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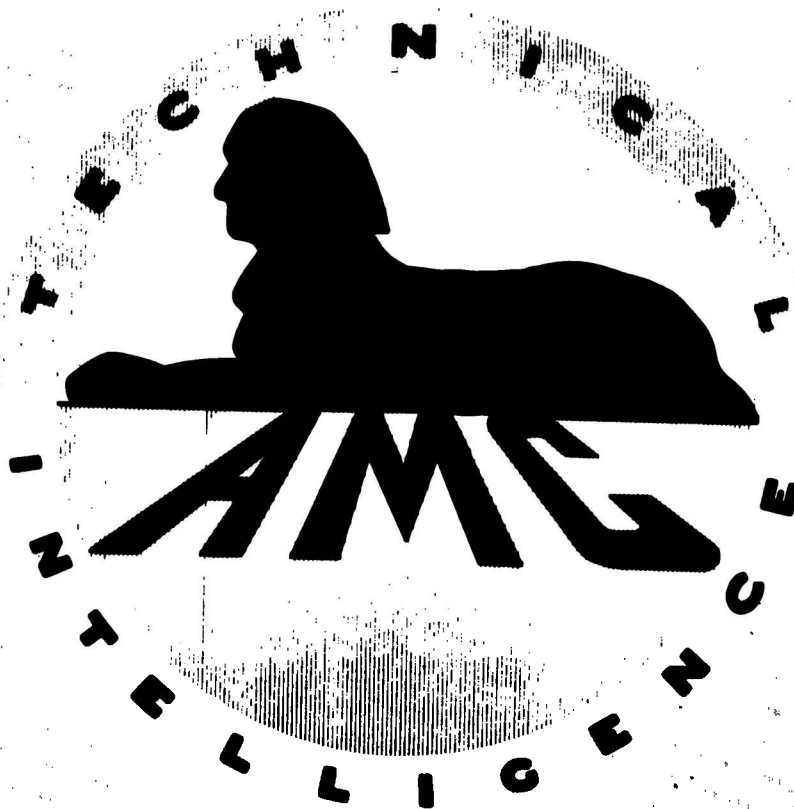
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# HIGH VOLTAGE OXIDE COATED VACUUM RECTIFIERS

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Report 892

December 19, 1945

HIGH VOLTAGE OXIDE COATED VACUUM RECTIFIERS

Abstract

Conventional diode rating methods are discussed and a new rating method based on anode dissipation is proposed. Diode design considerations are surveyed and applied to the development of an oxide coated cathode diode rated at 20 KV inverse and 100 milliamperes average. Life test data on the Raytheon QK95 are also included.

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Title page  
Table of Contents  
16 numbered pages

TABLE OF CONTENTS

|                                                                             | <u>PAGE NO.</u> |
|-----------------------------------------------------------------------------|-----------------|
| I. General Problem of Diode Specifications                                  | 1               |
| 1.1 Introduction                                                            | 1               |
| 1.2 Causes of Failure and Shortcomings of the<br>Conventional Rating Method | 1               |
| 1.3 Proposed Anode Dissipation Method for<br>Establishing Ratings.          | 3               |
| 1.4 Technique of Determining Anode Dissipation Rating.                      | 4               |
| II. External Anode Rectifier - R.L. 12                                      | 8               |
| 2.1 Factors Affecting Design                                                | 8               |
| 2.2 Anode Dissipation                                                       | 8               |
| 2.3 R.L. 12 Design                                                          | 9               |
| III. Summary of QX95 Life Test Data                                         | 15              |

## HIGH VOLTAGE OXIDE COATED VACUUM RECTIFIERS

### I. General Problem of Diode Specifications.

#### 1.1 Introduction.

The conventional method of rating a rectifier is to give maximum values for peak plate current and average or d.c. output current for a series of inverse voltage ratings. These ratings are based primarily on tube performance in conventional 60 cycle rectifier circuits and, as will be shown, do not necessarily apply for other types of service such as pulse operation. Since the conventional methods of rating do not apply to all types of service it has been customary to write a specific rating for each new application and to perform life tests under the exact circuit conditions required to establish this rating. This often leads to considerable confusion and excessive life testing.

An examination of the causes of failure of oxide diodes indicates that it should be possible to establish a rating method based on anode dissipation, which would cover all types of applications, and a rating that could be established by life tests under relatively few conditions

#### 1.2 Causes of Failure and Shortcomings of the Conventional Rating Method.

End of life is usually specified as failure to give some minimum current at a given anode voltage (resulting from loss of emission), or failure to rectify.

Failure to rectify, i.e., the presence of conduction in the reverse direction, is due to emission from the anode. Anode emission is affected by (1) anode temperature, (2) presence of barium on the anode, which causes emission to rise rapidly as the anode passes a critical temperature, (3) degree of vacuum and (4) inverse voltage.

Because of other design considerations, cathode size is usually greater than necessary to provide adequate emission. Cathode failure, however, may be caused by (1) improper processing, (2) over-heating due to back emission, which causes evaporation of the oxide coating or, in some cases, the melting of the cathode structure.

As can be seen from the above remarks, the primary cause of failure is back emission and, for a given tube design, this is closely connected with anode temperature.

