A RADIO-FREQUENCY HIGH-VOLTAGE SUPPLY USING GRID RECTIFICATION

by

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RADIO-FREQUENCY POWER-SUPPLIES

Early Practice With the development of television it has become necessary to produce ever higher accelerating voltages for the receiver picture tubes. In the early receivers the accelerating voltage was usually produced by stepping up the 60 cycle line voltage with a transformer, rectifying it, and filtering it with resistance-capacitance filters. Servicing these sets was hazardous because of the large currents which might be drawn from the high-voltage transformer upon bodily contact, and the large capacitors necessary for filtering were dangerous when charged to a high voltage. These capacitors were also bulky and expensive.

Radio-Frequency Power Supplies Radio-frequency power supplies were developed to produce high voltages at low, limited currents for use as accelerating voltages for cathode-ray tubes. A schematic diagram of a basic radio-frequency power-supply is presented on page 5. The circuit consists of an oscillator tube T_1, a rectifier tube T_2, a high-voltage filter capacitor C_2, and a step-up coil having a primary L_1, a high-voltage-secondary L_2, a grid winding L_4, and a filament winding L_3. High frequency oscillatory voltages are produced by the oscillator tube. These voltages are stepped up in the high-voltage coil, and are rectified by the rectifier tube. The rectified voltage

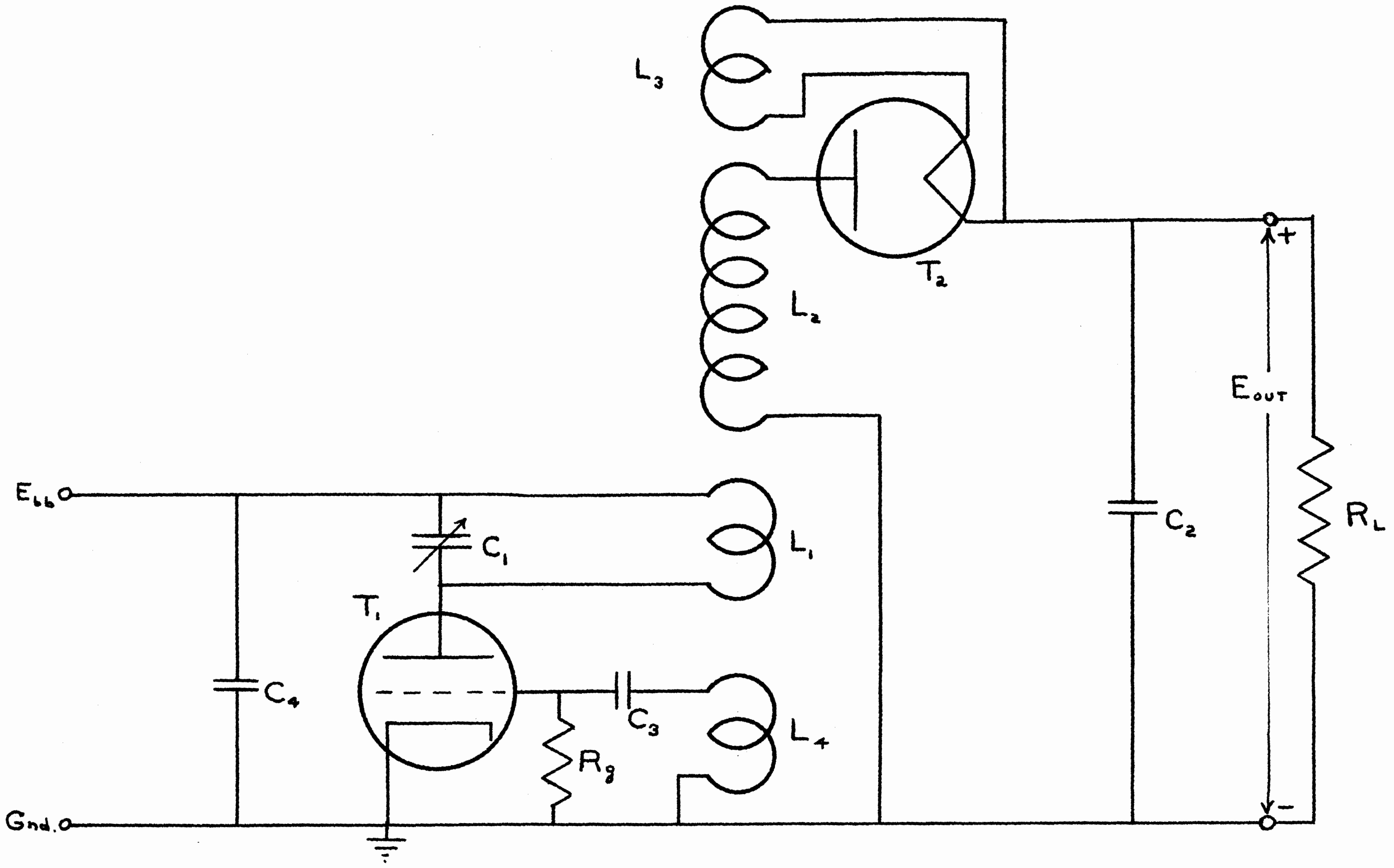

Fig. 1 Basic Radio-Frequency High-Voltage Supply

is filtered by the filter capacitor and is fed to the cathode-ray tube, indicated as R_L in the diagram. The radio-frequency power-supply may be built cheaply and compactly, since the filter capacitors constitute one of the principal expenses of any high voltage supply, and small capacitors may be used when the ripple frequency to be filtered out is high. Radio-frequency power-supplies ordinarily operate at frequencies from ten to three-hundred kilocycles. The maximum output of the oscillator tube limits the high-voltage output current to a small value if the output is short circuited. The use of small filter capacitors greatly lessens the danger of disastrous results occurring from accidental bodily contact with the live high-voltage circuit. The step-up coil is an air core coil, which is compact and very light in comparison with a 60 cycle step-up transformer of the same output voltage. With a radio-frequency power-supply it is possible to control the output voltage by varying the oscillator plate voltage, or, if a pentode is used, the screen voltage. By sampling the output voltage and feeding back a porportional voltage to control the screen voltage of the oscillator, the output voltage may be held very nearly constant over the range of currents for which the supply is designed.[1]

Radio-frequency high-voltage supplies of the type

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[1] V. K. Zworykin and others, *Electron Optics and the Electron Microscope* (New York: John Wiley and Sons, Inc., 1945) P. 234-235

described have been extensively investigated and developed by RCA.[2] A special rectifier tube, the type 1B3-GT/8016, was developed especially for radio-frequency applications. The filament of this tube consumes only one quarter watt of power, and receives its voltage from a small winding on the step-up coil.

Present Practice At the time of this writing radio-frequency high-voltage supplies similar to the one described, with slight modifications, are being almost universally used in commercial television receivers. however, the cost of the high-voltage supply is still a considerable part of the cost of small television receivers. An inexpensive high-voltage supply for small receivers would be a substantial contribution toward lowering receiver prices. The cathode ray tubes in use in receivers at the present time require about 6,000 volts at currents as high as 800 microamperes; accordingly, a useful high-voltage supply should be capable of producing voltages and currents of this order of magnitude.

The Circuit Investigated The radio-frequency high-voltage supply investigated in this research represents a radical departure from the usual type of high-voltage supply. The schematic diagram of the circuit used is shown on page 8. The most notable characteristic of the circuit is its extreme simplicity. It is simply an

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2. R. S. Mautner and O. H.Schade, "Television High Voltage R-F Supplies", RCA Review Vol. 8, March 1947

