R. H. Newman
(94)

PBM PBM
WHB WB
JMS
CWH
PSS PSS
RHBE RHB
GLC

GENERAL ELECTRIC
COMPANY
SCHENECTADY, N. Y., U. S. A.

DATA FOLDER No. 77886
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Title METHODS OF CALCULATING OPTIMUM TUBE OPERATING CONDITIONS

By

Electronic Tube Engineering Div.

Information prepared for

Tests made by

Information prepared by H. L. Thorson

Countersigned by K. C. DeWalt

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METHODS OF CALCULATING OPTIMUM TUBE OPERATING CONDITIONS

In order to make optimum adjustment of transmitting tube operating conditions, it is necessary to visualize clearly the effect on tube operation, and hence on circuit output, of varying grid bias voltage, grid drive, plate voltage, and plate circuit impedance.

A complete sample set of calculations will be made for the various classes of operation, for the GL-889A. All of the work is based on use of the "constant-current" curves, and experience has shown that the results so obtained correlate closely with actual operating test results.

Several sets of calculations should be made for any particular class of operation to be sure that the optimum conditions are met as far as plate efficiency and grid drive are concerned. Operating conditions should be chosen so as to always fall within the maximum ratings..

CLASS C AMPLIFIER AND OSCILLATOR

Certain conditions of operation are arbitrarily assigned, as follows:

1. DC plate voltage equal 7500 volts
2. Grid bias voltage equal -800 volts
3. Peak grid voltage swing equal 1800 volts
4. Plate voltage swing equal 6,000 volts

All of the above values may be obtained in practice by applying them directly and by varying the grid drive or load impedance.

Referring to Fig. 1, the first step is to determine the operating line A-A', as established by the four assigned conditions of operation. The point "A" is determined by the DC plate voltage and grid bias voltage. As the plate voltage swings down and the grid voltage rises in sinusoidal fashion, their instantaneous values describe a straight line, terminated at A'. The point A' is automatically determined, having chosen "A" as the starting point and having previously determined the amplitude of grid and plate voltage swing.

The point "A" is set at a point corresponding to a plate voltage of 7500 volts and grid bias of -800 volts. With a grid swing of 1,800 volts and a plate swing of 6000 volts, the point A' is located at a grid voltage of 1000 volts and a plate voltage of 1500 volts. Thus the operating line A-A' is determined.

The rest of the work is simply mechanical integration. The instantaneous values of plate voltage and current, and grid voltage and current are tabulated as in Fig. 2. By simple relations indicated in Fig. 2, the operating conditions are completely determined.

By going through this set of calculations, it is possible to determine;

1. DC plate input kw
2. Plate output kw
3. Plate efficiency
4. Grid excitation power
5. Grid bias loss
6. DC grid current

It will be found that the location of the point A' affects the tube operation very greatly since a small change in its position changes the working range in the high grid current and plate current region.

A few sets of calculations will indicate the optimum operating conditions for the installation under consideration. By referring to Fig. 3, a general idea may be gained as to the relation of the various factors involved.

CLASS C R-F POWER AMPLIFIER-PLATE MODULATED

The operation of a tube under plate modulation conditions may be analyzed in a manner similar to that for a class C oscillator, unmodulated. In this type of service, operating conditions are specified for carrier conditions. Modulation is applied by superimposing the signal voltage on the applied DC plate potential. 100% modulation means that the applied plate potential varies from zero to twice the DC applied voltage, throughout the audio cycle, as shown in Fig. 4.

In establishing the operating lines for plate modulated service, the carrier conditions are determined. It will be noted that the maximum anode dissipation for carrier conditions is less than that for Class C oscillator rating. This must be so since when 100% modulation is applied, the plate input, and plate dissipation increase 50%, the additional plate input being supplied by the modulator.

When establishing the operating line for carrier conditions, it must be borne in mind that a second line must be drawn for conditions obtained at double the DC plate voltage. This second line corresponds to the conditions under which the tube is operating, at the peak of the modulating voltage. Certain relations, as enumerated below must exist between these two lines, in order that the output be free from distortion.

