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MICROWAVE ENERGY CONVERSION

E. M. Sabbagh
Purdue University

WADD TECHNICAL REPORT 61-48
PART I

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E. M. Sabbagh

School of Electrical Engineering
Purdue University...Lafayette, Indiana

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FLIGHT ACCESSORIES LABORATORY
WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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Contract Nr AF 33(616)-7355

Project Nr 3145

Task Nr 61098

WRIGHT AIR DEVELOPMENT DIVISION
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report was prepared by the School of Electrical Engineering at Purdue University on Air Force Contract AF 33(616)-7355 under Task Nr. 61098 of Project Nr. 3145 "Microwave Energy Conversion". The work was administered under the direction of Flight Accessories Laboratory, Wright Air Development Division, Mr. D. R. Warnock, Task Engineer for the laboratory.

The studies presented began in July 1960; were concluded in January 1961, and represent a joint effort of the Energy Conversion Group of the School of Electrical Engineering at Purdue University. Professor E. M. Sabbagh was the Project Coordinator responsible for research activity of the School of Electrical Engineering. Although the studies were a group effort, the chief contributors and their fields were: Professors Y.F.Chang, R. H. George and A. K. Kamal, Semiconductor Theory and Experimentation, Professors W. H. Hayt and H. J. Heim, Vacuum Tube Theory and Experimentation, Professor F. V. Schultz, Electromagnetic Fields and Plasma.

This report concludes the work on Part 1 of Contract AF 33(616)-7355.

ABSTRACT

MICROWAVE ENERGY CONVERSION

Plasma Diode. Operating conditions for the microwave absorber are set forth. A tapered coaxial load is proposed in which the outside of the load is also the cathode of the plasma diode which should operate at temperatures of 2000 - 2500° K. The load and cathode temperature must be raised from about 300°K to operating temperature by microwave power.

A test set up is proposed for making the necessary measurements of conductivity, thermal and mechanical properties of the more promising absorber-cathode materials. Some of the test equipment is not yet available but tests at room temperature on conductivity at microwave frequencies are now in progress on carbon, zirconium carbide and silicon carbide. The thermodynamic problems of the microwave absorber-cathode are discussed.

Direct Rectification by Semi-conductor Diodes. Test have been made on a considerable number of diodes at 60 cycles, 600 Mc. and 2500-3000 Mc. with resistance loads, with and without capacitance filters, and at power levels of 370 milliwatts at 600 Mc. and 200 milliwatts per diode at microwave frequencies. The best measured efficiencies obtained with resistance-capacitance loads were between 40 and 63% at microwave frequencies. When storage batteries were used as the load at microwave frequencies maximum efficiency with a two volt load was 72% and with a four volt load it was 65%. Higher efficiencies are anticipated with full-wave and bridge type rectifiers using a new higher power source.

ABSTRACT

Conversion by Acceleration of Electron Beams

Klystron Converter. A theoretical model is described and the equations presented. The computer results are not complete but it appears that for high power the klystron converter is not much better than the closed spaced diode which may reach actual efficiencies of 65 to 70%.

Inverted Magnetron. Theoretical equations are presented for a parallel plane type of magnetron, and some results have been obtained on a computer. At 3000 Mc. efficiencies of 25 - 35% were computed. The work is still in progress.

Vacuum Diode. The vacuum diode has been investigated theoretically and the results presented in curve form. From the curve efficiencies for a close space diode of 65 - 70% appear to be feasible. Experimental results are described which would indicate reasonably high efficiencies at microwave frequencies.

PUBLICATION REVIEW

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF SYMBOLS

mc	megacycle
mw	milliwatt
rf	radio frequency
i	current
V, E	voltage
η	efficiency
P	power
w	angular velocity
t	time in seconds
v	velocity
B	magnetic flux density
d	distance
e	electron charge
m	mass of electron

I. INTRODUCTION - PLASMA DIODE

There are several direct thermal-to-electrical converters: high-vacuum diodes, MHD generators, magneto-thermionic generators, etc. For the present task it was decided to concentrate efforts on the plasma diode.

The basic principles of the cesium-filled plasma diode have been well known for sometime. Lewis and Reitz have presented a fairly thorough theoretical study of the plasma diode by considering the diode as a thermocouple consisting of hot and cold plates with a high temperature plasma between them. The plasma diode essentially converts thermal energy to electrical energy of low electric potential.

The available voltage of the operational plasma diode is of the order of 1 volt. If a higher output voltage is desired, a new solid-state d.c.-to-d.c. converter may be used to obtain these higher voltages. This device has an efficiency of more than 80%.

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For the present ask of converting microwave power to d.c., or low-frequency a.c. power, Purdue University proposed that a plasma diode be used, and that the cathode of the plasma diode be heated by a microwave load, which would absorb the microwave energy and convert it to thermal energy. In September 1960, WADD requested that, on the present project, Purdue restrict its efforts to an investigation of the microwave absorber, and this has been done.

A. The Microwave Absorber

It is necessary that the microwave absorber and the cathode of the plasma diode be in intimate contact in order to achieve an efficient transfer of heat. The required operating temperature is of the order of 2000-2500 degrees, Kelvin, so, if the absorber and the cathode are of different materials, mass transfer of these materials will occur. Consequently, it is highly desirable that the absorber and cathode form a single structure, made of one material.

The necessary conditions on the microwave absorber, which will be used directly as the cathode of the plasma diode, are:

(1) Uniform distribution of temperature over the surface of the cathode.

(2) Configuration of the microwave absorber must be such that no backward propagation of the microwave energy occurs, hence, there will be no standing waves and thus local heating of the absorber will be avoided which would result in pitting and shortening of the absorber life.

(3) Prevention of arcing inside the guide, which would result in local heating or damaging of the guide walls.

(4) Simple configuration, adaptable to existing operational plasma diodes.

(5) Minimum heat radiation loss from the cathode.

(6) Simple configuration for ease of construction.

Conditions (4), (5), and (6), listed above, lead one to the conclusion that it is desirable that the microwave absorber form the outer conductor of the termination of a coaxial line. The outer surface of this cylindrical absorber would then act as the cathode of the plasma diode and this cylindrical cathode would be surrounded by the cylindrical anode of the diode.

Because of the absorption of microwave power as the wave moves axially down the absorber, the surface density of microwave power flow into the walls of the absorber will decrease as the wave progresses down the axis of the absorber. This would result in uneven heating of the absorber-cathode. To prevent this from occurring one might make the absorbing capacity of the load vary axially. It is believed, however, that a better solution is to taper the load, as shown in Figure 1.

Essentially two major problems must be investigated in this study of an absorber-cathode. First, the most suitable material must be found for use in constructing the absorber-cathode; second, the structure must be so designed as to achieve an even distribution of temperature over the outer surface of this absorber-cathode. A third, minor, problem is that of insuring that the absorber be matched satisfactorily to the coaxial line over the wide temperature range involved.

B. Investigation of Materials

Microwave loads that are used to terminate microwave transmission circuits by dissipating the microwave power as heat have been available for many years. Most of these loads operate at essentially room temperature, although one now is on the market that operates at a temperature of about 800 degrees, Kelvin. The difficulty in developing a microwave load, or absorber, for heating the cathode of the plasma diode is that this cathode must operate at 2000 or 2500 degrees, Kelvin, so the microwave absorber must operate at temperatures at least this high. The microwave absorber must, of course, be brought from an initial temperature of perhaps 300 degrees, Kelvin, to its operating temperature of 2000-2500 degrees, Kelvin, and it is desirable for this heating-up process to be done by the microwave power. Consequently, in order to build the microwave absorber one must have information concerning the following properties of the absorber material over the above mentioned temperature range: electrical conductivity, thermal expansion, heat conductivity, mechanical strength, possible chemical changes, etc. Such information is not presently available for temperatures above about 1000 degrees Kelvin.

In investigating the properties of possible materials, the first step is to measure the electrical conductivities of likely materials from 300 to perhaps 2500 degrees, Kelvin. It will be desirable for the material to have a fairly low conductivity and one which does not vary too widely over this temperature range. It may be possible, however, to use mechanical methods, such as roughening of the surface of the absorbing material, in order to cause the absorber to exhibit the desired electrical properties. Also, a servo-controlled line matching device might be used to keep the load matched to the transmission line as the load is brought up to temperature.

After the conductivities are determined, the thermal and mechanical properties of the most promising material or materials will need to be measured.

The first experiment for measuring the electrical conductivities of the various materials is illustrated in Figures 2 and 3, which are largely self-explanatory. The absorber-cathode material is formed into a cylindrical shape, as shown in Figure 2, which forms the termination of a coaxial transmission line. The termination can be heated up to perhaps 1000 degrees, Kelvin, by means of a tungsten filament shown in Figure 2. To achieve higher temperatures it is planned to use an rf induction heater, with a coil surrounding the termination, as shown in the figure. By measuring the termination impedance which is formed by this disk of absorber-cathode material, over the desired range of temperature, the desired information can be obtained as to the variation of the conductivity with temperature, as well as the relative conductivities of the various materials. It is recognized, of course, that the condition of the surface of the material will be very influential in determining the termination impedance and this effect will have to be considered. The impedance measurements are made as shown in Figure 3.

Since some of the equipment shown in Figures 2 and 3 is not yet available, preliminary results are being obtained by use of a simpler experimental set-up which is operated at atmospheric pressure and which allows absorber operating temperatures of only a few hundred degrees, Centigrade. No publishable results are yet available, but this preliminary experiment does allow the location and correction of "bugs" with less loss of time than would occur in using the more complex set-up.

