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Polytechnic Institute of Brooklyn
55 Johnson Street
Brooklyn 1, New York

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(6) Oxide Cathode Coating Impedance,

STI

by

~~G. C. Dalman~~*

and

~~H. J. Miller~~**

(10) G. C. Dalman
H. J. Miller

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* Polytechnic Institute of Brooklyn, Brooklyn, N. Y.
** RCA Victor Division, Harrison, N. J.

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A. Abstract

Experimental determination of the impedance characteristics of a cut-off "ideal" parallel plane diode and an analysis of the results obtained have demonstrated the importance of the characteristics of the oxide coated cathode on tube behavior at high frequencies. Based upon the fundamental field equation and guided by the experimental results, the impedance of the oxide coating has been derived. The analysis shows that the impedance properties of the coating are governed by the effective conductivity, the effective dielectric constant, and the effective Maxwell "time of relaxation" of the coating. These are properties influenced by the chemical composition of the coating and its physical characteristics as well as temperature and frequency of operation. Suggestions as to further experimentation are given as well as some discussion on the influence of the impedance of the oxide coating on the impedance properties of tubes.

B. Impedance Equations

1. Oxide Coating Impedance

As a starting point in describing the behavior of the oxide coating we assume that for plane waves harmonic in time, the fundamental equation may be applied:

$$I = (\sigma_e + j\omega\varepsilon_e)E,$$

where

I is the total current density in amperes per unit area (centimeters)^2.

E is the electric field intensity in volts per centimeter.

σ_e is the effective conductivity in mho per centimeter.

ε_e is the effective dielectric constant in farad per centimeter

ω is the angular velocity in radians per second.

Let t be the thickness of the oxide coating, then if V is the a-c voltage appearing across the coating,

$$E = \frac{V}{t} \qquad (2)$$

Therefore

$$I = (\sigma_e + j\omega\varepsilon_e)\frac{V}{t} \qquad (3)$$

Thus the oxide coating impedance becomes:

$$Z_c = \frac{V}{I} = \frac{t}{\sigma_e + j\omega\varepsilon_e}, \qquad (4)$$

or

$$Z_c = \left[\frac{\sigma_e}{\sigma_e^2 + \omega^2 \varepsilon_e^2}\right] t - j\left[\frac{\omega \varepsilon_e}{\sigma_e^2 + \omega^2 \varepsilon_e^2}\right] t \qquad (5)$$

2. Cut-Off Diode Impedance

Assume an ideal parallel plane diode having an oxide coated cathode operating with a highly negative voltage between the anode and the cathode. Neglecting the influence of the electrons in the virtual cathode and the impedance of any blocking layers in the oxide cathode we can write for the impedance of the cut-off diode:

$$Z_d = \frac{1}{j\omega C} + Z_c = \left[\frac{\sigma_e}{\omega^2 \varepsilon_e^2 + \sigma_e^2}\right] t - \frac{j}{\omega C}\left[1 + \left(\frac{\omega^2 \varepsilon_e C}{\omega^2 \varepsilon_e^2 + \sigma_o^2}\right) t\right] \qquad (6)$$

where C is the capacitance between the anode and the surface of the coating. Equation (6) shows thatthe impedance contains, in addition to a capacitive component, a real component of impedance.

Two extreme cases are of interest: In the first case the period of the test frequency is much greater than the effective Maxwell "time of relaxation"

$$\left(T_r = \frac{\varepsilon_e}{\sigma_e}\right) \qquad \text{Thus} \qquad \frac{\omega \varepsilon_e}{\sigma_e} \ll 1 \qquad (7)$$

In this case the conduction current greatly predominates over the displacement current and Eq. (6) simplifies to:

$$Z_d = \frac{t}{\sigma_e} - \frac{j}{\omega C}\left[1 + \frac{\omega^2 \varepsilon_e C}{\sigma_e^2} t\right]. \qquad (8)$$

In the other extreme case the period of the test frequency is much less than the relaxation time and

$$\frac{\omega \varepsilon_e}{\sigma_e} \gg 1. \qquad (9)$$

For this case the displacement current predominates over the conduction current and Eq. (6) can be written as:

$$Z_d = \frac{\sigma_e}{\omega^2 \varepsilon_e^2} t - \frac{j}{\omega C}\left[1 + \frac{C}{\varepsilon_e} t\right]. \qquad (10)$$

Both Eqs. (8) and (10) are subject to the assumptions made regarding Eq. (6). For a diode having finite series lead inductances, an inductive reactive component must be added to Eqs. (6), (8), and (10).