THIRD ANGLE PROJECTION

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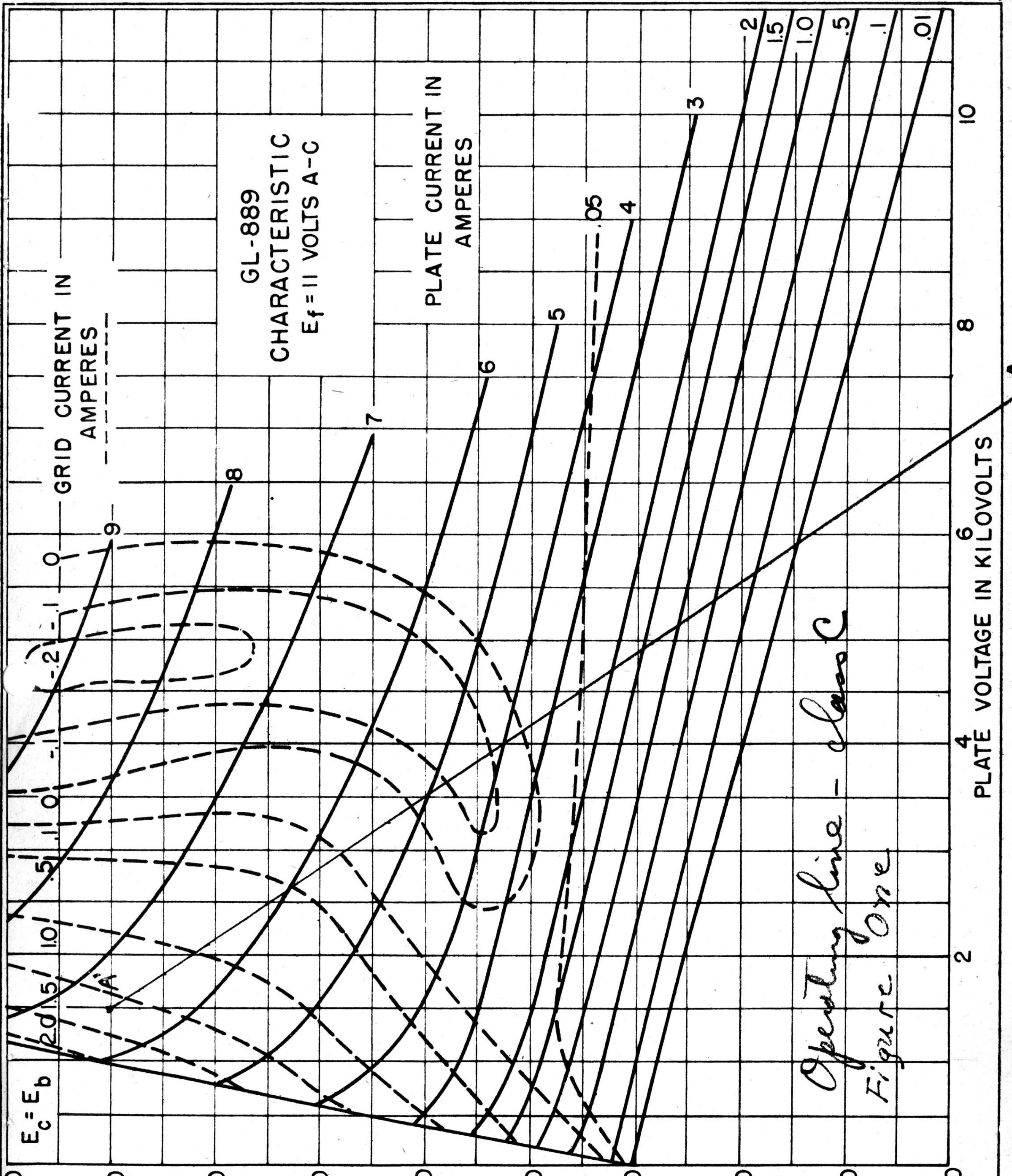

Figure One

1 SEPT-26-44 B Bishop JK-2845

REVISIONS

MADE BY D.BURRETT JUNE 23,1943

RE
INSPECTED BY SEPT-26-44

JJ-7206

VT 2
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TYPE GL-889 CALCULATION OF TYPICAL OPERATING CONDITIONS BY ________ DATE ________

Telegraph
CLASS C ~~AMPLIFIER~~ SERVICE

Angle Degrees	Sine	e_p Volts	i_p Amps.	Prod. Sine Amps.	e_g Volts	i_g Amps.	Prod. Sine Amps.
0	0	7500		--	-800		--
5	.087	7000					
15	.258	5900					
25	.423	5000	1.25	.529			
35	.574	4100	3.80	2.18		.020	.0115
45	.707	3300	5.20	3.68		.02	.0141
55	.819	2600	6.0	4.91		.50	.409
65	.906	2100	6.4	5.80		.90	.815
75	.966	1700	6.5	6.28		1.25	1.208
85	.996	1500	6.5	6.48		1.70	1.692
90	1.00	1500	(*)	--		(*)	--
5-85 Incl. ______		Summation Divide By	35.65 18	29.85 18		4.350 18	4.126 18
Average Current ______		Ib =	1.98	1.66	(Ig) =	.242	.229

0° ________ Eb = 7500 ________ Ec = -800

90° ________ ep = 1500 ________ eg = 1000

Difference (Swing) 6000 (Swing) 1800

Plate Input = Eb x Ib = 7500 1.98 = 14.85

Plate Output = Plate Swing x Average Product Sine Amps. =6000 x 1.66 = 9.95

Efficiency = $\frac{\text{Output}}{\text{Input}} = \frac{9.95}{14.85}$ = 670

Total Grid Excitation Power = Grid Swing x Avg. Product Sine Amps.= 1800 x .229 = 410.

or Total Grid Excitation Power = (approx.) Grid Swing x Ig = 1800 x .242 = 435

Grid Bias Loss = Ig x Ec = 800 x .242 = 193

* Peak value - for reference only - omit from calculation of avg. currents.