In the conventional method of diode rating, the limitation of average current is an attempt to limit anode heating, however anode dissipation is not proportional to average current. If the tube were

a pure resistance, an r.m.s. current rating would be satisfactory, but the tube is a non-linear impedance whose resistance is proportional to  $I^{-1/3}$ . The usual diode peak current rating is to prevent gas being released from the anode possibly due to electron bombardment or surface heating.

The effect of anode current wave form on anode heating is shown in Tables I and II. These tables are based on a rectangular wave form to simplify calculations, the values of tube drop during the conducting period being taken from the experimental characteristics of the 6X95 diode shown in Figure 9. The anode dissipation is the product of tube drop, peak current and percentage time of conduction. Table I shows the variation in anode watts for constant average current and varying peak current and Table II shows the variation in anode watts for constant r.m.s. current and varying peak current.

| Conduction Time % of cycle | Peak Current Ampe | Average Current Amps | r.m.s. Current Amps | Peak Tube Drop Volts | Anode Dissipation Watts |
|----------------------------|-------------------|----------------------|---------------------|----------------------|-------------------------|
| 20                         | .500              | .100                 | .223                | 350                  | 35                      |
| 40                         | .250              | .100                 | .158                | 204                  | 20.4                    |
| 100                        | .100              | .100                 | .100                | 108                  | 10.8                    |

TABLE I

| Conduction Time % of cycle | Peak Current Amps | Average Current Amps | r.m.s. Current Amps | Peak Tube Drop Volts | Anode Dissipation Watts |
|----------------------------|-------------------|----------------------|---------------------|----------------------|-------------------------|
| 9                          | .500              | .045                 | .150                | 350                  | 15.8                    |
| 36                         | .250              | .090                 | .150                | 204                  | 18.4                    |
| 100                        | .150              | .150                 | .150                | 142                  | 21.3                    |

TABLE II

It is evident from these tables that anode wattage can vary widely for either constant average, or constant r.m.s. current. Hence neither of these represent an accurate method of rating. They are useful only in a specific circuit, such as 60 cycle rectifier service, where the current wave form is relatively fixed. Since conduction in the reverse direction is largely dependent on anode temperature, it would seem more logical to base diode ratings on anode dissipation.

### 1.3 Proposed Anode Dissipation Method for Establishing Ratings.

In general, a diode of given design will have a maximum inverse voltage rating that is relatively independent of anode dissipation. The structure of the tube, such as spacing of the elements, breakdown of insulators, etc., and the residual gas pressure determine this voltage. The maximum inverse voltage rating can be determined by life tests at relatively low currents, and it will hold below those values of anode dissipation at which any appreciable back emission can occur. In Figure 1, point B represents the maximum allowable anode dissipation at maximum inverse voltage.

A given diode design will also have a maximum anode dissipation above which the anode temperature is such that back emission rises very rapidly. The diode cannot be operated above this dissipation even at very low inverse voltage. However, it is usually possible to operate at this dissipation up to an inverse voltage of considerable value. Point C in Figure 2 represents the maximum inverse voltage at maximum anode dissipation. The shaded region of Figure 2, bounded by the line A, B, C, D, represents safe values of anode dissipation and inverse voltage as determined by two life-test conditions. For absolute maximum ratings the line A, B, C, D would be some form of smooth curve, but for most practical purposes two test points can be used to determine the boundary conditions.

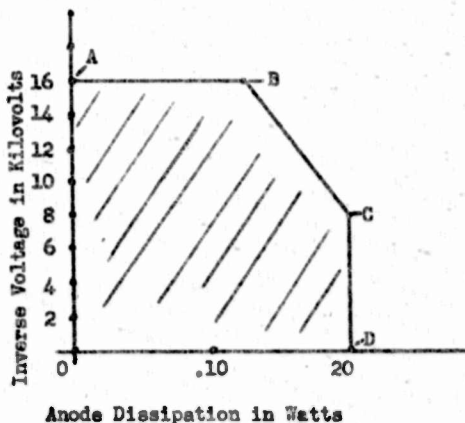


Figure 1

The permissible peak current which may be drawn is not usually limited by the cathode, but by anode gassing. For very short pulses, i.e., 1 to 2 microseconds, current may be limited by the cathode, but for longer pulses there will be a series of peak current ratings dependent upon the duration of the pulse and upon the inverse voltage. Since this limitation is to prevent anode gassing and is not dependent upon anode dissipation, it should be possible to determine values of peak current without life tests. Several test points at maximum inverse voltage should give a curve showing safe limits of peak current and current duration.

#### 1.4 Technique of Determining Anode Dissipation Rating.

To determine diode anode dissipation, it is necessary to measure r.m.s. current and r.m.s. forward voltage of the diode in the particular circuit application. A thermocouple voltmeter and ammeter are used to obtain r.m.s. values, and a second diode is placed in series with the tube under measurement to keep the inverse voltage from the voltmeter. Figure 2 shows the connections for a half-wave negative hot rectifier circuit.

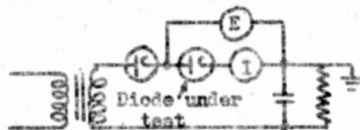


Figure 2.