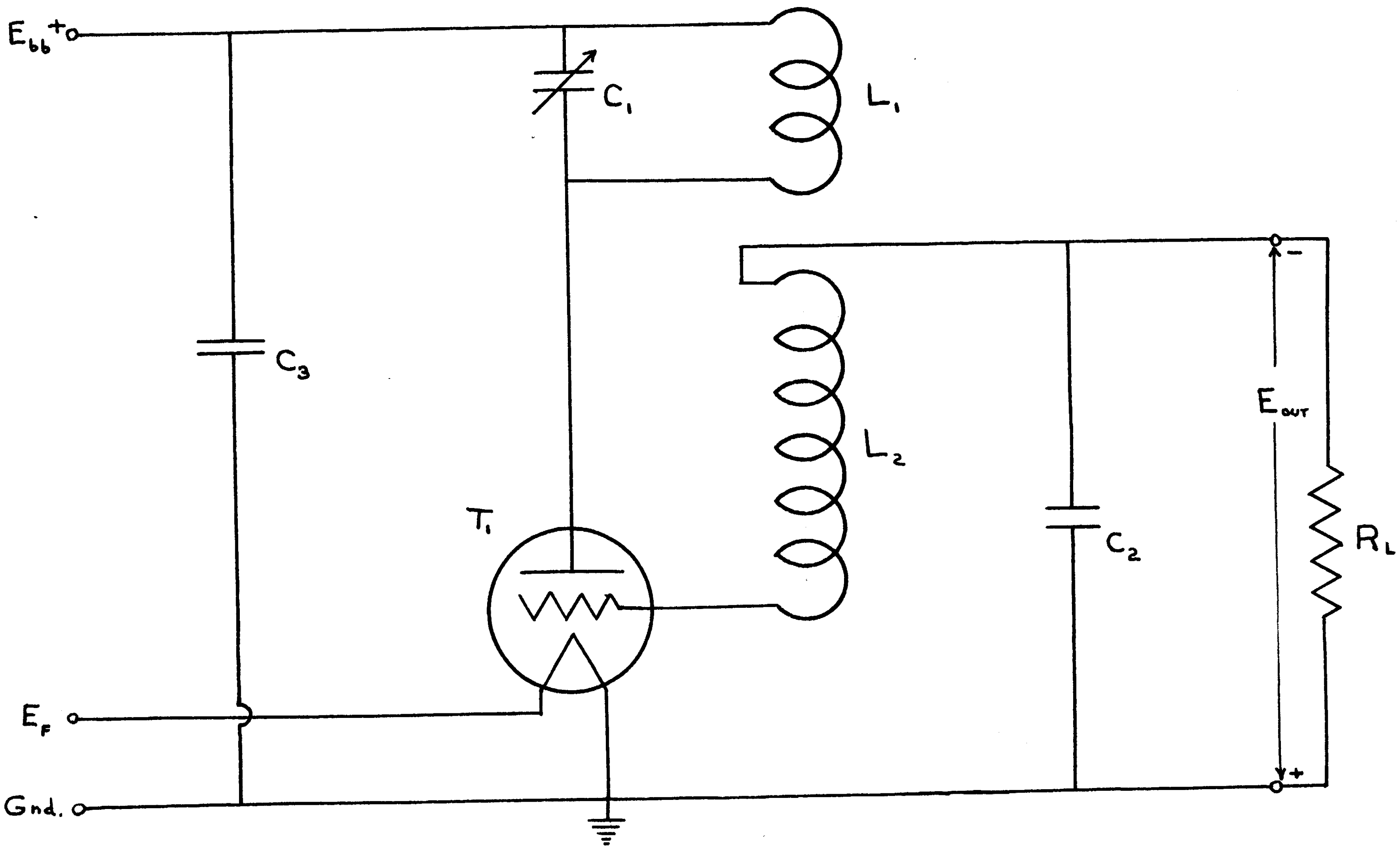

Fig. 2 Circuit Investigated

oscillator tube whose grid is driven by the high-voltage-secondary of the step-up coil. The grid, when driven positive with respect to the cathode, acts as a diode to rectify the high voltage. The output is filtered and used as the accelerating voltage for the cathode ray tube. The circuit makes the use of a separate rectifier tube unnecessary, and simplifies the construction of the high-voltage step-up coil. This represents a considerable saving in cost as compared with the usual high-voltage supply.

CONSTRUCTION OF THE EXPERIMENTAL SUPPLY

Coils The high-voltage-secondary coil, which had to be wound especially for this project, was wound to the specifications given by RCA[3] for a coil designed to produce 4,000 volts. The dimensions of the coil are shown below.

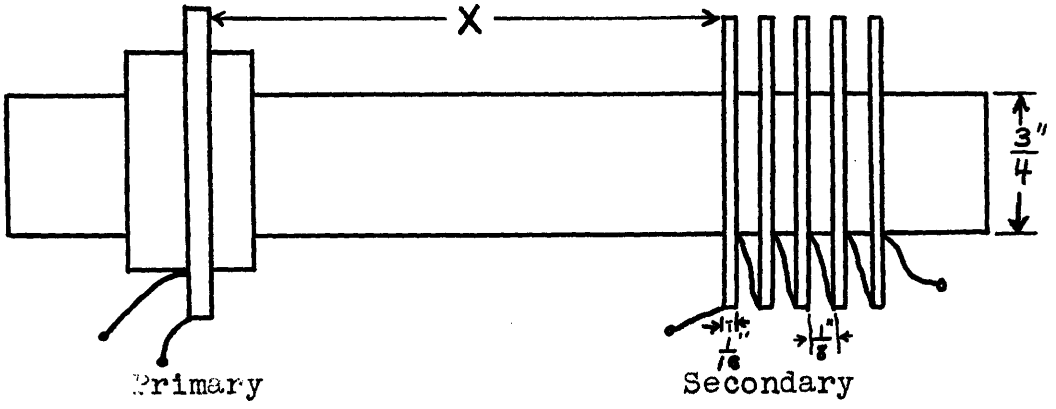

Fig. 3 Step-up Coil

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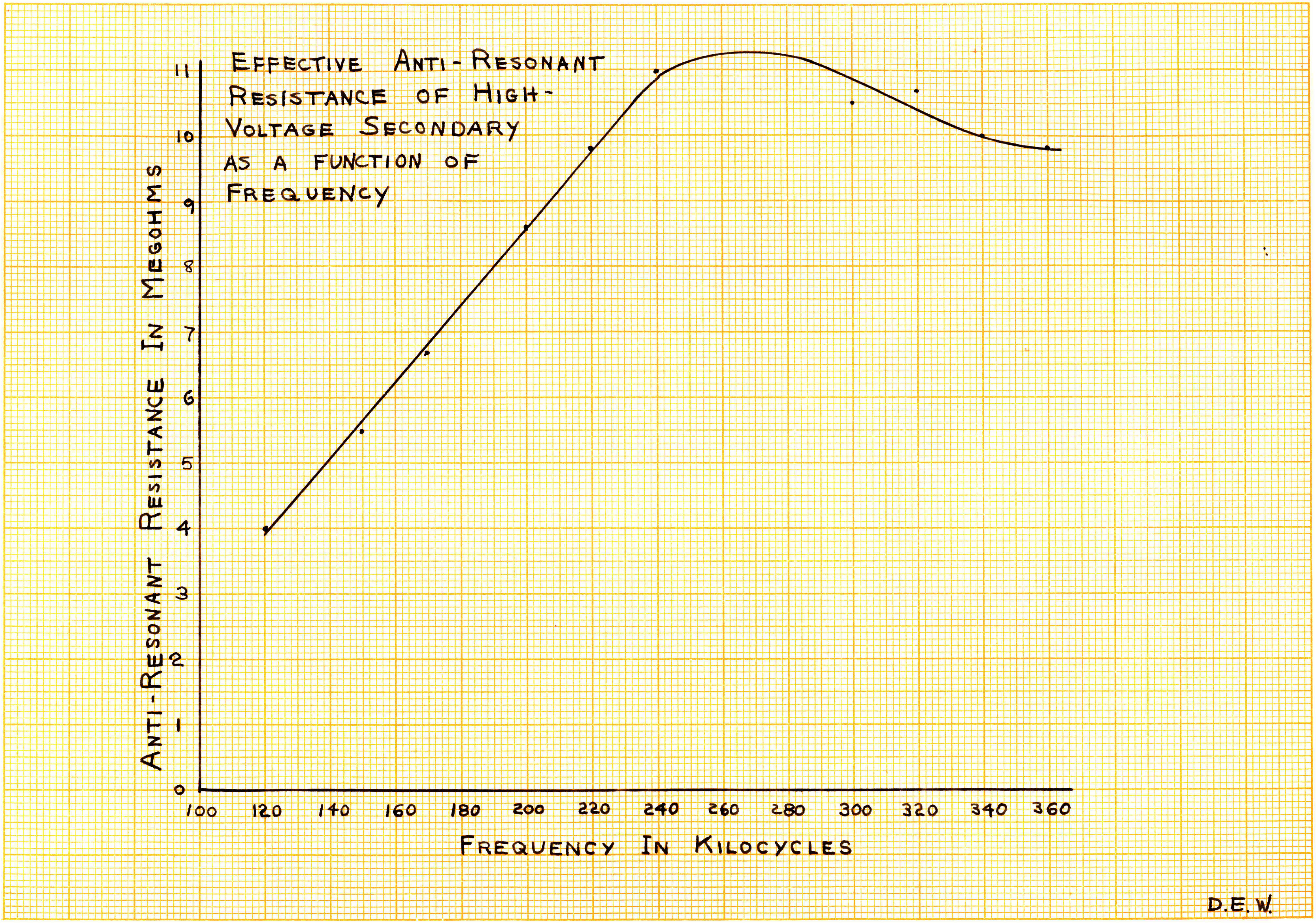
[3] R. S. Mautner and O. H. Schade, <u>Op. Cit</u>., P. 48

The secondary coil consists of five pies having 350 turns of 3/41 Litz wire per pie, and has a D.C. resistance of 200 ohms. A plot of effective anti-resonant resistance as a function of frequency for the secondary is presented on page 11. The primary coil was not wound on the same form as the secondary so that different primary coils and different amounts of magnetic coupling between the two coils could be used. Several primaries were tried. These included two coils taken from an old radio and several coils wound by hand.

