

## APPLICATION BULLETIN #5

### TUBE PERFORMANCE COMPUTER FOR R-F AMPLIFIERS (CLASS B, C, AND FREQUENCY MULTIPLIERS)

It is quite easy to make a close estimate of the performance of a vacuum tube in radio-frequency power-amplifier service, or an approximation for harmonic-amplifier service. Such estimates will predict r-f output power, d-c input power, grid driving power and all d-c current values.

These estimates can be made easily by using the Eimac Tube Performance Computer and the characteristic curves of a tube, plotted on anode-voltage/grid-voltage coordinates (constant-current curves). Only the ability to multiply numbers obtained from the curves by means of the computer is required.

By graphically laying out the trace of the anode and grid voltages as they rise and fall about the applied d-c anode voltage and d-c grid bias, a clear understanding of the action taking place within a tube is possible. With such an understanding the operation conditions can be altered readily to suit one's particular requirements.

#### Simple Action in Class C R-F Amplifiers

In an amplifier, a varying voltage is applied to the control grid of the tube. Simultaneously, the anode voltage will vary in a similar manner, due to the action of the amplified current flowing in the anode circuit. In radio-frequency applications with resonant circuits, these voltage variations are smooth sine-wave variations, 180° out of phase (as the grid voltage rises and becomes more positive, the anode voltage falls and becomes less positive), as indicated in Fig. 1. Note how the variations center about the d-c anode voltage and the d-c control-grid bias.

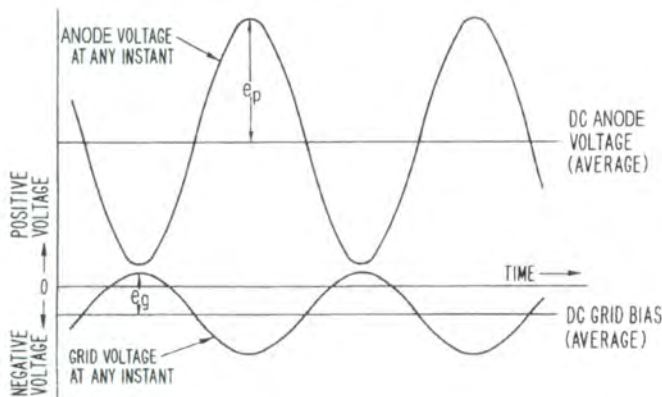


Figure 1

Fig. 2 illustrates how such variation of the anode and grid voltages of a tube appear on the constant-current curves for that tube. These variations have been indicated in Fig. 2 next to the anode-

voltage and grid-voltage scales of a typical constant-current curve. At some instant of time, shown as "t" on the time scales, the grid voltage has a value, which is represented by "eg" on the grid-voltage sine wave. On the anode voltage curve, point "ep" represents the instantaneous plate voltage corresponding in time to "eg" on the grid curve. Point A, overlaying the constant-current curves, represents the intersection of the horizontal and vertical lines drawn through points "eg" and "ep", which represent the instantaneous grid and anode voltages for a time "t".

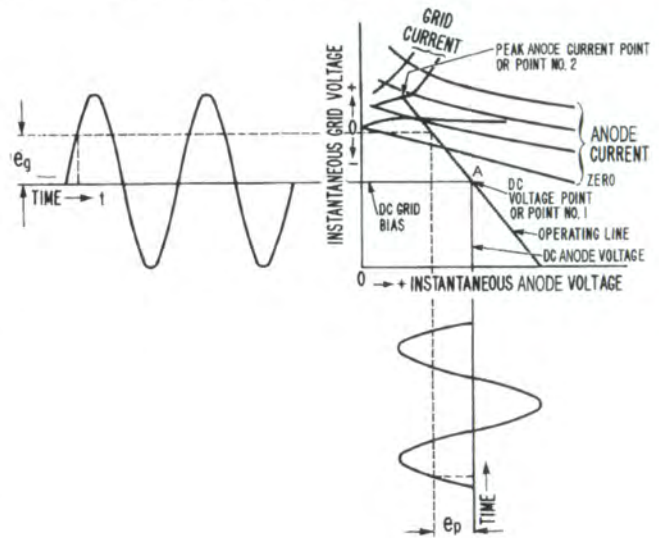


Figure 2

As time varies, Point A will represent a straight line overlaying the constant-current curves. This straight line is called the "operating line."