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Fig. 2

MADE BY H A Wheeler
JK 7800
INSPECTED BY.: JAN-2-46 AF

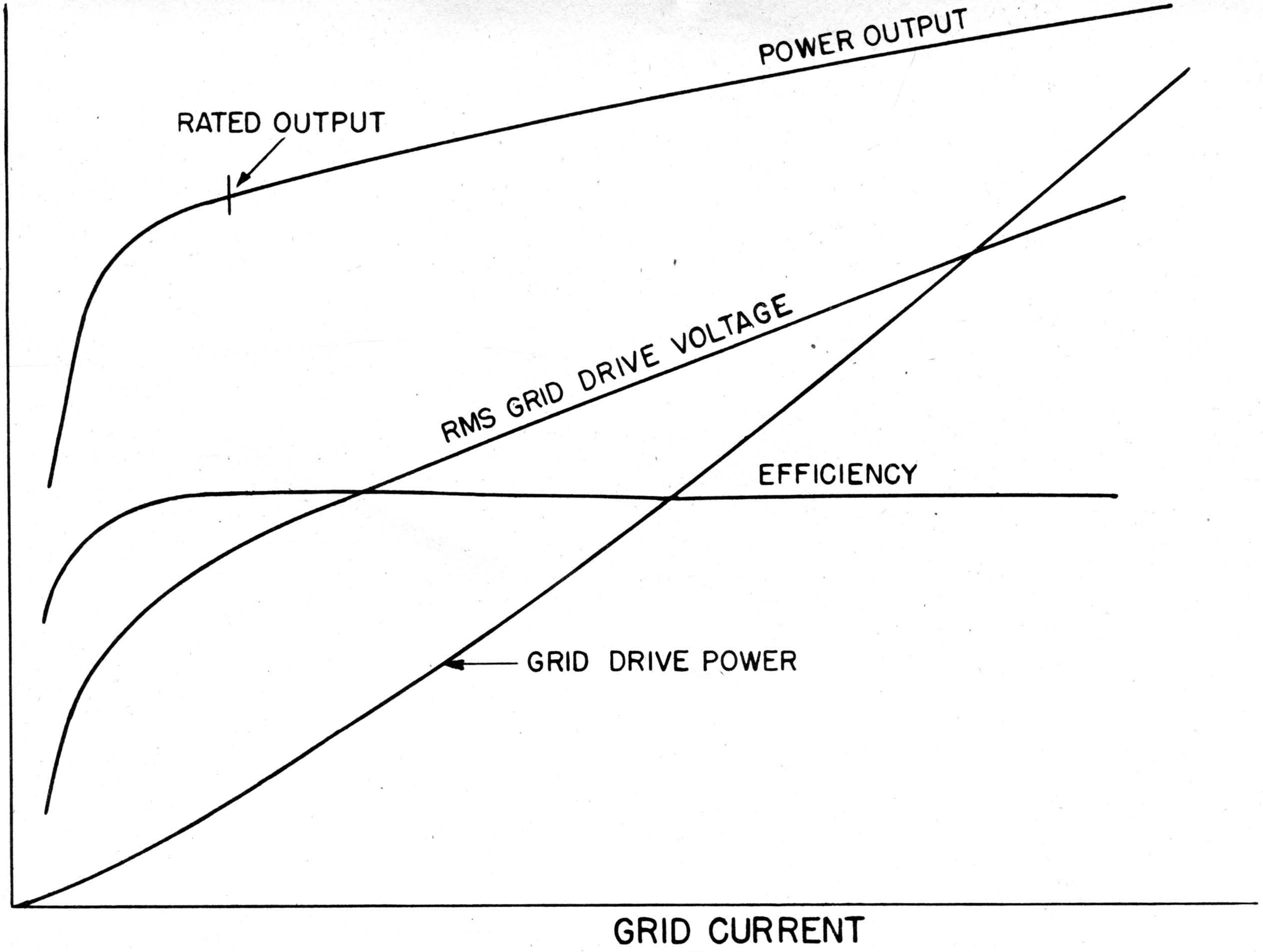


FIG. 9

PERFORMANCE CURVES FOR CLASS C AMPLIFIER AND OSCILLATOR 9' 7'

Figure 3

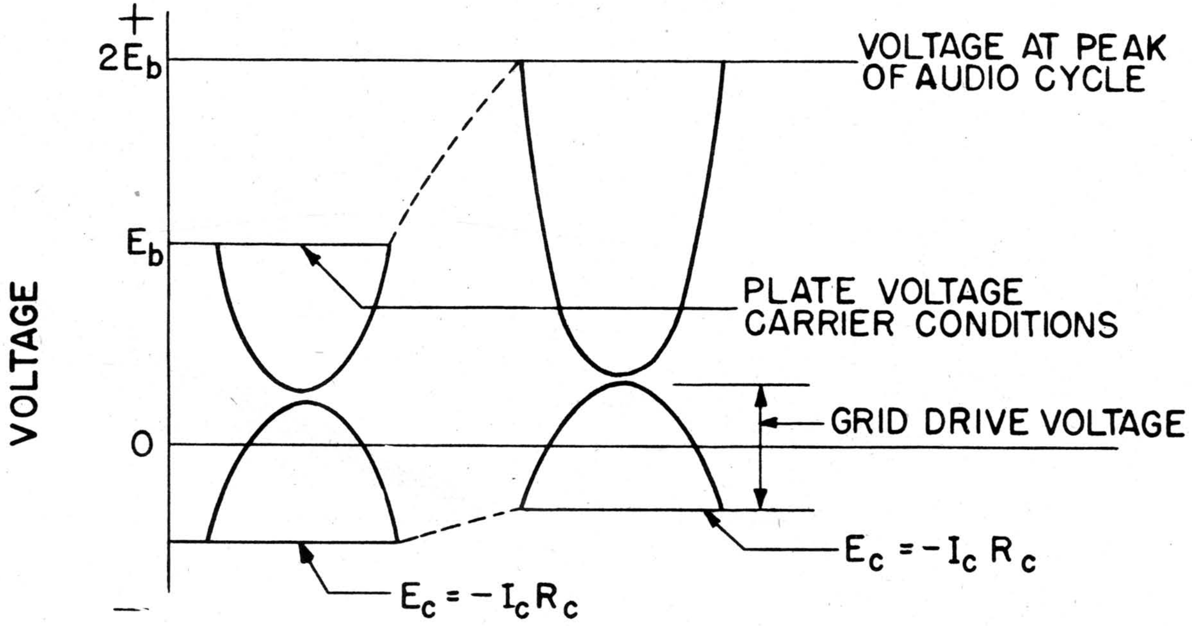


FIG. 10
WAVE SHAPES SHOWING PLATE VOLTAGE VARIATION

MADE BY Wheeler, H.A.
JK 7805
INSPECTED BY: JAN-2-46 AP

9'
7'

Figure 4

1) If the modulation is to be free from distortion, a linear relation must exist between the RF voltage and current. Therefore, for 100% modulation, at the peak of the modulation cycle, the RF voltage and current must be double that of the carrier condition, while at the other extreme of the modulation cycle the RF voltage and current are zero.

2) The operating line for the peak of the modulation cycle must be drawn so that the load impedance will be the same as for the operating line at carrier conditions.