Of the two coils taken from an old radio one produced a much higher output voltage. The other, which was of low Q, was discarded. The first had an unknown number of turns, but by measurement of its inductance and physical dimensions, the number of turns was calculated, using published charts,[4] to be 230. This coil, which was the primary which produced the highest output voltage, was a single pie 1/8" wide, 5/32" high, with an inside diameter of 1¼ inches and a Q of 80 at the operating frequency of 250 kilocycles. After calculations had shown that a lower impedance primary should produce higher outputs, other primary coils were wound by hand, each having 100 turns of wire on a 1¼" diameter form. The only one of these having a Q sufficient for stable operation was one having 100 turns of 20/36 Litz wire, and a Q of 120 at 250 kilocycles.

[4] R. T. Beatty, Radio Data Charts (London: Iliffe and Sons, Ltd., 193?)


EFFECTIVE ANTI-RESONANT RESISTANCE OF HIGH-VOLTAGE SECONDARY AS A FUNCTION OF FREQUENCY
ANTI-RESONANT RESISTANCE IN MEGOHMS
0
1
2
3
4
5
6
7
8
9
10
11
100
120
140
160
180
200
220
240
260
280
300
320
340
360
FREQUENCY IN KILOCYCLES
D.E.W.

Tube Because of the high voltages impressed upon the grid of the tube, it was decided that a small transmitting tube with a grid lead brought out through the glass envelope would be used, since this would give good grid insulation. A type 3C24 tube was used in the experimental work. This tube is similar to the Heintz and Kaufmann type 24"Gammatron" tube, but has both the plate and grid leads brought out through the glass envelope. The constant current characteristics of the tube, plotted from data sheets published by Heintz and Kaufmann are presented on page 13. Other data are given below.

Type 3c24 Tube

Maximum Plate Dissipation 25 Watts

Filament: 6.3 Volts, 3 Amperes

Maximum Plate Voltage 2,000 Volts.

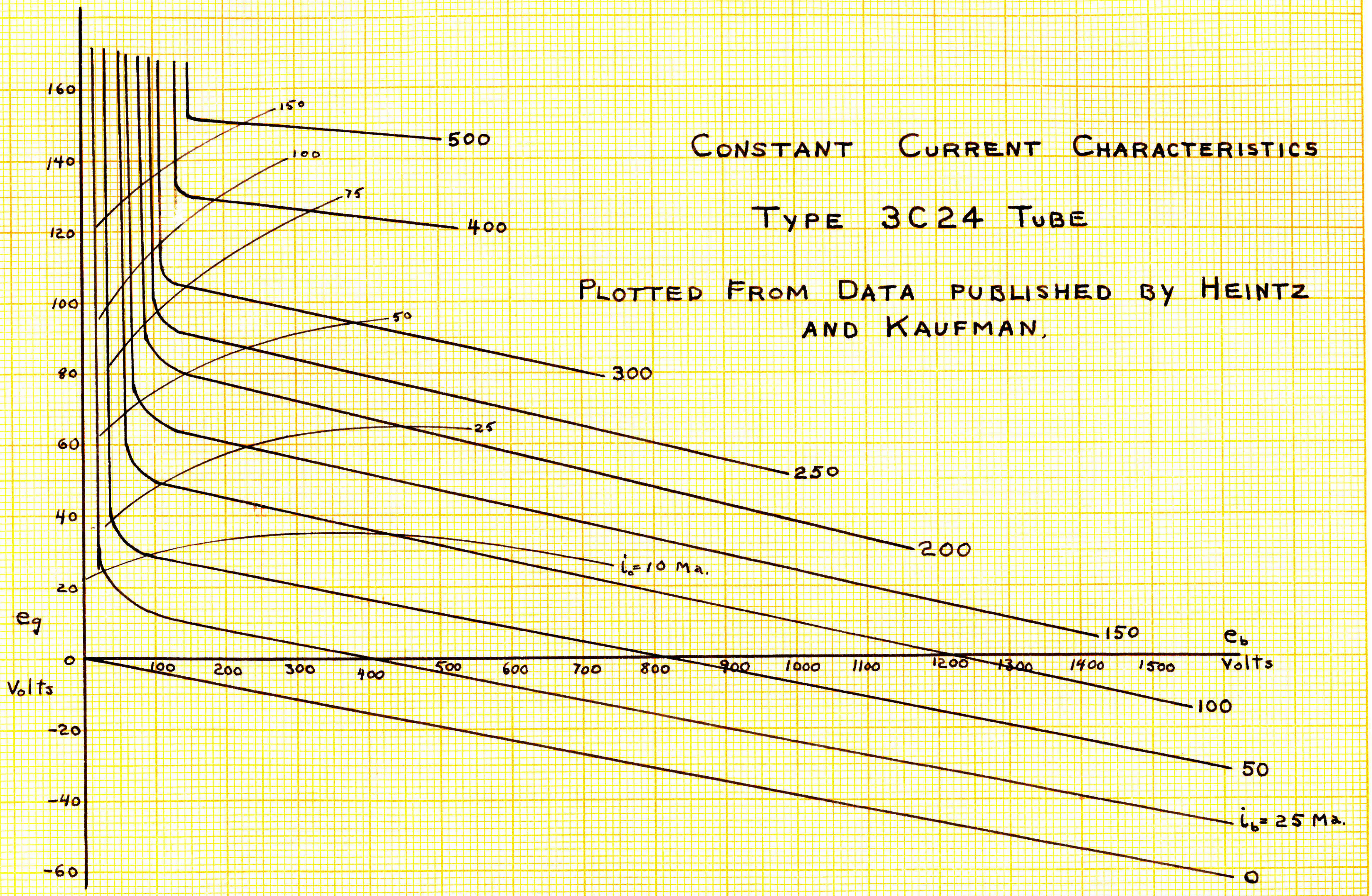
Amplification Factor 25

Interelectrode Capacitances in Micro-Microfarads:

Grid to Filament 2.5, Grid to Plate 1.7, Plate to filament .4

The type 3C24 tube is designed as a class C amplifier and is expected to draw about 5 milliamperes of grid current in normal operation.

Capacitors High-voltage filter capacitors were available having capacitances of .1 and..003 microfarads. The .003 microfarad capacitor was used since it gave good filtering and better stability of the circuit than the .1 microfarad capacitor. Capacitor C_1 was a variable