First the ammeter is inserted in the circuit to obtain the r.m.s. current under normal operating conditions. Then the second diode and the voltmeter are added to the circuit; the r.m.s. current is set to the value previously measured and the r.m.s. voltage read. The product of r.m.s. values of current and voltage is the anode dissipation.

It is recognized that the insertion of the additional resistance (the second diode) will affect the peak current, but when the r.m.s. current is set to the normal value the loss in peak current is compensated for by an increase in the duration of the time of current flow. An increase in average current will also result. The actual difference is quite small (of the same order of magnitude as the probable error of measurement) and is in the direction of increased safety.

To establish the tube ratings by the anode dissipation method, it is necessary to carry on life tests. A series of tests were conducted on the 6X95 diode.

Since a rating of  $\pm 10\%$  on filament voltage was desired, most tests were conducted at  $\pm 10\%$  on the filament. The over-volted filament raises quiescent cathode temperatures some 50 to  $60^{\circ}\text{C}$ , resulting in somewhat higher quiescent anode temperatures. The higher initial cathode and anode temperatures appreciably lower the anode dissipation which is permissible if the marginal condition which may result in failure to rectify is to be avoided.

The low filament voltage condition is essentially an emission problem. In the case of the 6X95, the large cathode area of approximately 2.6 sq. cm. limits current densities (at 8 amps total, density = 3.25 amp/sq. cm.) sufficiently to prevent any marked degree of temperature limited emission.

In addition, a few spot checks of anode dissipation were made under widely differing applications at both plus and minus  $10\%$  of nominal filament voltage. No appreciable difference in anode dissipation resulted from the  $20\%$  change in filament voltage.

To establish the high-dissipation, low-inverse rating a series of life tests were conducted at several levels. One group was run at about 6.5 KV inverse voltage and anode dissipations of 21 to 25 watts. These test points are plotted in Figure 3 as group I. A second group was tested at inverse voltages of 10 to 11 KV and anode dissipations of 21 to 23 watts, and is plotted as group II in Figure 4. A third group was tested at 8 KV inverse voltage and anode dissipations of 20 to 21 watts, and is plotted as group III of Figure 4.

Those tubes tested at 6.5 KV inverse voltage with 21 watts anode dissipation show low values of leakage current throughout tests of more than 500 hours. Those run at 25 watts anode dissipation were early failures (failure to rectify). The tubes run at 11 KV inverse voltage and 21 to 22 watts anode dissipation were either marginal or early failures. The tubes run at 8 KV inverse and 20 to 21 watts anode dissipation showed low values of leakage current for 500 hours. Beyond 500 hours the leakage was slowly increasing, but had not reached marginal values at 600 hours when the tests were concluded. From these tests it seems apparent that 20 watts is the maximum safe anode dissipation for values of inverse voltage up to 8 KV, and is plotted as point B in Figure 3.

Typical data from a number of preliminary tests at 17 KV inverse voltage, 12.5 watts anode dissipation, and 6.5 KV inverse voltage at 21 watts are tabulated in Table III. Operation at the higher inverse voltage represents a less severe condition, as is indicated in these data by the appreciably smaller values of leakage measured.