The materials on which experiments are presently being conducted are carbon, zirconium carbide, and silicon carbide. Samples of the other materials of interest will be obtained shortly.

C. Thermodynamic Problems

As mentioned previously, it is essentially that the outer, electron-emitting, surface of the absorber-cathode operate with a uniform surface temperature. This means that the inner taper of the absorber-cathode, as shown in Figure 1, must be correctly determined to achieve this result. This is a difficult problem involving considerations of microwave power flow into the absorber surface, conduction of heat from the inner to the outer surface of the absorber-cathode, conduction of heat from the absorber-cathode to the coaxial transmission line, and radiation of heat from the absorber-cathode back into the transmission line and to the plate of the plasma diode. It must be recognized, also, that the electrical conductivity, the thermal conductivity, and the emissivity of the absorber-cathode material are functions of temperature. An analytic solution of this problem would be extremely difficult and only a bare beginning has been made on it. Very likely it will be necessary to resort to experimental methods to obtain a suitable solution.

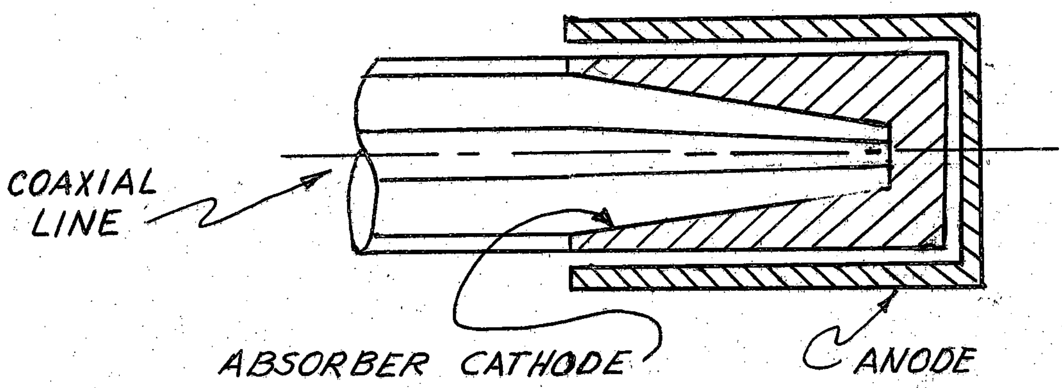

FIGURE 1. MICROWAVE ABSORBER

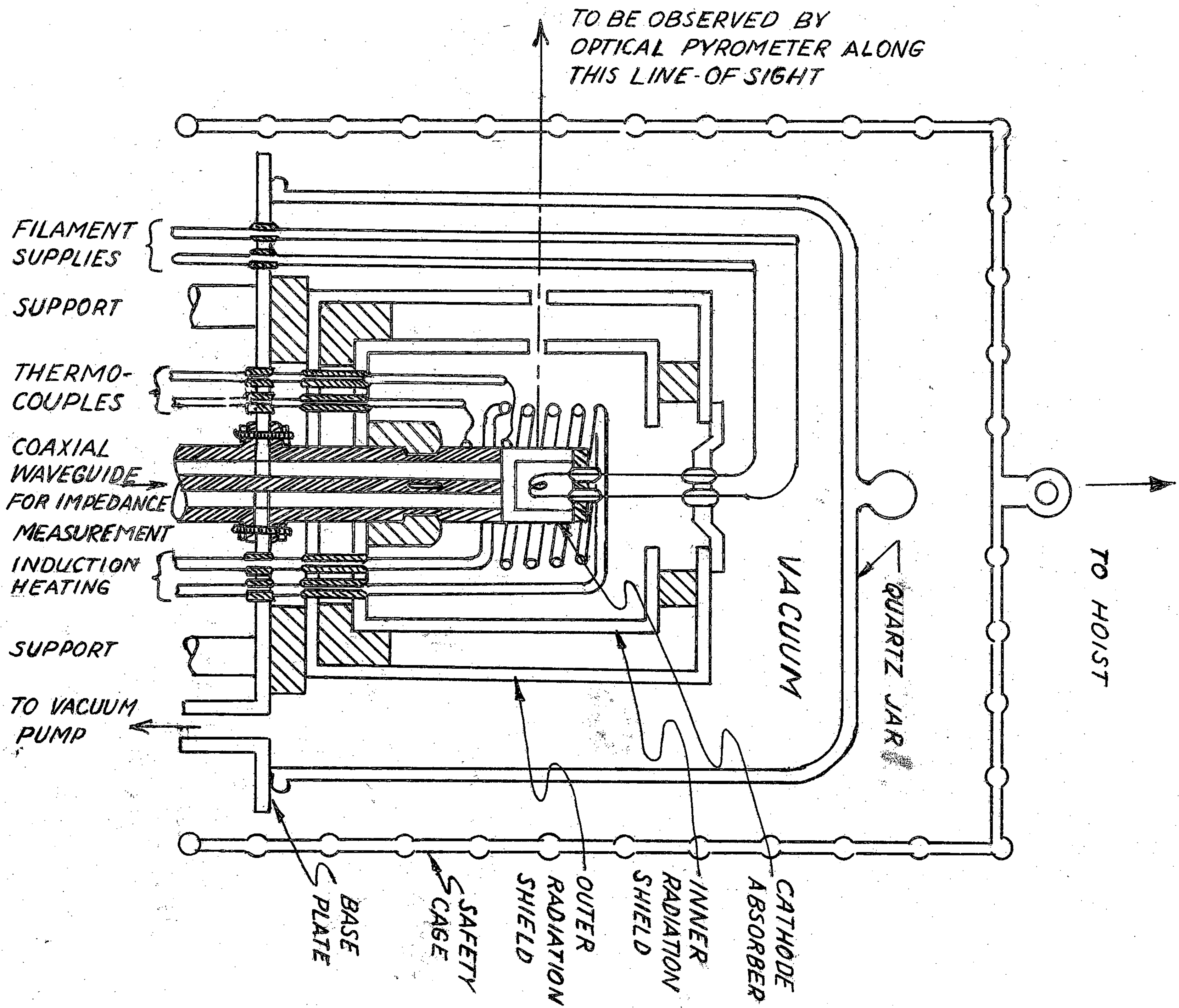

FIGURE 2. TYPICAL MICROWAVE LOAD CELL IN EVACUATED ENVIRONMENT

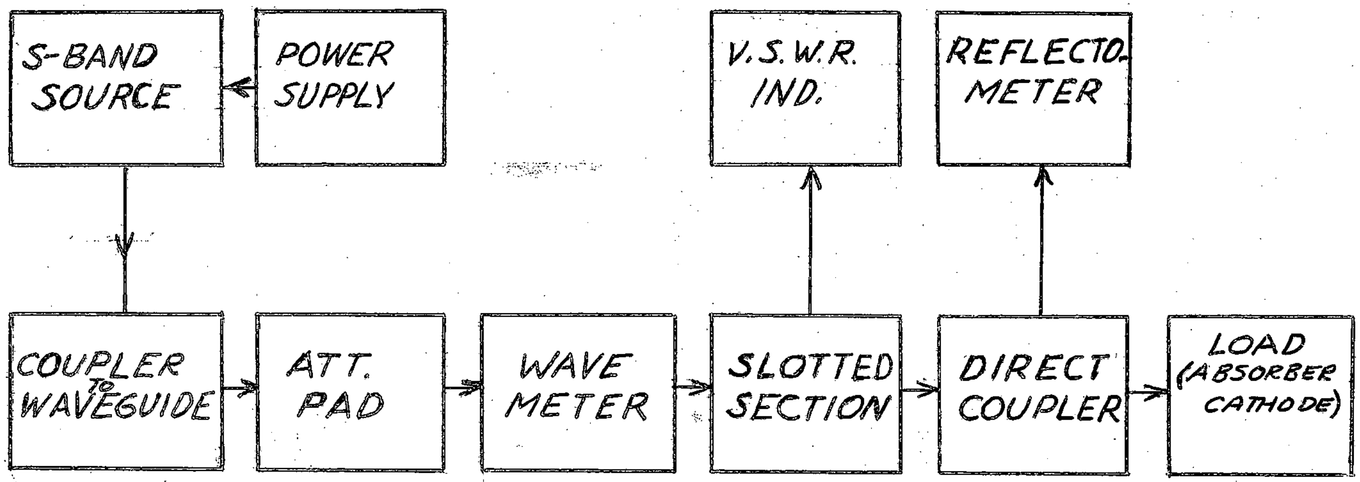

FIGURE 3. BLOCK DIAGRAM OF IMPEDANCE MEASUREMENT SYSTEM

II. DIRECT RECTIFICATION OF MICROWAVE ENERGY USING SEMICONDUCTOR DIODES

The rectification efficiency of an ideal diode used without any filtering is 40.5%. Filtering with ideal inductor and capacitors will improve this efficiency to 100%. Actual rectifiers will perform at 35% efficiency into a resistive load and at about 80% efficiency into an ideal filter. Therefore, the maximum efficiency to be expected from a microwave rectifier cannot be greater than 80%. The rectification efficiency of semiconductor point-contact microwave diodes is somewhat less than that of large diodes. The efficiency with resistive load is about 20%, and that with ideal filtering is 60-70%. Since such high efficiency has been measured at 3,000 megacycles, we have concentrated our attention on the problem of obtaining usable power levels.