3) It will be found upon examination of the constant current curves that in order to double the current, at double the voltage when operating at the peak of the audio cycle, it will be necessary to work to rather high peak currents. This will require that the grid be driven to a considerably higher positive peak than for the carrier conditions. It is not generally desirable to modulate the grid drive, but the higher positive grid drive may be accomplished in practice by two factors. If a combination fixed and grid resistor bias is used, the bias voltage developed will be reduced at the peak of the audio cycle. This will be true since the minimum plate voltage on this operating line is higher than for the carrier operating line, which results in working the tube in a lower grid current region. This reduces the grid current, and hence the bias voltage. Thus with constant grid excitation, the positive grid voltage peak will be raised by the amount of reduced grid bias. In actual practice, with reduced loading of the grid excitation supply, the grid drive voltage will increase to some extent, thus further increasing the positive peak grid voltage.

CLASS B AUDIO AMPLIFIER

Operating conditions will be examined, and calculations will be made for a two tube push-pull amplifier, since this is the type of circuit generally encountered in this class of service.

The applied conditions of operation must first be determined as follows:

1) The DC plate voltage is arbitrarily assigned to be 7,500 volts.

2) The plate current is to be chosen for zero signal input.

Fig. 5 represents a composite plate characteristic curve for two tubes[1]. Use of this curve clarifies the analysis which is complicated by the fact that the plate current of the two tubes both act on a common magnetic circuit in the output transformer. The composite curve is formed by placing two sets of static plate characteristic curves back to back as indicated in the figure.

Since the plate currents for the two tubes act through the output transformer in opposite directions, only their differences contribute to useful output. Therefore, the dotted lines indicate useful composite plate characteristics for the two tubes, the grid voltage lines now corresponding to signal voltages.

The output operating line is shown as X-Y. The individual tube operating lines are YAB and XCD.

The individual tube operating lines of figure 5 are based on a zero signal plate current of .2 ampere. In general a value of 10 to 15% of the average plate current is used. If too high a value of zero signal current is used, the distortion, and plate dissipation are excessive.

3) The grid bias voltage is established, since a DC plate voltage of 7,500 volts, and a zero signal plate current of 0.2 ampere has been chosen for this set of calculations. From the plate current curves, this would require -300 volts bias.

4) Assume a peak positive grid voltage of 550 volts. This is an arbitrary value, and may be applied by a suitable driving stage. The peak grid swing is then 850 volts. If too high a value of positive grid voltage is chosen, the driving power will be greatly increased with little increase in power output.

5) For this set of calculations a plate voltage swing of 6,000 volts will be used. This again is an arbitrary value, and ordinarily is approximately 80% of the D.C. plate voltage. If too low a minimum plate voltage dip is used, excessive distortion and grid drive will result. If too high a minimum plate voltage dip is used, plate efficiency is sacrificed. The value of the load impedance in the plate output circuit to give this swing will be determined from the ratio of the plate voltage swing to the peak plate current as determined later, in the calculations.

Summarizing the above, the following conditions of operation have been established thus far:

1) DC plate voltage = 7,500 volts

2) Grid bias voltage = -300 volts

3) Peak grid voltage swing = 850 volts - This results in a maximum positive grid voltage of 550 volts, at maximum signal.

4) Peak plate voltage swing = 6,000 volts - This results in a minimum plate voltage dip of 1,500 volts at maximum signal.

1. April 1933, IRE, pg. 591 "Push-Pull Audio Amplifier" by B.J. Thompson

The above conditions completely determine the operating line X-Y Fig. 5.

Efficient operating conditions for class B audio amplifiers normally result in some distortion. This can be tolerated since the even order harmonics are eliminated from the output in the push-pull amplifier. However, this makes it impossible to draw a straight operating line between points A and B, Fig. 4, as was done in the case of the class C amplifier, for calculation of operating conditions. However, items 1 through 4 above do define the extreme points of grid and plate voltage and current excursions, as shown by points "X" and "Y", Fig. 5, and "A" and "B", Fig. 6.

Reference is now made to Fig. 5. The load line X-Y must be straight, since the load current must vary directly with the plate voltage, the load impedance being constant. Working from Fig. 5, the operating line A-B Fig. 6 is laid out so that the grid voltage for any value of plate voltage corresponds on the two curves. For example, on figure 5, for a grid voltage of plus 300 the plate voltage is 2,700. This then determined one of the points, "P" along which the curve A-B, Fig. 6, was to lie. Having laid out the operating line A-B, Fig. 6, it remains to calculate the tube operation, as shown in Fig. 7.

Complete tube performance may thus be determined for the chosen set of conditions, as follows:

1) DC plate input kw (per tube)
2) Plate output kw (per tube)
3) Plate Dissipation
4) Plate efficiency
5) Grid excitation power
6) Load resistance - plate to plate
7) DC grid current
8) Grid bias loss

All of the above results are for maximum signal operation. The maximum anode dissipation, however, will be found to occur at a signal less than unity, approximately at $S = \frac{2}{K\pi}$, where:

K = ratio of plate voltage swing to the DC plate voltage, at maximum signal, S=1.

S = ratio of the signal under consideration (grid swing), to the maximum signal, as used in the sample calculation.

Thus for the conditions of operation chosen for the sample calculation, the signal for maximum anode dissipation is determined as follows:

$$K = \frac{6,000}{7,500} = .80$$

$$S = \frac{2}{.8 \times 3.14} = .794$$

The maximum signal grid swing (S = 1), in the example, Fig. 7, was 850 volts. For "S" equal .794, the grid swing will be 675 volts, with a maximum positive grid voltage peak of 375 volts. The operating line for S = .794 is then A-C, Fig. 6. Carrying through calculations for this operating line, similar to those on Fig. 7, it will be found that that anode dissipation is 4.42 kw. Since this value is within the rated anode dissipation of the tube, the conditions chosen for operating line A-B are satisfactory.

If the operating line A-B, Fig. 6, deviates greatly from a straight line, it is an indication that distortion is present, and the output should be checked for harmonic content.

CLASS B RADIO FREQUENCY POWER AMPLIFIER

In class B radio frequency amplifier service, the R.F. current and voltage relations are as indicated in Fig. 8.

If the amplifier output is free from distortion, the plate voltage and plate current will vary linearly with the grid swing. Thus for a maximum modulation factor of 1.0, at the crest of the audio cycle the R.F. voltage and currents will be double those for the carrier conditions.