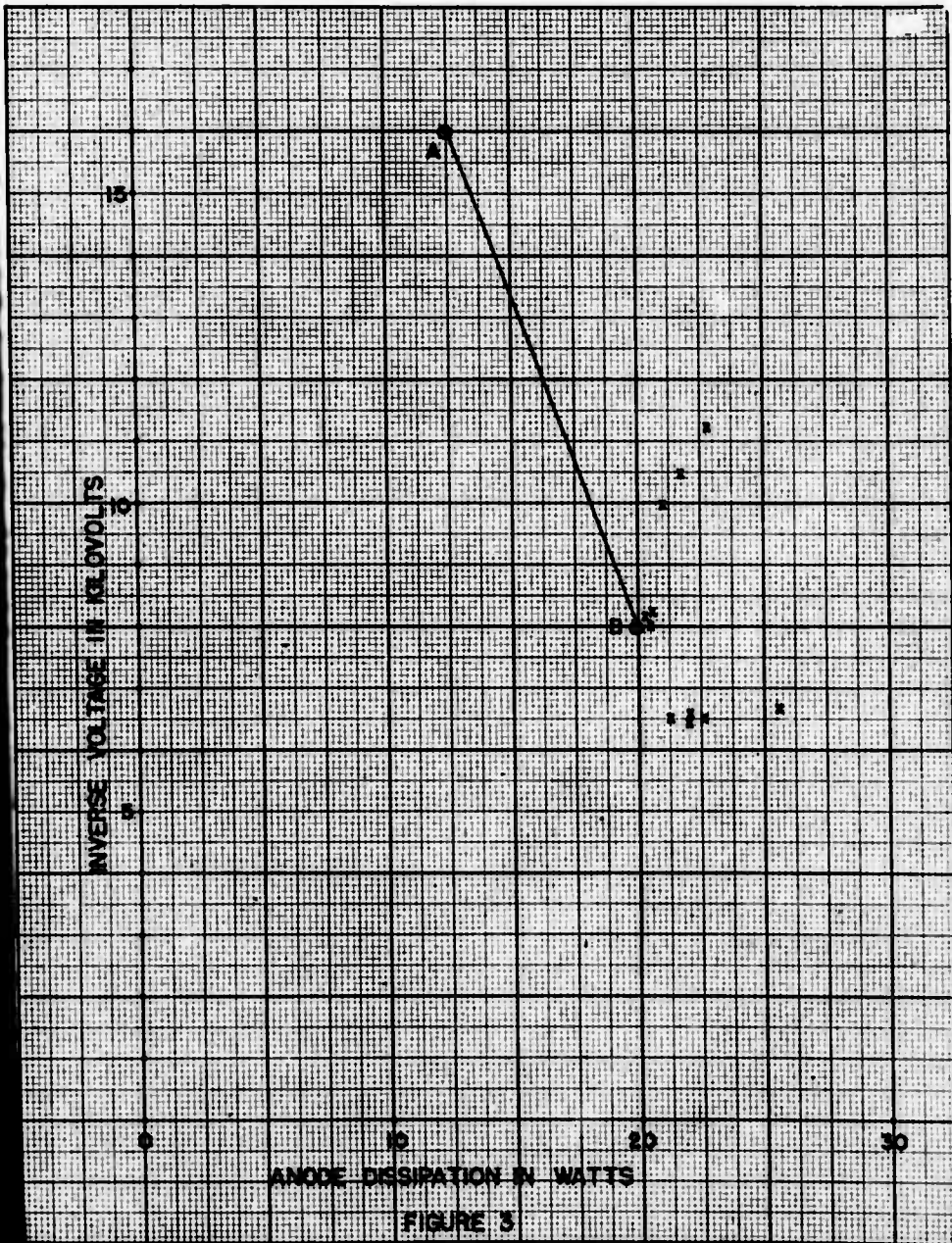
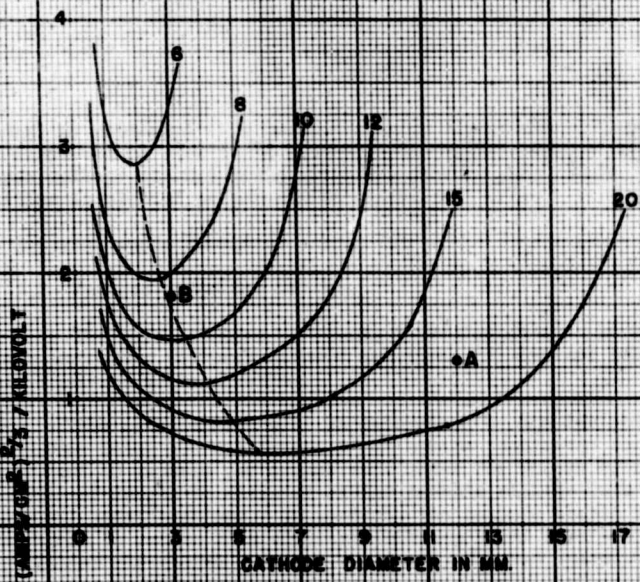


FIGURE 3

PARAMETER: ANODE DIAMETER  
IN MM  
CATHODE IS UNIT AREA



POINT A IS OKS8  
POINT B IS RL 12

FIGURE 4

| Tube No. | Inverse voltage<br>in KV | Anode<br>Dissipation<br>in Watts | Leakage current<br>in $\mu$ Amps. |
|----------|--------------------------|----------------------------------|-----------------------------------|
| 29       | 17                       | 12.5                             | 30                                |
|          | 6.5                      | 22.6                             | 180                               |
| 48       | 17                       | 12.5                             | 25                                |
|          | 6.7                      | 21.9                             | 40                                |

TABLE III

Although no extensive life tests at the 17 KV inverse voltage condition were conducted in view of the above preliminary tests, a rating of 16 KV inverse voltage at 12.5 watts anode dissipation seems safe. This condition is plotted as point A in Figure 3.

## II. External Anode Rectifier - R.L. 12.

### 2.1 Factors Affecting Design.

The major factors affecting diode design are (1) average cathode emission, (2) peak cathode emission, (3) desired tube drop, and (4) inverse voltage rating.

The cathode area will be determined by the desired emission, safe values being 100 milliamperes per square centimeter for average current and 10 amperes per square centimeter for pulsed or peak emission. The ratio of length to diameter of the cathode will be determined by structural considerations. In general, the cathode should be as long as possible to reduce tube drop and increase anode dissipation; however, long slender structures may be mechanically unsound, particularly with single-ended mounting.

Anode diameter will depend on the cathode diameter. The anode-to-cathode spacing should be as small as possible, taking into consideration ease of assembly and back emission from the anode.

It can be shown that for each cathode diameter there is an optimum anode diameter with respect to variation in tube drop with alignment. Figure 5 is a family of curves in which amperes per sq. cm. to the two thirds power per kilovolt is plotted against cathode diameter for several anode diameters. The curves derive from the general emission equation  $I = KV^{2/3}$ , and the anode and cathode diameters at the minima represent optimum values.