CONSTANT CURRENT CHARACTERISTICS

TYPE 3C24 TUBE

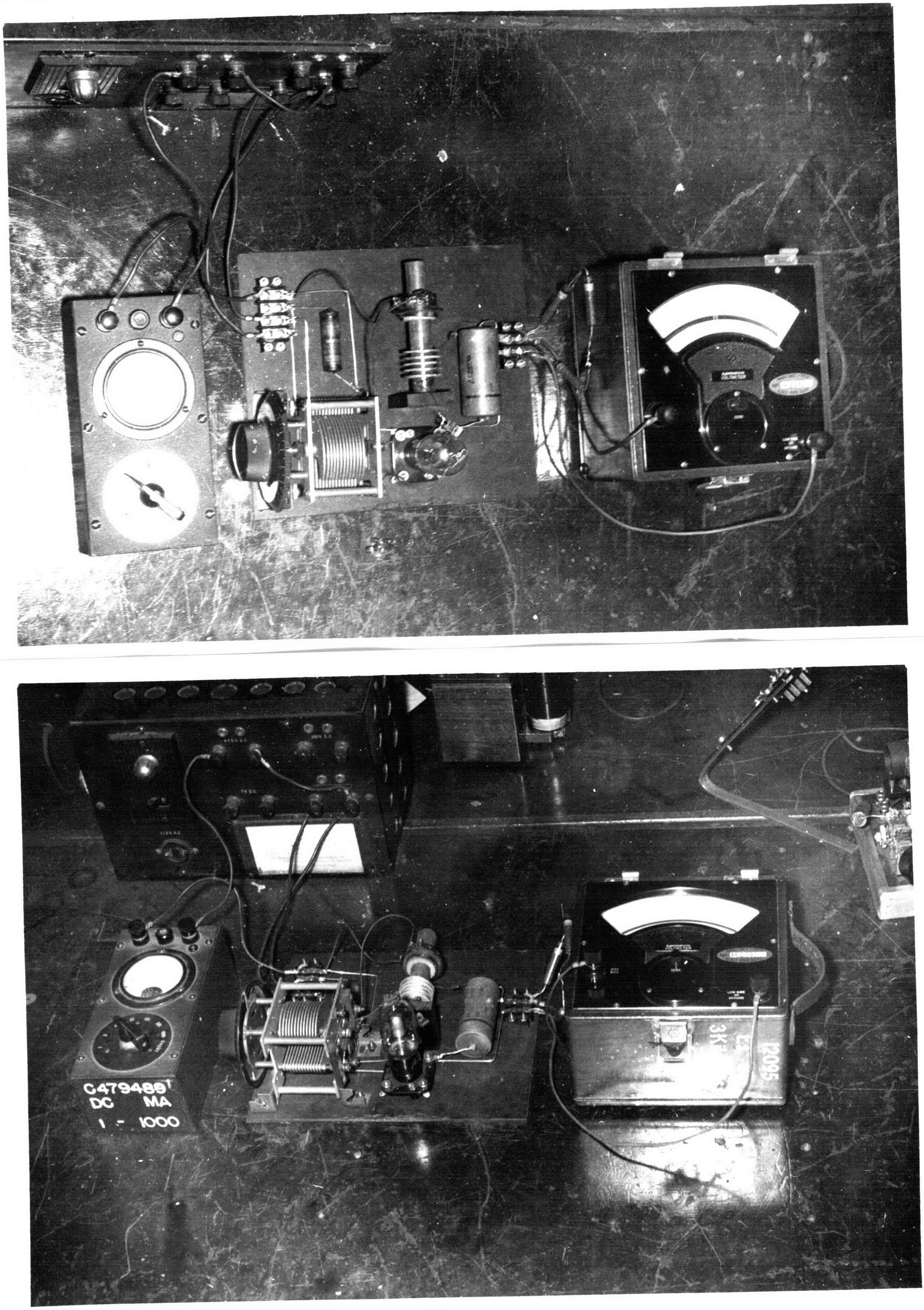
PLOTTED FROM DATA PUBLISHED BY HEINTZ AND KAUFMAN.

D. E. W.

capacitor of about 500 micro-micorfarads maximum capacitance, used to tune the primary coil to the resonsnt frequency of the secondary coil. It was found that reduction of the high frequency plate current path by the insertion of capacitor C_3 between the plate supply side of the primary coil and the filament of the tube increased the output voltage of the supply. The circuit components with the exception of the load resistors were mounted on a Masonite board. Photographs on page 15 show the final circuit with meters for reading plate current and output voltage.

EXPERIMENTAL RESULTS

Voltage Obtained The maximum voltage obtained from the circuit was 1975 volts. This was obtained with a 530 volt plate supply, a three megohm load, and the 230 turn radio coil as a primary. This is the primary coil shown in the photographs. It is shown in the position which gave the amount of magnetic coupling for maximum voltage output. As will be shown later, it was predicted analytically that the output would be greater if a primary coil having a lower inductance were used. Accordingly, the 100 turn coil was wound, but it was found that the oscillator functioned intermittently with the low impedance primary coil unless the high-voltage output current drawn was more than about 1.5 milliamperes. At the high output currents where the oscillator functioned correctly

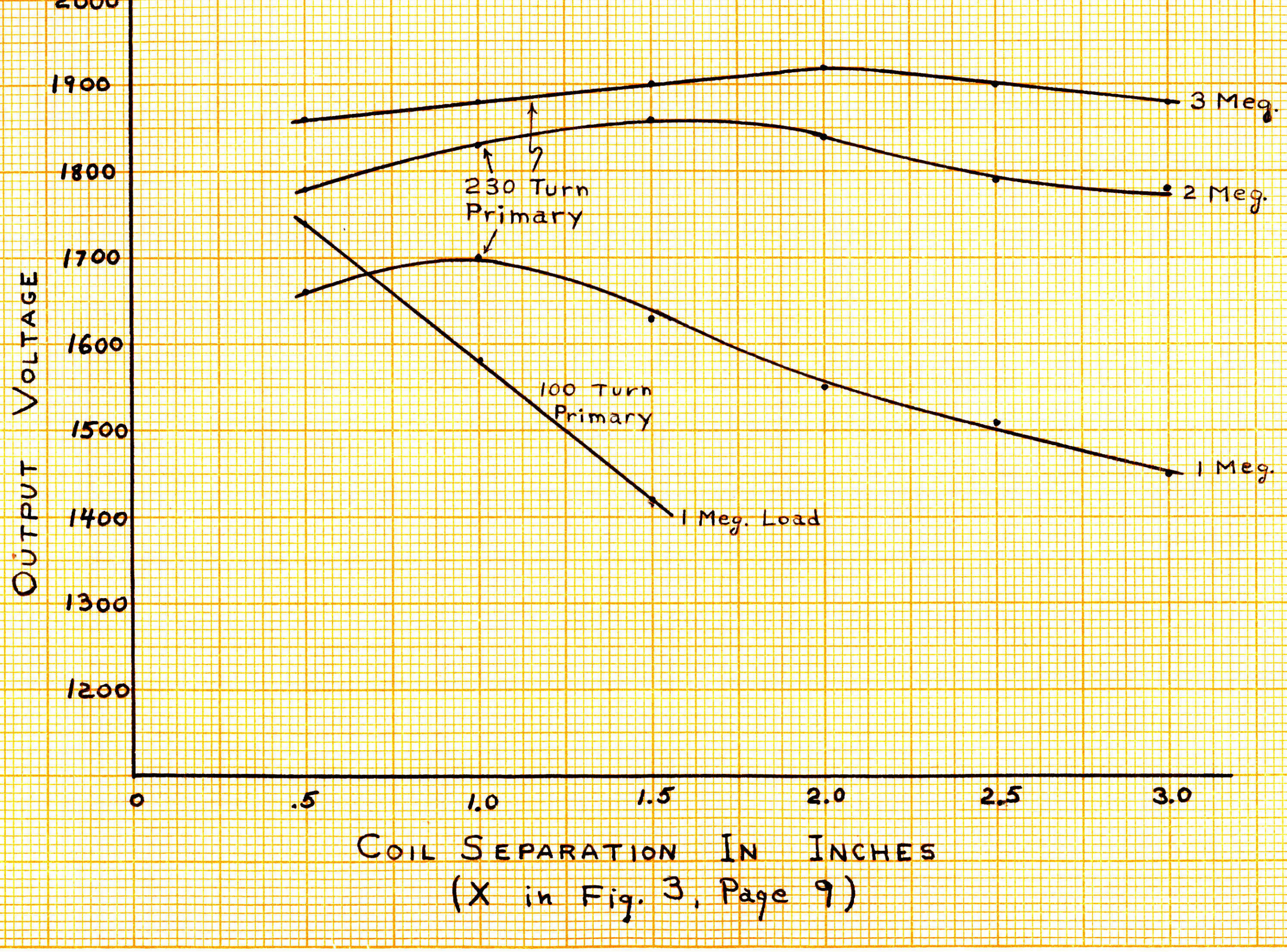


Final Circuit

with either coil, the low impedance primary produced a slightly higher output voltage than the high impedance primary. However, the currents were higher than desired and the voltages were lower than those produced by the high impedance primary at the desired currents. This can be seen from the courves on page 17, which include curves for both primary coils with a one megohm load resistor. The two primary coils were also used together, with varying coupling between them, in order to obtain greater and smaller primary inductances. Increased inductance above that of the 230 turn coil (about 4,000 microhenries) helped to stabilize the oscillator operation but did not raise the output voltage for any given load. Decreased primary inductance resulted in intermittent operation at low currents.

Coupling The coupling between the primary and secondary coils, if increased beyond the critical coupling which produces maximum voltage, produces a lower output voltage but results in better oscillator stability and higher efficiency. The effect of varying the coupling between the coils is presented on page 17 as a plot of output voltage as a function of distance between the coils for different loads. The curves show that the coupling for maximum voltage is a function of the load. The necessary coupling increases as the load increases. The curves show that the output voltage regulation is also a function of the coupling, the regulation increasing as the coupling becomes less.

OUTPUT VOLTAGE AS A FUNCTION OF COIL SEPARATION
CIRCUIT OF FIG.



D.E.W.