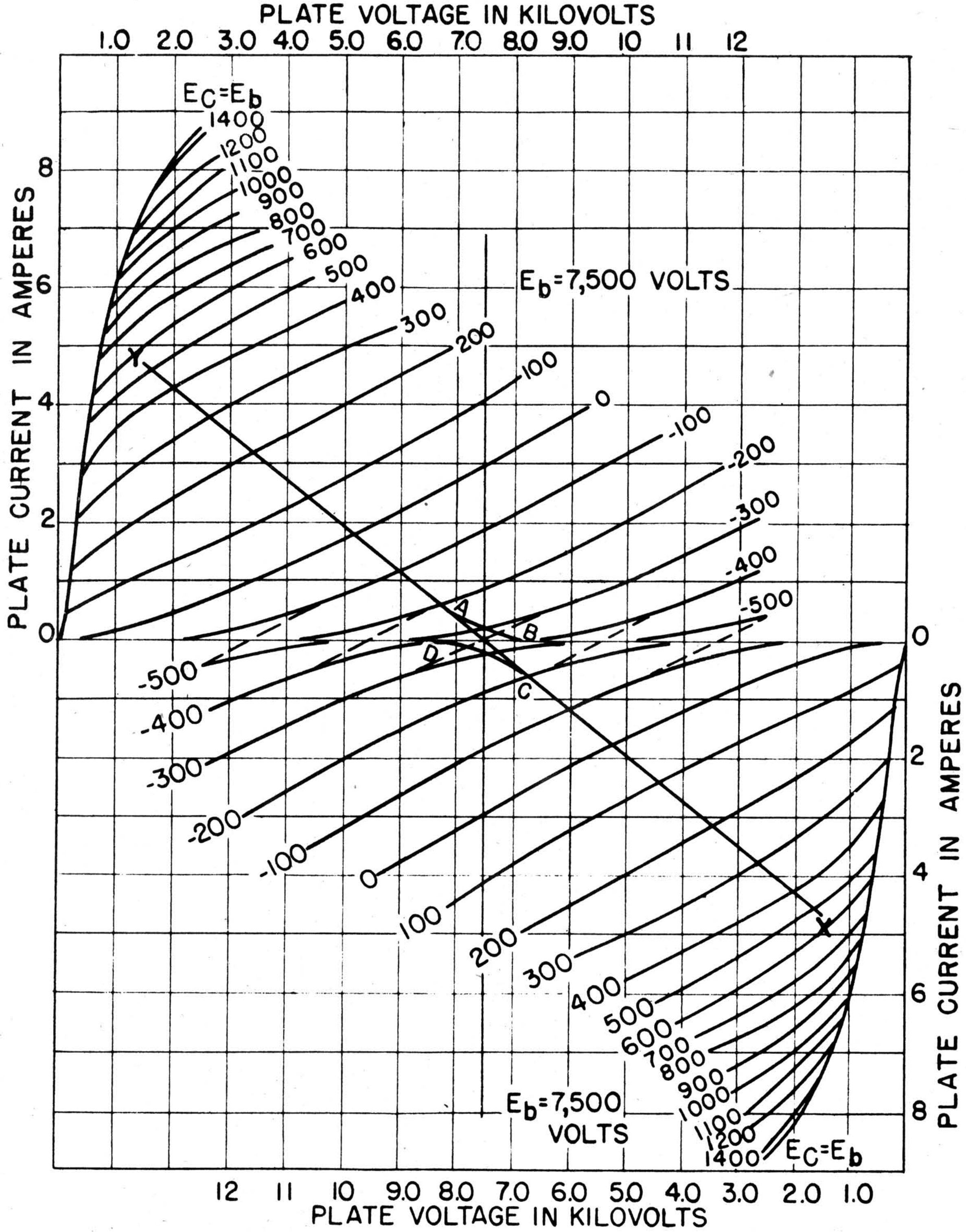
In calculating the performance of the class B, RF amplifier, the operating line AB, Fig. 9, must be established by the following steps;

1) Point A depends upon the value of DC plate voltage and grid bias chosen. The higher the plate voltage the greater the power capabilities of the tube. The grid bias voltage is such as to allow a zero signal plate current of 10 to 15% of the average DC plate current under carrier conditions. The same factors apply as explained under class B audio service. In the curve, Fig. 9, the point A is located at a plate voltage of 7,500 volts, and a grid voltage of-300 volts.

2) The location of point B depends upon a number of considerations. If it approaches too close to the diode line, the grid drive, and distortion are likely to become excessive for maximum modulation.

GL-889-A

COMPOSITE PLATE CHARACTERISTICS FOR COMBINED TUBES AND TRANSFORMER
CLASS B AUDIO SERVICE



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INSPECTED BY DEC-11-45
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Figure 5