### 2.2 Anode Dissipation.

The chief diode limitation is anode heating. The equation for tube drop in a diode is,

$$E = \left( \frac{J}{2\pi \times 2.33 \times 10^{-6}} \right)^{\frac{2}{3}} (V\beta^2)^{\frac{2}{3}}$$

in which  $J$  is current in amperes per unit cathode length,  $V$  is anode radius and  $\beta^2$  a factor dependent on the ratio of anode to cathode radii. Figure 5 is a graph in which anode watts per sq. cm. are plotted against anode diameter. The points on the curve AB of Figure 5 were calculated from the above equation by holding the cathode area and diameter constant. The values of anode wattage plotted are due

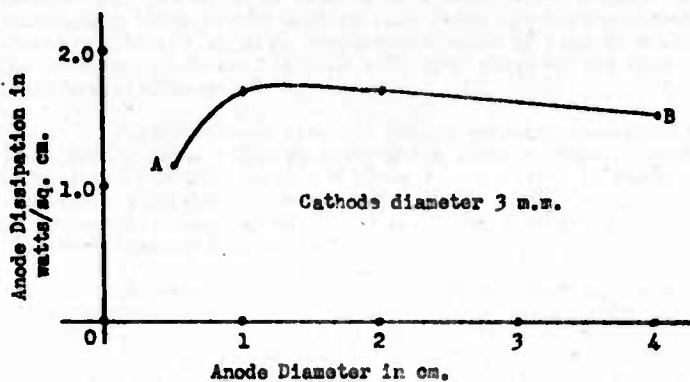


Figure 5.

entirely to tube drop, and do not include any energy radiated from the cathode. It should be noted that, as the anode diameter increases, the total watt dissipated at the anode increases, and as is evident from Figure 5, an increase in this diameter will not result in an increase in tube rating.

An increase in tube rating can be obtained by an increase in effective anode and cathode length, by the addition of dissipating fins to the anode, or by air or water cooling of the anode. The effectiveness of cooling fins is limited by the heat conductivity of the anode material; water cooling, though effective, adds complications. The use of air-cooled anode seems to be the simple, effective way to increase tube rating.

### 2.3 R.L. 12

The R.L. 12 is a high vacuum diode designed for 20 KV inverse, 100 milliamperes average and 10 amperes peak.

In designing this tube a conservative cathode area of 1.5 square centimeters was chosen and, on the basis of 3 millimeters diameter, the coated length was 1.6 centimeters. This gave overall cathode sleeve dimensions, including the uncoated ends, of approximately .120 inches by .875 inches, which seemed a reasonable design from the standpoint of mechanical strength. The anode diameter was chosen on the basis of the curves in Figure 4, and came out approximately 9 millimeters; the actual value used was .350 inches. This gave an anode-to-cathode spacing of .116 inches, which proved to be adequate for an inverse voltage of 20 KV.

Figure 6 is a drawing of diode R.L. 12 showing significant dimensions. The anode is made up of a kovar disc, a machined copper barrel, and light copper cooling fins which are hard-soldered in a single operation. A high temperature paint is used to protect the copper. The metal-to-glass seal is made with 7052 glass to the kovar. The press leads are also kovar.

Figure 7 shows d.c. and pulsed emission characteristics, taken with 9 watts filament power which gives a cathode temperature of approximately 750°C. Figure 8 shows the variation of anode temperature with anode dissipation for one tube. Temperatures were measured with a thermocouple touching the anode barrel at the bottom edge of the cooling fins when drawing d.c. current.

In processing the tube, certain precautions are necessary to assure thorough degassing of both the anode and cathode. A bake-out at 450°C for one half hour followed by cathode conversion and activation with the oven at a temperature of 300°C was used with satisfactory results. Care was taken to bring the cathode to a high temperature (1050-1100°C) for a time sufficiently long to thoroughly degas the cathode and at the same time, emission was drawn to heat and degas the anode. The tube was allowed to cool, the barium getter was flashed, and the tube tipped off. It is possible to use such high temperatures and to use a large getter without difficulties due to the presence of barium on the anode because of the low anode temperatures.

One tube was life tested at 21 KV inverse, .100 amps. average, and .575 amps. peak current. The tube was run with 9 watts heater power and was still good after more than 600 hours. The maximum inverse current measured at any time was 1-1/2 microamperes.

R.L. drawings TC6477A to K give the complete details of the R.L. 12 design.