C. Cut-Off Diode Impedance Measurements

Some preliminary measurements were made by the authors on the type 559 Lighthouse diode which illustrate, in a general way, the validity of the equations given in the preceding section. As can be seen from the sketch of the diode, shown in Fig. MRI-10798, the tube is to a fair degree of accuracy an ideal parallel plane diode having very small lead inductances. The test data were taken at a frequency of 200 mc/sec. using the test circuit given in Fig. MRI-10799.

Due to an uncertainty of the exact value of C in Eq. 6 and the small influence of the lead inductances only the real component of the measured cut-off diode impedance is studied. A typical calculation of this component, from the experimental data, is given in the Appendix.

1. Real Component as a Function of Cathode Coating Thickness

Fig. MRI-10800 shows an experimentally determined curve of the real component of impedance of the cut-off diode, at 200 mc/sec., as a function of cathode coating thickness. Each point represents an average of 3 or more tubes having cathodes sprayed to the specified nominal coating thickness and density. Since the curve shows an approximate straight line relationship, the broad aspects of the assumptions regarding the negligible influence of the electrons in the virtual cathode and impedances of blocking layers in the oxide cathode are justified at 200 mc/sec.

2. Real Component as a Function of Heater Voltage

Fig. MRI-10801 shows an experimentally determined curve of the real component of 200 mc/sec. impedance of the cut-off diode as a function of heater voltage. These results show that at low heater voltages the real component is very small but increases to a maximum as the heater voltage is increased and then decreases again to a low value upon further increase of the heater voltage. This is to be expected, since for semiconductors, the following equation applies approximately:

$$\sigma_e = A_e^{BT} \qquad (11)$$

where T is the absolute temperature of the cathode coating and A and B are constants, or slightly temperature dependent constants. It is evident that at the low heater voltages σ_e is very small so that ε_e / σ_e is large. Thus Eq. (10) is valid and the real component increases with increasing cathode coating conductivity (heater voltage). At the higher heater voltages σ_e becomes large and ε_e / σ_e small. Eq. (8) then applies and, for this case, the real component decreases with increasing conductivity (heater voltage). For intermediate values of heater voltage the relaxation time is of the same order of magnitude as the period of the test frequency and the complete expression given by Eq. (6) must be used. An inspection of this equation shows that, as a function of σ_e, a maximum value should occur. These expected results are broadly confirmed by the experimental results shown in Fig. MRI-10801.

D. Notes Regarding Further Experimentation

The experiments run have been exploratory in nature, having served the purpose of verifying the coating impedance equation in its broad sense. Improvements in the experimentation have suggested themselves and are discussed briefly below.

It is evident that for accurate determinations of σ_e, ε_e and T_H it is essential to use a diode having no lead inductances, known anode to cathode spacing so that C, in Eq. (6), can be calculated. It would then be possible to obtain the coating impedance by subtracting $(1/j\omega c)$ from the experimentally determined cut-off diode impedance. Since the ratio of the imaginary to real component of this impedance is given by

$$\operatorname{Tan} \theta = \frac{\varepsilon_e}{\omega \sigma_e} \qquad (12)$$

where θ is the impedance angle, the values of σ_e and ε_e are readily determined from Eq. (5). The results, of course, are subject to the assumptions made in deriving Eqs. (5) and (6).

A second method which could be developed would be an elaboration of the adjustable anode-cathode spacing diode used in studies of the cathode coating interface characteristics.[1] In this case the anode could be adjusted to contact the surface of the cathode coating, after the normal activation procedures are complete and Eq. (5) could then be applied directly. In order to eliminate thermal gradients in the coating which might cause errors in the experimental results it would be desirable to heat the anode by means of an auxiliary heater, until the temperature of the anode equaled, or differed from by a specified amount, the temperature of the cathode base metal.