Current and Stability Since currents of the order of 800 microamperes were the highest currents sought, current conditions above 2 milliamperes were not investigated. At currents above about 1.5 milliamperes drawn by the high-voltage load the oscillator operation is dependable, but the output voltage drops considerably. It is at low currents that difficulties are encountered. Below a certain point which depends on the size of the filter capacitor used, the tuning of the plate circuit, the coil coupling, the inductance of the primary coil, and the plate supply voltage used, the operation of the oscillator will become intermittent or stop altogether. It was found that the primary coil had to be of about 4,000 microhenries inductance, as well as of high Q in order to have dependable operation at low currents. Primary coils of low Q were found to produce very low output voltages when sufficient current was drawn for stable operation. With the 230 turn primary, load resistances higher than three megohms caused intermittent operation, while load resistances higher than one megohm caused intermittent operation with the 100 turn primary. Lower load resistances caused currents far in excess of those desired. Analytical investigation of stability in a circuit of this type is an extremely complex and uncertain problem. For this reason the conditions found experimentally to produce stable operation are presented and no explanation will be attempted here.

Operating Frequency

The frequency of operation of the circuit with a type 3C24 tube was found to be 250 kilocycles. This is set by the resonant frequency of the high-voltage-secondary coil when tuned by its stray capacitance plus the capacitance added by the grid of the tube. The primary coil must be tuned to the same frequency in order to obtain appreciable output from the circuit.

Efficiency

The overall efficiency of the circuit if the filament power consumed by the tube is neglected was found to be approximately 45% at the maximum output voltage. This is the power dissipated in the resistor R_L as a percentage of the power drawn by the circuit from the plate supply. The efficiency was found to be a function of the coupling between coils, the tuning of the primary coil, and the current drawn by the load.

Replacement of Tubes

Analytical investigation shows that the output voltage is determined principally by the mutual conductance of the oscillator tube if the plate supply voltage is constant. Therefore, replacement of a tube by one of slightly different mutual conductance will cause a corresponding change in output. From the three tubes used in the experimental work, maximum voltages from 1750 to 1975 were obtained.

ANALYTICAL INVESTIGATION

The type of circuit studied was an oscillator having an extremely high grid bias. This type of circuit was known to be unstable in operation under certain conditions, so the first problem was to find out if it was possible to operate the circuit successfully in practice. Accordingly, in contrast to the usual procedure, the circuit was first constructed and investigated experimentally before extensive calculations were made. When the experimental results showed that the circuit operated successfully under certain conditions, but failed to produce the desired voltages, the reason was investigated analytically.

Assumptions The analytical work is similar to the usual class C amplifier analysis in that the grid voltage and A.C. plate voltage are assumed to be sine waves. In these calculations the further assumption was made that the plate voltage is constant during the time that conduction takes place. This assumption is justified by the fact that the conduction angle of the tube is so short that the plate voltage change during conduction, assuming a sinusoidal A.C. plate voltage, is less than 15 volts for all calculated points and of the order of 5 volts for most points. The voltage across the high-voltage filter-capacitor was also considered constant, since the voltage change across a .003 microfarad capacitor is less than 1.1 volts for the currents considered at an operating frequency of 250 kilocycles.

Procedure The calculations consist of picking the desired output voltage, output current, and minimum plate voltage for each point. From the characteristics of the tube it is then possible to determine graphically the peak positive voltage applied to the grid of the tube. From this it is possible to plot the plate current pulse, and graphical integration of this pulse gives the average plate current. The product of the average plate current times the plate supply voltage is the power supplied to the circuit from the plate supply. This power may be compared with the power dissipated by the high voltage output of the circuit. If the circuit were 100% efficient, the high-voltage output power would be equal to the plate supply input power.

In the calculations the grid voltage waveform is taken to be a sine wave and the positive peak of this voltage is similar to that plotted on page 27. In order to plot the grid current pulse it is necessary to know the grid current as a function of grid voltage for a given plate voltage. The published data were insufficient to plot curves of grid current as a function of grid voltage which would be dependable at low grid currents, so these regions were investigated experimentally. The results are presented as curves on page 26. From these curves and a grid voltage pulse of assumed amplitude it is possible to plot the grid current pulse. The average output current is found by performing a graphical integration of the current pulse and averaging the current over one R-F cycle. The procedure is to pick a desired output current, output voltage, and minimum plate voltage, and then assume a peak positive grid voltage. The grid current pulse is then plotted and graphically integrated. If its average value over one cycle is equal to the desired output current, the assumed peak grid voltage was correct; if not, another peak grid voltage must be assumed and the process repeated. In this way the peak positive grid voltage may be found by a process of trial and error for any specified output current, output voltage, and minimum plate voltage. When the peak positive grid voltage has been found for picked conditions, the plate current pulse may be plotted from the curves of plate current as a function of grid voltage which are presented on page 25. The plate current pulse is then graphically integrated to obtain the plate current and is averaged over one R-F cycle.

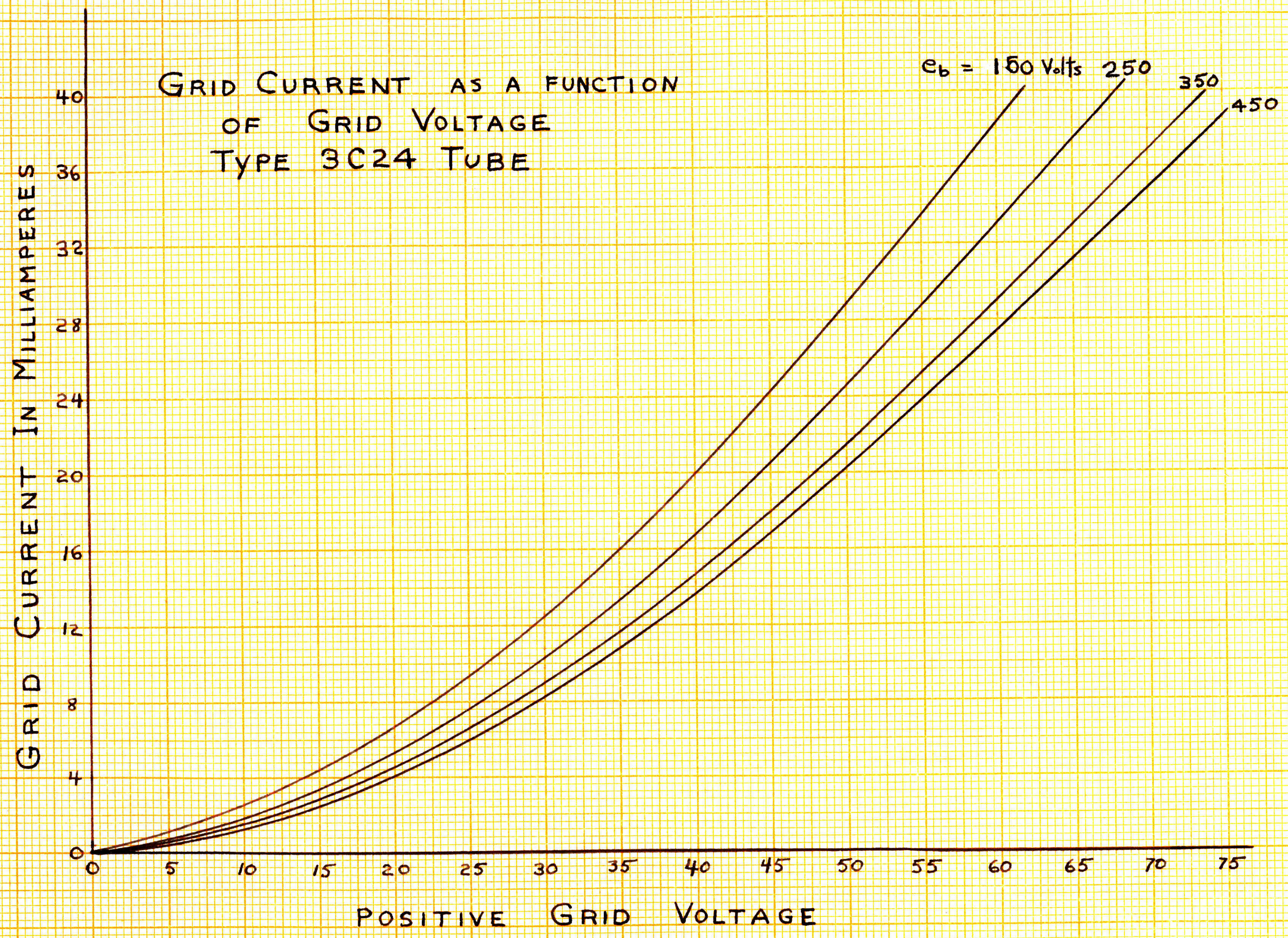
The average plate current was multiplied by a plate supply voltage of 500 volts to find the power delivered to the circuit by the plate supply, so that comparisons could be made between the amount of power furnished to the circuit under various conditions and the amount of output power needed to satisfy these conditions. In calculating the power consumed in the output of the circuit, the anti-resonant resistance of the high-voltage coil when operated at 250 kilocycles and connected to the grid of the tube was taken to be ten megohms. The output power is then the sum of the power dissipated in the coil and the power dissipated in the load resistor R_L. Measured anti-resonant resistance of the high-voltage coil used as a function of frequency has been presented on page 11. The calculations and graphical integrations described were carried out for output currents of 200, 500, and 800 microamperes, for output voltages of 1000, 1500, 2000, 3000, 4000, and 5000 volts, and for minimum plate voltages of 150, 250, 350, and 450 volts. The results are presented as curves on pages 29, 30, and 31, and are tabulated on pages 32 and 33.