Any point on the operating line (when drawn on constant-current curves as in Fig. 2 or Fig. 4) represents the instantaneous values of anode, screen and grid current which must flow when the corresponding values of grid and anode voltage are applied to the tube. Thus, by noting the values of the currents along the operating line and plotting them against time "t", one can obtain a curve of instantaneous anode and grid current for the operating conditions defined, See Fig. 3.

If the anode and grid-current values shown in the graphs are analyzed, it can be seen that a d-c component of the current can be described by the intersection of the baselines of the grid and anode voltage curves. Also, it can be predicted that if the anode current flows through a properly loaded resonant r-f circuit, a certain amount of radio-frequency power will be delivered to that

circuit. If the circuit is tuned to the fundamental frequency (same frequency as the r-f grid voltage) the power delivered will be due to the fundamental, or principal, radio-frequency component of the anode current. If the circuit is tuned to a harmonic of the grid-voltage frequency, e.g., two or three times the frequency, the power delivered will be due to a harmonic component of the plate current.

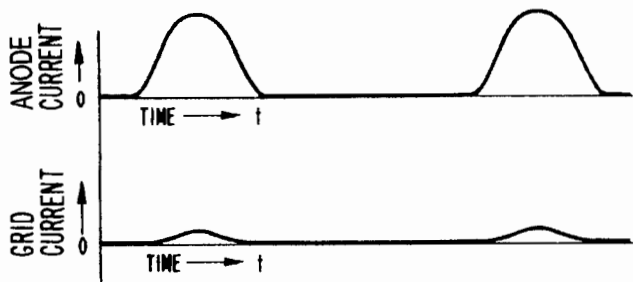


Figure 3

### Use of the Eimac Tube Performance Computer

The Eimac Tube Performance Computer provides a means to make the simple calculations to predict a tube's performance under a defined operating condition. It is a means to determine the d-c component, the fundamental r-f component or the approximate harmonic component of the current flowing in a tube when it is operating as a radio-frequency amplifier, and to predict what meter readings to expect and to predict the r-f output power and the

required driving power. With these factors known, one is able to forecast what will happen when any of the operating parameters are changed.

The Eimac Tube Performance Computer is a simple aid to enable selecting suitable values from the characteristic curves of a tube, and, by means of simple calculations, to forecast the performance of the tube in radio-frequency power amplifiers.

The basic steps are outlined under "Instructions" on the computer. This requires selecting d-c anode and grid-bias voltages, being guided by the typical operating values given on the technical data sheet for the tube type, and, by general experience. Next, a suitable "operating line" must be chosen on the constant-current curves for the tube type (plotted on the grid-voltage/anode-voltage coordinates).

The Tube Performance Computer, when properly placed over this operating line, enables one to obtain instantaneous values of the currents flowing at every 15° of the electrical cycle. The formulas given on the computer were derived by Chaffee<sup>1</sup> to yield the various average and harmonic components of the resulting currents. Knowing these current component values and the radio-frequency voltage values, one can readily calculate the complete performance of the tube.

The fundamental methods of making such computations, and the considerations necessary to stay within rating of the tube types while accomplishing various forms of modulation have been covered in the literature,<sup>2,3,4,5,7</sup> The method for harmonic-amplifier service is approximate and should be used only for tetrode

