. A suitable formula is

$$\% \text{ Attenuation} = \frac{R \times \ell}{R \times \ell + R_o} \times 100$$

where R is the series resistance per unit length of line, ℓ is the total length of the transmission line, and R_o is the characteristic resistance of the loaded line.

2. Characteristic of Type RG-62/U Cable

Type RG-62/U coaxial cable is standard for transmission of pulses throughout the rest of the computer system; it is necessary, therefore, to investigate the suitability of this type of cable for transmission of the deflection voltages. Pertinent characteristics of RG-62/U cable are as follows:

$$R_o = 93 \text{ ohms}$$

$$C = 13.5 \ \mu\mu f/ft$$

$$R = 5.4 \times 10^{-2} \text{ ohm/ft}$$

The first two figures are nominal values which appear in specification JAN-C-17A. No nominal figure is given in the specification for the d-c resistance per foot; the figure quoted above was obtained by measuring the d-c resistance of two two-foot lengths of the cable on a d-c wheatstone bridge and averaging the result. Special precautions were taken to eliminate contact resistance errors in the measurements, and it is believed that the figure obtained is accurate to ± 5% for the particular lot of cable from which the samples were obtained. A figure for the series inductance is now calculated:

$$L = R_o^2 C = (93)^2 (13.5) (10)^{-12} = 0.117 \times 10^{-6} \ h/ft$$

When the cable is loaded the effective capacitance per unit length is the capacitance of the cable itself plus the loading per unit length. The loading at each tap is equal to the plate-to-ground capacitance of one deflection plate plus twice the plate-to-plate capacitance of one deflection plate pair, plus a small allowance for wiring capacitance; this amounts to 15 $\mu\mu f$ per foot for WWI and 30 $\mu\mu f$ per foot for WWII. Value of characteristic resistance for the loaded line is then:

$$\text{WWI: } R_o = \sqrt{\frac{0.117 \times 10^{-6}}{28.5 \times 10^{-12}}} = 64 \text{ ohms}$$

$$\text{WWII: } R_o = \sqrt{\frac{0.117 \times 10^{-6}}{43.5 \times 10^{-12}}} = 52 \text{ ohms}$$

Delay per unit length of loaded line is:

$$\text{WWI: } T = \sqrt{(0.117 \times 10^{-6}) \ (28.5 \times 10^{-12})} = 1.82 \times 10^{-9} \text{ sec/ft}$$

$$\text{WWII: } T = \sqrt{(0.117 \times 10^{-6}) \ (43.5 \times 10^{-12})} = 2.26 \times 10^{-9} \text{ sec/ft}$$

If unterminated lines are used, the total capacitance to be driven is (with a 10% allowance for extra connecting cables):

WWI: $C_t = (32)\,(28.5 \times 10^{-12})\,(1.1) = 10^{-9}$ farad

$= 1000\ \mu\mu f$

WWII: $C_t = (640)\,(1/2)\,(43.5 \times 10^{-12})\,(1.1) = 15 \times 10^{-9}$ farad

$= 15{,}000\ \mu\mu f$

If a terminated connection is used, the total delay in the line will be:

WWI: $T_t = (32)\,(1.82 \times 10^{-9}) = 58 \times 10^{-9}$ sec $= 0.058\ \mu$sec

WWII: $T_t = (320)\,(2.25 \times 10^{-9}) = 720 \times 10^{-9}$ sec $= 0.72\ \mu$sec

In the case of a terminated connection attenuation in the line will be:

WWI: $$\text{Attenuation} = \frac{(5.4 \times 10^{-2})\,(32)}{(5.4 \times 10^{-2})\,(32) + 64} \times 100 = 2.6\%$$

WWII: $$\text{Attenuation} = \frac{(5.4 \times 10^{-2})\,(320)}{(5.4 \times 10^{-2})\,(320) + 52} \times 100 = 25\%$$

3. Characteristics of a Recommended Type of Line

Since the characteristics of capacitance-loaded RG-62/U coaxial cable are very unfavorable, especially from the standpoint of impedance and attenuation, it is desirable to seek a type of line which is more suitable. It was pointed out earlier that an air-insulated line gives the best ratio of characteristic impedance to delay in the line. The character of the load and voltage to be supplied to the load suggests the use of a shielded, balanced two-wire line. Use of a line conductor size somewhat larger than that found in RG-62/U is indicated to reduce attenuation in the line. In order to meet these requirements a special kind of line must be designed and built. A suggested design suitable for WW use has the following dimensions:

Outer shield - 1 1/4 in. i.d. thin-wall copper tubing
Inner conductors (2) - No. 18 AWG (0.0403 in. dia.) plain copper
Spacing of inner conductors: 0.65 in. on centers

Electrical characteristics of this line may be computed by the following method:

Let D = inside diameter of shield
d = diameter of inner conductors
h = spacing of inner conductors on centers

Define $$a = \frac{h}{D} = \frac{0.65}{1.25} = 0.52$$

$$b = \frac{h}{d} = \frac{0.65}{0.0403} = 16.1$$

Then R_o (of unloaded line) $\approx 276 \log_{10} \left[2b \frac{1 - a^2}{1 + a^2} \right]$

$$\approx 276 \log_{10} \left[(2)\ (16.1)\ \frac{1-(0.52)^2}{1+(0.52)^2} \right]$$

$$\approx 350 \text{ ohms}$$

Compute inductance and capacitance per foot of line:

$$L = (1.016)\ (10^{-9})\ \sqrt{\epsilon}\ R_c \text{ h/ft}$$

$$= (1.016)\ (10^{-9})\ (350) = 3.56 \times 10^{-7} \text{ h/ft}$$

$$C = (1.016)\ (10^{-9})\ \frac{\sqrt{\epsilon}}{R_c} \text{ f/ft}$$

$$= (1.016)\ (10^{-9})\ \frac{1}{350} = 2.90 \times 10^{-12} \text{ f/ft}$$

When used to make storage-tube deflection-plate connections, the line will be loaded with a capacitance of approximately 7 $\mu\mu f$ per tap. Characteristic resistance of the loaded line is calculated to be:

WWI: $Rc = \sqrt{\frac{3.56 \times 10^{-7}}{10^{-11}}} = 190$ ohms

WWII: $Rc = \sqrt{\frac{3.56 \times 10^{-7}}{17 \times 10^{-12}}} = 145$ ohms

Delay per unit length of loaded line is:

WWI: $T = \sqrt{(3.56)\ (10^{-7})\ (10^{-11})} = 1.90 \times 10^{-9}$ sec/ft

WWII: $T = \sqrt{(3.56)\ (10^{-7})\ (1.7)\ (10^{-11})} = 2.46 \times 10^{-9}$ sec/ft

If unterminated lines are used, the total capacitance to be driven is (allowing 10% for extra connecting cables):

WWI: $C_t = (32)\ (10^{-11})\ (1.1) = 352\ \mu\mu f$

WWII: $C_t = (640)\ (1/2)\ (17)\ (10^{-12}) = 5{,}450\ \mu\mu f$

Total transmission delay in the line, assuming a terminated connection, will be:

WWI: $T_t = (32)\ (1.90)\ (10^{-9}) = 0.061\ \mu sec$

WWII: $T_t = (320)\ (2.46)\ (10^{-9}) = 0.79\ \mu sec$

If standard annealed copper wire is used for the inner conductors the d-c resistance per foot of line will be 1.28×10^{-2} ohms. Total attenuation in a single traverse of the line will be:

$$\text{WWI: Attenuation} = \frac{(1.28 \times 10^{-2})\ (32)}{(1.28 \times 10^{-2})\ (32) + 190} \times 100 = 0.2\%$$

$$\text{WWII: Attenuation} = \frac{(1.28 \times 10^{-2})\ (320)}{(1.28 \times 10^{-2})\ (320) + 145} \times 100 = 2.8\%$$

4. Comparison of Two Line Types

When comparing the characteristic resistance and total capacitance figures given above for the two types of transmission line, one must keep in mind that the first set of figures quoted are line-to-ground in a balanced system, whereas the second set of figures are for line-to-line characteristics. This makes it necessary to double the second total capacitance figure and halve the corresponding characteristic resistance before comparing the two sets of figures. Comparison on this basis then shows that the second type line gives approximately a 50% improvement in characteristic resistance, a 30% improvement in total capacitance, and a 90% improvement in zero-frequency attenuation, all at a cost of less than a 10% increase in total delay.

APPENDIX B

DESIGN OF DEFLECTION-VOLTAGE GENERATOR WITH BINARY-WEIGHTED DECODER

In order to use the binary-weighted decoding scheme described above in a deflection-voltage generator for WWI or WWII, the elementary decoder must be associated with an amplifier having a large power gain and good gain stability. The amplifier must have negative feedback to achieve the required stability; this feedback may be arranged to give either a high resistance or a low resistance at the amplifier input terminals. If the arrangement is such that a low resistance appears at the input, this resistance may be used as the common load resistance (R1 on drawing B-30333) of the binary-weighted decoder. A design for WWI based on this scheme is discussed below. A complete circuit diagram is given on drawing R-30623. No attempt will be made in the discussion to cover the calculations required to choose every component; rather, only the major features are covered in detail.

A suitable starting-point in the design procedure is the choice of constants for the decoding circuit. These constants should be chosen to give the shortest practicable delay in establishing equilibrium voltage at the input to the amplifier; in general this will mean using low resistances to keep time constants small. The extent to which one may go in reducing the decoder resistances is limited by the current rating of the switch diode used in series with the binary resistor of weight sixteen, since reducing the voltage across the decoding resistors reduces the output in direct proportion. A germanium-crystal diode will be used because of its freedom from thermal and "contact potential" e.m.f.'s, its low forward resistance, its low internal capacitance, and its low capacitance to ground. A crystal diode capable of passing 50 milliamperes continuously in the forward direction is now under test by Sylvania, and will be available for use in these circuits. A supply voltage of 250 volts will be used for the decoder. Resistance of the sixteen's increment (R_6 on drawing B-30333) will then be:

$$R_6 = \frac{250}{50 \times 10^{-3}} = 5000 \text{ ohms}$$

This figure neglects voltage drop in the crystal diode. The drop is small and can be taken care of either by using a slightly lower resistance (approximately 4950 ohms) or, preferably, by using a stock resistance which measures slightly over 5000 ohms and shunting it with a value of resistance (to be determined experimentally) which gives just 50 milliamperes current through the crystal when a potential difference of 250 volts is held across the crystal and resistors. Nominal values for the other decoding resistors are then:

$$R_2 = 80{,}000 \text{ ohms}$$

$$R_3 = 40{,}000 \text{ ohms}$$

$$R_4 = 20{,}000 \text{ ohms}$$

$$R_5 = 10{,}000 \text{ ohms}$$

In each instance, the resistance should be adjusted to draw its correct current when a potential difference of 250 volts is held across the resistance and its associated crystal; the adjustments should be made with an accuracy of ± 1/2% or better. Wire-wound or metallic-film resistance units should be used throughout to insure stability of resistance values. Power ratings of the resistors should be at least four times the actual power dissipated. This leads to the use of resistors rated as follows:

$$R_2 = 5 \text{ watts}$$

$$R_3 = 10 \text{ watts}$$

$$R_4 = 15 \text{ watts}$$

$$R_5 = 25 \text{ watts}$$

$$R_6 = 50 \text{ watts}$$

A maximum value for the ratio R_2/R_1 can now be specified. Because the complete decoder will consist of two binary-weighted resistor groups working in opposition, the linearity requirement is not particularly severe. Referring to drawing A-38252-G a value of 500 for R_2/R_1 gives a maximum deviation of approximately 6% between the actual slope of the output function and the mean slope of the function. This or any greater value of R_2/R_1, then, should be satisfactory. Accordingly, the input resistance of the amplifier should not exceed 160 ohms.