The use of semiconductor diodes at microwave frequencies for rectification is limited to silicon point contacts. Thus far, we have been unable to find any junction device capable of good rectification at microwave frequencies. This report shall describe the various experiments performed on microwave diodes at 60 cycles, 600 megacycles, and 3,000 megacycles.

A. Low-Frequency Experiments

The low-frequency rectification efficiency of microwave diodes has been measured for several interesting cases with a resistive load of one thousand ohms. The frequency of the experiment was 60 cycles; the input power was measured and varied up to 20 milliwatts per diode. The rectification efficiency was calculated and plotted against the input power. The five cases studied are: a simple rectifier circuit with a single diode, the same circuit with two, three and four diodes in series, and a bridge circuit. The results are shown in Graph #1, (Figure 4.).

In this Graph, it is interesting to note that the number of series diodes reached something of an optimum around three. The fourth series diode does not contribute to the total effort. The reason for the higher efficiencies with two and three diodes in series is because of the poor reverse characteristics of these microwave diodes. They have rather high reverse leakage and low breakdown voltage. It is also quite apparent from this graph that the bridge rectifier circuit is about twice as efficient as the series circuit. This is simply because it is a full-wave rectifier circuit. These interesting results will be repeated at higher frequencies.

B. <u>600 Megacycle Measurements</u>

For the sake of convenience, these measurements have been taken under slightly different conditions than those above. The input power was held constant at 370 milliwatts, the load was a capacitance-input filter with nearly ideal elements. The load was varied over a wide range of values up to a few hundred ohms. The rectification efficiency is plotted against the load resistance in Graph #2, (Figure 5.).

In this Graph, again note the ineffectiveness of the fourth series diode. As a matter of fact, even the addition of the third series diode is of questionable value. Comparison of these results with those above for low-frequencies shows that the filter did not improve the performance of the bridge circuit as much as it did the simple circuit. This is to be expected, since one is half-wave and the other full-wave rectifiers. The encouraging

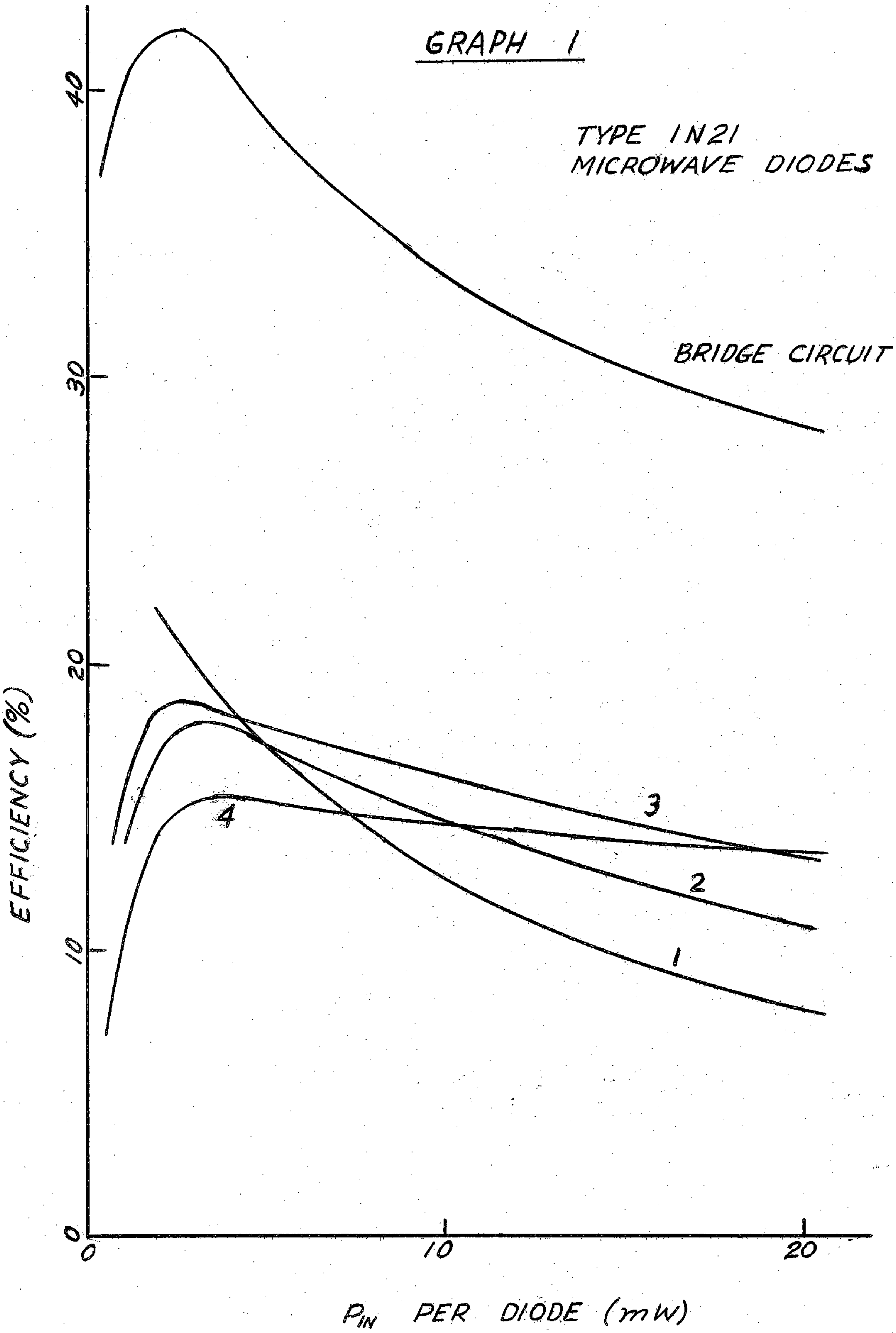

FIG. 4. RECTIFIER EFFICIENCIES AT 60 CYCLES

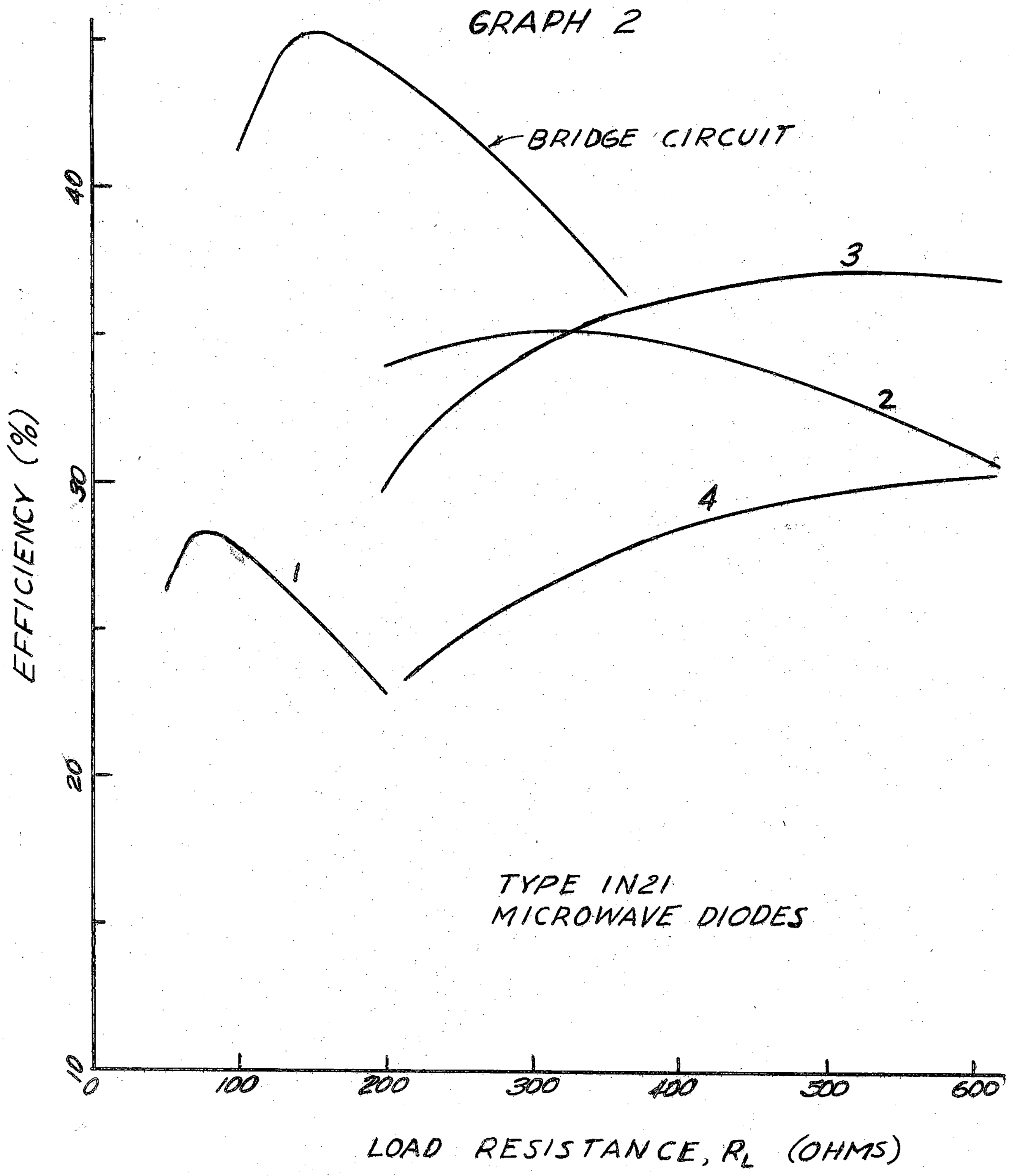

FIG. 5 RECTIFIER EFFICIENIES AT 600 MEGACYCLES

result from these measurements is the fact that the high efficiency can be maintained up to this appreciable fraction of a watt (370 milliwatts). We are limited here by the output of the oscillator and not by the power-dissipating capability of the diodes.