Results The plots on pages 29, 30, and 31 indicate why it is not possible to obtain the voltages and currents desired from this circuit using a 3C24 tube with a 500 volt plate supply. The straight lines show the power required by the high-voltage section of the circuit, while the curves show the power delivered to the circuit by the plate supply. The plate supply power must furnish the power consumed by the output as well as the losses, and it is impossible for the circuit to operate in a region where more power is required than is supplied to it. The plots show that even if the circuit were 100% efficient, the maximum output voltage would be less than 3500 volts. Under the conditions of the experimental work, where a plate supply of 530 volts was used and the minimum plate voltage was approximately 250 volts, with an overall efficiency of about 45%, the curves predict approximately 1700 volts output from the circuit at a current of 500 microamperes. This voltage checks reasonably well with the voltages from 1750 to 1975 at currents of about 600 microamperes experimentally observed. Since the curves are the product of the plate supply voltage and the average plate current, a change in either of these will change the output porportionately. Thus the output voltage may be increased by using a higher plate supply voltage, or by using an oscillator tube which conducts large currents during the conduction time, and thus draws a larger average plate current.

CONCLUSIONS

The output voltage obtained from the experimental circuit, while being far short of the voltage desired, is nevertheless sufficient to operate some of the smaller television picture tubes such as the 5BP4 or 7JP4, although the brilliance of the picture obtained will not be great. The circuit is a practical one for cathode-ray tube supplies in oscilloscopes where accelerating voltages of less than 2500 volts are commonly used. By connecting the cathode of the cathode-ray tube to the high-voltage output of the circuit, while connecting the an~~n~~ode of the cathode-ray tube to the plate supply, accelerating voltages of 2400 volts may be obtained. The 3C24 tubes showed no sign of deterioration with use, giving very consistent results in the way of output voltage. The variation in output upon replacement of tubes is not great enough to be serious. The disadvantage of the 3C24 tube is the high filament power required. It would be preferable if a suitable tube requiring much less heater power could be found. The complete overall efficiency of the circuit is actually less than 10% because of the amount of power consumed by the 3C24 filament.

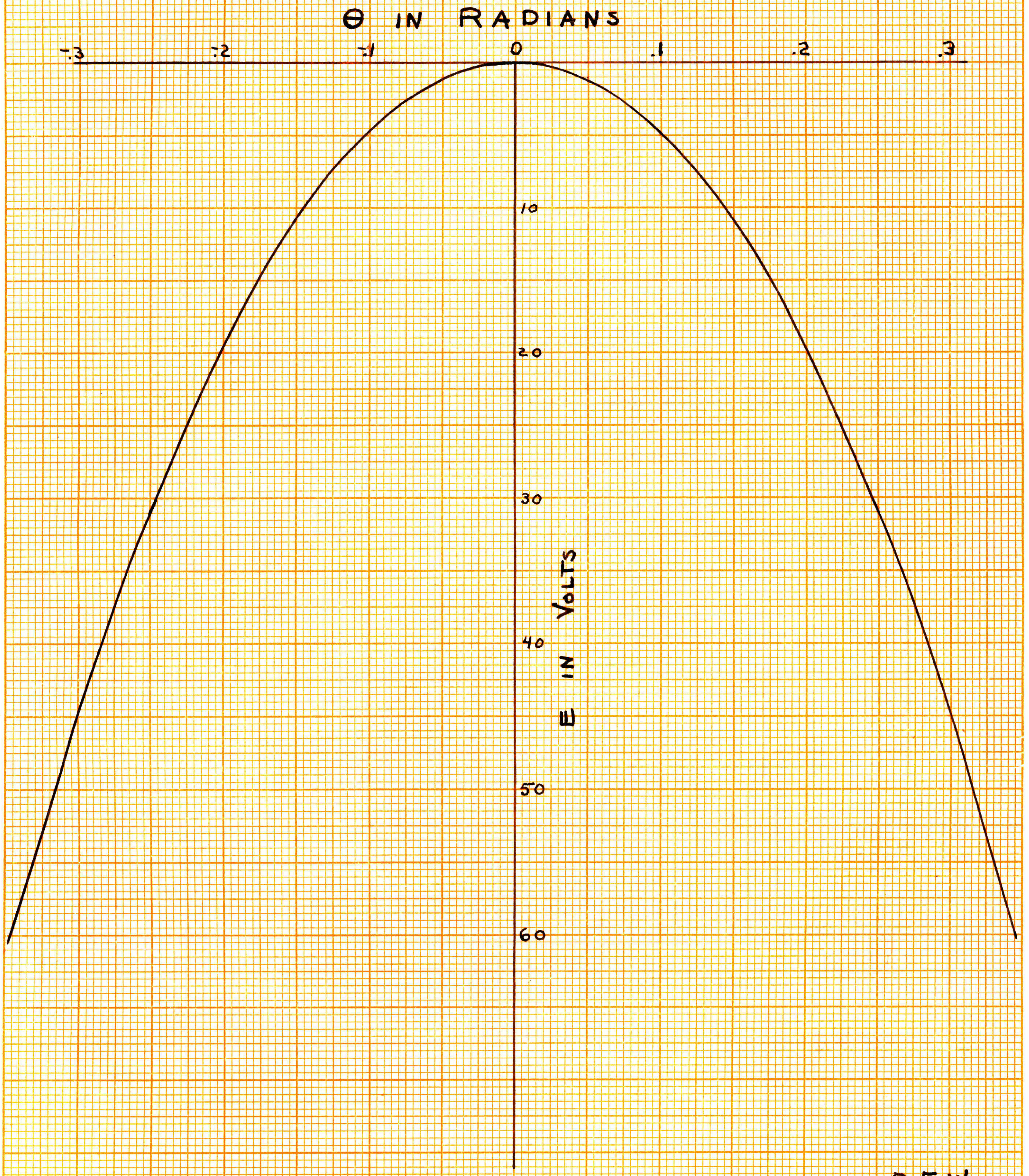
From the experimental and analytical results it appears that it would be impossible to produce a voltage much higher than 2,000 volts with the proposed circuit using a 3C24 tube with a 500 volt plate supply. However, with a properly designed tube it should be possible to produce much higher voltages provided that the operation of the circuit can be made stable at higher voltages. Calculations show that this tube should be capable of conducting large plate currents of the order of 800 milliamperes, with low plate voltages of the order of 100 volts, and with peak positive grid voltages of the order of thirty volts. The tube should have a rated plate dissipation of about five watts or more. It need not have the high filament power consumed in the 3C24, and it need not necessarily be a triode. Unless a tube having the characteristics described as well as excellent grid insulation can be obtained, this circuit must be limited to a voltage output which is too low for ideal operation of the small television picture tubes now in common use.



GRID CURRENT AS A FUNCTION OF GRID VOLTAGE TYPE 3C24 TUBE

D. E. W.

PEAK OF CURVE: $E = 1000 \cos \theta$ (Volts)