Design of the amplifier itself may next be accomplished. Because of the nature of the signal which is to be amplified, the response of the amplifier must be uniform from essentially zero frequency up to a fairly high frequency. If, as in the present case, the input signal is always of the same polarity, zero frequency response can be approximated by an amplifier having R-C coupled stages with clamping diodes used as d-c restorers at each interstage coupling. Such non-linear couplings, however, introduce considerable difficulty into the analysis of the amplifier (which in the present case has appreciable feedback) for stability and frequency response. For this reason, a direct-coupled amplifier is chosen. It is assumed that the length of a line on the storage surface will be three inches and that the deflection factor of the storage tube will be 67 volts per inch. The output from each of the two amplifiers which work in opposition must then be 100 volts peak. With R_2/R_1 equal to 500, peak output of the decoder will be:

$$E_{31} = 250\left(\frac{31}{500 + 31}\right) = 14.6 \text{ volts}$$

The amplifier must have a gain of

$$A = \frac{100}{14.6} = 6.86$$

In Appendix A a type of transmission line was described which would have a characteristic resistance of 190 ohms line-to-line when loaded as it would be in WWI. This is equivalent to a load of 95-ohms line-to-ground. An amplifier must be designed, then, which has an input resistance of 160 ohms or less, a peak output of 100 volts across 95 ohms, and a gain of 6.9 or more; in addition, the gain of the amplifier must be related to the input resistance by the relation:

$$A = \frac{1.03 \times 10^3}{R_1} + 0.4$$

The duty-factor of the tubes in the output stage is not easily calculated, but under some conditions of operation it will be quite high; consequently tubes must be chosen which will work well within rating when conducting peak current continuously, and which, further, will conduct peak current with a grid voltage of zero or less. In the present instance, the peak incremental current required is:

$$\triangle i_b = \frac{100}{95} = 1.05 \text{ amperes}$$

A suitable output stage can be made up of 3 type 715-C beam-power tetrodes in parallel, using a 250-volt plate supply and a 150-volt screen supply, and having the deflection-plate connecting line placed directly in the plate circuit. Construction of the load-line on the static plate family for this tube shows that a grid swing of 21 volts is required to give a 100-volt plate swing. This is a gain of 4.8 for the stage. Plate current for each tube, when the grid is at cathode potential, is 408 milliamperes; plate voltage under the same condition is 134 volts. Peak plate dissipation per tube is 55 watts, as compared with a rating of 60 watts for the tube. Screen dissipation will be 5 watts, as compared with a rating of 8 watts. Input capacitance of this stage will be approximately 150 $\mu\mu f$; output capacitance will be approximately 50 $\mu\mu f$.

In order to maintain the amplifier stable with the amount of feedback that is to be used, it is necessary to have the time constant of one of the interstage couplings very much greater than the time constants of the other couplings. If the amplifier is to respond fast enough for the present application, however, the greatest time constant cannot exceed about 0.2 microsecond.

A suitable driver stage is one which has a gain of 1.4 or greater, which has an output impedance low enough to give a time constant of 0.2 microseconds or less, which can swing the grid of the following stage between the limits of zero and -21 volts, and which does not produce a phase inversion. Such an amplifier may be designed around a type 3E29 dual beam-power tetrode. Only an approximate design can be carried out on the basis of static characteristics at present available on the 3E29 tube; this has been done and the final adjustment of components made in the laboratory to secure proper d-c operating levels for the input and output. The resulting driver stage has an effective gain of 2.8 and gives a time constant for the interstage coupling of 0.11 microsecond.

The over-all gain of the cascaded stages is the product of their individual gains:

$$A = (4.8)(2.8) = 13.4$$

The input resistance of the amplifier is then required to be:

$$R_1 = \frac{1.03 \times 10^3}{A - 0.4} = \frac{1.03 \times 10^3}{13.0} = 79.5 \text{ ohms}$$

Feedback is applied through a voltage divider from the plates of the output stage to the grid of the input stage. In the present design the feedback ratio is chosen to give the proper d-c voltage level at the control grid of the input stage, and the ratio is 0.67. The input resistance, taking into account feedback, may be computed by Bode's formula:

$$R_{fb} = R_o \frac{1 - A_{\ell s}}{1 - A_{\ell o}}$$

where R_{fb} is the effective input resistance, R_o is the input resistance neglecting feedback, $A_{\ell s}$ is the amplification around the feedback loop with the input terminals shorted, and $A_{\ell o}$ is the amplification around the loop with input terminals open. Substituting figures from previous calculations:

$$R_o = 79.5 \quad \frac{1 + (13.4)(0.67)}{1 + 0} = 795 \text{ ohms}$$

If the feedback divider is made up of a 1200-ohm resistance from the plate of the output stage to the grid of the input stage and a 2500-ohm resistance from the grid of the input stage to the negative bias potential, both the feedback ratio and the input impedance of the amplifier will be substantially correct.

The calculations just made neglect the effect of the feedback resistance on the operation of the output stage. Although this effect is fairly easy to calculate, there is no necessity of doing the calculation, since the action of the feedback is such as to minimize the reduction of amplifier gain and change of d-c levels within the amplifier caused by the connection of the feedback divider from the output to a negative bias supply. It must be emphasized also that in order to secure optimum operating conditions some adjustment of component values will almost certainly be made after the amplifier is built and preliminary tests are started.

Both the interstage-coupling voltage divider and the feedback voltage divider must be capacitance-compensated to keep phase-shift in the amplifier to a minimum. A value of capacitance is chosen which makes the time constant of the capacitor and the upper leg of the divider across which it is connected just equal to the time constant of the input capacitance of the stage which the divider feeds and the lower leg of the divider.

A multi-stage feedback amplifier such as this may oscillate if certain stability criteria are not met. In the present case, the only criterion which is applicable is a particularly simple one; if the gain around the feedback loop is less than unity when the phase-shift around the loop is exactly 360 degrees, then the amplifier is stable. Application of this criterion yields a value of less than 0.2 for the loop gain of the amplifier when the loop phase-shift is 360°, so that the amplifier is not rendered unstable by the application of feedback.

Associated with each pair of decoder resistors is a flip-flop switching circuit with cathode-follower buffers which serves to transfer current from one resistance to the other. These circuits present no special problems in design, it being necessary merely to provide sufficient swing at the cathode of the buffers to insure that the decoding resistances are switched completely in or out of the circuit.

The deflection-voltage generator discussed above has one very serious defect; the decoder resistors, the resistor which terminates the transmission line, and the feedback resistors all must have a very stable resistance, both with respect to time and changes in load; but the power dissipated in the resistors is quite large and varies appreciably during operation. Non-inductive wire-wound resistors can be obtained in power ratings large enough to insure adequate stability, but such resistors are physically quite large. To use these resistors the circuit must be spread out over a considerable area; long leads between components will result and consequently there will appear in the circuit appreciable stray capacitances, lead inductances, and stray couplings, none of which can be estimated in advance. Considerable difficulty may be experienced in arranging and adjusting the circuit elements so that these stray parameters do not render operation unsatisfactory.

APPENDIX C

DESIGN OF DEFLECTION-VOLTAGE GENERATOR WITH EQUAL-INCREMENT DECODER.

Elaboration of the simple circuit of Drewing B-30751 into a design for a 32-position decoder for use in WWI is a fairly simple matter. Such a design is discussed below.

A 32-position electronic switch is required for each half of the decoder. A switch suitable for this application (with minor modifications) is described in reference C. The design of the switch will be improved for use in the interim storage of WWI and need not be discussed here. It is sufficient to point out that the final switch will be capable of selecting one of the 32 output gates fast enough that the "set-up" pulse required for decoder operation may be passed through the switch within 0.5 microsecond after receipt of the storage order by the switch input gates.

A circuit for one increment of the decoder is given on Drawing B-31118. All of the increments in the decoder are identical. This design assumes use of the special transmission line described in Appendix A above, which gives a line-to-ground resistance of 95 ohms.

Choice of a suitable tube for the unit current source (V1) is made on the basis of a number of factors. The half of the tube which is "on" must conduct a current of:

$$I_b = \frac{1}{31} \times \frac{100}{95} \times 10^3 = 34 \text{ milliamperes}$$

with its grid at ground potential. When conducting this current continuously, the plate of the tube should not dissipate more than one-half rated power. The dynamic plate resistance of the tube should be high, preferably 10^5 ohms or more, when the action of the cathode resistor is taken into account. An operating point should be chosen such that the required current flows with the cathode considerably positive with respect to the control grid in order to minimize the effect of slight changes in control-grid potential. A type 3E29 tube meets the requirements quite well. If a plate supply of +350 volts and a screen supply of +150 volts are used, a cathode bias of ten volts is required: this gives a value of approximately 275 ohms for the cathode resistor. It may prove desirable to make the cathode resistor adjustable in order to allow compensation to be made for tube-to-tube variation of plate current or to allow the shape of the output-versus-input function of the decoder to be changed. An adjustable screen voltage supply will allow adjustment of the scale factor of the decoder to secure the proper peak output voltage.

Switching of the current in V1 is controlled by a flip-flop (tubes V3 and V4). This flip-flop is similar to the one used in the registers and arithmetic element of WWI. It differs from the standard flip-flop mainly in that it has a plate load resistance composed of two resistors coupled by a diode in such a way that the plate of the "off" tube of the flip-flop rests at ground potential.

A "clear" pulse is coupled to the "reset" grid of the flip-flop. This pulse is supplied from the control circuits which govern the sequence and timing of operations in the storage system. The "set" grid of the flip-flop is fed a pulse from the plate of V2, which is an amplifier in the one-way line. This same pulse is inverted by transformer T1 and fed into the grid of the corresponding amplifier in the next section of the one-way line. A pulse may be fed to the grid of V2 from either of two sources. First, a pulse may come from the output of the 32-position switch. Second, a pulse may come from the plate of the preceding amplifier tube in the one-way line. Either pulse will cause switching of current in the flip-flop controlled by V2 and also all flip-flops in following sections of the decoder. Flip-flops in preceding sections of the decoder will, however, remain unaffected. Limiting at the grid of V2 is employed to assist in maintaining the amplitude of a pulse passing down the line approximately constant.

Drawing B-30751 shows the elementary decoder connected in such a way that a clear pulse resets the decoder to the zero position. It is desirable, in order to reduce operating time and to make power dissipation in the transmission line terminating resistors more nearly equal, to connect the decoder in such a way that it resets either to the sixteenth or seventeenth position. This may be done quite easily; a block diagram of a connection which may be used is given on Drawing A-31119. For the sake of simplicity the drawing shows an eight-position decoder which resets to the fourth position.

It is estimated that a total time of not more than 1.8 microseconds will be required to establish equilibrium voltage at all points on the transmission line. This time is broken down as follows:

Operation of 32-position switch	0.5 μsec
Transit of pulse in one-way line	0.5 μsec
Rise time of flip-flop	0.4 μsec
Rise time at plate of V1	0.3 μsec
Transit of voltage on deflection-plate transmission line	0.1 μsec
Total	1.8 μsec.

This design should be suitable for use in WWII simply by changing the resistor in the cathode circuit of V1 to give a higher current, since the plate dissipation of V1 will not be excessive even when the decoder is required to produce a swing of 100 volts across a resistance of 75 ohms and since the additional delay in the transmission line will still leave the operating time of the circuit under 3 microseconds.

APPENDIX D

TESTS ON A 32-POSITION BINARY-WEIGHTED DECODER WITH FEEDBACK CATHODE FOLLOWER

Drawing No. E-30401 gives the schematic circuit diagram of an experimental decoder which was built and tested in the laboratory in March and April of this year. Drawings A-31120, A-31121, A-31122, and A-31123 are views of the decoder showing the type of construction. This construction was chosen to facilitate testing: important points in the circuit are easily available, while the layout is as compact as possible in order to reduce stray capacitances. Although the operation of the decoder was not satisfactory, the tests brought out a considerable amount of information concerning both the principles on which the decoder was designed and the component circuits.

Basically, the decoder was derived from the circuit of Drawing B-30333. In order to increase the output obtainable with good linearity for a given current in the diodes of the switching circuit, the output voltage was fed back to the power supply for the decoder resistors in such a way as to compensate in part for the drop across the output resistor. The feedback was accomplished by connecting the low end of the decoder resistors to the output of a cathode follower (V18) whose grid was tied to the output line through two type VR-150 tubes (V16, V17). VR-tube coupling was used in order to obtain a proper average voltage level at the grid of V18 without the loss of feedback amplitude entailed by a voltage-divider resistance coupling and without the loss of zero-frequency response entailed by capacitor coupling. Switching of decoder resistors was accomplished by a simple triode-diode arrangement as shown in Drawing B-30333 with the grid of each triode switch tube directly connected to the plate of a flip-flop.