The question of the power-dissipating capability of the microwave diodes is being studied. We are studying this problem by the use of high-power pulses. Only inconclusive results have been obtained up to this time. It is our hope that a multi-contact diode can be made to dissipate as much as a few watts.

C. Measurements at Microwave Frequencies

Measurements of rectification efficiency at 3,000 Mc. and also of the d-c forward and backward resistance were made on 44 point contact rectifiers. These include 38 Sylvania 1N21B crystals; three Western Electric 1N21B crystals, and three Microwave Associates 1N23C crystals. These diodes were operated in a tuned crystal mount as half-wave rectifiers with a filter capacitance of approximately 200 micro-microfarads and a d-c load resistance of 420 ohms. The input power was approximately 8 milliwatts.

The results are as follows:

% Efficiency	Number of Crystals	% Efficiency	Number of Crystals
67.5 - 70.0	1	42.5 - 45.0	4
62.5 - 65.0	1	37.5 - 40.0	6
60.0 - 62.5	4	35.0 - 37.5	1
55.0 - 57.5	3	25.0 - 27.5	1
52.5 - 55.0	2	20.0 - 22.5	4
50.0 - 52.5	3	17.5 - 20.0	1
47.5 - 50.0	7	7.5 - 10.0	1
45.0 - 47.5	4		

Note: Many of these crystals had been used prior to these tests.

TABLE I, Efficiency vs Number of Crystals

These crystals will be checked for barrier capacitance as soon as the new capacitance bridge arrives.

Another oscillator with a 200 milliwatt output at a somewhat lower frequency, was made available for the tests and the test equipment was improved also.

The improved test equipment is comprised of a low power oscillator, a coaxial slotted line, a coaxial to S-band waveguide transition, a precision attenuator, a directional coupler and power meter, a transition from waveguide to coaxial line, a PRD tunable crystal mount model 612A, and a vacuum tube voltmeter and load resistance.

Measurements are being made on a number of crystals at input power levels of 50, 100 and 200 milliwatts. The results from two types of crystals are presented by the curves of Figures 6 and 7. It may be noted from Figure 7 that it is possible to obtain relatively high efficiency even from a halfwave diode with a capacitance filter providing the peak inverse voltage is not too high for the particular type of crystal.

Some data were taken in which the output of the crystal was fed into either a 2, 4 or 6 volt storage battery. The highest efficiency was obtained with an input of 50 milliwatts and a four volt battery as a load. The effiency was 72%. With a six volt battery load the highest efficiency was about 65% at an input of 100 milliwatts.

It is believed that with an untuned bridge type rectifier mounted in waveguide, and more power input it may be possible to obtain efficiencies of better than 60% at an output voltage of 10 to 12 volts. Such tests will be possible in the next few days when a 100 watt CW magnetron power supply operating at 2440 megacycles will be available.