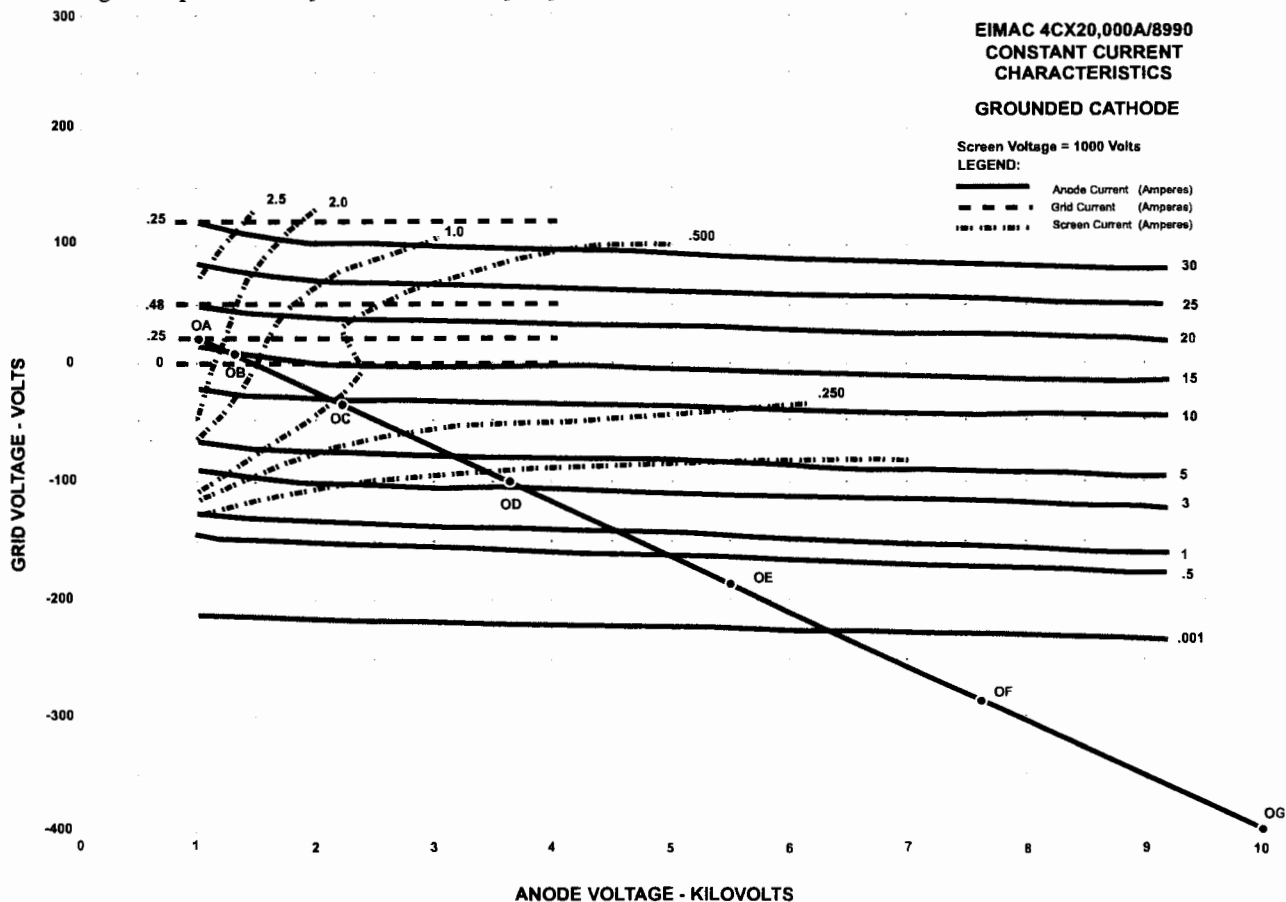


Figure 4

and pentode tubes where the anode voltage has little effect on the amount of anode current flowing. A more exact method, showing that for harmonic operation the operating line is a simple Lissajou figure, has been described by Brown.<sup>8</sup>

The results obtained by using this computer for power-amplifier service can be applied in combination with the other methods given in the literature to give good accuracy with simpler procedures. The resulting accuracy is well within the normal variation of the tube characteristics due to the normal variation in manufacturing dimensions of the a tube. Since the published tube curves are only typical of the characteristics to be expected from a particular tube type, the calculated performance is well within the values obtained when different tubes of a given tube type are operated under the assumed conditions.

### Example Showing Detailed Use of the Eimac Tube Performance Computer

#### Radio-Frequency Power Amplifier, Class-C (Telegraphy of FM)

Assume that we have an EIMAC 4CX20,000A/8990 tetrode and want to make it work efficiently. Also assume that we have a 10 kilovolt dc power supply available.