Tests on the circuit included static voltage output, internal voltage level, and transient response tests. All static tests were made merely by setting the flip-flops manually and reading voltages with a high impedance (100,000 ohms/volt) d-c voltmeter. Drawing A-30456 is a block diagram of the dynamic test set-up used. The number which appears in each block is the drawing number of a schematic circuit diagram of the unit.

When the circuit was tested, its operation was unsatisfactory on two counts. First, the device was far from stable: its output was subject both to slow drifts and to small, moderately-frequent fluctuations, and it tended to break into more or less violent oscillation when any attempt was made to look at its internal waveforms with a synchroscope. Second, the output was very far from a linear function of the input number.

Investigation revealed that the lack of stability is due to a number of causes. Basically, the defect is that the feedback applied is regenerative. Moreover, the feedback ratio changes as the decoder resistors are switched in or out. Positive feedback does not necessarily introduce any drift into the system, but it does magnify the effects of changes in the circuit components which are embraced by the feedback loop.

Most of the slow drift in the experimental model was traced to changes in value of various resistors with changing load and ambient temperature. This merely indicates that the resistors, although carrying less than rated load, were operating at temperatures higher than should be allowed. Resistors of higher rating should have been employed. Although no definite proof could be obtained, it is believed that the small random fluctuations in output were caused by random changes in the voltage drop across the V-R tubes in the feedback loop. These changes are very slight, but would be magnified by the feedback action.

At first it appears that, although the feedback is regenerative, the feedback factor is very small and no oscillation troubles should result. As a matter of fact, the device broke into oscillation only when capacitive loading was attached to certain points in the circuit. These oscillations were always of a very high frequency, so high in fact that a resistance of as little as 500 ohms in series with the synchroscope probe would prevent oscillation when certain points were under observation. A few points in the circuit were not stable unless the series probe resistance was at least 1000 ohms. As little as 5 $\mu\mu$f of shunt capacity to ground added at some points was sufficient to cause oscillation; other points required 15 to 20 $\mu\mu$f loading before the circuit became oscillatory. Although the large number of stray parameters and the complex nature of the feedback loop (including non-linear elements such as the IN34 crystals and the V-R tubes) render a stability analysis very difficult, it is apparent that for high frequencies the gain of the feedback cathode follower becomes much greater than unity.

Because of the instability of the circuit, it was difficult to discover all of the causes of the output non-linearity. Static tests did bring out, however, that the majority of the non-linearity was caused by failure of the flip-flops to cut off completely the plate current of the triodes used for switching purposes. Some evidence also was found that the heater-cathode leakage of the triodes was appreciable. Neither of these defects is fatal.

The flip-flop design used was the best one available at the time the experimental decoder was built. For use in this circuit, however, it suffered from two main defects: the voltage swing at its plates was too small, and neither end of the swing was at a fixed reference level. As a result of these difficulties a new flip-flop was designed which gives a large plate swing with approximately the same time constant and which is arranged to have the plate of the non-conducting tube at plate-supply potential. (The circuit is essentially that of the flip-flop on Drawing B-31118). Heater-cathode leakage currents could be reduced to completely negligible proportions by arranging to have the average voltage of the heater and cathodes the same. Another way to overcome both effects would be to insert a second diode between the cathode of the switch triode and the decoder resistor, returning the cathode of the switch triode to ground through a high resistance.

Although a reworking of the design, both mechanically and electrically, probably could overcome the major portion of the defects found, such a redesign was not undertaken because it was felt that the regenerative character of the feedback renders doubtful the possibility of securing resistors, crystals, and tubes whose characteristics are sufficiently stable for successful maintenance of the required tolerances on output amplitude.

List of References:

A. 6345 Report No. R-110, ELECTROSTATIC STORAGE TUBES.

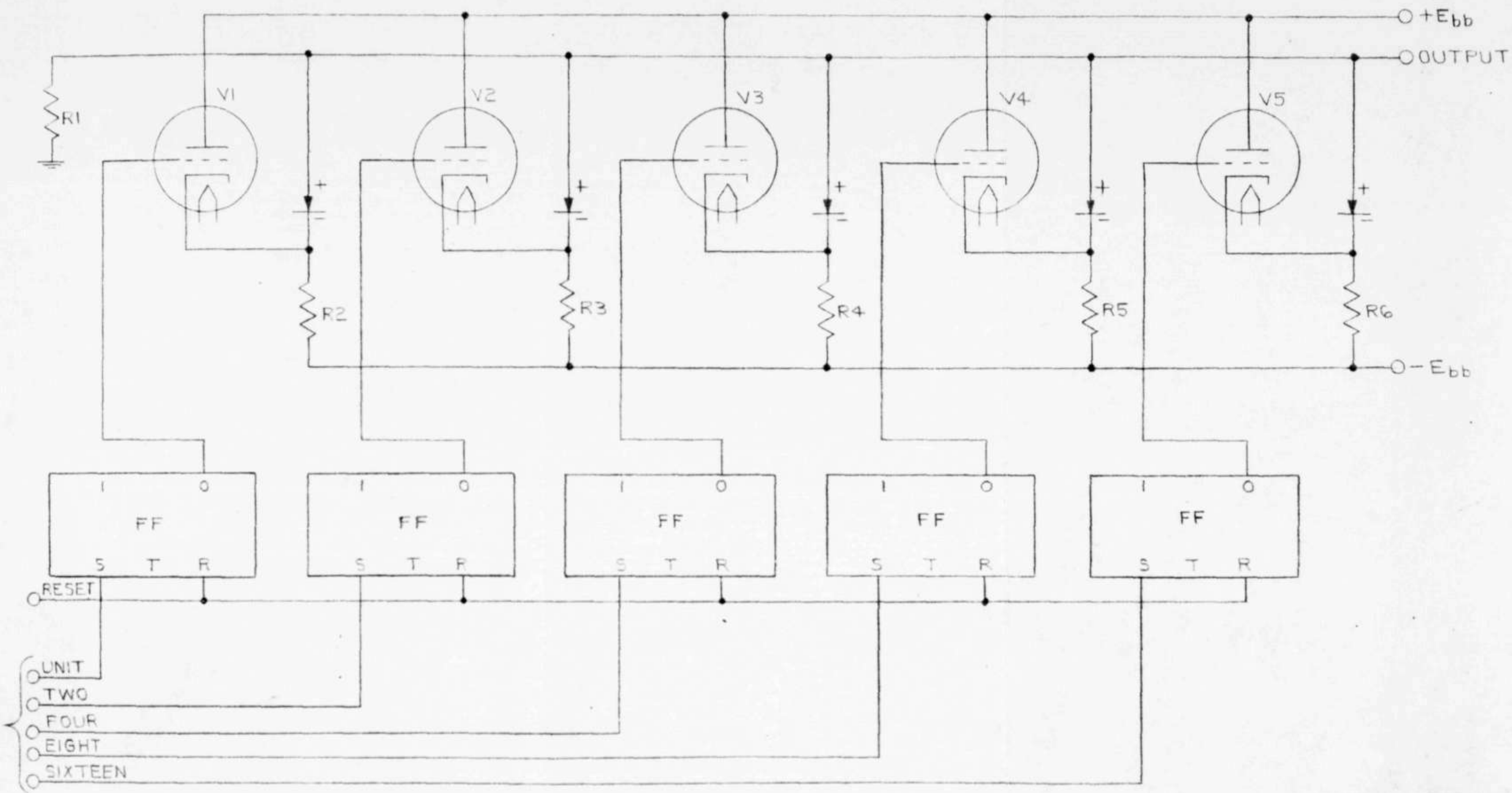
B. 6345 Memorandum No. M-102, STORAGE TUBE PROGRAM, PROJECT WHIRLWIND

C. 6345 Report No. R-123, THE 32-POSITION SWITCH

List and Order of Drawings:

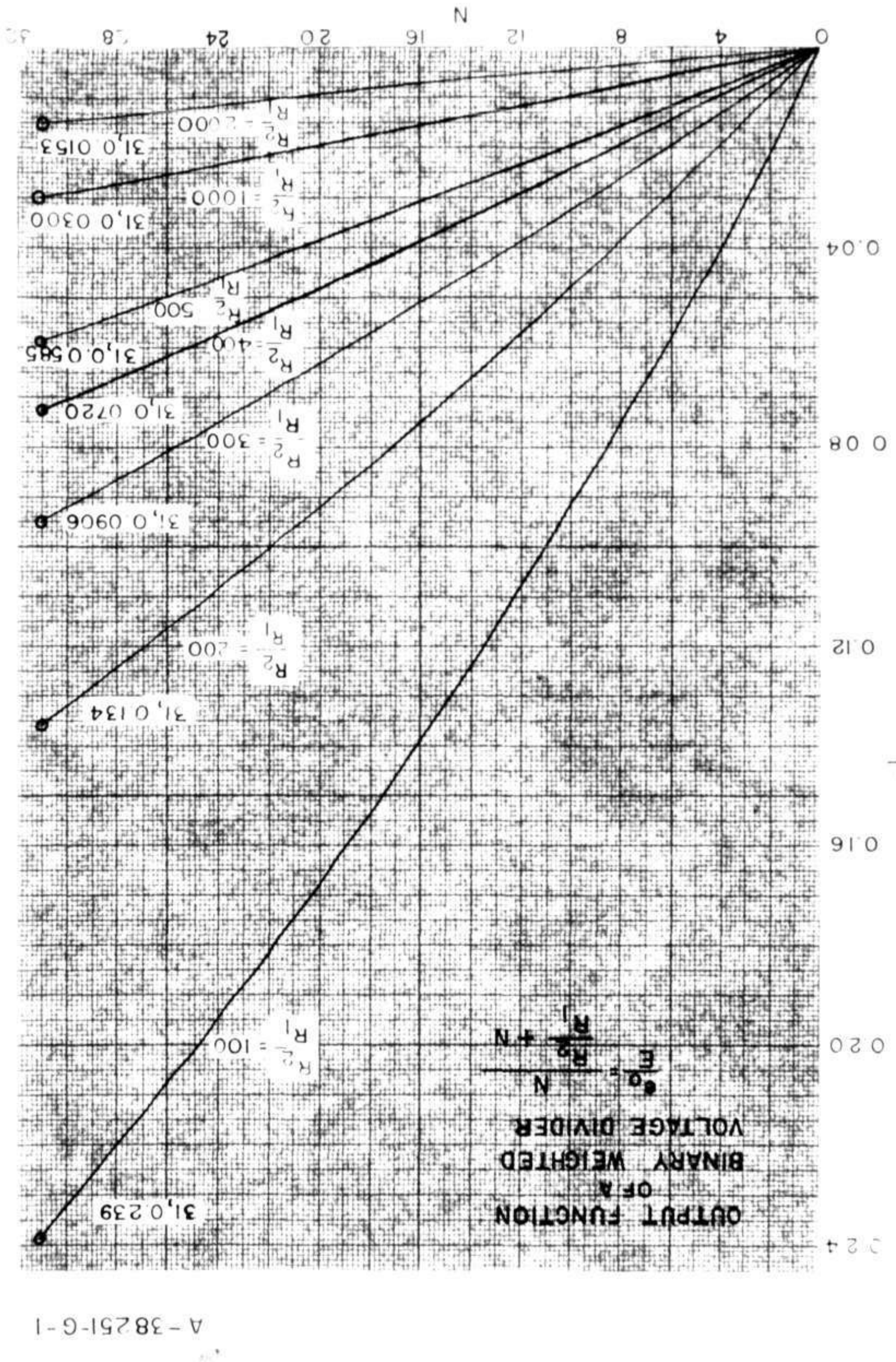
B-30333
A-38251-G
A-38252-G
B-30751
R-30623
B-31118
A-31119
B-30401 30461
A-31120