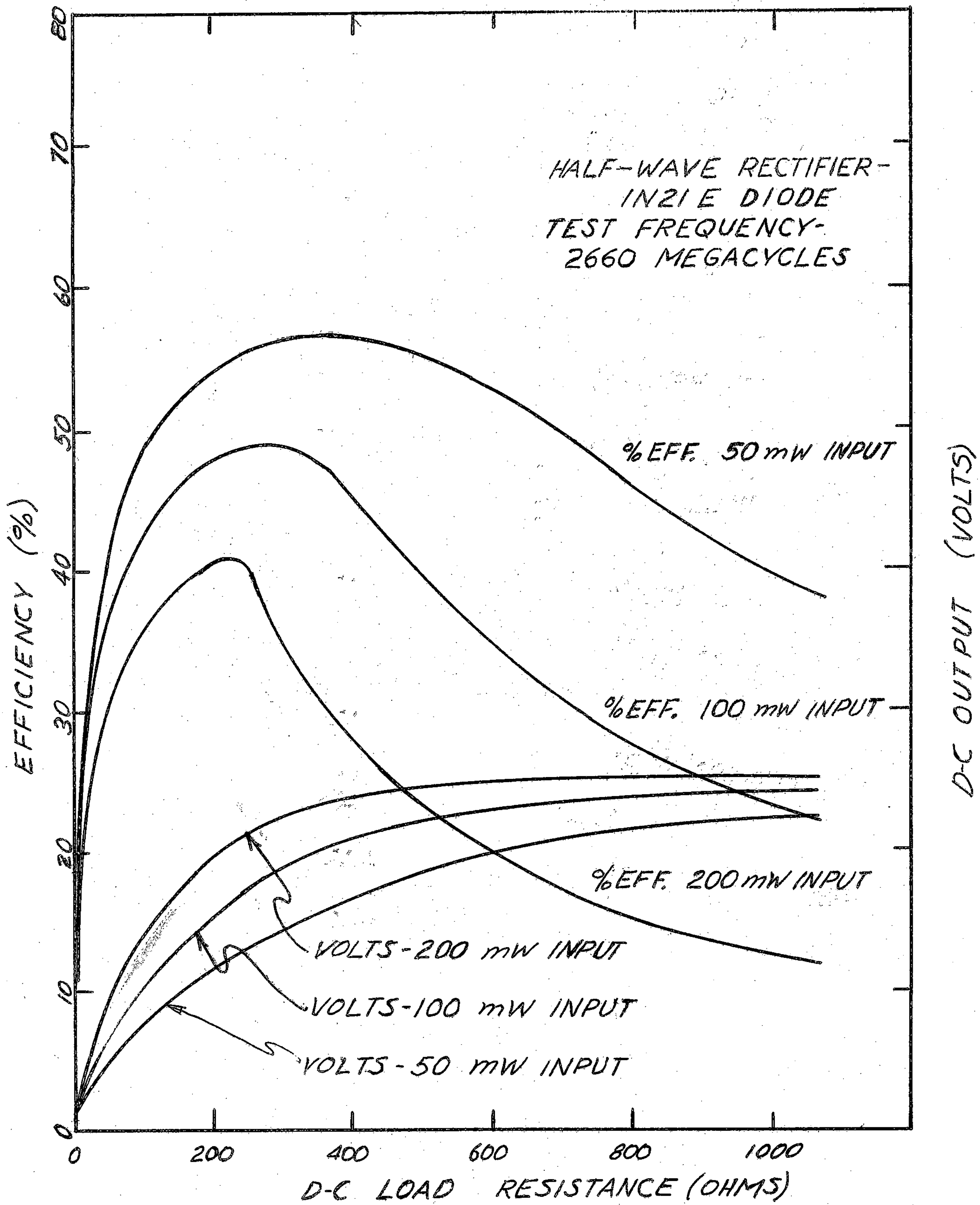

FIG. 6 - RECTIFIER EFFICIENCY AND OUTPUT VOLTAGE

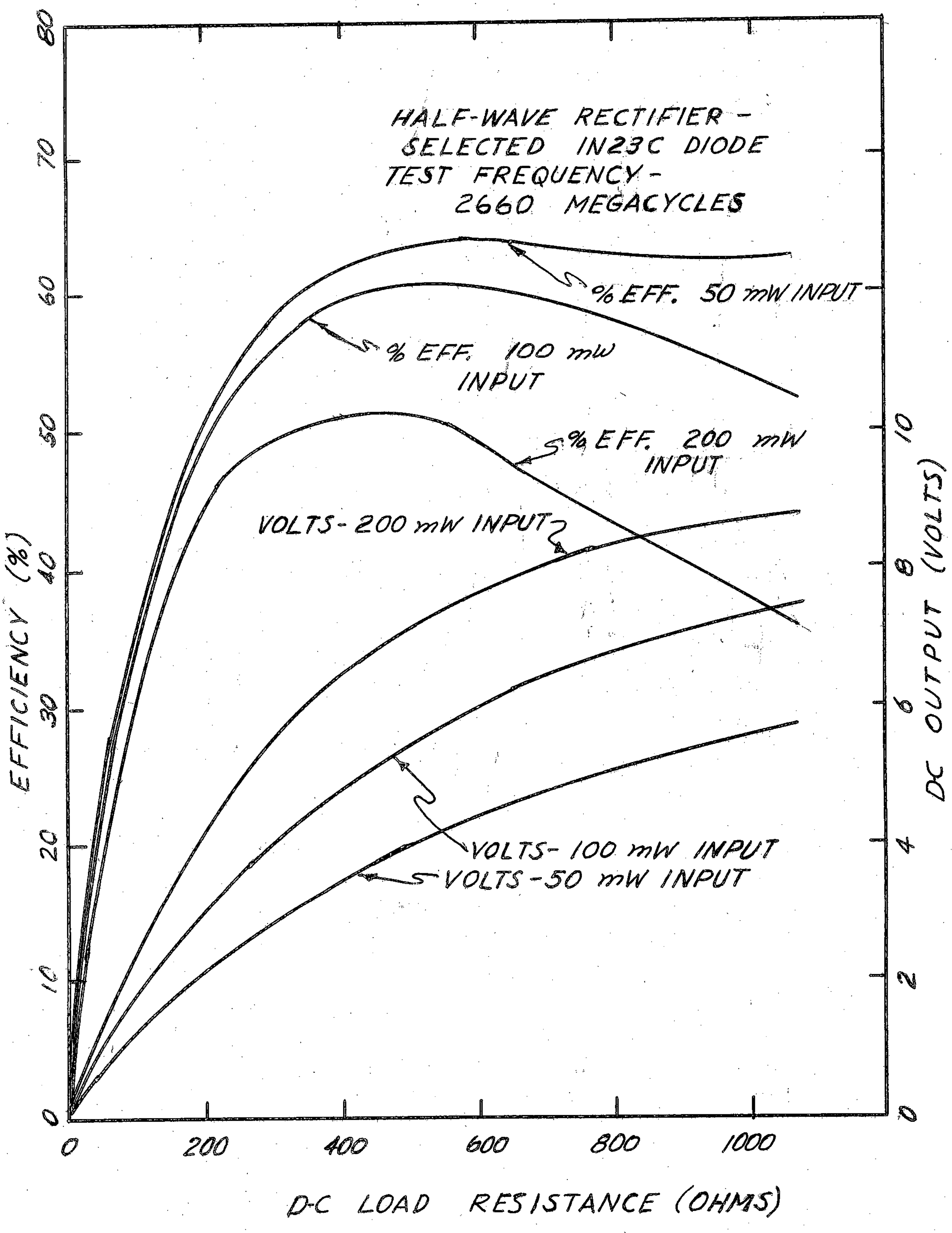

FIG. 7 - RECTIFIER EFFICIENCY AND OUTPUT VOLTAGE

III. CONVERSION BY ACCELERATION OF ELECTRON BEAMS

A. Klystron Converter Project

In order to study the operation of a klystron-type microwave energy converter, a "model" klystron has been devised. The problem, therefore, breaks down into two major sub-problems:

a) a description of the behavior of the "model" klystron

b) an understanding of how closely the "model" approximates a physically realizable device

The characteristics of the model as shown in Figure 8 are as follows:

1. An electron-gun section accelerates an electron beam to an energy of V_B(electron) volts. The beam current is I_B amperes and the beam is ideally focussed by an infinitely strong longitudinal magnetic field. Velocity spread in the electron beam is negligible.

2. The electron passes through a first gridded gap which forms part of the buncher cavity. A small portion of the available RF power is applied to the buncher cavity to velocity-modulate the electron beam. The amplitude of the bunching voltage is restricted to "small-signal" conditions. (The RF power dissipated in the buncher cavity is neglected in the computation of conversion efficiency).

3. After velocity-modulation in the buncher, the electron beam drifts in a field-free region for one-quarter of a space-charge (plasma) wavelength. At this point the RF current carried by the beam is at a maximum, and we assume that the peak RF current, I_1 is just equal to the dc beam current, I_B. In other words, the beam current is 100% modulated at the end of the drift space, (Ref. 1) and only the fundamental frequency is present.

Ref. 1: See Beck, Space Charge Waves, Pergamon Press, 1958, page 191, for a discussion of the validity of this assumption. "Small signal" theory predicts a maximum modulation of 88%, but the 100% figure is retained for simplicity.

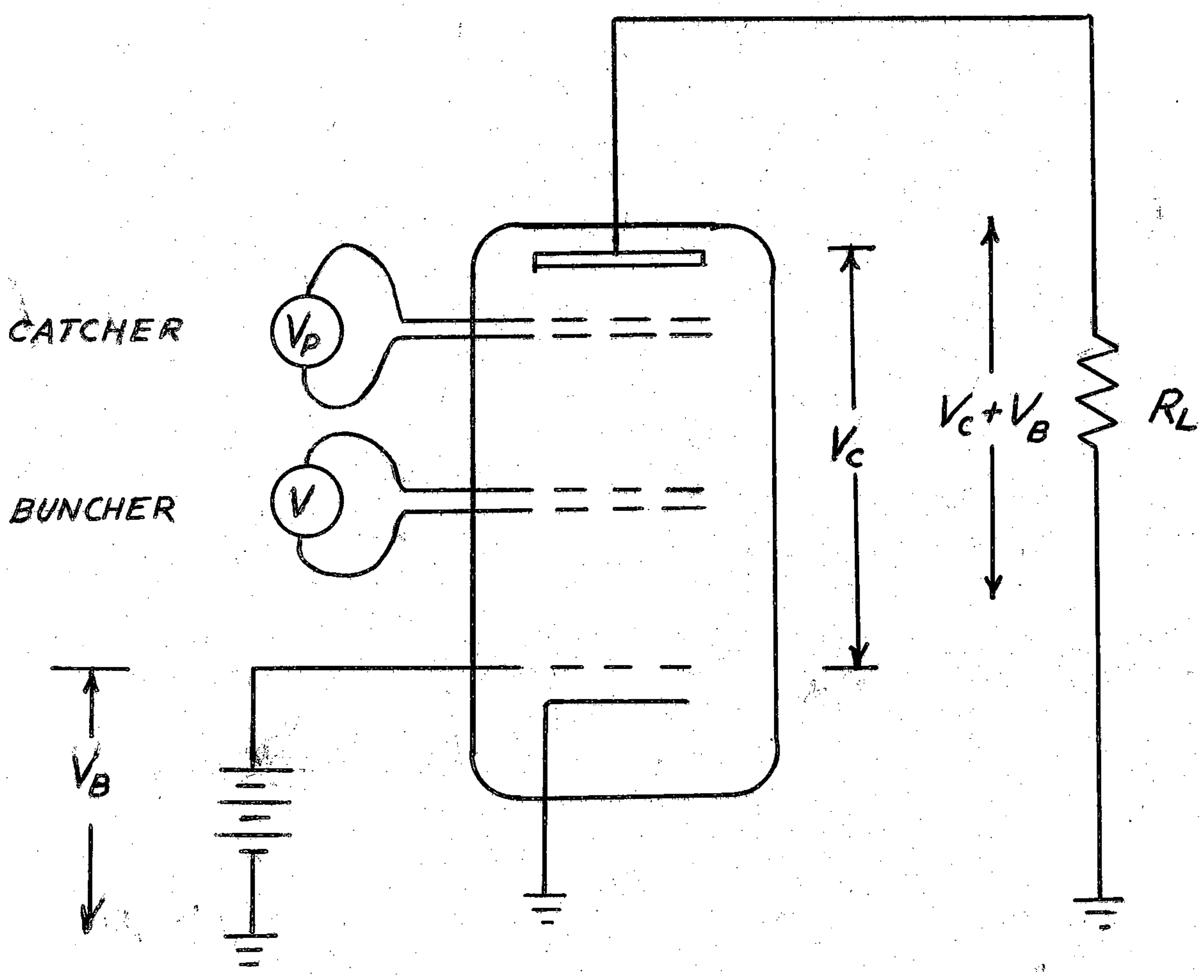

FIGURE 8- CIRCUIT DIAGRAM OF KLYSTRON

4. The catcher gap is centered about the point of maximum RF current. The catcher gap is ideally gridded, so that electron interception is negligible. The major portion of the available RF power is applied to the catcher cavity, so that an RF voltage with an amplitude of V_p volts appears across the catcher gap. Space-charge effects are neglected in the catcher gap and, (this is perhaps the most significant assumption), the transit time of electrons across the catcher gap is considered negligible.

5. Beyond the catcher gap is a collector electrode to which is applied a retarding potential, V_c, measured with respect to the accelerating anode. The dc component of the collector current is I_c. The ideal grids* of the catcher gap shield the remainder of the tube structure from the effects of the collector field.

6. An electron which arrives at the collector electrode with a net positive energy will be collected by the collector and will contribute to I_c. All other electrons are rejected by the collector. For the purposes of this discussion, these rejected electron can be considered to constitute a catcher current, I_r, where $I_r = I_B - I_c$.

7. The "excess" energy of the collected electrons is dissipated as heat at the collector. <u>In this model the thermal loss at the collector is the major cause of inefficiency.</u>

According to these assumptions, the normalized energy of an individual electron arriving at the collector is simply

$$E = V_B + V_c + V_p \sin(wt + \phi_1)$$

where E must be equal to or greater than zero in order to contribute to collector current. ϕ_1 is an arbitrary phase angle.

The collector current is of the form:

$$i_c = I_B + I_B \sin (wt + \phi_2)$$

for that portion of a cycle for which E is positive. For E negative:

$$i_c = 0$$

The dc output power from the converter is just $P_o = -I_c(V_c + V_B)$

The conversion efficiency can be computed from a "black box" approach as the dc output divided by the total power input to the converter.

$$\eta = \frac{P_o}{P_o + P_c + P_q + P_f}$$

where P_c = power dissipated as heat at the collector

P_q = power lost due to the finite Q of the "cold" catcher cavity

P_f = filament or heater power

Both P_q and P_f can be made relatively small, at least for the special case of the large, high power klystron. Therefore, the equation for efficiency reduces to

$$\eta = \frac{P_o}{P_o + P_c}$$

In order to reduce the number of independent variables, we introduce the normalized parameter:

$$R = \frac{V_c + V_B}{V_p}$$

We are now completing the details of the efficiency calculations in terms of the normalized voltage parameter R.

From the analysis completed thus far some tentative conclusions can be drawn. The klystron, in this simple form, does not offer any striking advantages over the simple vacuum-diode rectifier. If the electron beam can be very tightly bunched, then collector dissipation can be minimized, and the klystron approach can be justified. However, very tight bunching implies strong debunching forces and it may be necessary to operate at very low beam-current density to achieve high efficiency (Ref.2).