THIRD ANGLE PROJECTION

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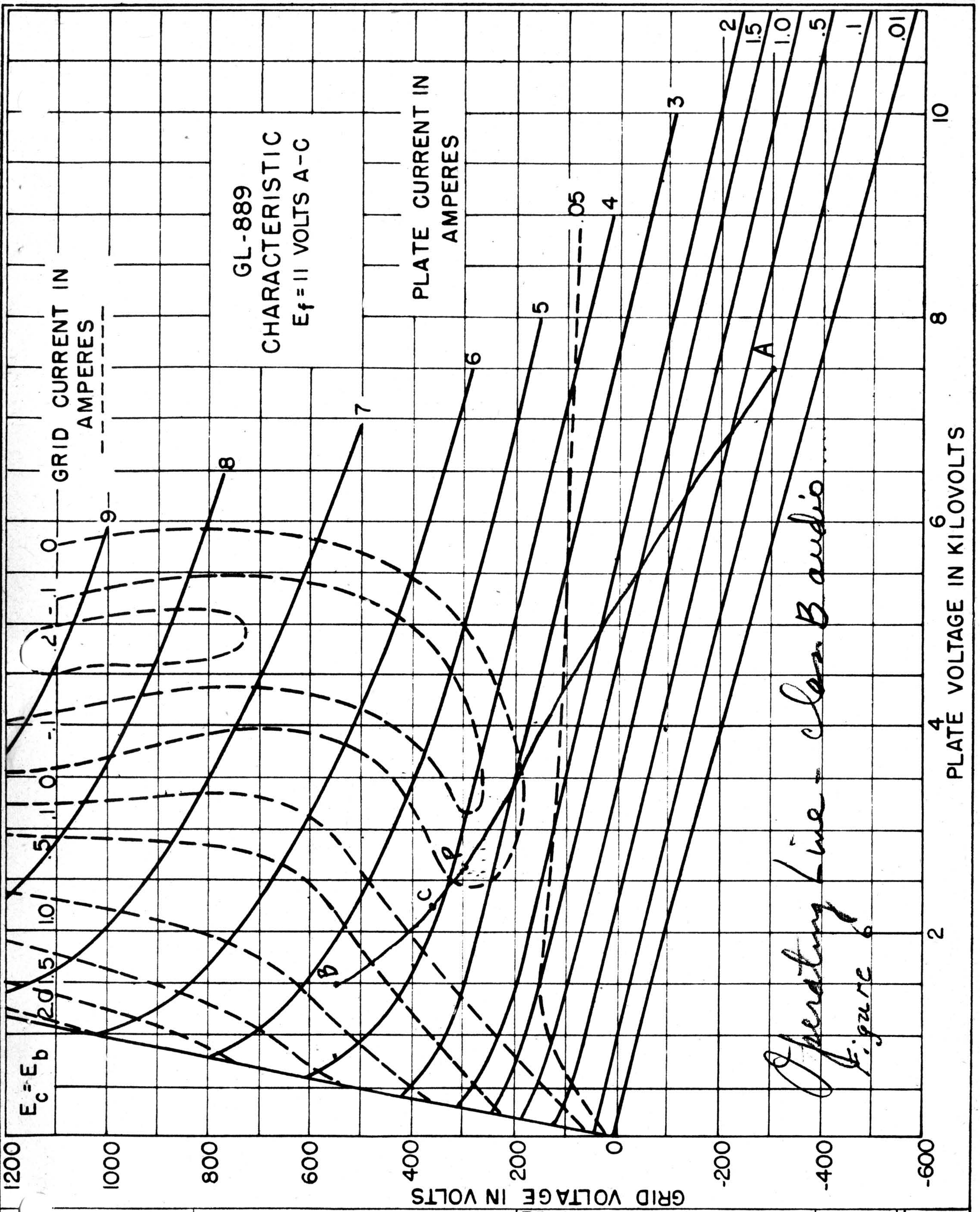

1 SEPT-26-44 B.Bishop JK-2845	MADE BY D.BURRETT JUNE 23,1943	RE INSPECTED BY SEPT-26-44	JJ-7206
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TYPE GL-889A CALCULATION OF TYPICAL OPERATING CONDITIONS BY ________ DATE ________

B Audio
CLASS ~~C~~ AMPLIFIER SERVICE

Angle Degrees	Sine	ep Volts	Plate Swing Volts	ip Amps.	Prod. ~~Sine Amps.~~ Plate Swing & ip	eg Volts	ig Amps.	Prod. Sine Amps.
0	0	7,500			--	-300		--
5	.087	7,000	500	.5	250	-226		
15	.258	5,900	1,600	1.3	2,080	- 81		
25	.423	4,800	2,700	2.1	5,670	+ 59	.05	.021
35	.574	3,700	3,800	2.95	11,200	187		
45	.707	2,700	4,800	3.8	18,250	300		
55	.819	2,100	5,400	4.2	22,700	395	.10	.082
65	.906	1,800	5,700	4.5	25,700	470	.40	.362
75	.966	1,600	5,900	4.6	27,100	520	.70	.676
85	.996	1,500	6,000	4.7	28,200	547	.75	.746
90	1.00	1,500		(*)	--	550	(*)	--

		ip Amps.	Prod. Plate Swing & ip	eg Volts	ig Amps.	Prod. Sine Amps.
5-85 Incl.	Summation Divide By	28.65 18	141,150 18		2.00 18	1.887 18
Average Current	Ib =	1.59		(Ig) =	.111	.105

0° Eb = 7,500 Ec = -300

90° ep = 1,500 eg = 550

Difference (Swing) 6,000 (Swing) 850

Plate Input = Eb x Ib = 7,500 x 1.59 = 11.92 kw

Plate Output = ~~Plate Swing x Average Product Sine Amps.~~ = 1$ $\frac{141,150}{18}$ = 7.83 kw

Plate Dissipation = Plate Input - Plate Output 4.09 kw

Efficiency = $\frac{\text{Output}}{\text{Input}}$ = $\frac{7.83}{11.92}$ = 65.6%

Total Grid Excitation Power = Grid Swing (850) x Avg. Product Sine Amps. (.105) = = 89.2 watts

~~[illegible]~~ =

Grid Bias Loss = Ig x Ec = .111 x 300 = 33 watts

* Peak value - for reference only - omit from calculation of avg. currents.