A-31121
A-31122
A-31123
A-30456
B-39081-2
A-30457
A-30458
A-30459
A-30460

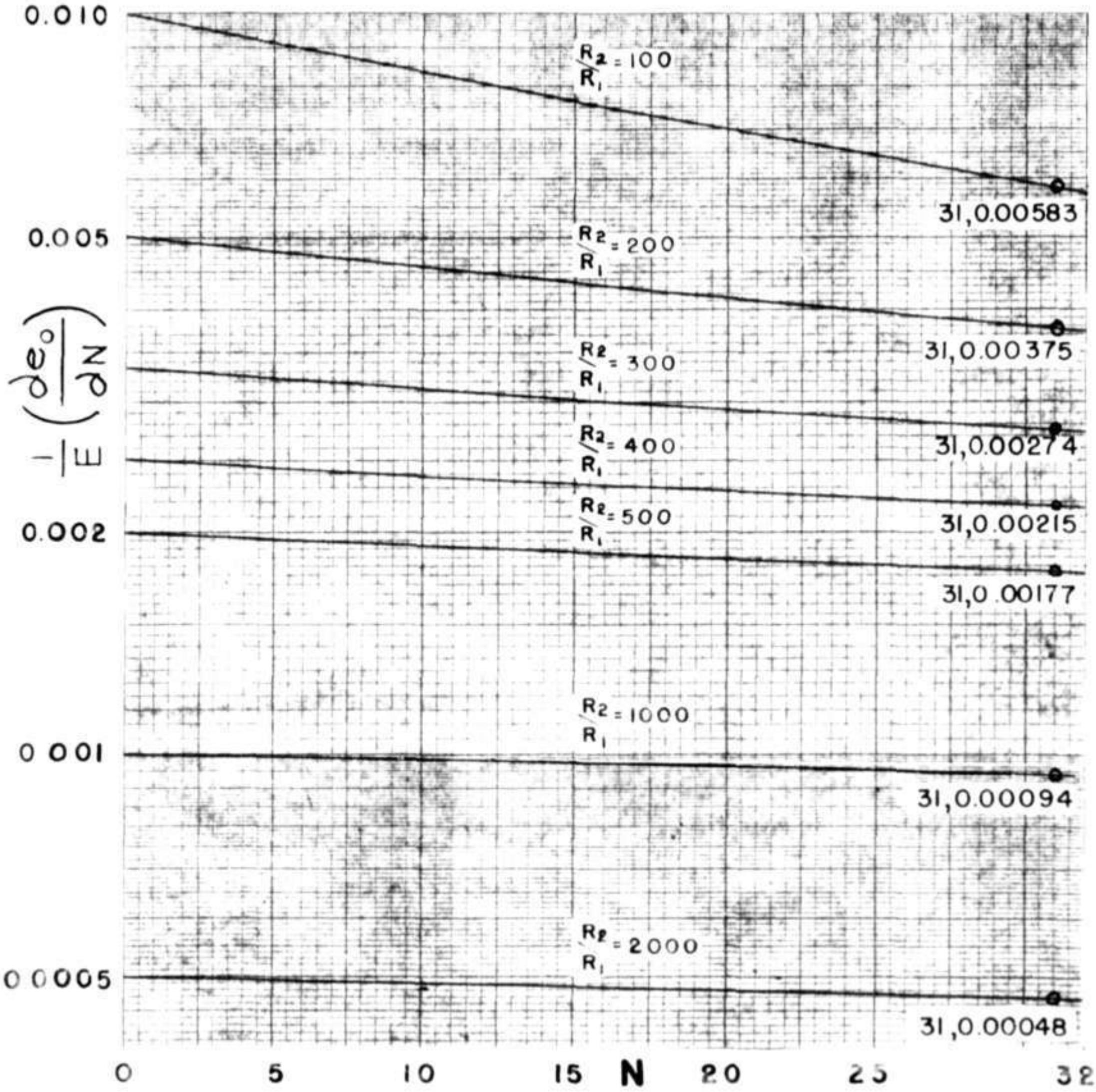


BINARY-WEIGHTED VOLTAGE-DIVIDER DECODER FOR STORAGE TUBE DEFLECTION CIRCUIT.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY SERVOMECHANISMS LABORATORY		
D.I.C. NO. 6345	DR. DLO 2/18/47	CK. TL 2/18/47
ENG. JE.	APP.	B-30333



A-38251-G-1 USED IN 6345 REPORT R-120



SLOPE OF THE OUTPUT FUNCTION
OF A
BINARY-WEIGHTED VOLTAGE DIVIDER

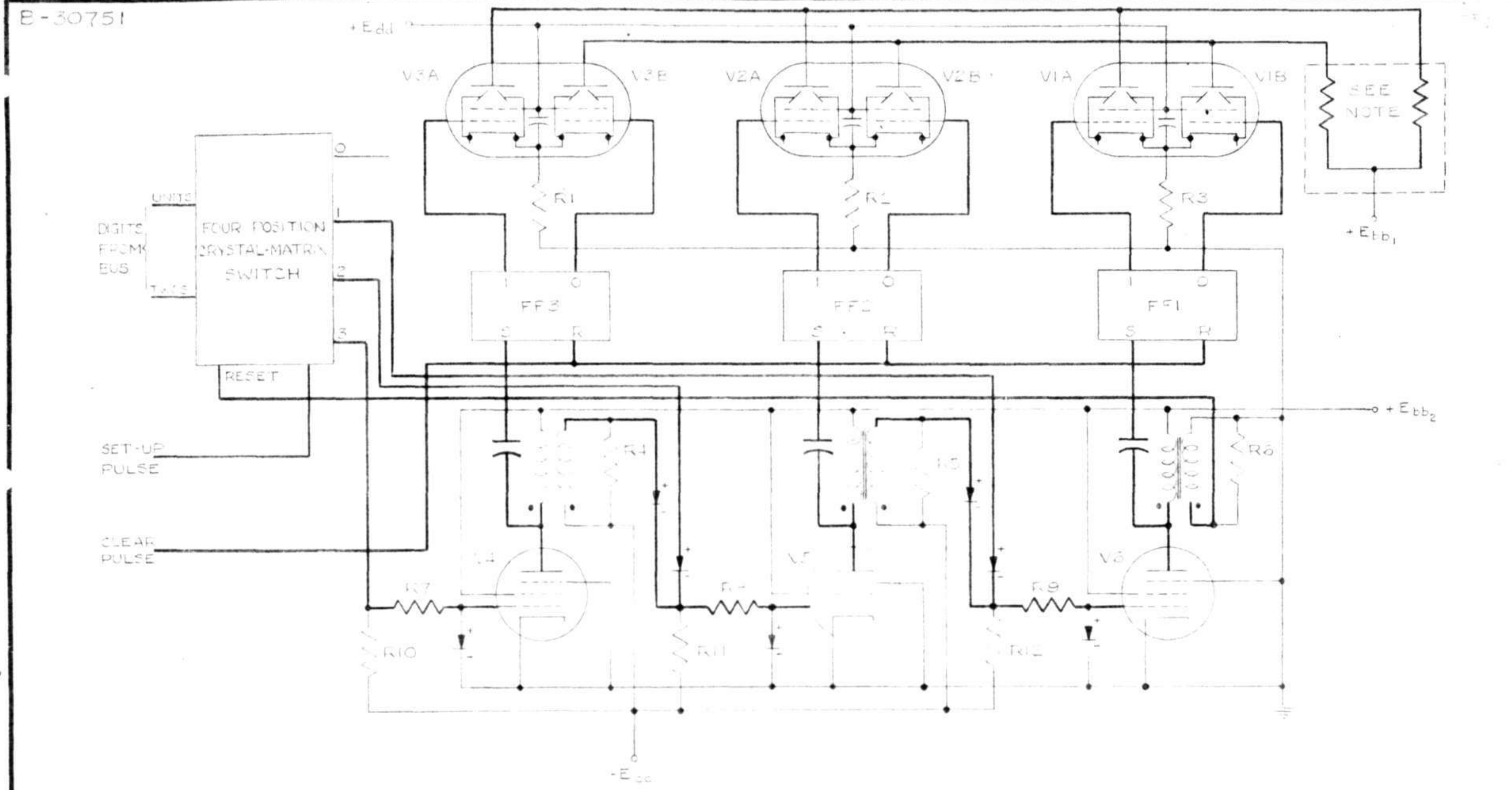
$$\frac{1}{E}\left(\frac{de_o}{dN}\right) = \frac{\frac{R_2}{R_1}}{\left(\frac{R_2}{R_1} + N\right)^2}$$

USED IN 6345 REPORT R-120

A-38252-G-1

MASSACHUSETTS INSTITUTE OF TECHNOLOGY SERVOMECHANISMS LABORATORY		
D.I.C. NO. 6345	DR. R.V.W.	CK.
ENG. J.O. ELY	APP. A-38252-G-1	

B-30751



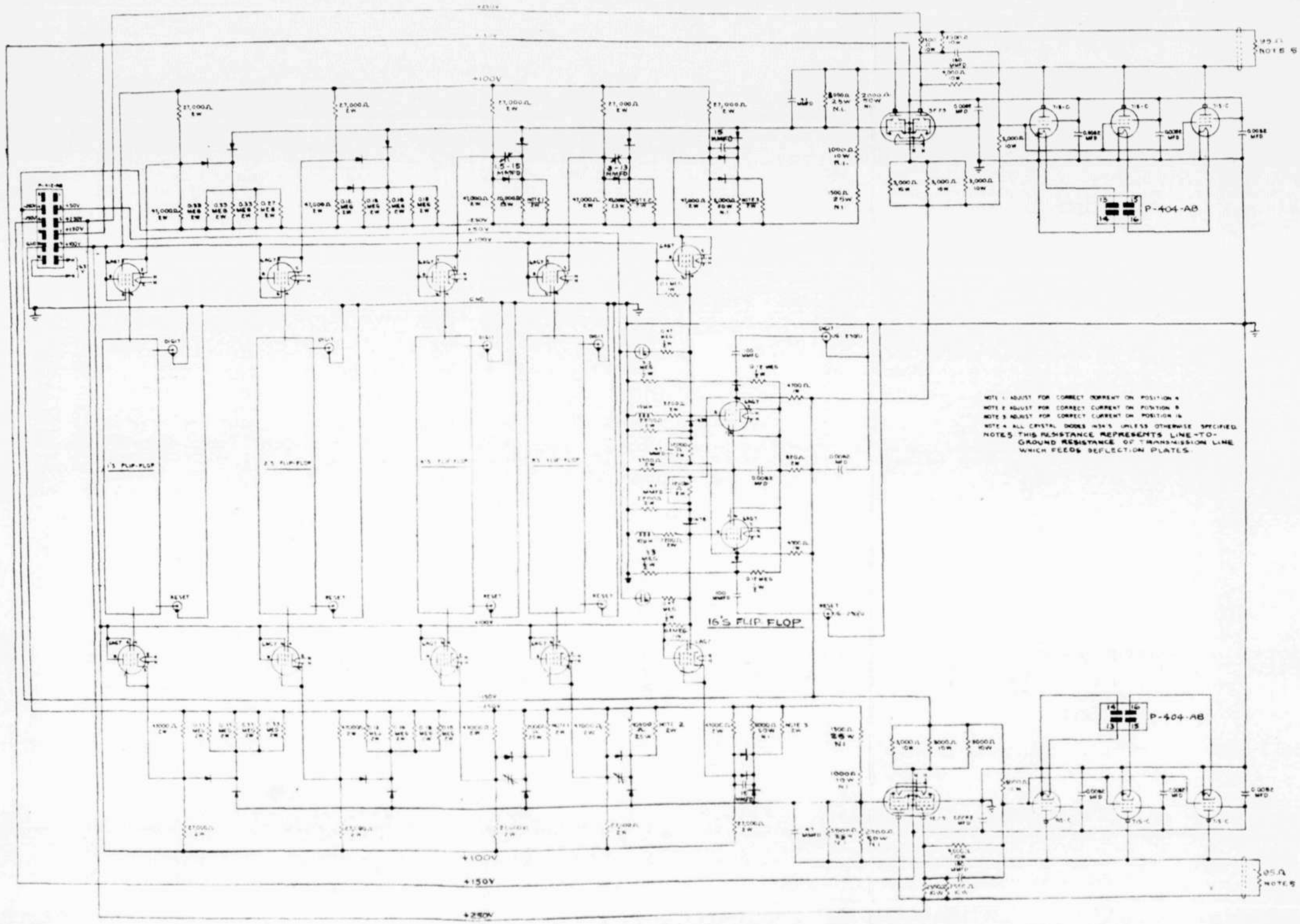
NOTE:
THESE RESISTANCES REPRESENT THE CHARACTERISTIC RESISTANCE OF THE BALANCED 2-WIRE LINE WHICH CONNECTS THE DEFLECTION PLATES TOGETHER.