In either method, if lead inductances are present, their influences are readily corrected for.

E. Conclusions

From considerations of the field equation for plane waves harmonic in time an approximate expression for the high frequency impedance of the oxide coating is derived here and experiments have been performed which, at least in an approximate manner, verify the validity of the assumptions made. Since, in tubes having oxide cathodes, both displacement and conduction currents must flow through the coating in order to reach the cathode base metal, this coating impedance must be accounted for in calculations of total tube impedance. As a particular example, the influence of the coating impedance on the impedance of a cut-off ideal parallel plane diode has been studied. Extensions to other modes of operation and tube types are obviously possible.

Although the experimental results were of a preliminary nature, the following estimates of the order of magnitude of the effective conductivity, dielectric constant, and "time of relaxation" are of interest:

$$\sigma_e = 10^{-3} \text{ to } 10^{-4} \text{ mho/cm.}$$

$$\varepsilon_e < 20 \times 10^{-14} \text{ farad/cm.}$$

$$\frac{\varepsilon_e}{\sigma_e} = Tr = 10^{-8} - 10^{-9} \text{ sec.}$$

These apply for the following conditions:

Cathode coating: triple carbonates.
Cathode base metal: Grade A nickel.
Cathode coating density: 0.8 - 1.8 grm./cubic cm. (nominal)
Cathode temperature: 1025°K
Test frequency: 200 mc/sec.

Refinements of the techniques used promise to be useful in making accurate determinations of σ_e, ε_e, and Tr as a function of cathode material, cathode temperature, and frequency of operation. The preliminary results already obtained have indicated that cathode spray density markedly affects the value of Tr.

A significant conclusion to be derived from the experimentation is that the high resistance known to exist at the interface region[1,2,3] of the Grade A nickel cathode does not appear to be present in the experimentally determined coating resistance. This is undoubtedly due to the relatively large capacitance which shunts the blocking layer resistance (i.e. an effective large "time of relaxation") causing the blocking layer to have a very low capacitive reactance at 200 mc/sec.

It is also interesting to note the important role played by the dielectric constant and the "time of relaxation". While many references on the conductivity characteristics of the oxide cathode have appeared in the literature, no references, in the knowledge of the writers, have been made to these two important properties.

Further analysis and experimentation on the behavior of tubes having oxide cathodes at high frequencies are under way as part of a thesis program of one of the authors,* for the degree of doctor of electrical engineering.

* G. C. Dalman

Appendix

Since the general methods of measuring impedances using a Q meter are well known, the following calculations are presented in a condensed form.

To determine the realcomponent, for Q's greater than 10, we have:[4]

$$r = \frac{C + C_1}{C^2} \frac{1}{\omega} \frac{Q_1 - Q_2}{Q_1 \; Q_2} \qquad (13)$$

where r is the real component of Eq. (6).
c is the capacitive component of Eq. (6), farads.
ω is 2π x test frequency, (cps).
Q1 is the Q of the Q meter with the unknown impedance (cathode not heated).
Q2 is the Q of the Q meter with the unknown impedance (cathode heated).

Typical calculation:

Filament voltage = 6.3 volts.
f = 200 mc/sec.
Q_1 = 245.
Q_2 = 85.
$C_1 + C_2$ = 17.5 uuf.
Total anode-cathode capacitance = 2.7 uuf.
Stray capacitance $\approx$ 1.0 uuf.
C = 2.7 - 1.0 = 1.7 uuf.
Cathode area = 0.33 cm.^{2}
Cathode thickness $\approx 3 \times 10^{-3}$ inches.
Cathode coating density $\approx$ 0.8 gms./cm.^{3}
Calculated value of r, applying Eq. (19):

$$r = \frac{17.5}{(1.7)^2} \cdot \frac{10^6}{2\pi \cdot 200} \cdot \frac{245 - 85}{245 \cdot 85} \frac{1}{0.33} = 31.5 \text{ ohms/cm.}^2$$

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1. G.C. Dalman - "Some Studies of Oxide Coated Cathodes" - M.E.E. Thesis Polytechnic Institute of Brooklyn - June 1947.