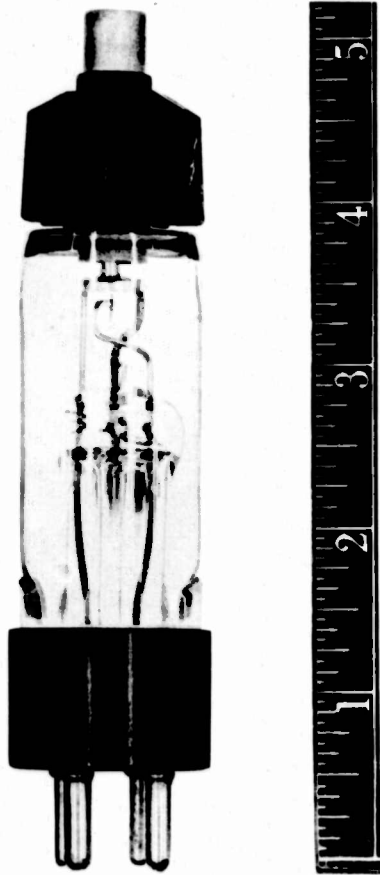


FIGURE 6B -R.L.12

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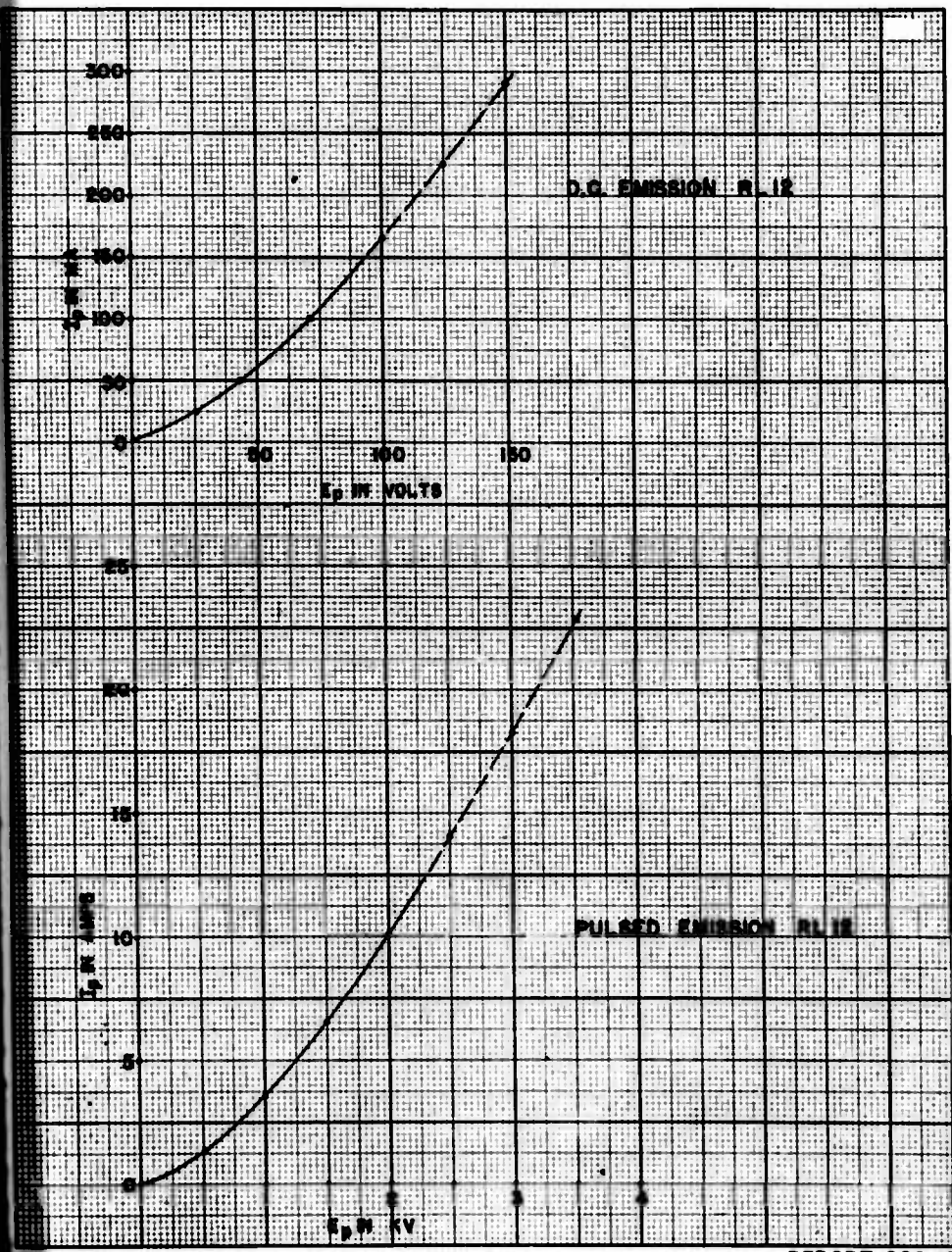