USED IN 6345 REPORT R120

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

FOUR-POSITION [illegible] DECODER FOR DEFLECTION OF ELECTROSTATIC STORAGE TUBE

SCALE:	DR. [illegible]	B-30751
ENG. [illegible]	CK. [illegible]	APP.



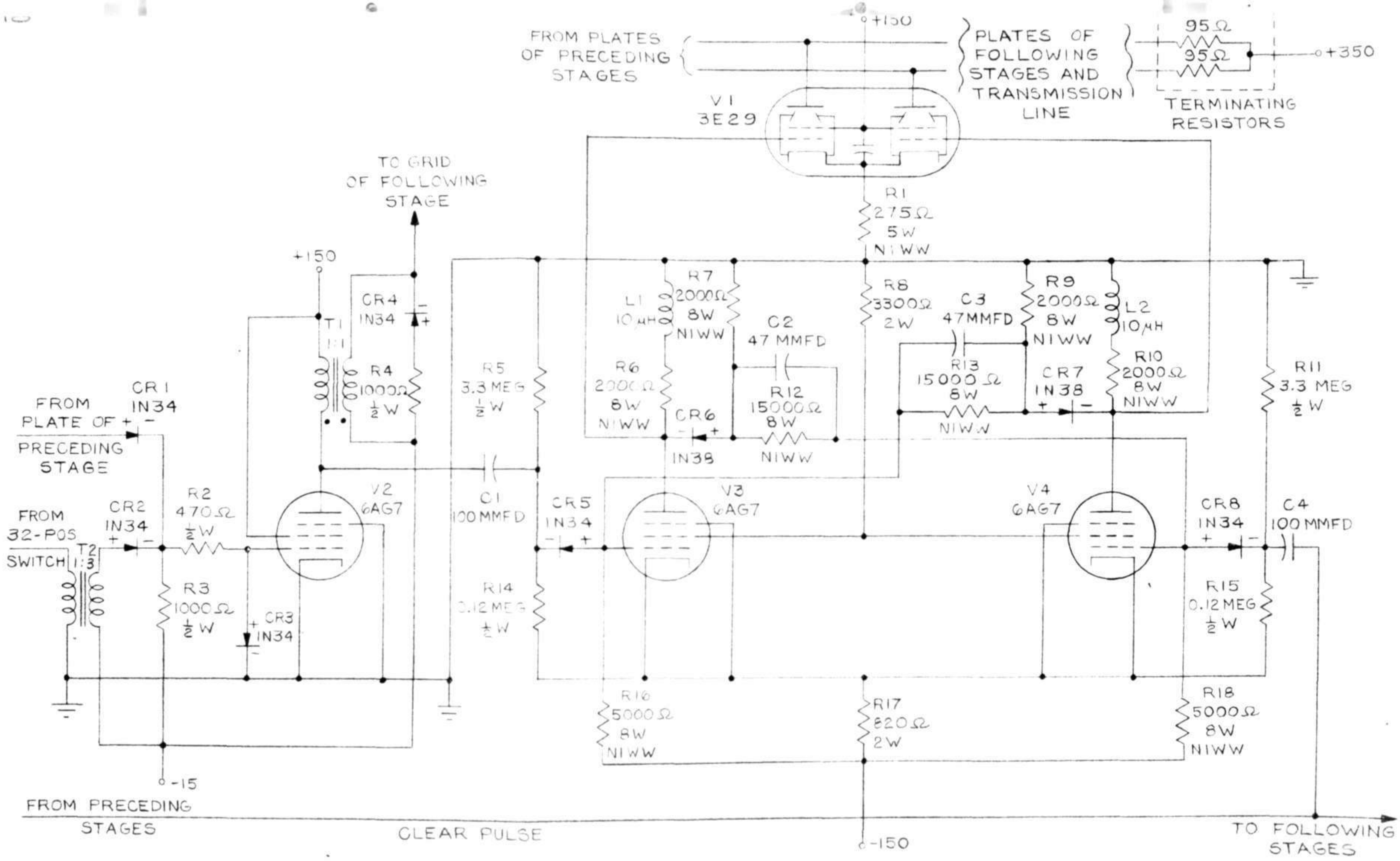
32-POSITION DECODER FOR DEFLECTION CIRCUIT

USED IN 6345 REPORT R-120

D.L.O. 10/28/47

R-30623
B REDUCTION

6345



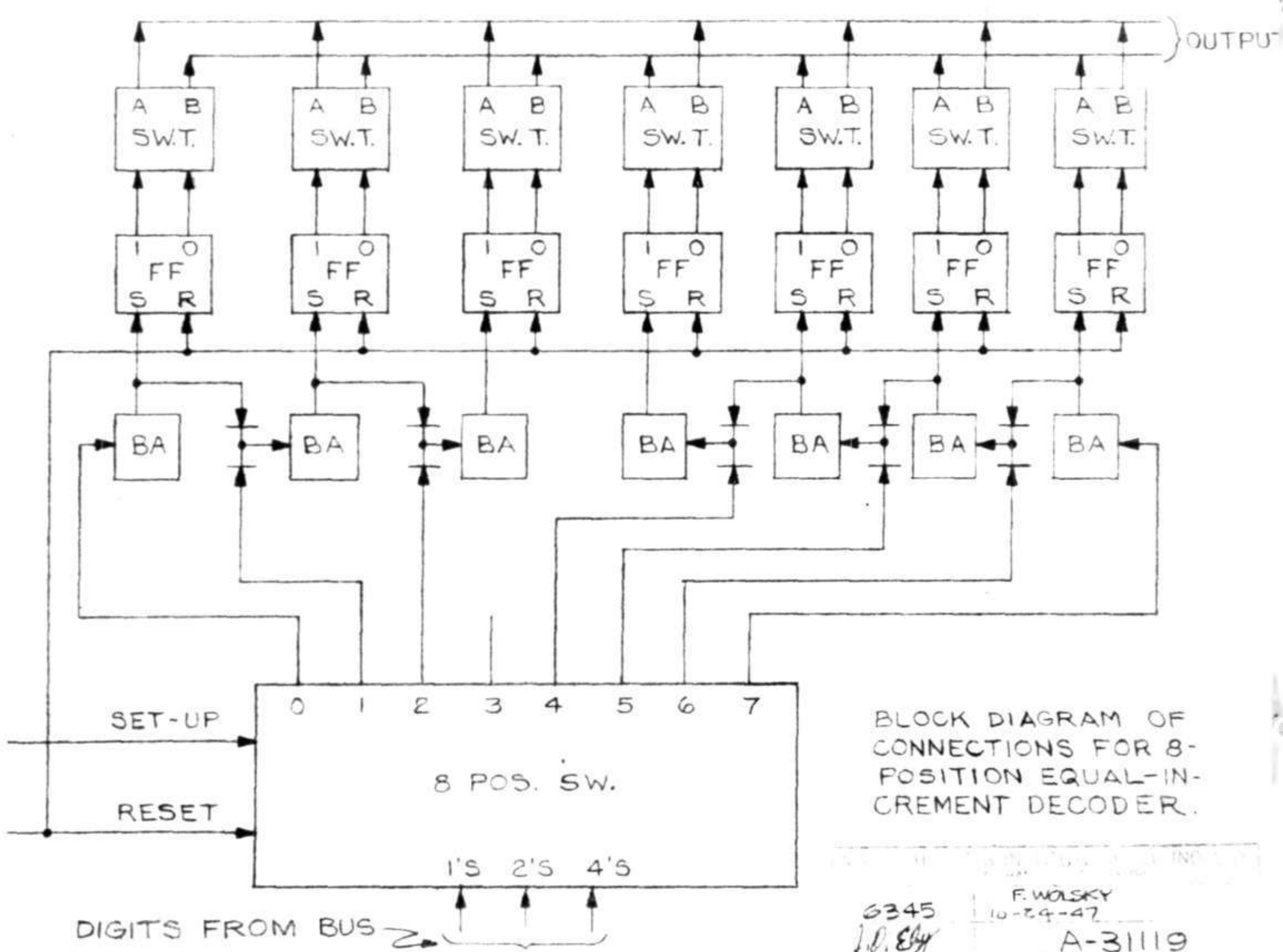
ONE INCREMENT OF 32-POSITION EQUAL-INCREMENT DECODER

6345 F. WOLSKY

B-31118

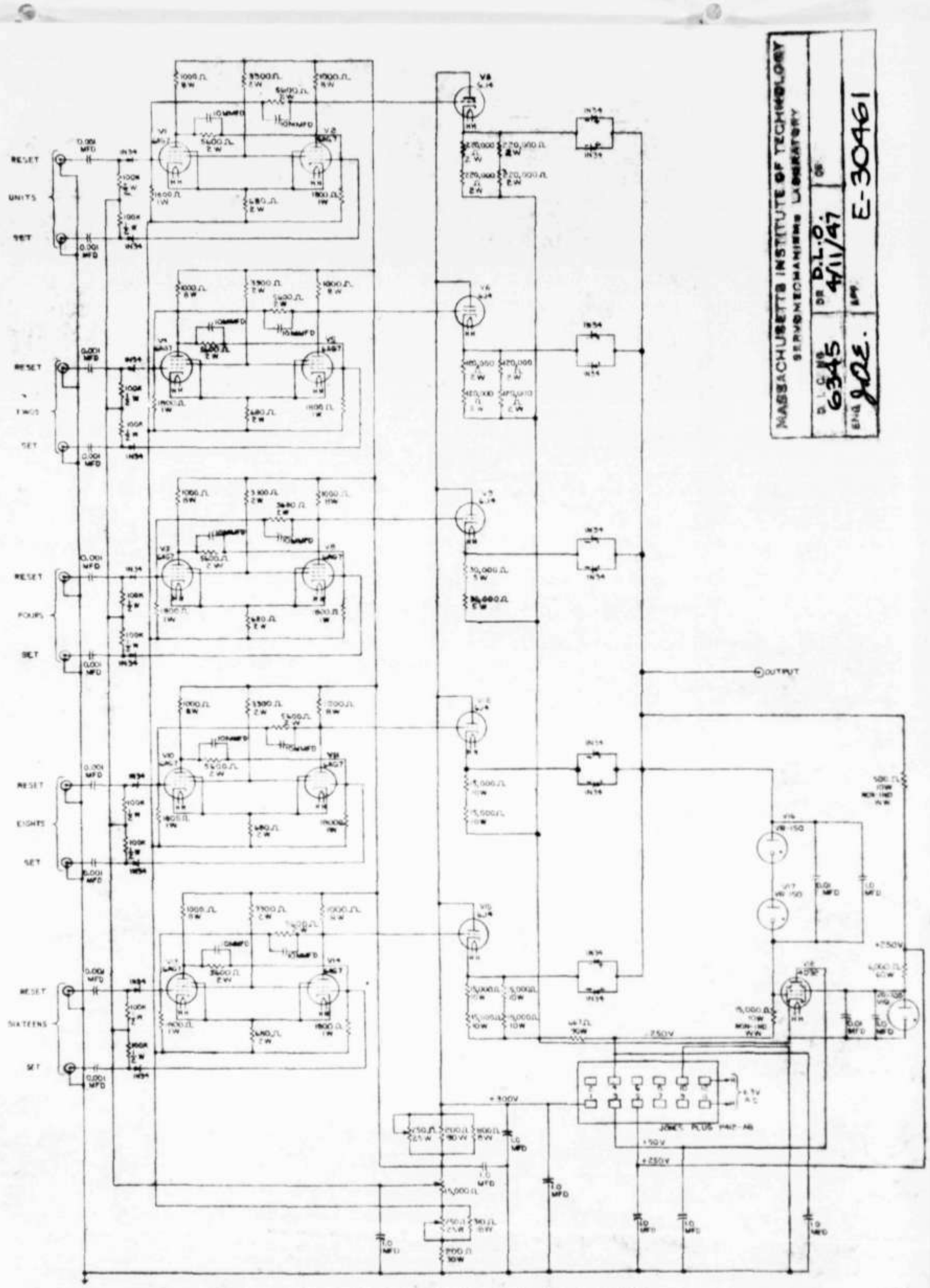
USED IN 6345 REPORT R-120

A-31119 USED IN 6345 REPORT R-120



BLOCK DIAGRAM OF CONNECTIONS FOR 8-POSITION EQUAL-INCREMENT DECODER.