Within frequency limits, we know that a tube should be able to run in Class C amplifier service with about 75% efficiency or higher, or, in other words, to convert 75% of the dc anode input power to RF output power. The difference, or 25% of the input power, is dissipated and lost as heat on the anode of the tube. The dc anode input power is then about four times the power dissipated on the anode.

The 4CX20,000A/8990 tetrode has a maximum rated anode dissipation of 20 kilowatts. To illustrate performance near the maximum rating, we will choose an input power about 1.5 to 2 times the dissipation rating, or about 30 - 40 kilowatts. At 10 kilovolts the dc anode current must then be 3 to 4 A. We will use 3.2 Amperes of anode current for our example, striving for 80% efficiency. We hope to obtain at least 25 kilowatts of output power. It is normal practice with tetrodes and medium or low  $\mu$  triodes in Class C amplifier service for the dc grid bias voltage to be roughly two to three times the grid voltage necessary to cut off the flow of anode current. By referring to the curves for the 4CX20,000A/8990, it is decided to use a dc grid bias voltage of -400 volts. Higher bias voltage may be employed in applications where highest possible efficiency is desired (and additional drive power is available). In such a case, points will have to be established below the bottom-most line in the data sheet, which is -400 Volts, by scaling a new grid voltage line horizontally below the existing line. Scaling for higher anode voltage can also be done in this way (within the absolute maximum ratings established for a given tube type).

Now locate the operating line on the constant-current curves for the 4CX20,000A/8990. (See Figure 4). First, mark the point where the dc grid bias and dc anode voltage cross. The operating line must go through this point, which can be referred to as "Point No. 1." Next, the peak value of the anode current and how low we can let the instantaneous value of anode voltage ( $eb_{\min}$ ) be when the tube is passing this much current must be decided. This is nec-

essary in order to locate the other end of the operating line, e.g., "Point No. 2".

The peak value of anode current in Class C amplifiers can range from three to five times the value of average dc anode current, the actual value being determined by the conduction angle (narrower conduction angles result in a higher peak-to-dc ratio). Less than 120 degrees is a typical conduction angle and a peak-to-average ratio of 5 is typical in high efficiency class-C service. The minimum value of  $eb_{\min}$  is usually limited by the fact that if it is too low, the grid current in triodes or the screen current in tetrodes will be needlessly high, resulting in high grid or screen dissipation. Little will be gained as far as output power is concerned if the tube is driven "harder." The minimum value of anode voltage is usually in the region where the anode constant-current curves bend upward (entering saturation, see Figure 4.) In the case of triodes, this is near the "diode line," where the instantaneous anode and grid voltages are equal. The practical procedure in calculating tube performance is to arbitrarily choose Point No. 2, complete the calculations, and compare the data to target values and repeat the process until the desired results are obtained.

In the case of the 4CX20,000A/8990, let us choose a peak value of anode current about five times that of the dc anode current of 3.2 Amperes, or approx. 16 A. Let us choose a minimum instantaneous anode voltage of 1 kilovolt, the same value of screen voltage used when the curves were taken. This defines the upper end of the *operating line*. Locate this point on the tube curves, and refer to it as Point No. 2 in Figure 4. (The anode currents which flow at various combinations of anode and grid voltages are shown by the anode-current lines.) The value of current for each line is noted. In-between values can be estimated closely enough for our purposes. Draw a straight line between Points 1 and 2. This line is the *operating line*, and shows the current and voltage values at each instant in the RF cycle when the current is being taken from the tube. The nonconducting half of the RF cycle would be shown by extending the line an equal distance on the opposite side of Point No. 1. There is little to be gained by this line extension, since no current flows during this half of the cycle.

The EIMAC Tube Performance Computer can now be used to obtain the average currents (what will become meter readings in actual operating conditions) and anticipated power values from this *operating line*. Overlay the computer on the constant-current curve so that the "guide lines" of the computer are parallel with the *operating line*. Slide the computer (without turning it) until the line **OG** passes through the dc voltage point No. 1, and line **OA** passes through the peak-current Point No. 2. Be sure the guide lines are still parallel to the *operating line*.