Load Resistance = $\frac{\text{Peak plate voltage swing}}{\text{Peak plate current}}$ = $\frac{6000}{4.7}$

= 1276 ohms

Effective load, plate to plate = 4 x 1276 = 5100 ohms

H-5172866

FIG. 7

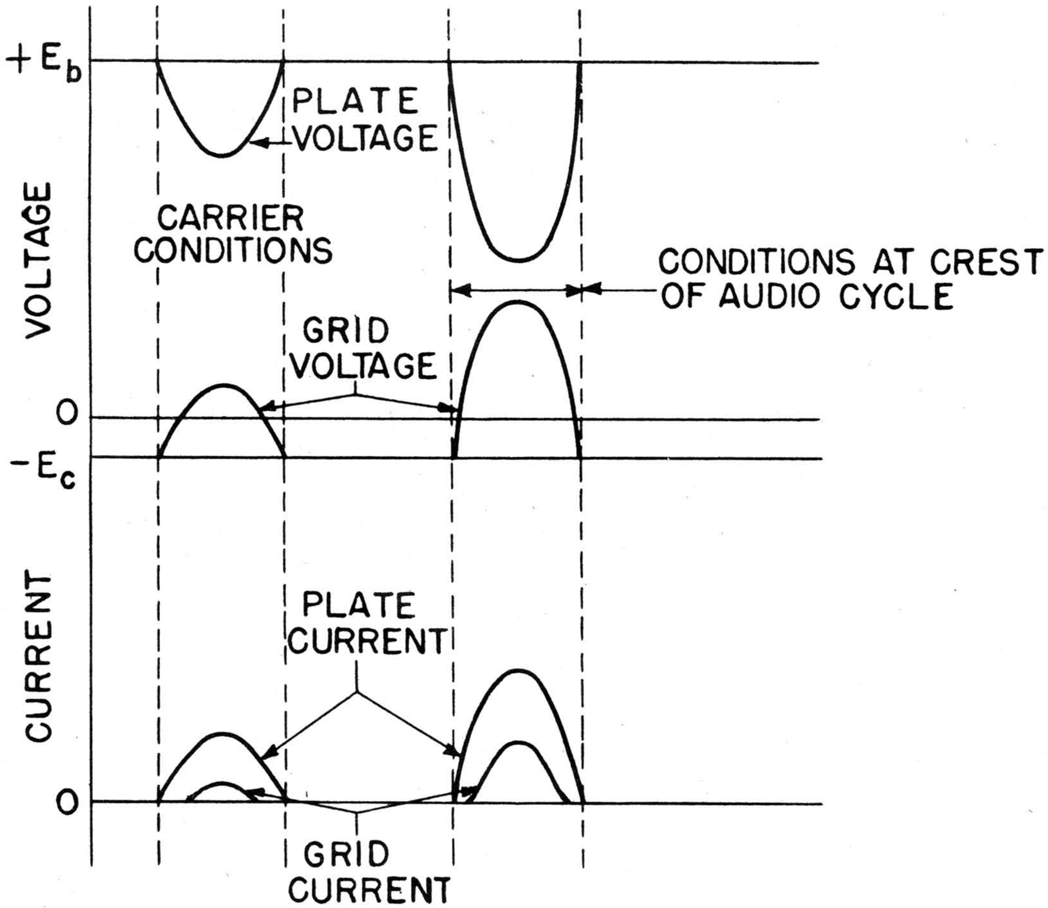

FIG. 14

INSTANTANEOUS R-F VOLTAGE AND CURRENT RELATIONS

MADE BY William Wheeler
JK 7800
INSPECTED BY: JAN-3-46 AP

9'
7'

Figure 8

If "B" is located too high in the positive grid region, the grid drive would be increased at maximum modulation. It is usually necessary to make several sets of calculations to determine the optimum conditions for minimum distortion at the desired power output, and maximum efficiency. Taking the above factors into account, the point B for the curve on Fig. 9, was located at a plate voltage of 2,500 volts and a grid voltage of +700 volts.

As in the case of the class C oscillator the operating line on Fig. 9, is a straight line connecting points "A" and "B".

Calculations for maximum modulation conditions will then be identical to those described for class C operation, operating over the entire line from A to B.

Under carrier conditions, the tube operates over the same line, but the grid and plate swing are only one half that for maximum modulation. Therefore, for carrier conditions similar calculations are made to those for maximum modulation, but the operating line extends only from A to C. Maximum plate dissipation occurs under carrier conditions, so the value of dissipation calculated should be checked to see that the maximum ratings are not exceeded.

It is advisable to plot the plate current versus the grid voltage for the conditions chosen for maximum modulation, and to analyze the current wave for excessive distortion. This curve may be plotted from points on the operating line AB, Fig. 9.

CLASS A AMPLIFIER CALCULATIONS FOR RESISTANCE LOADS

Examples of calculations for the other classes of service will be for the GL-889A. However, that tube was not designed for class A operation. Tube applications do not generally require that a tube of high power rating be operated under class A conditions, since in large tubes operating efficiency becomes an important factor, and the more efficient class B linear service is resorted to. Therefore, the sample calculations on class A operation will be made for the GL-845.

Referring to Fig. 10, it is first necessary to draw the load line A-B about the operating point "O". The following factors should be considered in locating the operating line:

1) The point "O" must be located so that the product of the plate current and plate voltage at that location does not exceed the maximum rated anode dissipation.