6345 F. WOLSKY 10-24-47 A-31119

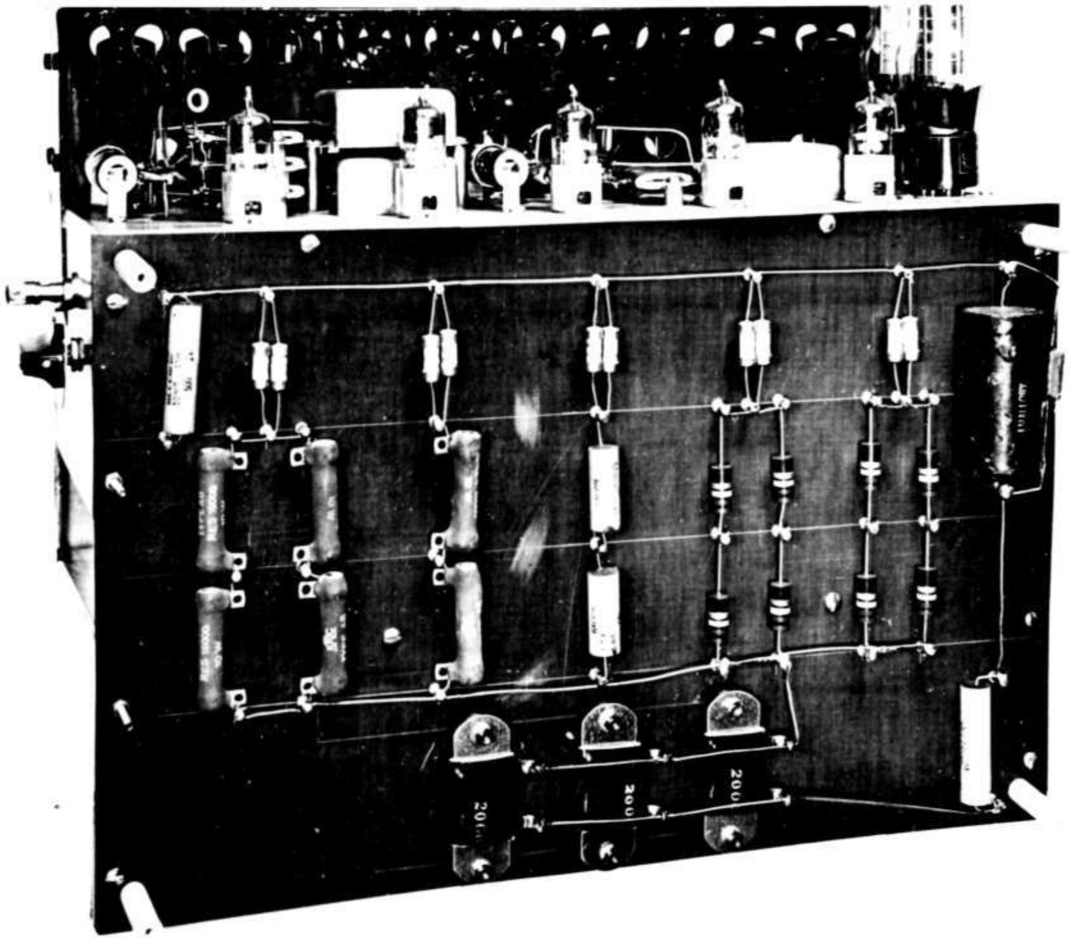


32-LEVEL BINARY-WEIGHTED VOLTAGE-DIVIDER DECODER

E-30461

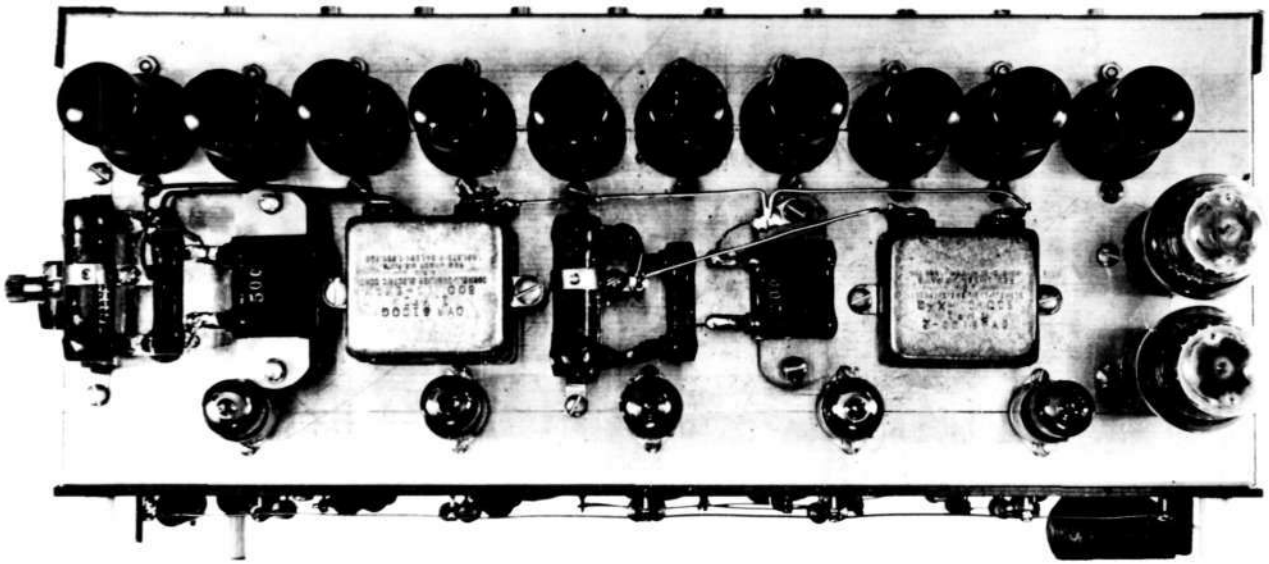
A-31120

USED IN 6345 REPORT R-120



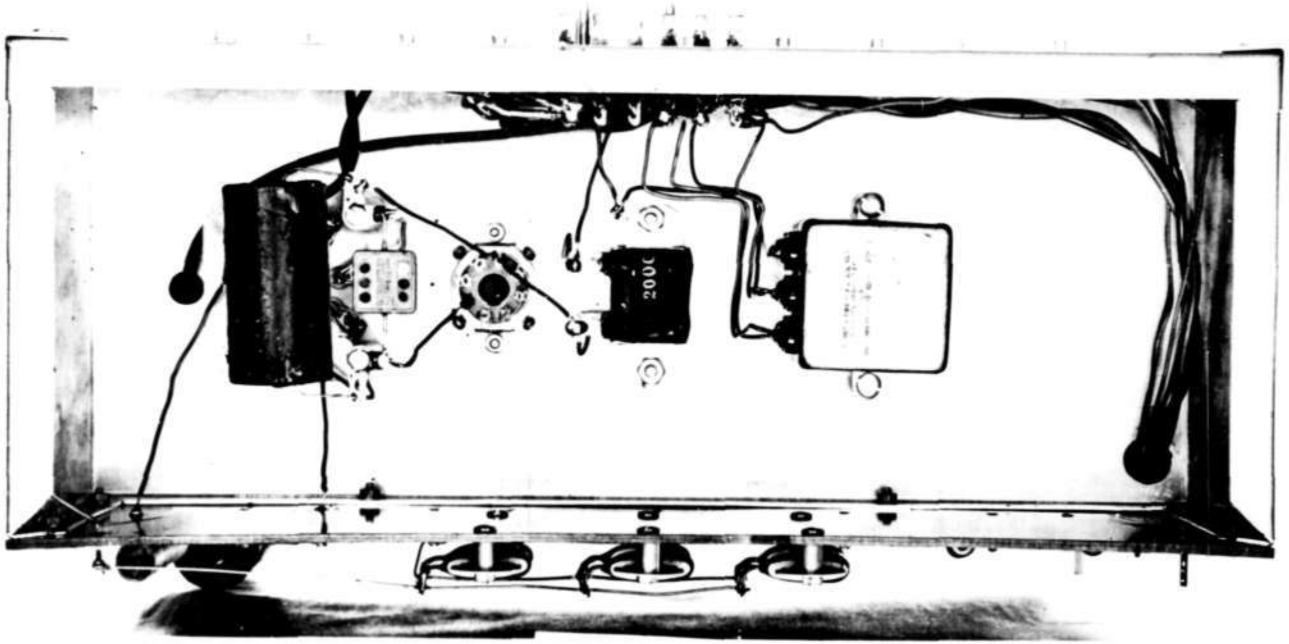
32 – POSITION BINARY – WEIGHTED DECODER CHASSIS
FRONT VIEW

A-31120

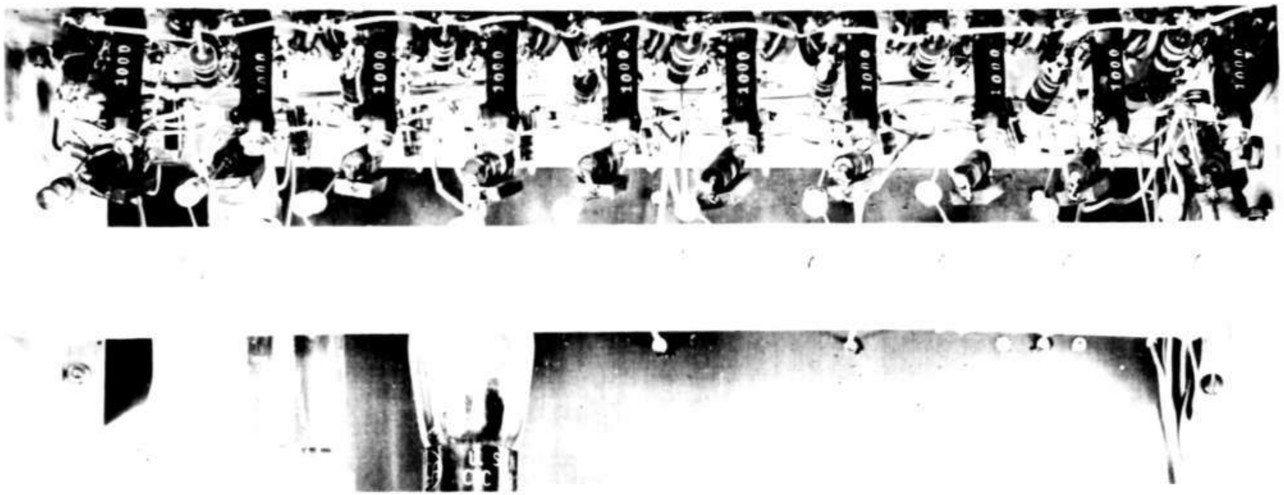


32 -POSITION BINARY - WEIGHTED DECODER CHASSIS
TOP VIEW

A-31121

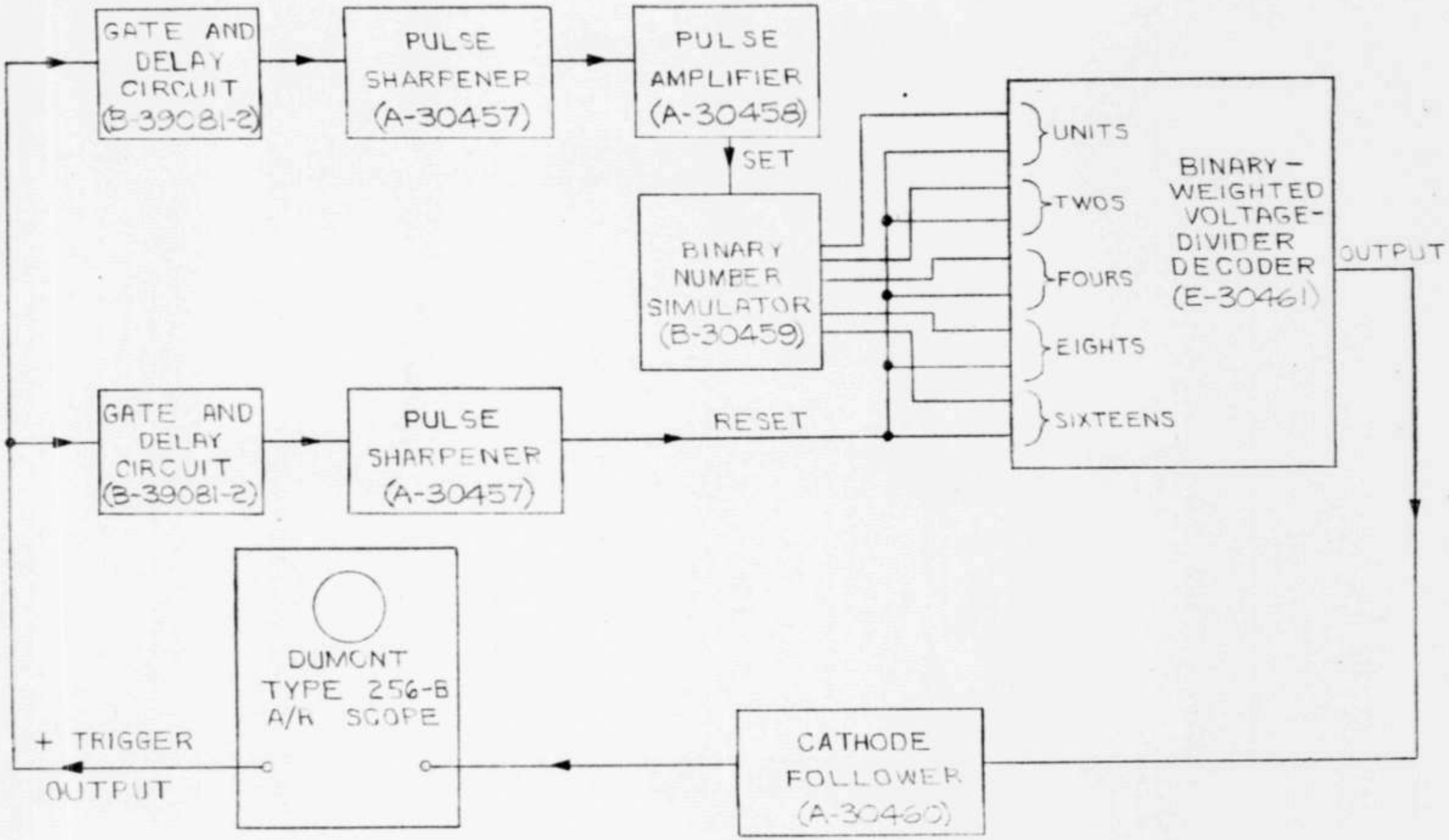