FIGURE 7

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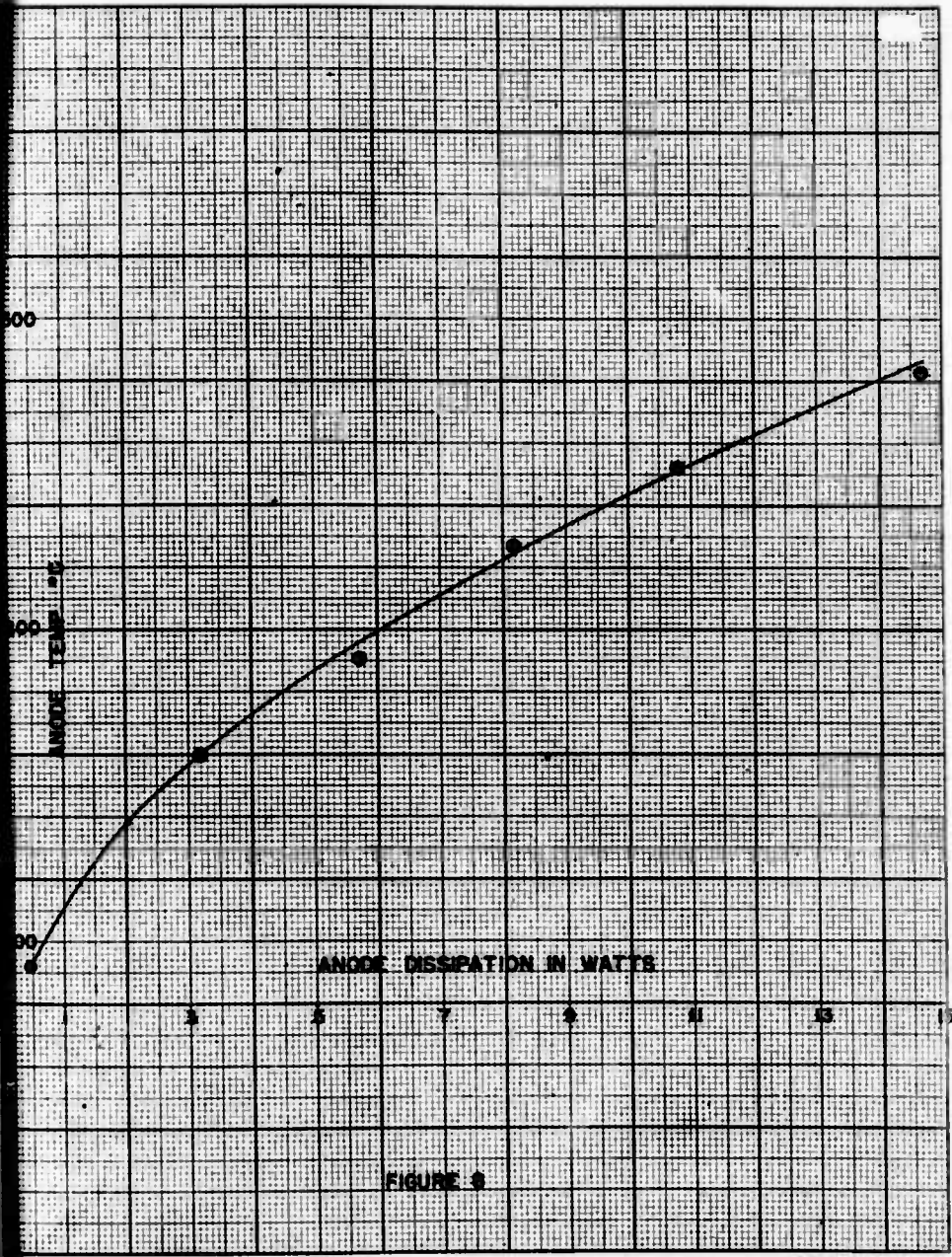