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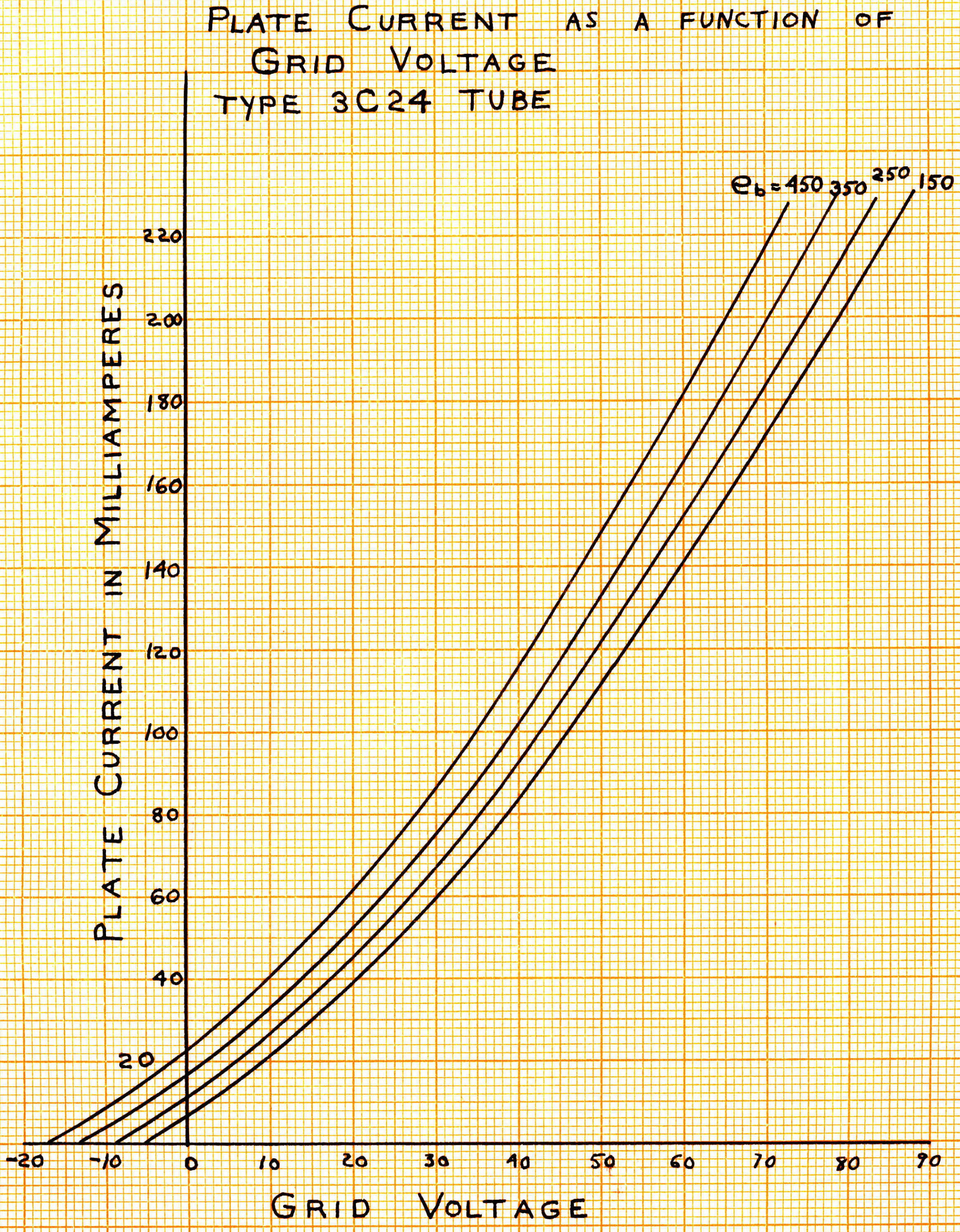
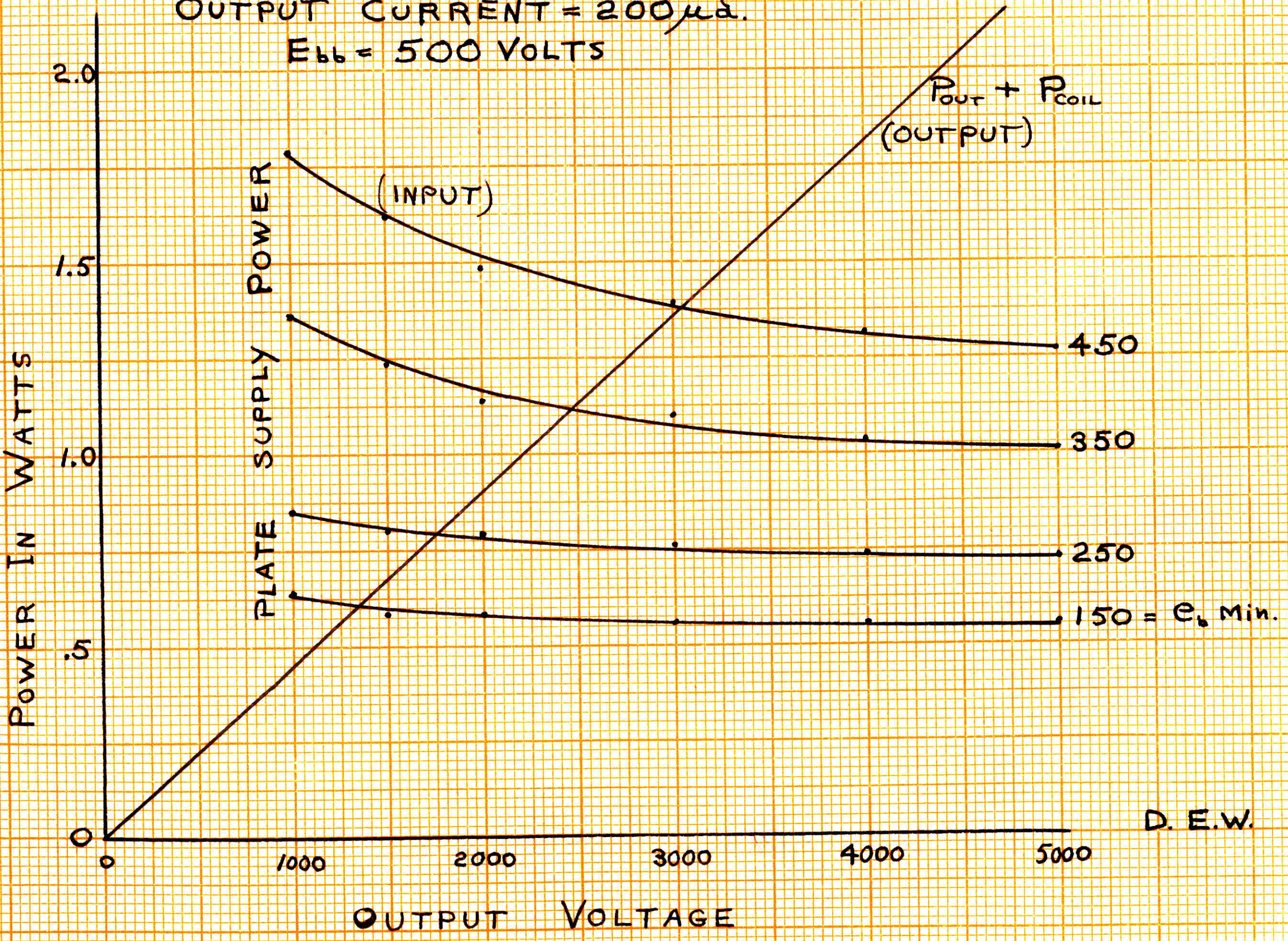