32 - POSITION BINARY - WEIGHTED DECODER CHASSIS
BOTTOM VIEW



32 – POSITION BINARY – WEIGHTED DECODER CHASSIS
FLIP-FLOP WIRING

A-30456

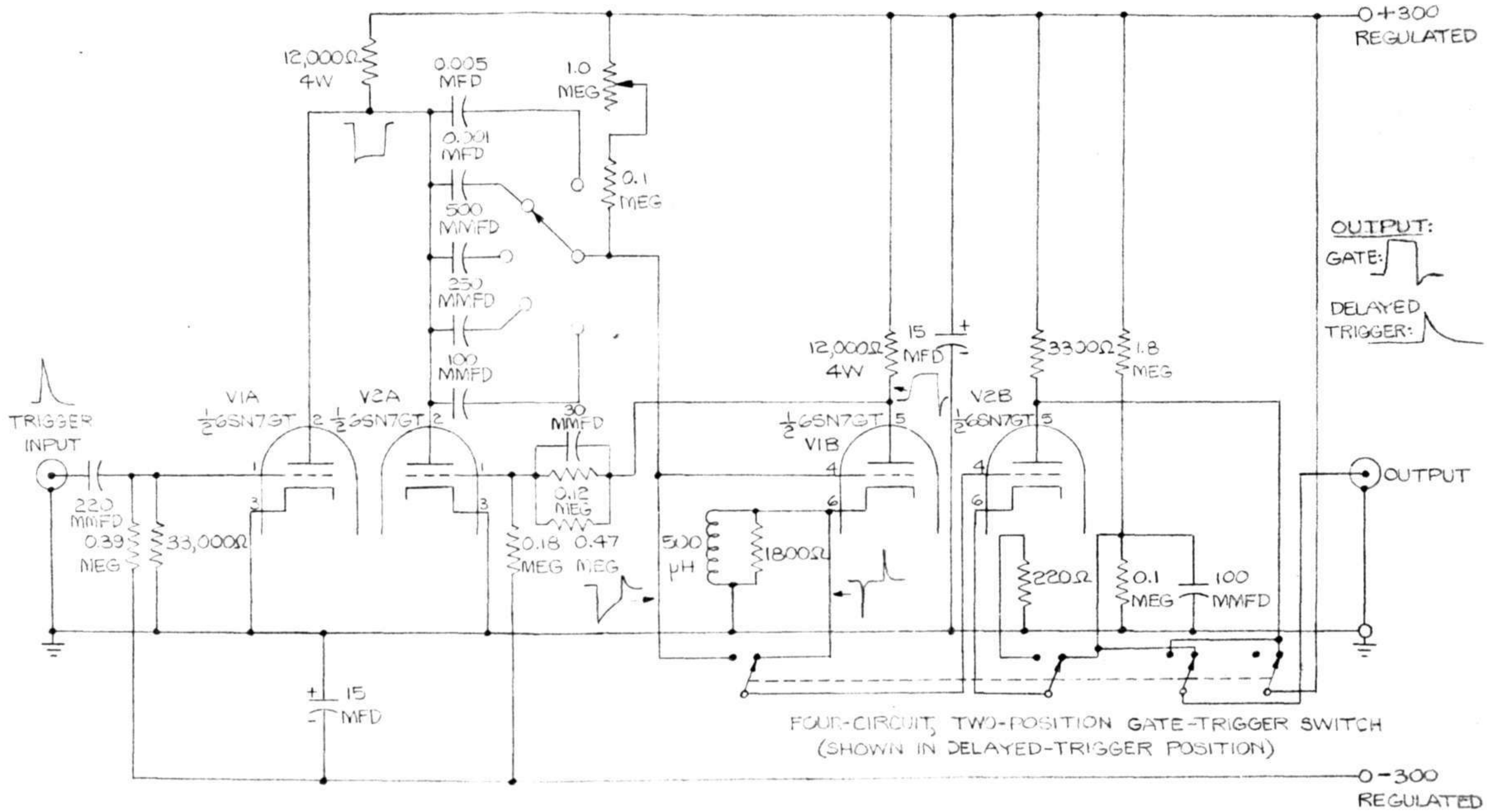


BLOCK DIAGRAM OF CONNECTIONS FOR TRANSIENT-RESPONSE TESTS OF BINARY-WEIGHTED VOLTAGE-DIVIDER DECODER.

USED IN 6345 REPORT R-120

MASSACHUSETTS INSTITUTE OF TECHNOLOGY SERVOMECHANISMS LABORATORY		
D.I.C. NO. 6345	DR DLO 4/12/47	CH TL 4/12/47
ENG	APP	A-30456