THIRD ANGLE PROJECTION

K-8074637

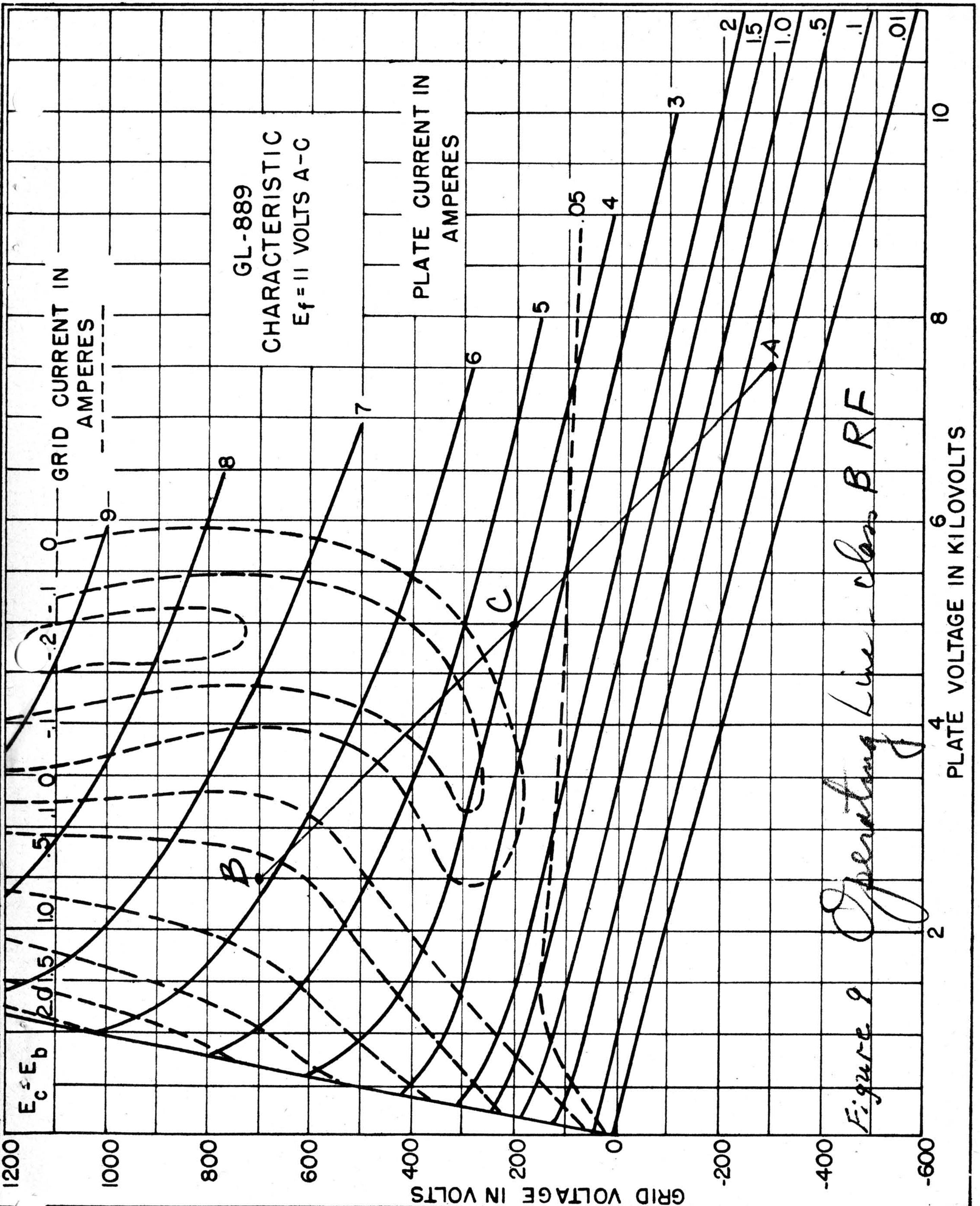

Figure 8 Operating Line Class B RF

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2) The position of point "O" on a proposed operating line must be such that the grid swing does not go past the zero bias curve, as shown at "A". At the extreme negative grid swing, point "B", operation should not extend appreciably into the non-linear portion of the curves. In general, point "B" should not be below 10 to 15% of the plate current at point "O". The grid swing from "O" to "A" is equal to the grid swing from "O" to "B".

3) In the calculations it will be shown that the power output is proportional to the product of the total plate current and plate voltage change when operating over the load line from "A" to "B". It is thus apparent that lowering the point "O" would reduce the possible plate current swing and therefore the power output. To raise it, would cause the anode dissipation rating to be exceeded, as explained above.

Having thus located the line A-B, Fig. 10, it is possible to calculate specific conditions of tube operation, as follows:

1) Power output $= \frac{(E_{max} - E_{min})(I_{max} - I_{min})}{8}$

From Fig. 1:
E_{max} = plate voltage at B = 2030 volts
E_{min} = plate voltage at A = 380 volts
I_{max} = plate current at A = .159 amperes
I_{min} = plate current at B = .010 amperes
Power output $= \frac{(2030-380)(.159-.010)}{8}$
$= 30.6$ watts

2) Plate dissipation is the product of the plate current and the plate voltage at operating point "O".

Plate dissipation, from figure 1 = .080 x 1250 = 100 watts

3) Required load resistance is equal to the ratio of the plate voltage change to the plate current change, on the load line A-B. From Fig. 10, the load resistance is calculated as follows:

Plate current at "A" = 159 ma
Plate current at "O" = 80 ma
Plate voltage at "A" = 380 volts
Plate voltage at "O" = 1250 volts
$R_L = \frac{1250 - 380}{159 - 80} = 11{,}000$ ohms

4) The D-C plate current will be equal to the value of plate current at the point "O", or from Fig. 10, this value is 80 ma.

5) Some distortion is always present due to non-linearity. This distortion is comprised almost entirely of a second harmonic. The allowable percentage of second harmonic is generally specified as 5 percent maximum and may be calculated from the following relation:

$$\% \text{ 2nd harmonic} = \frac{\frac{1}{2}(I_{max} + I_{min}) - I_o}{I_{max} - I_{min}} \times 100$$

where, referring to Fig. 1:

I_{max} = plate current at "A" = 159 ma.

I_{min} = plate current at "B" = 10 ma.

I_o = plate current at "O" = 80 ma.

then percent second harmonic is:

$$\frac{\frac{1}{2}(159 + 10) - 80}{159 - 10} \times 100 = 2.8\%$$

The above calculations set up conditions of operation which would deliver the maximum power possible, yet not exceeding any of the maximum ratings of the tube. Several sets of calculations may be required to obtain the optimum operating conditions to fulfill other special requirements, such as operation at reduced power output, reduced plate voltage, different load impedance or combinations of the above.

H. L. Thorson

H. L. Thorson
ENGINEERING
TUBE DIVISION

1-2-46

Countersigned:
KCDeWalt
Jan 3, 1946

(KC DeWalt
(OW Pike
(AC Gable
WB Gillen
JH Campbell
RW Newman ✓
TA Elder