B. Inverted Magnetrons

Summary of Incompleted Researches

(A.) Parallel-Plane Type

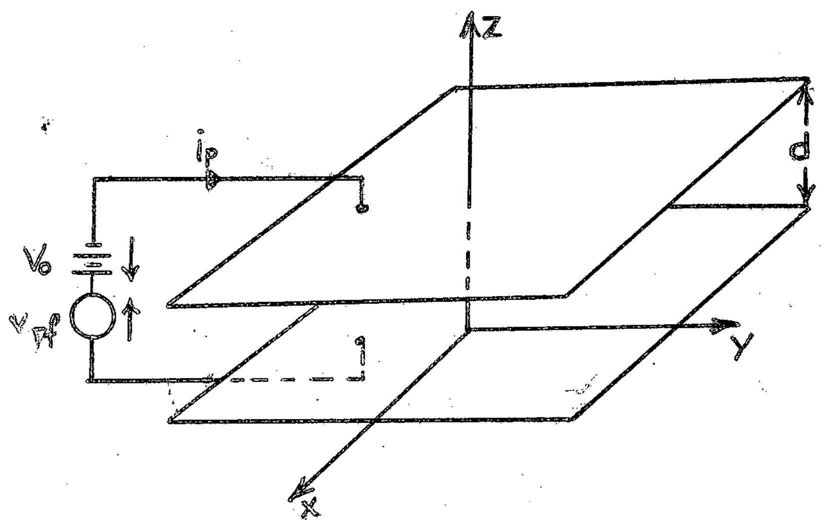

FIGURE 9. PARALLEL-PLANE MAGNETRON

The analysis of the inverted magnetron as sketched in Figure 9, utilizes Lorentz's force equation and neglects the effects of space charge. From the analysis, the following equations result for the trajectories of single electrons leaving the cathode during the conduction portion of the

---

Ref. 2: Beck, op. cit., p. 205
discusses the use of multicavity klystrons to obtain high efficiency. Unfortunately, most of the references are unpublished.

applied r. f. voltage at a departure time t_d and having zero initial velocity.

$$z = \frac{\alpha k}{w^2 - w_o^2} \Big\{ (\cos wt_d) \cos w_o (t - t_d) - \frac{w}{w_o} (\sin wt_d) \sin w_o (t - t_d)$$

$$- \cos wt - \left(\frac{w^2 - w_o^2}{\alpha w_o^2}\right) + \left(\frac{w^2 - w_o^2}{\alpha w_o^2}\right) \cos w_o (t - t_d) \Big\} \quad (1)$$

$$v_z = \frac{\alpha k}{w^2 - w_o^2} \Big\{ w \sin wt - w_o (\cos wt_d) \sin w_o (t - t_d) \quad (2)$$

$$- w (\sin wt_d) \cos w_o (t - t_d)$$

$$+ \left(\frac{+ w^2 - w_o^2}{w_o^2}\right) \sin w_o (t - t_d) \Big\}$$

(Valid for $0 \leq z < d$)

The parameters are defined as follows:

$z = z$ - displacement of electron

$v_z =$ z-component of electron velocity

$t =$ time in seconds

$\alpha = \frac{V_1}{V_o}$

$k = \frac{e}{m} \frac{V_o}{d}$ (3)

$d =$ plate spacing

$w = 2\pi f_{rf}$ - applied frequency

$w_o = \frac{e}{m} B$ - betatron frequency

$V_o =$ the dc load voltage

$V_{rf} = V_1 \cos wt$ = applied r.f. voltage

$B =$ magnetic flux density

$\frac{e}{m} =$ electron charge-to-mass ratio

It is known that the current induced in an external circuit by a single electron in an interaction space is given by the expression

$$\delta i = -\frac{e}{d} \quad v(t, t_d) \qquad (4)$$

Hence, the incremental amount of current, produced in the external circuit at time t, which results from a packet of electrons leaving at t_d and having a departure density of $N(t_d) \Delta t_d$, is

$$\Delta i = -\frac{e}{d} \quad v_z(t, t_d) \quad N(t, t_d) \Delta t_d \qquad (5)$$

where

$$N(t_d) = \text{no. of electrons leaving the cathode at } t = t_d \qquad (6)$$

Equation (5) enables the determination, through computer methods, of the waveform of the plate current, since the total current at a particular instant of time will be given approximately by the sum of all current contributing packets in the interaction space at that instant. A typical waveform for the device is shown in Figure 10, where the symbols may be interpreted according to equations (3) and Figure 9. The dc and fundamental components, which are used to calculate the electronic efficiency of the device, can be found through a graphical Fourier analysis of these waveforms.

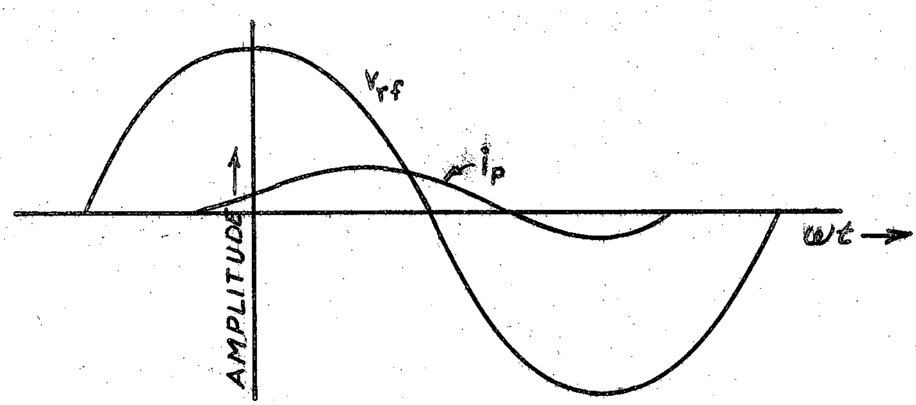

FIGURE 10. APPLIED R-F VOLTAGE AND PLATE CURRENT

Considerable time has been spent in developing a digital computer program capable of determining these current waveforms for different sets of parameters. (See Table II for parameters). The master tape was prepared for a relatively slow computer, manufactured by Royal Precision Electronics, called the LPG-30. Typically, the waveform program ran from two to three hours for each set of parameters. An additional hour was spent in hand-calculating the dc and fundamental current components from the machine-computed waveform. The results of these efforts are displayed in Table II.

Theoretical Efficiencies of Certain Diodes

α	V_o volts	d mm	$\frac{w_o}{w}$	f_{rf} kmcs	percent efficiency
3	1000	2	0.980	6.0	*[1]
3	1000	2	0.250	6.0	0.35%
3	1000	2	0.010	6.0	*[1]
3	1000	1	0.001	3.0	25%
2	1000	1	0.200	3.0	32%
2	1000	1	0.001	3.0	35%

*[1] By observation, these efficiencies were small.

Table II.

Although this solution for plate current neglects the effect of space charge, it should indicate the influence of the plate spacing and field conditions. A better solution would account for the Poisson potential effect in the interaction space, but perhaps under high electric field intensities caused by the r.f. source, it may be possible that space charge effects may be negligible. This point is worth investigating.

It should be mentioned that the efficiency calculated by this method is almost the measure of the over-all efficiency of the device. The power required by a cathode-heater should be considered as an additional loss which would decrease the efficiencies tabulated in Table 1. However, that part of the loss which is associated with the back-bombardment of the cathode by those electrons that re-enter the cathode during retarding field conditions (the negative portion of i_p) may be utilized to provide thermionic emission during the conduction portion of rf cycle. If this is possible, a cathode heater would only be necessary for starting the device.

(B.) Cylindrical Type

A similar analysis for a cylindrical configuration is also being studied. Figure 11 represents this device as a microwave rectifier, having an axial magnetic field. Again space charge has been neglected, and it has been assumed that an electron leaves the cathode (r = a) at time t with zero initial velocity. The differential equation which governs the radial motion of a single electron under the above assumptions is

$$\frac{d^2 r}{dt^2} = \frac{k}{r}\left[\alpha \cos wt - 1\right] - \frac{w_o^2}{4}\left[r - \frac{a^4}{r^3}\right] \qquad (7)$$

(Valid for $a \leq r \leq b$)

where

$\frac{d^2r}{dt^2}$ = radial acceleration

r = radial displacement

a = cathode radius

b = anode radius

$k = \frac{e}{m}\frac{V_o}{\ln b/a}$

$\alpha = \frac{V_1}{V_o}$

$w_o = \frac{e}{m} B$

$w = 2\pi f_{rf}$

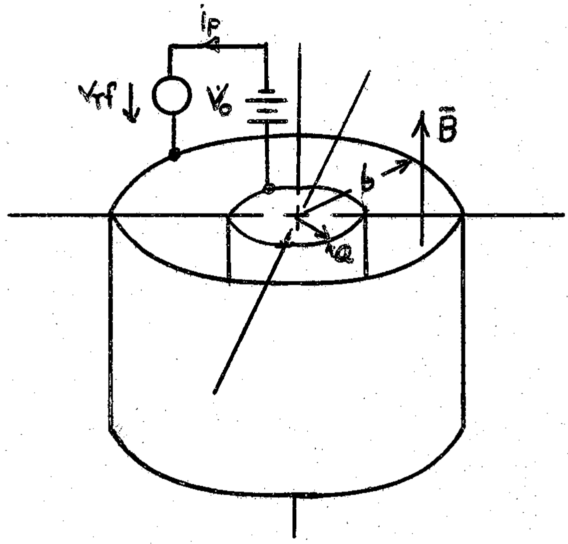

FIGURE 11. CYLINDRICAL TYPE MAGNETRON

Since equation (7) cannot be solved in closed form, iteration methods must be employed to provide a numerical solution. The Runge-Kutta methods have been widely used in computer routines to solve second order differential equations numerically. Consequently, equation (5) has been used once again to solve for the current waveform (i_p) through the use of a computer routine which first solves the differential equation (7).