B-39081-2



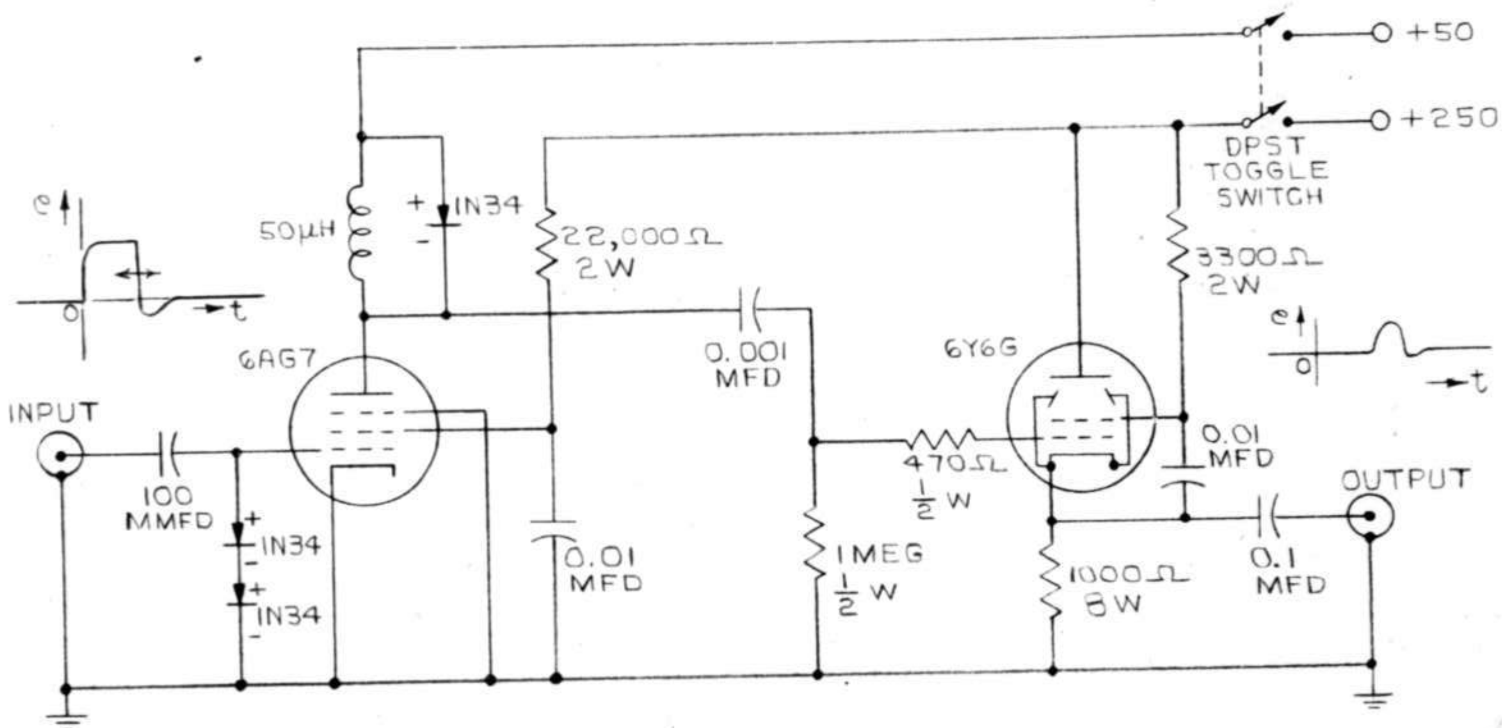
GATE GENERATOR OR DELAY BOX

P.C.G. 9/30/46

6345 B-39081-

USED IN 6345 REPORTS R-112 & R-120

A-30457

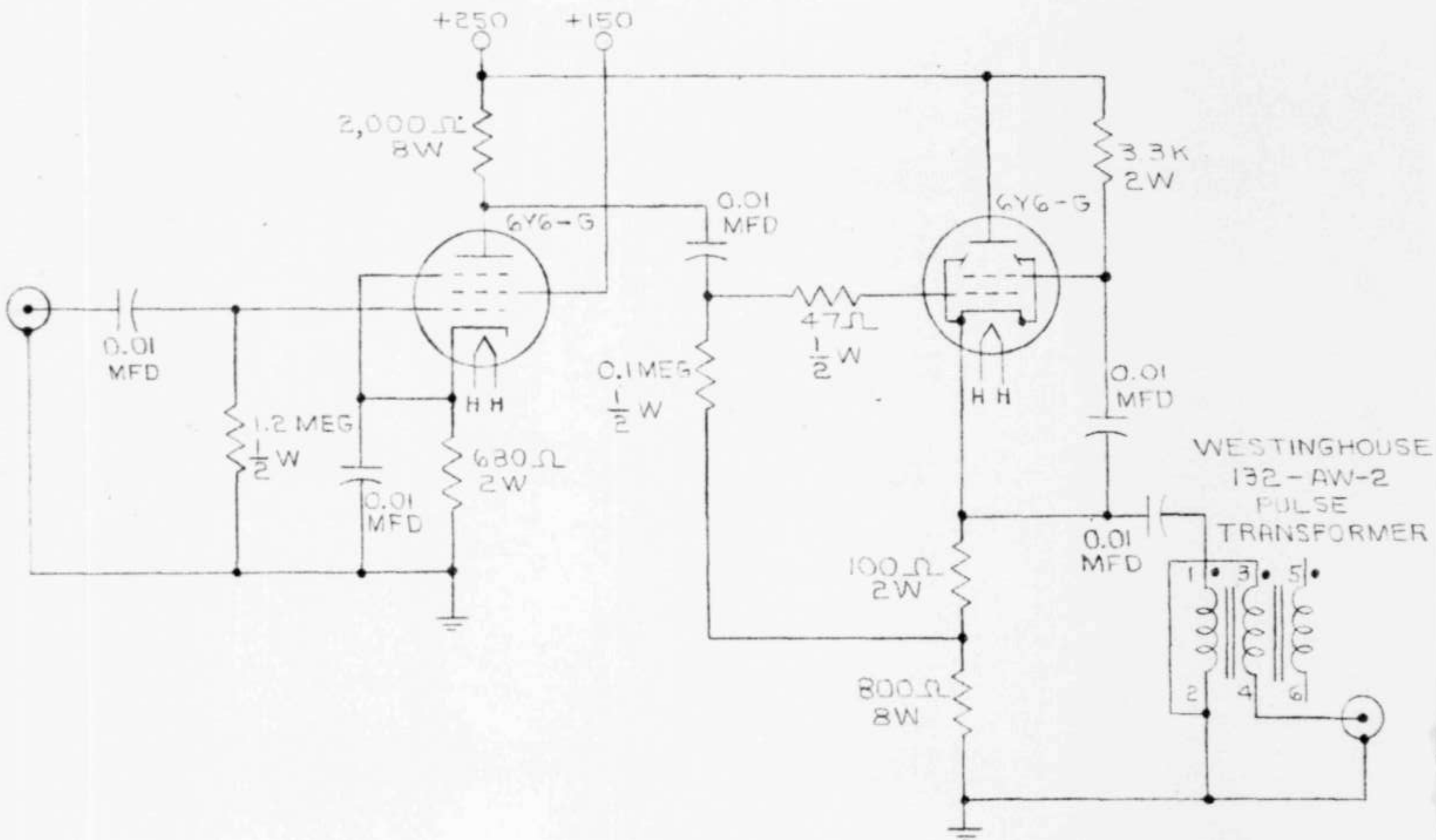


PULSE SHARPENER

USED IN 6345 REPORTS R-120 & R-123

6345 | DLO 4/12/47 | TL 4/12/47 | A-30457

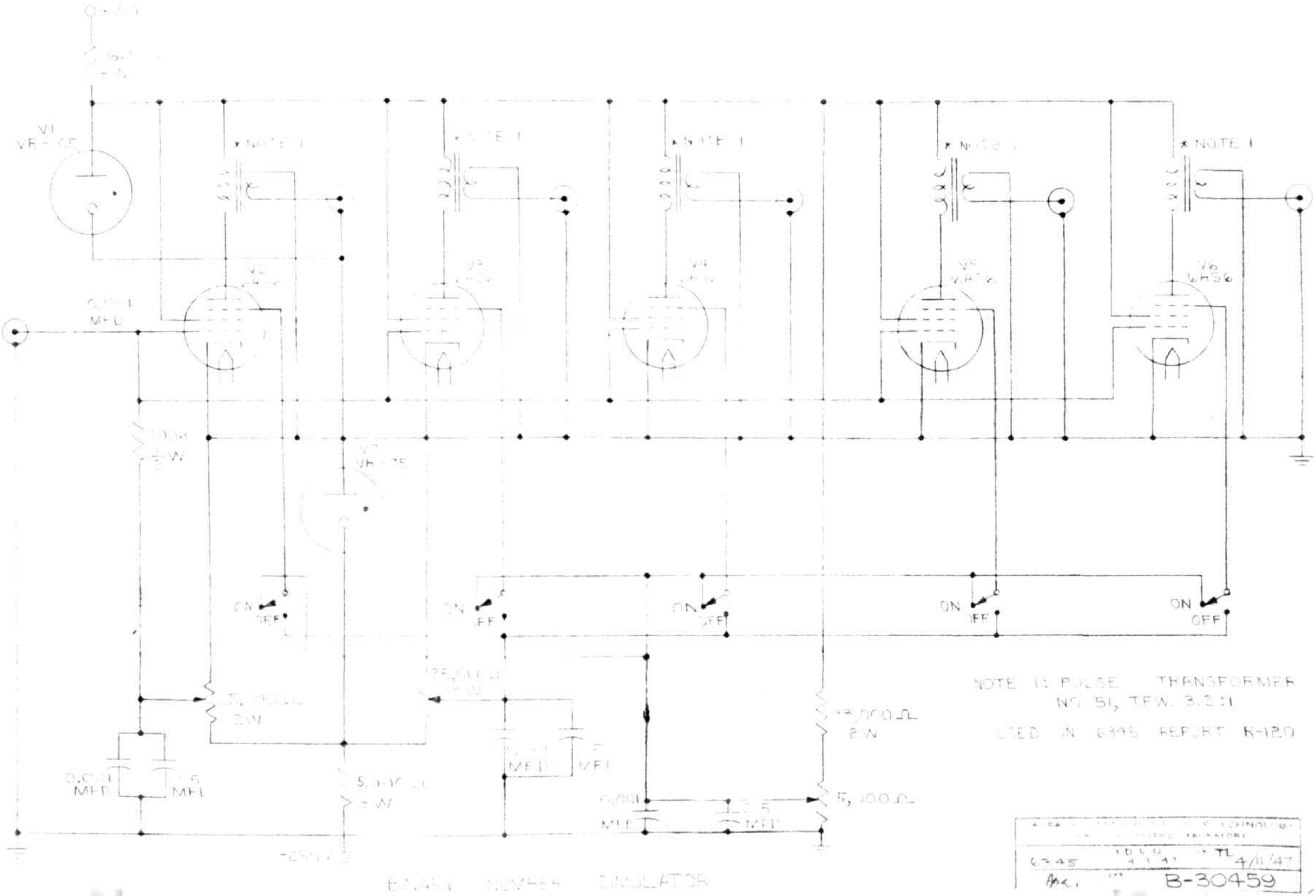
A-30458

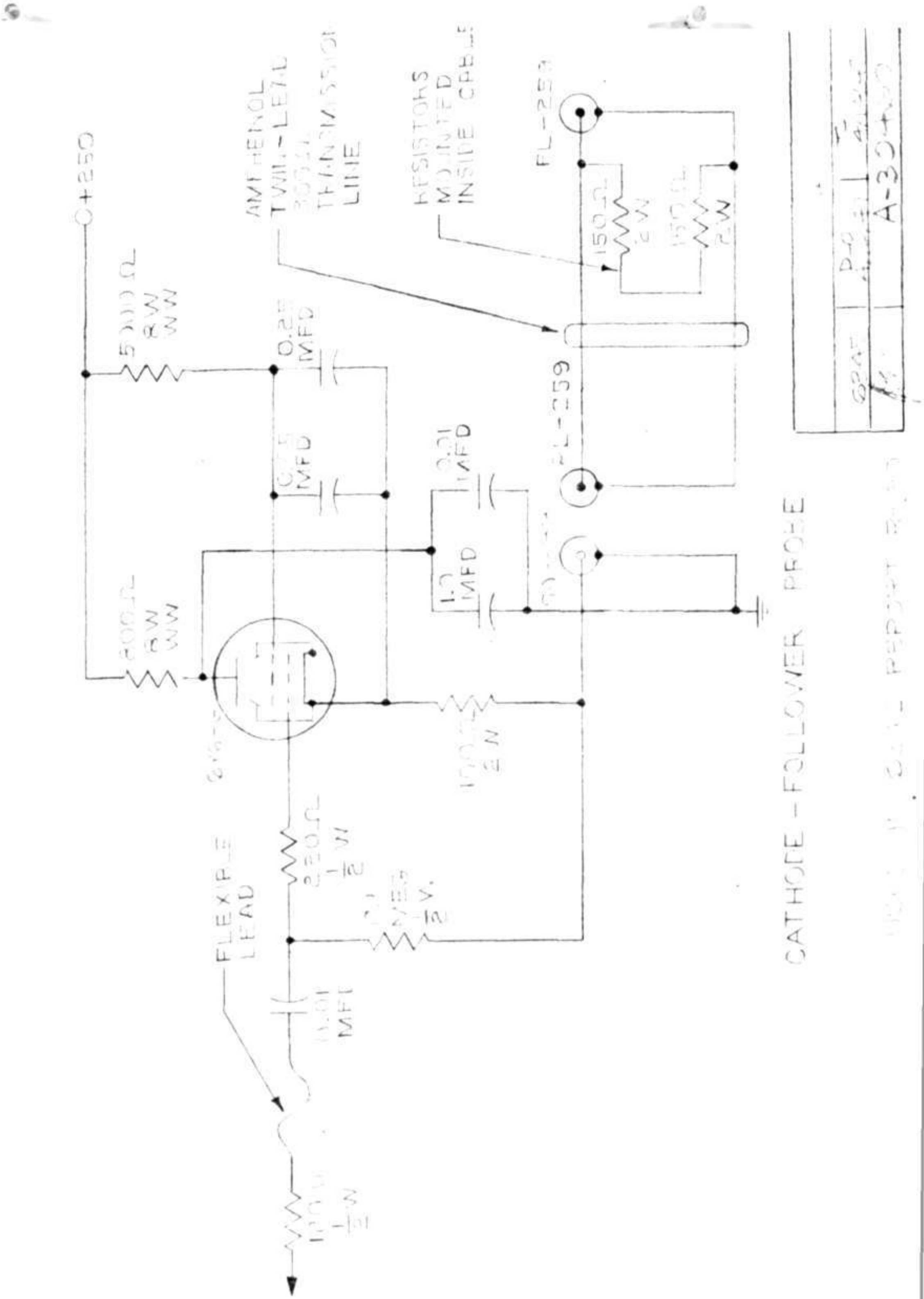


FULSE AMPLIFIER

USED IN 6345 REPORT R-120

MASSACHUSETTS INSTITUTE OF TECHNOLOGY SERVOMECHANISMS LAB.
6345 | DLO 4/13/47 | TL 4/12/47
A-30458


V1
V5
6H56
V6
6H56
★NOTE I
ON
OFF
0.001 MFD
5,000 Ω
25,000 Ω
2W
NOTE I: PULSE TRANSFORMER
NO. 51, TFW. 3:2:1
USED IN 6345 REPORT R-120
B-30459
BINARY NUMBER SIMULATOR


+250
5000 Ω
8W
WW
0.25
MFD
AMPHENOL
TWIN-LEAD
TRANSMISSION
LINE
RESISTORS
MOUNTED
INSIDE CABLE
PL-259
150 Ω
2W
0.01
MFD
1.0
MFD
8W
WW
FLEXIBLE
LEAD
CATHODE - FOLLOWER PROBE