FIGURE 3

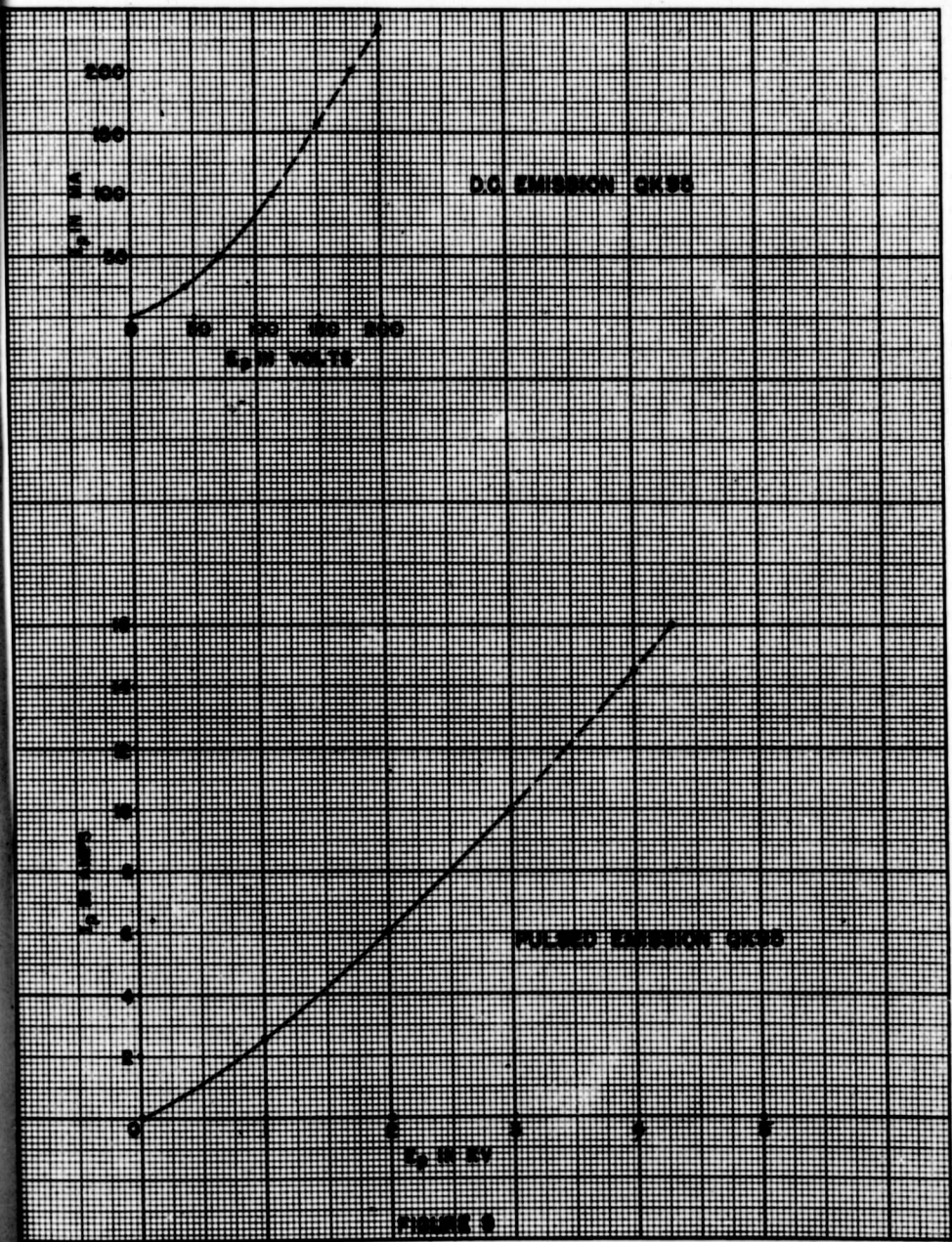


FIGURE 3

### III Summary of Life Tests of 6X95

Table IV lists results of life tests at R.L. on 6X95's. All 6X95 tubes received have been tested for pulsed emission, and 5% were below 8 amps. at 3 KV. All tubes have been aged from 5 minutes to 2 hours at 17 KV inverse, and 12.5 watts anode dissipation. A few needed no ageing but the vast majority had high leakage currents which decreased during ageing; approximately 5% had such high leakage that destruction would have resulted had they remained more than a few minutes on ageing. The high leakage seemed to be due to the presence of appreciable quantities of gas. In some cases, a gas discharge of low intensity was observed, in other cases, with somewhat lower leakage, the presence of gas was indicated by large and rapid fluctuations in the leakage.

The life tests indicated a considerable variation in quality from one tube to another, and it seems advisable to include a limitation on leakage current of 50 or 60amps with the tube operating at 8 KV inverse and 20 watts anode dissipation.

| Tube No. | Hours | V<br>E <sub>f</sub> | KV<br>E <sub>px</sub> | mA<br>I <sub>px</sub><br>(final) | Ave.<br>I <sub>p</sub> | r.m.s.<br>I <sub>p</sub> | W <sub>p</sub> | Type of<br>service | Remarks                |
|----------|-------|---------------------|-----------------------|----------------------------------|------------------------|--------------------------|----------------|--------------------|------------------------|
| #69      | 486   | 2.5                 | 9.75                  |                                  | .270                   |                          | 38             | Shunt<br>Diode     | Failure to<br>rectify. |
| A0022    | 121   | 2.75                | 10                    |                                  | .218                   |                          | 23.2           | "                  | "                      |
| #19      | 26    | 2.75                | 6.5                   |                                  | .101                   |                          |                | rectifier          | "                      |
| #1       | 510   | 2.5                 | 5.8                   |                                  | .096                   | .160                     |                | "                  | O.K.                   |
| #14      | 510   | 2.5                 | 5.8                   |                                  | .096                   | .160                     |                | "                  | "                      |
| #13      | 510   | 2.5                 | 9.75                  |                                  | .096                   | .171                     |                | Hold off           | "                      |
| A0119    | 95    | 2.75                | 11.2                  | 30                               | .089                   | .163                     | 22.3           | rectifier          | Failure to<br>rectify  |
| A0035    | 80    | 2.75                | 6.7                   | 110                              | .096                   | .167                     | 25.7           | "                  | "                      |
| #2       | 614   | 2.75                | 6.5                   | 25                               | .101                   | .157                     | 21.3           | "                  | O.K.                   |
| #31      | 597   | 2.75                | 6.6                   | 8                                | .101                   | .157                     | 22             | "                  | "                      |
| #48      | 501   | 2.75                | 6.7                   | 65                               | .099                   | .165                     | 21.9           | "                  | "                      |
| #29      | 501   | 2.75                | 6.5                   | 1.2                              | .099                   | .165                     | 22.6           | "                  | "                      |
| A0121    | 670   | 2.75                | 8.1                   | 3.5                              | .080                   | .151                     | 20.4           | "                  | "                      |
| A0070    | 668   | 2.75                | 8.1                   | 14                               | .088                   | .150                     | 20.7           | "                  | "                      |
| A0024    | 670   | 2.75                | 8.1                   | 25                               | .087                   | .148                     | 20.8           | "                  | "                      |
| A0020    | 666   | 2.75                | 8.2                   | 7.5                              | .086                   | .148                     | 20.5           | "                  | "                      |
| A0069    | 579   | 2.75                | 8                     | 3.5                              | .083                   | .146                     | 20.2           | "                  | "                      |

K. J. Gernschausen  
K. J. Urquhart  
October 12, 1948

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