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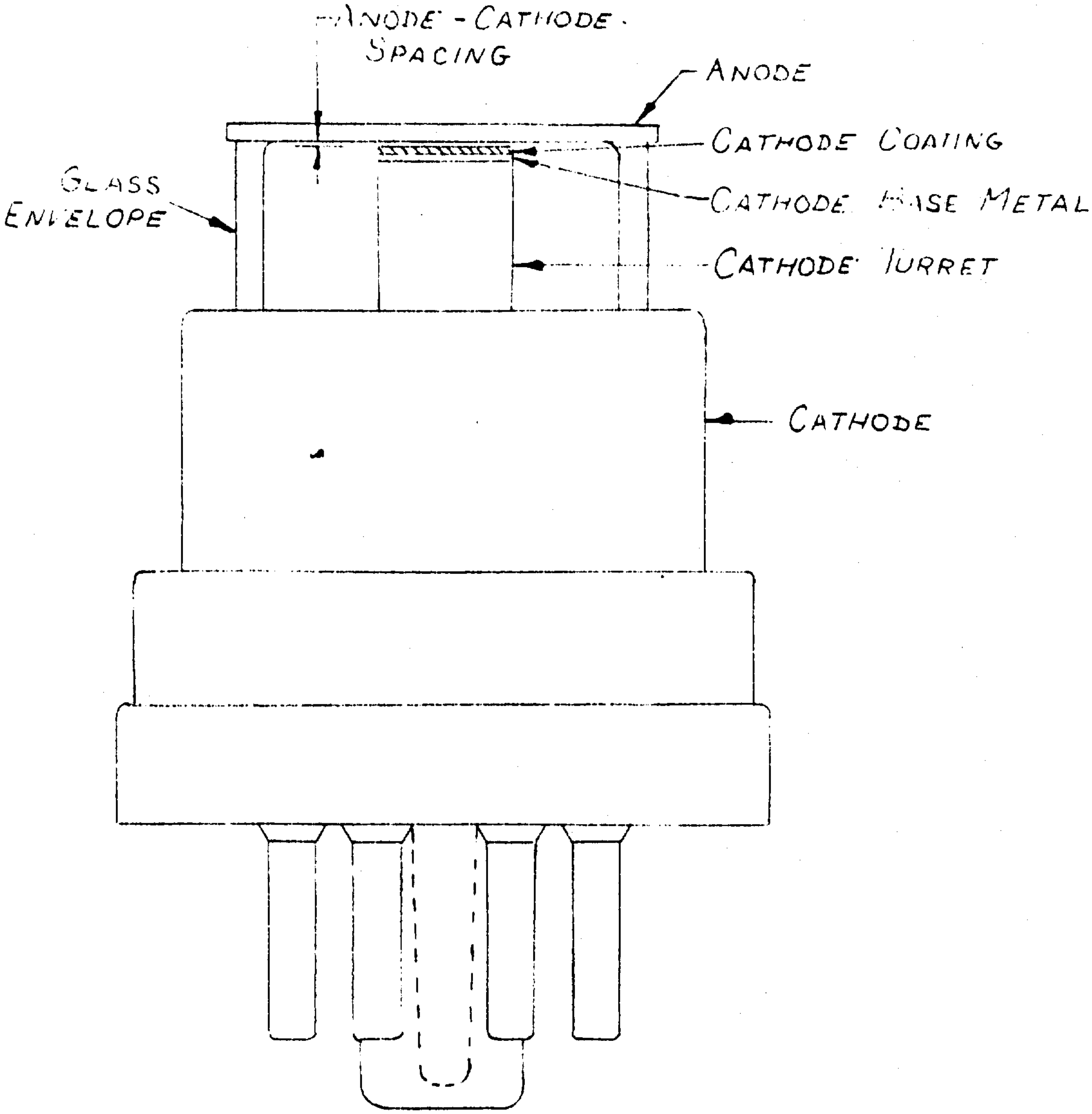
3. W. E. Mutter - "Rectification Characteristics of an Oxide Cathode Interface" Abstract HI, p. 18, Bulletin of the American Physical Society, V22, No. 3, June 19, 1947, Montreal Meeting, Montreal, Canada.