The programming has been completed and initial trials have been attempted, but no results are available yet.

C. <u>Vacuum-diode</u>

At high voltage and power levels, the vacuum-diode appears to offer promise as a microwave-to-dc energy converter. Reasonable efficiencies should result from the reduction in transit-angle which occurs with larger applied voltages.

The problem has been studied in detail by analyzing a model which has the following characteristics:

1) Parallel-plane configuration and the simple field structure associated with this.

If $d = 0.007''$, $V_1 - V_o \geq 11.3V$. Since V_o and V_1 are of the order of hundred or thousands of volts, this restriction is of little consequence.

Also, $t_m \leq T$

This merely requires the interaction space to be swept clear before the next cycle starts. The condition is easily met.

<u>10 cm results</u>

$f = 2800$ mcs.

$$\eta = \frac{V_o}{V_1} \; \frac{1 - \frac{4}{3} 10^4 \frac{d}{\sqrt{V_1}} \sqrt{\frac{V_1 + V_o}{V_1 - V_o}}}{1 + \frac{4}{3} 10^4 \frac{d}{\sqrt{V_1}} \left\{ \sqrt{\frac{V_1 + V_o}{V_1 - V_o}} - \frac{4}{3} \sqrt{\frac{2 V_1}{V_1 - V_o}} \right\}} \qquad (23)$$

Let $D = 10^5 \dfrac{d}{\sqrt{V_1}}$

$$\eta = \frac{V_o}{V_1} \; \frac{1 - \frac{4}{30} D \sqrt{\frac{1 + V_o/V_1}{1 - V_o/V_1}}}{1 + \frac{4}{30} D \left\{ \sqrt{\frac{1 + V_o/V_1}{1 - V_o/V_1}} - \frac{4}{3} \sqrt{\frac{2}{1 - V_o/V_1}} \right\}} \qquad (24)$$

Using (24), η is plotted in Figure 14.

Example of the use of Figure 14:

$d = .007'' = 1.78 \times 10^{-4} m$, $V_1 = 1000$, $V_o = 800$

$D = \dfrac{17.8}{\sqrt{1000}} = .564$ $\quad \dfrac{V_o}{V_1} = .8$ $\quad \therefore \eta = 68\%$

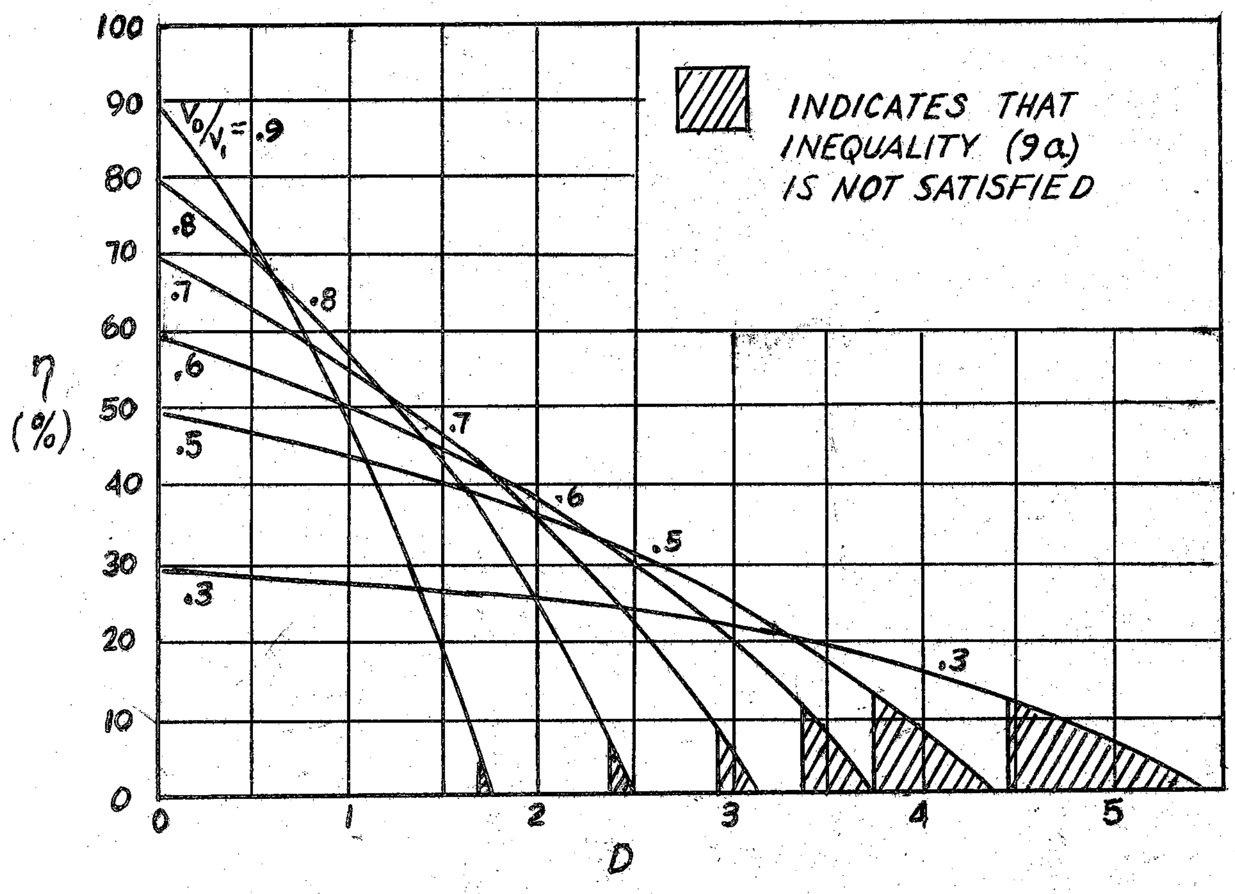

FIGURE 14. RECTIFICATION EFFICIENCY η VS NORMALIZED D, VOLTAGE RATIO V_0/V_1 AS PARAMETER

The Diagram in Figure 15 shows the interval of t during which an electron emitted at $t = t_d$ is in transit. It is useful in determining the integration limits for each of the four ranges.

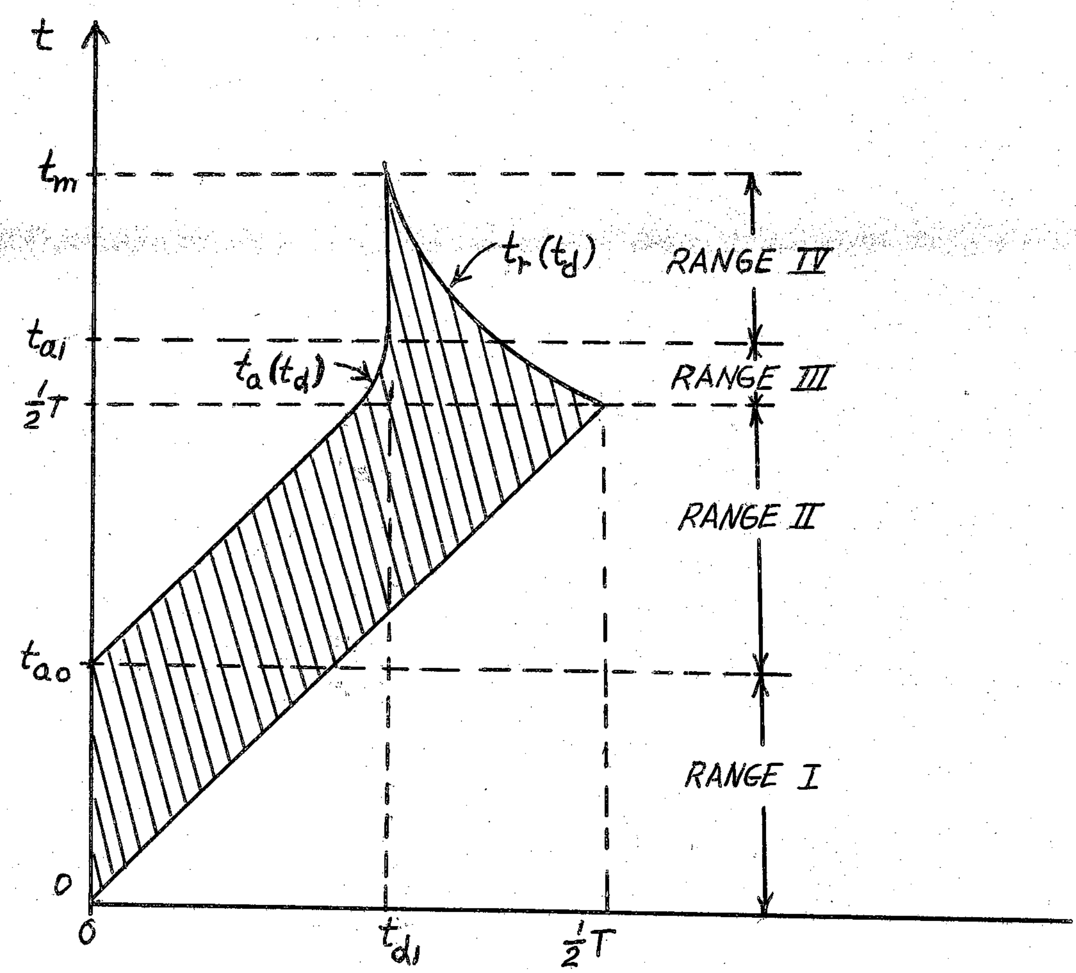

FIG. 15. ARRIVAL AND RETURN TIME t AS A FUNCTION OF DEPARTURE TIME t_d.