Note that the lines **OB**, **OC**, **OD**, **OE**, and **OF** all cross over the *operating line*.

At each point where the lines **OA**, **OB**, etc. cross the *operating line*, we must determine the instantaneous values of anode current and grid current (and screen current if a tetrode or pentode is used) which are flowing at that particular moment in the RF cycle. Later, from these key values of current, values of anode current, grid current, screen current, and the RF components of the anode current may be calculated.

These current values should be listed for each point where the lines OA, OB, etc. cross the *operating line* so that they can be combined later to calculate the various tube currents. At points where OE and OF cross, the current values are insignificant or zero in Class C operation.

In the examples chosen, read off the instantaneous anode current values where these lines cross the operating line. At the point where the line OA crosses the operating line, the anode current is 16 A. Where OB crosses the operating line, the anode current is 15 A. At OC the anode current is about 9 A, OD is 3 A, OE is 0.25 A, and OF and OG are 0 mA. Similarly, the instantaneous screen current at the crossing of OA and the operating line is 2.25 A, and the instantaneous grid current is 0.25 A. Values are read for the other crossover points and written down. These values are put into columns for calculation:

Crossing of Line	Simplified name in Formulas	Instantaneous current values		
		Anode	Screen	Control Grid
OA	A	16A	2.25A	0.25A
OB	B	15	1.5	0.14
OC	C	9	0.5	0
OD	D	3	0.1	0
OE	E	0.25	0	0
OF	F	0	0	0

In order to obtain the dc value of anode, screen, and control grid currents the formula (see computer) indicated that the above values should be added, using only one-half the A values (giving 8 A for anode, 1.125 A for screen, and 125 mA for grid), and then divided by 12 (or multiplied by .0833), as follows

D-C meter reading = 1/12 times (0.5A+B+C+D+E+F)

Anode	Screen	Control Grid
8A	1.125A	125 mA
15	1.5	140
9	0.5	0
3	0.1	0
0.25	0	0
0	0	0

D-C current = 1/12 totals = (approximately)

2.9A	269mA	22mA
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To calculate the RF output power it is necessary to use the formula for the peak RF current which is present in the tube anode current. Since the tube is being used as a straight RF power amplifier, use the formula for "Peak Fundamental RF" as shown on the computer. If estimating the performance of a doubler or tripler, use the formula for "Peak 2nd Harmonic RF" or "Peak 3rd Harmonic RF."

From the computer, it may be seen that the formula for the peak fundamental RF current is:

$$1/12 (A+1.93B+1.73C+1.41D+E+0.52F)$$

A	=	8	=	16 A
1.93B	=	1.93 x 15	=	28.95
1.73C	=	1.73 x 9	=	15.57
1.41D	=	1.41 x 3	=	4.23
E	=	0.25	=	0.25
Total				65.0 A

Peak fundamental current = 1/12 total or 65/12 = 5.4 A

The various current values are now at hand. In order to calculate the powers involved, it is necessary to know not only the dc voltage values but also the greatest amount each value swings away from the dc value. This is known as the peak value of the RF voltage. Because the anode voltage swings from 10 kilovolts down to 1 kV, the peak RF anode voltage is the difference between these two Figures, or 9 kilovolts. Similarly, the grid voltage must rise and fall between the operating points No. 1 and No. 2, or from -400 volts to +20 volts. This is a peak swing of 420 volts, and the peak RF grid voltage is +20 volts. Now use the formula for output power and driving power: Output power = one-half RF anode current x peak RF anode voltage.

The peak RF anode current is found to be 5.4 ampere, and the peak RF anode voltage is found to be 9 kilovolts.

So: Output Power = 5.4 x 9000 x 0.5 = 24.3 kilowatts.  
and Input Power = dc Anode Current x dc Anode Voltage

$$= 2.9 \times 10,000 = 29 \text{ kilowatts}$$

Anode Dissipation = dc Input Power - RF Output Power = 29 - 24.3 = 4.7 kilowatts

Efficiency = r-f Output Power divided by

$$d - c \text{ Input Power}$$

$$= 24.3/29 = 83\%$$

Driving Power = dc Grid Current x Peak RF Grid Voltage

$$= 0.0265 \times 420 = 111 \text{ Watts}$$

The power consumed by the bias source is the product of the dc grid current and the dc grid voltage, or 0.022 x 400 = 88 Watts.