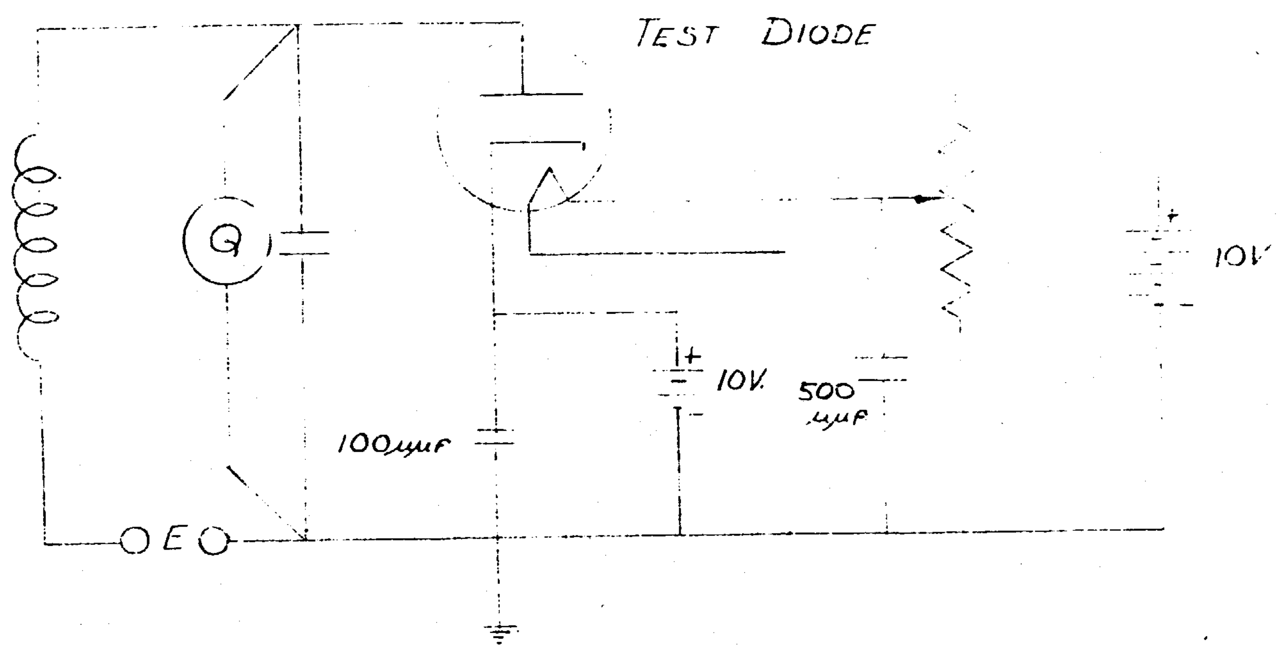
4. Instructions and Manual of Radio Frequency Measurements for Q-Meter type 170A, Boonton Radio Corp., Boonton, N. J.