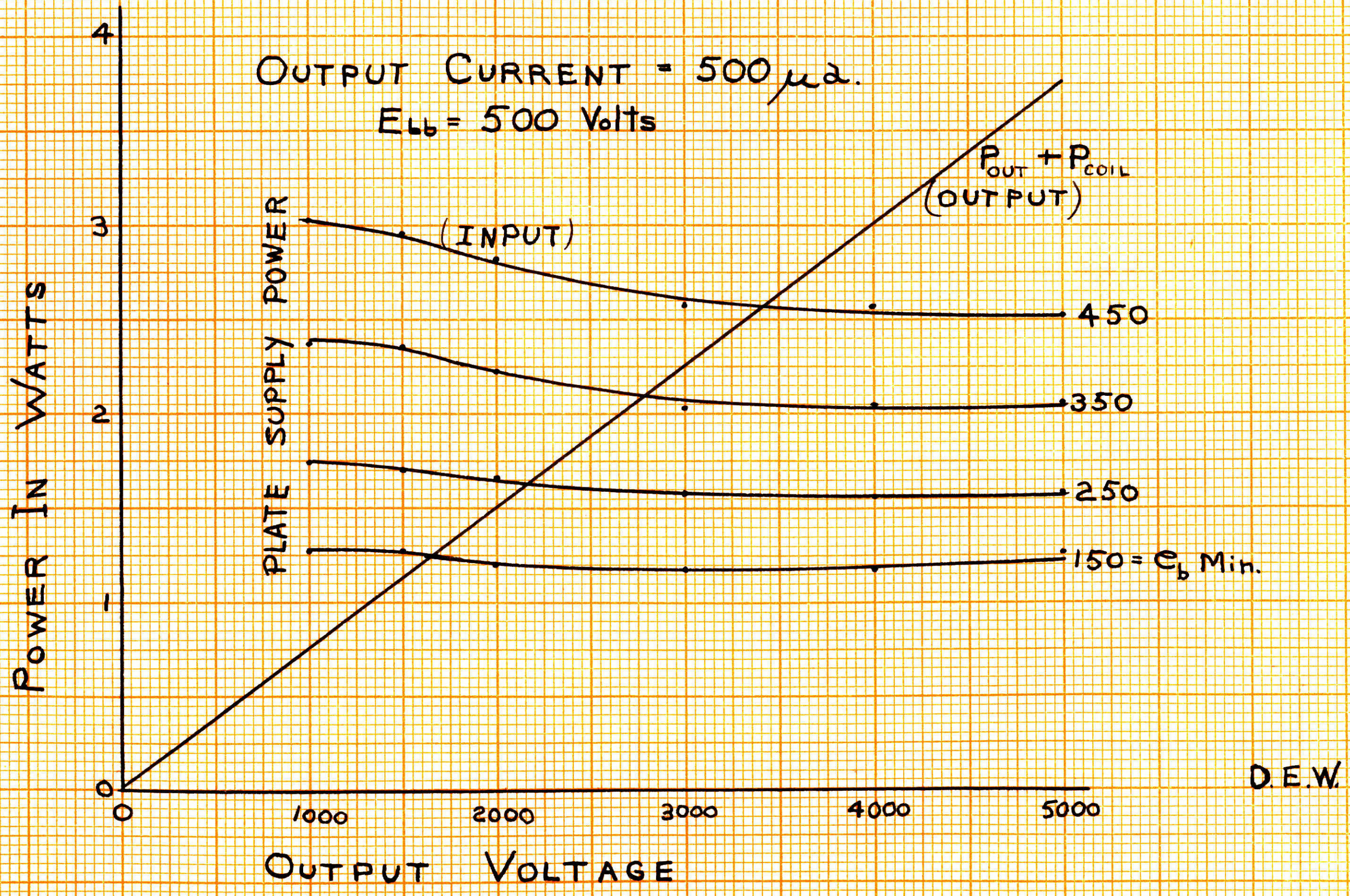
PLATE CURRENT AS A FUNCTION OF GRID VOLTAGE
TYPE 3C24 TUBE

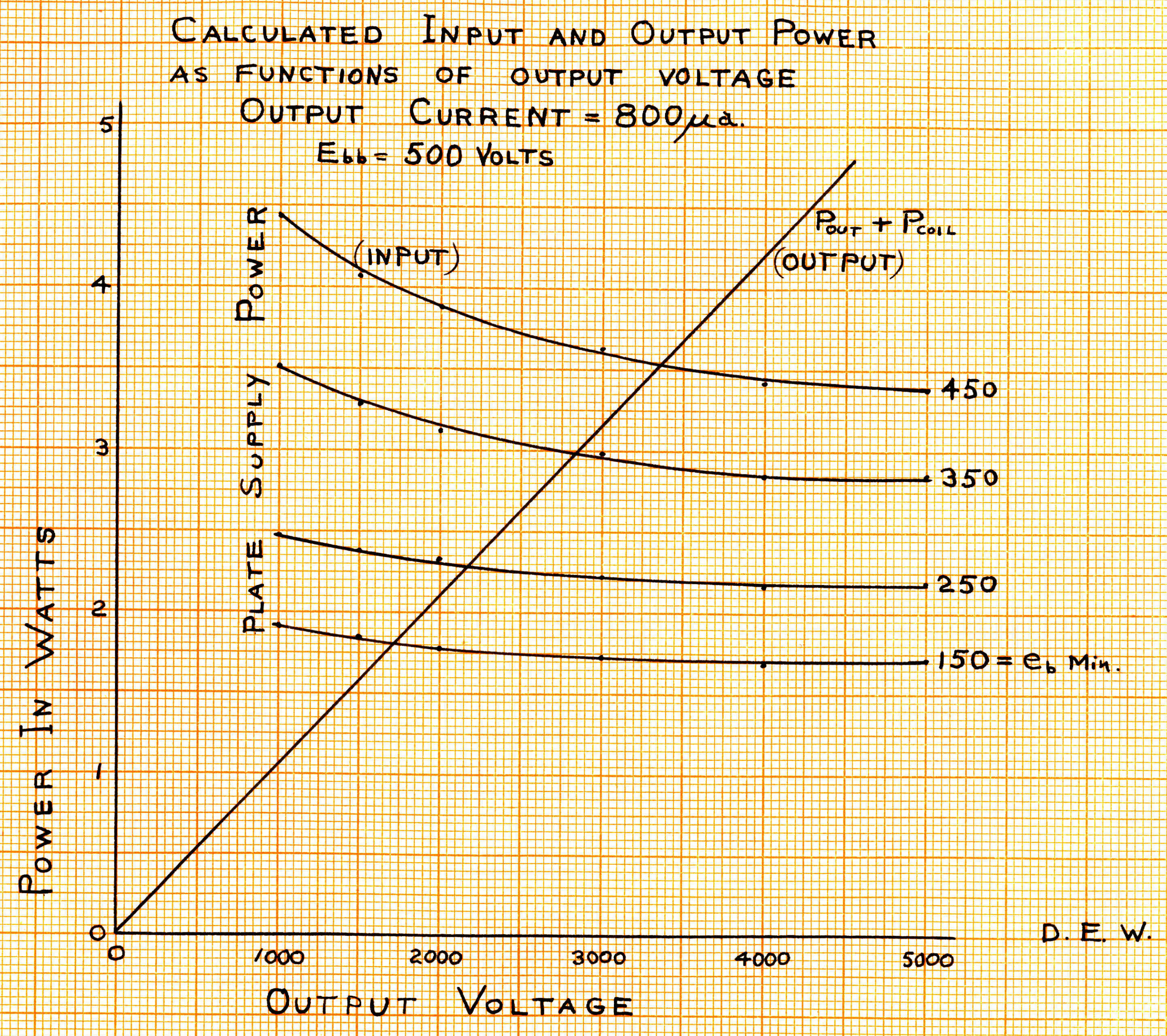
D.E.W.

CALCULATED INPUT AND OUTPUT POWER
AS FUNCTIONS OF OUTPUT VOLTAGE
OUTPUT CURRENT = 200 μa.
E_{bb} = 500 VOLTS



CALCULATED INPUT AND OUTPUT POWER AS FUNCTIONS OF OUTPUT VOLTAGE





CALCULATED INPUT AND OUTPUT POWER
AS FUNCTIONS OF OUTPUT VOLTAGE
OUTPUT CURRENT = 800 μa.
E_{bb} = 500 VOLTS

Data Tabulated From Graphical Integrations

Type 3C24 Tube

200 Microamperes Output Current

Output Voltage	Min. Plate Voltage	Max. Grid Voltage	Max. Plate Current (Ma)	Ave. Plate Current (Ma)
1,000	150	17	34	1.27
	250	18	43	1.70
	350	19	59	2.72
	450	19.5	74	3.56
1,500	150	19.5	38	1.15
	250	21	50	1.60
	350	22	67	2.45
	450	22.5	81	3.24
2,000	150	21.5	43	1.15
	250	23	54	1.58
	350	24	71	2.28
	450	24.5	87	2.96
3,000	150	23.5	47	1.11
	250	25.5	60	1.52
	350	27	78	2.19
	450	27.5	96	2.78
4,000	150	25	50	1.11
	250	27	63	1.48
	350	28	81	2.06
	450	28.5	100	2.63
5,000	150	27	54	1.11
	250	29	66	1.44
	350	30.5	88	2.02
	450	31	107	2.54

500 Microamperes Output Current

1,000	150	28	57	2.51
	250	31	72	3.48
	350	32	93	4.73
	450	33	115	6.05
1,500	150	33	67	2.51
	250	36	84	3.40
	350	38	112	4.70
	450	38.5	131	5.91
2,000	150	35	71	2.39
	250	38	90	3.32
	350	40	118	4.43
	450	41	140	5.64

Output Voltage	Min. Plate Voltage	Max. Grid Voltage	Max. Plate Current (Ma)	Ave. Plate Current (Ma)
3,000	150	39	82	2.35
	250	42	101	3.16
	350	44	129	4.07
	450	45	152	5.18
4,000	150	42	89	2.39
	250	45	111	3.12
	350	48	143	4.10
	450	49	167	5.13
5,000	150	46	102	2.51
	250	49	122	3.16
	350	51	152	4.12
	450	52	177	5.04
	800 Microamperes Output Current			
1,000	150	37	76	3.82
	250	40	96	4.96
	350	43	126	7.02
	450	44	150	8.88
1,500	150	42	90	3.70
	250	45	110	4.76
	350	48	142	6.57
	450	49	167	8.13
2,000	150	45.5	100	3.55
	250	48.5	121	4.68
	350	51	151	6.22
	450	52	179	7.75
3,000	150	50	112	3.46
	250	53	133	4.43
	350	56	168	5.96
	450	57	195	7.25
4,000	150	53	121	3.38
	250	56	143	4.31
	350	59	180	5.70
	450	60	202	6.84
5,000	150	56	129	3.42
	250	60	156	4.38
	350	63	190	5.70
	450	64	219	6.75

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