Cathode Bombardment Power

The kinetic energy of the electrons returning to the cathode may be used to provide cathode-heating. This power is easily determined as follows:

Let K.E. = kinetic energy of electron leaving cathode at $t = t_d$

$$K.E. = \frac{1}{2} m \left[v(t_d)\right]^2$$

where $v(t_d) = v(t, t_d)$ at $t = t_r$

Thus, $$v(t_d) = -k\left[(t_r - t_d) - \alpha(g_r - g_d)\right]$$

where $$t_r = \frac{t_d - 1/2\sqrt{\frac{2\alpha}{\alpha - 1}}\,T}{1 - \sqrt{\frac{2\alpha}{\alpha-1}}}$$

and $g_r = T - t_r$

Also, $$d(K.E.) = \frac{1}{2} m N_o v^2(t_d)\, d\,t_d$$

$$K.E. = \frac{1}{2} m N_o \int_{t_{d1}}^{\frac{1}{2}T} v^2(t_d)\, dt_d$$

and, $P_{C.H.} = f\,(K.E.)$

Collecting, $$P_{C.H.} = \frac{1}{3}\sqrt{\frac{mV_1}{e}}\; eN_o\; fd\; \frac{\alpha + 1}{\alpha}\sqrt{\frac{\alpha + 1}{\alpha - 1}}$$

Define: $$f_k = \frac{P_{C.H.}}{P_{A.C.}} = \frac{\frac{1}{3}\,\frac{\alpha + 1}{\alpha}}{1 + \frac{1}{2\,fd}\sqrt{\frac{eV1}{m}}\sqrt{\frac{\alpha - 1}{\alpha + 1}} - \frac{4}{3}\sqrt{\frac{2\alpha}{\alpha + 1}}}$$

If $f = 2800$ mcs and $D = 10^5$

then, $$f_k = \frac{\frac{1}{3}\,\frac{\alpha + 1}{\alpha}}{1 + \frac{7.5}{D}\sqrt{\frac{\alpha - 1}{\alpha + 1}} - \frac{4}{3}\sqrt{\frac{2\alpha}{\alpha + 1}}} = \frac{\frac{1}{3}(A + 1)}{1 + \frac{7.5}{D}\sqrt{\frac{1 - A}{1 + A}} - \frac{4}{3}\sqrt{\frac{2}{1 + A}}}$$

where $A = V_o/V_1 = 1/\alpha$

The results of this analysis are presented on a performance chart, Figure 16, which shows both conversion efficiency $\left(\frac{P_{out}\ dc}{P_{in}\ rf}\right)$ and the fractional power available for cathode heating $\left(\frac{P_{cath}}{P_{in}\ rf}\right)$ as functions of plate-cathode spacing (d), peak rf-voltage (V_1), and the ratio of the dc-output-voltage to peak rf-voltage ($A = V_o/V_1$). The chart is drawn for a frequency of 2800 mcs, but it may be used for other frequencies by letting d be the actual plate-cathode spacing times the ratio of the actual frequency to 2800 mcs.

It is interesting to attempt a comparison of the efficiency obtained for the square-wave vacuum-diode with that obtained for an identical parallel-plane inverted magnetron through the digital computer program. If a negligible magnetic field is applied to the magnetron, then it acts as a vacuum-diode; the analysis, however, utilizes sinusoidal excitation, which, although undoubtedly more realistic, makes comparison of questionable value. The following parameters:

$V_o = 1000$ v

$V_1 = 2000$ v

d = 1 mm

$f_{rf} = 2800$ mcs

B = negligible

inserted in the digital computer program yield an efficiency of 35%. If the amplitude of the square-wave is also assumed to be 2000 v, then the diode analysis yields an efficiency of 34%. Some reduction might be expected with the square-wave field, because larger kinetic energies are delivered to those electrons which leave during the unfavorable instant immediately prior to the onset of a retarding field, and also because these electrons are subjected to a larger retarding field. A compensating effect is introduced, however, by the larger energies imparted to the electrons during the most favorable transit interval. A similar comparison when V_1 is increased to 3000 volts without increasing V_0 leads to efficiencies of 25% for the sinusoidal excitation and 27% for the square-wave case.

The sinusoidal case which is provided by the choice of a small magnetic field for the inverted magnetron yields the more accurate result, but the length of the computer program has not permitted a large amount of data to be obtained.

The performance chart also indicates that the operating parameters may be chosen to deliver a desired fraction of the rf-input power to the cathode to provide a suitable temperature for emission. Efficiencies of 65 to 70% appear feasible.

Experimental studies are just now beginning on two different vacuum-diodes in the neighborhood of 3000 mcs. A comparison between the theoretical and experimental efficiencies is desirable.

A General Electric type 7266 diode has been loaded to full current carrying capacity of 2 ma. when mounted in a wave guide cavity and supplied with pulsed microwave energy at 3300 Mc. The average d-c voltage measured across the 100,000 ohm load resistor was 200 volts. This represents a rectified power of 0.4 watt. From known characteristics of the tube, the voltage across it under the above condition would be roughly 2 volts. The diode is thus operating at a high efficiency.

The load resistor used could be replaced by a 200 volt storage battery. Then, if this arrangement were to be used in multiple, the feasibility of worthwhile energy storage seems good.

Other diodes of higher current carrying capacity will be tried soon.

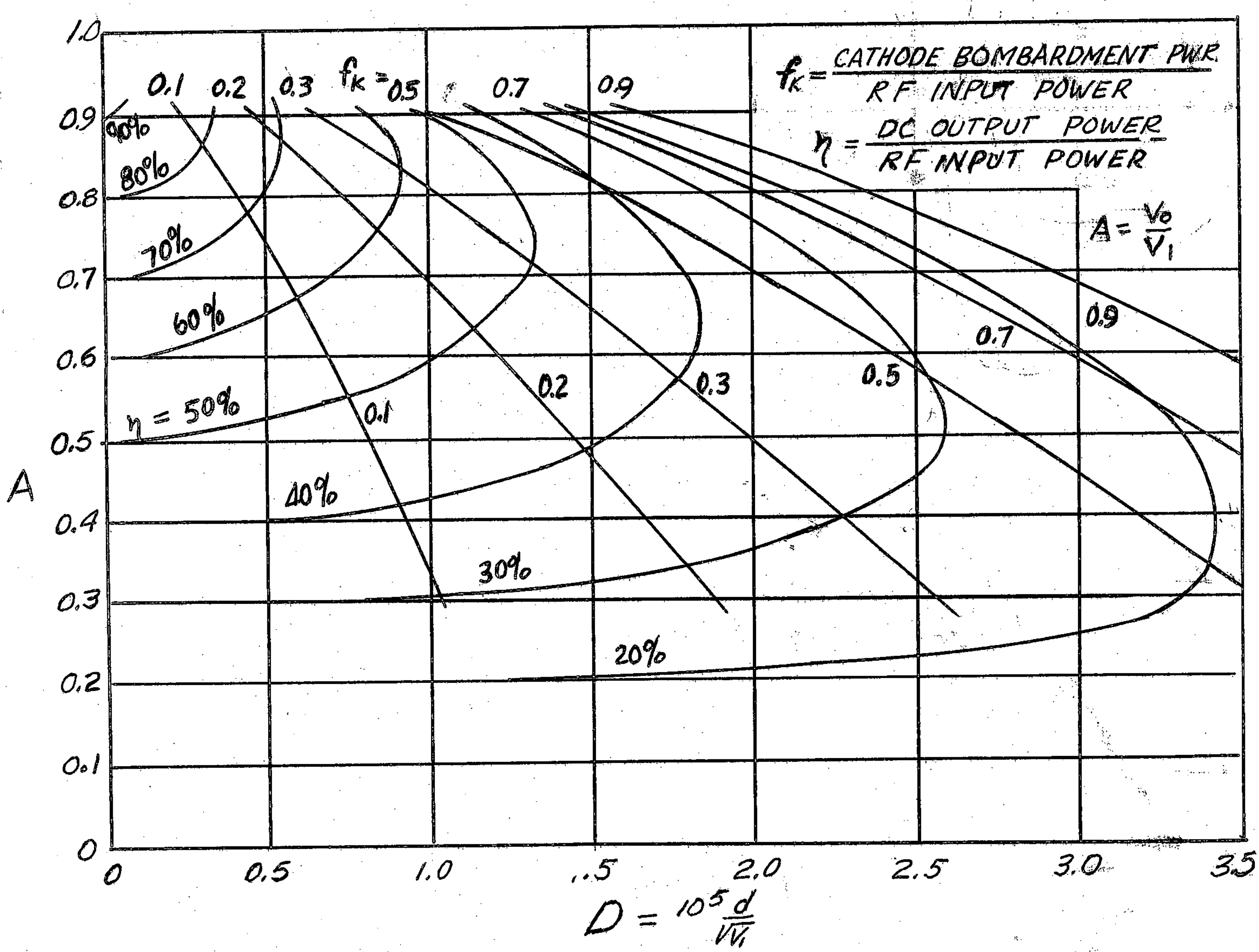

FIGURE 16. PERFORMANCE CHART (2800 mcs.)