Type 559
Lighthouse Diode



MRI 10798

SCHEMATIC OF Q-METER
TEST CIRCUIT

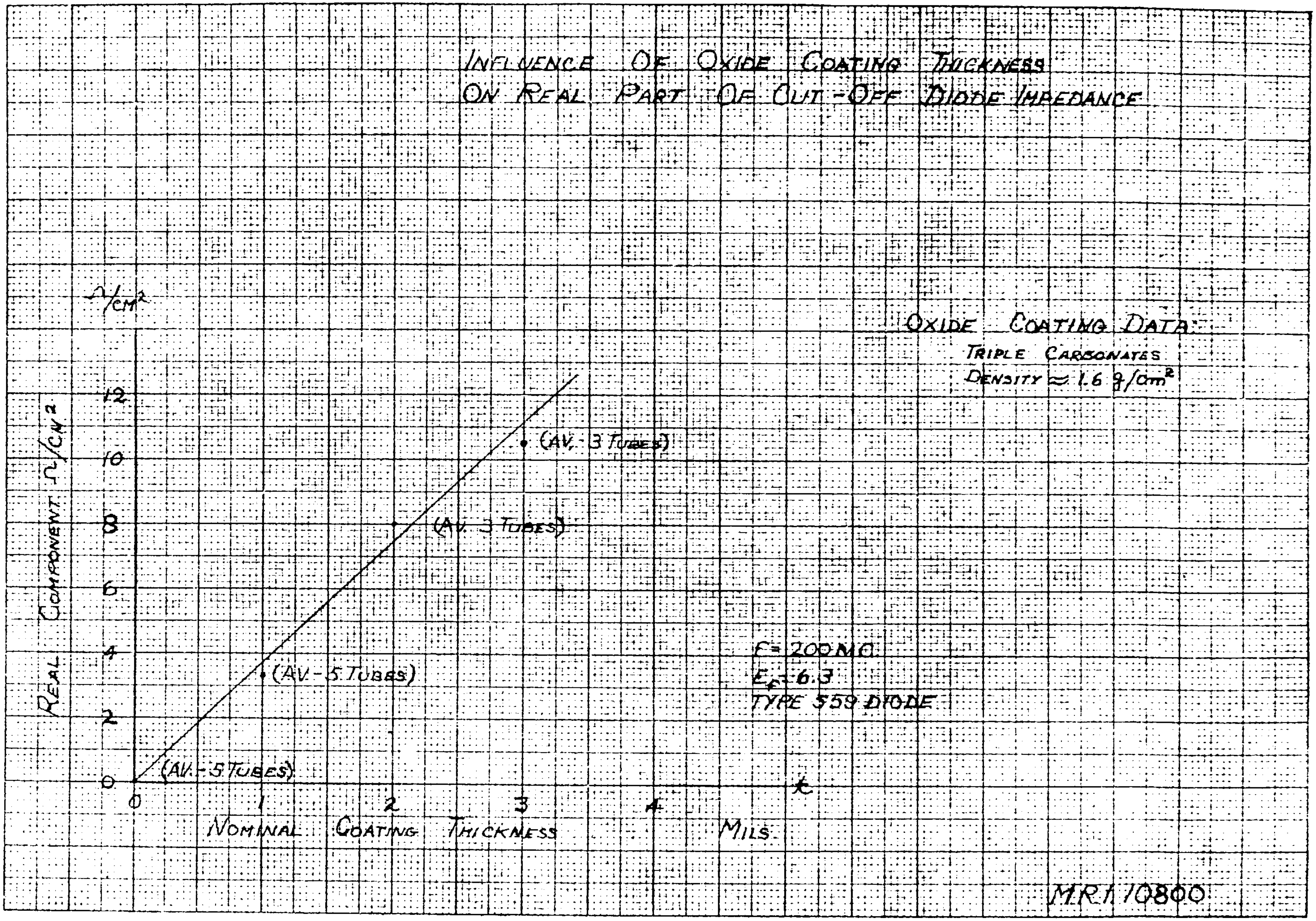


TEST FREQUENCY = 200 MC.

Q-METER : BOONTON RADIO CORP Q-METER TYPE 70A

TEST DIODE: 559 LIGHTHOUSE TUBE

M.R.I. 10799


INFLUENCE OF OXIDE COATING THICKNESS
ON REAL PART OF CUT-OFF DIODE IMPEDANCE
OXIDE COATING DATA:
TRIPLE CARBONATES
DENSITY ≈ 1.6 g/cm²
F = 200 MC
E_f = 6.3
TYPE 559 DIODE
Ω/CM²
REAL COMPONENT Ω/CM²
0
2
4
6
8
10
12
(AV. - 5 TUBES)
(AV - 5 TUBES)
(AV. 3 TUBES)
(AV. - 3 TUBES)
0
1
2
3
4
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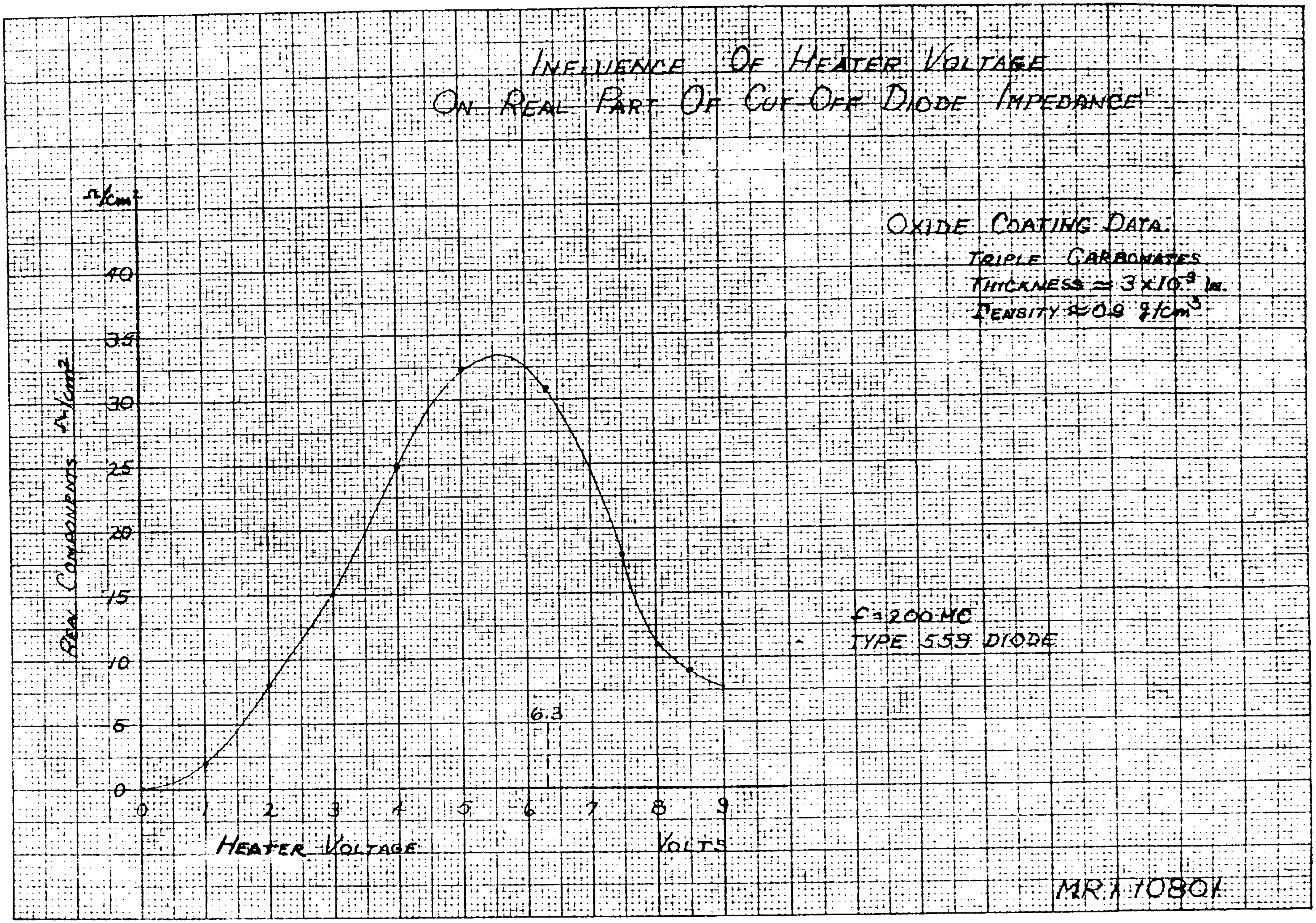
NOMINAL COATING THICKNESS MILS
MR1 10800



INFLUENCE OF HEATER VOLTAGE
ON REAL PART OF CUT-OFF DIODE IMPEDANCE
Ω/cm²
REAL COMPONENTS Ω/cm²
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
HEATER VOLTAGE
VOLTS
6.3
OXIDE COATING DATA.
TRIPLE CARBONATES
THICKNESS ≈ 3 X 10⁻³ in.
DENSITY ≈ 0.9 g/cm³
f = 200 MC
TYPE 559 DIODE
MR 10801