The difference between the driving power and the power consumed by the bias source is the power dissipated on the control grid, or 111 - 88 = 23 Watts.

The power dissipated on the screen grid is the product of the dc screen current and the dc screen voltage, because the screen grid has no impedance between it and the dc screen supply. Thus it is 0.269 x 1000 = 269 Watts.

The performance of the tube can be summarized:

dc Anode Voltage	10,000 Volts	Driving Power	111 Watts
dc Screen Voltage	1000 Volts	Grid Dissipation	23 Watts
dc Grid Voltage	-400 Volts	Screen Dissipation	269 Watts
dc Anode Current	2.9 A	Anode Input Power	29 kW
dc Screen Current	269 mA	Anode Output Power	24.3 kW
Peak RF Grid Voltage	420 Volts	Anode Dissipation	4.7 kW
calculated efficiency			83%

We see that the resulting calculated value of dc anode current (2.9 A) is lower than our initially chosen value of 3.2 by approx. ten percent, evidence that calculated efficiency of 83% is higher than the target value of 80% we initially anticipated. In the "real



world" actual transmitter output power will be somewhat lower than calculated values because of RF losses in the output matching network. One should also be aware that there may be variations in output from one tube to another due to varying electrical characteristics and that a tube that has been in service for an appreciable length of time may deliver less output than it did when it was new. Varying the dc screen voltage on a tetrode is an excellent method for varying output power and is employed for maintaining a fixed power requirement; as a given tube ages and loses emission from the filament its output power will decline. Compensating for losses over time is easily accomplished by using a voltage source for the screen that is adjustable by means of a closed-loop regulator system. If one wishes to calculate tube performance of a tetrode at screen voltages other than those at which the constant current curves were taken, a compensating factor using the three-halves power law can be employed. To account for loss of output over time a good designer will choose a tube that has output power capabilities well above the specified requirement, using as much conservatism as practicable. In the case of the 4CX20,000A/8990 in FM broadcast service actual tube life of 10,000 to 20,000 hours is common, indicating this tube is a good choice for supplying RF power from approx. 20 to 30 kilowatts in continuous commercial service.

### Use of EIMAC Tube Performance Computer for Class A, AB, and B Service

While the EIMAC Tube Performance Computer is primarily designed for use in Class C service, it may be used for Class A, AB, and B service where the idling (quiescent) anode current is not zero. To calculate performance for operating conditions having a large order of idling anode current, the anode current flow during

the positive half of the anode voltage swing becomes appreciable and cannot be ignored. When the tube functions over 180 degrees or more of the operating cycle, a full set of ordinate points must be employed for the computations. The computer is therefore used in a two-step process.

First, determine the operating line. The computer is used in the normal fashion to derive the instantaneous values of anode, screen, and grid current during the negative half of the anode voltage swing. These current points are logged as explained under the Class C service description.

Now, determine the instantaneous current points over the positive portion of the anode voltage cycle. Combine these with the points taken for the negative half of the cycle. This is done in the following fashion: a line is penciled on the computer over the operating line, and of equivalent length. The computer is now inverted and rotated 180° and again aligned with the chosen operating line on the constant current curve, so that inverted point A falls on the idling current value (Point No. 1) and inverted point A passes through a minimum peak current point representing maximum positive anode voltage swing. The penciled line on the computer now represents an extension of the operating line into the area of positive peak voltage swing. The extended operating line is a straight line, twice as long as the original operating line. Instantaneous values of anode, screen, and grid current (if any) are those observed where the reversed ordinate lines on the computer cross the extended operating line.

The current points measured with the computer inverted are logged and these, together with the points obtained in the first operation (computer right side up) provide a full set of instantaneous peak current values necessary for the calculation of Class A, AB, or B parameters. With the first set of computer readings termed A,

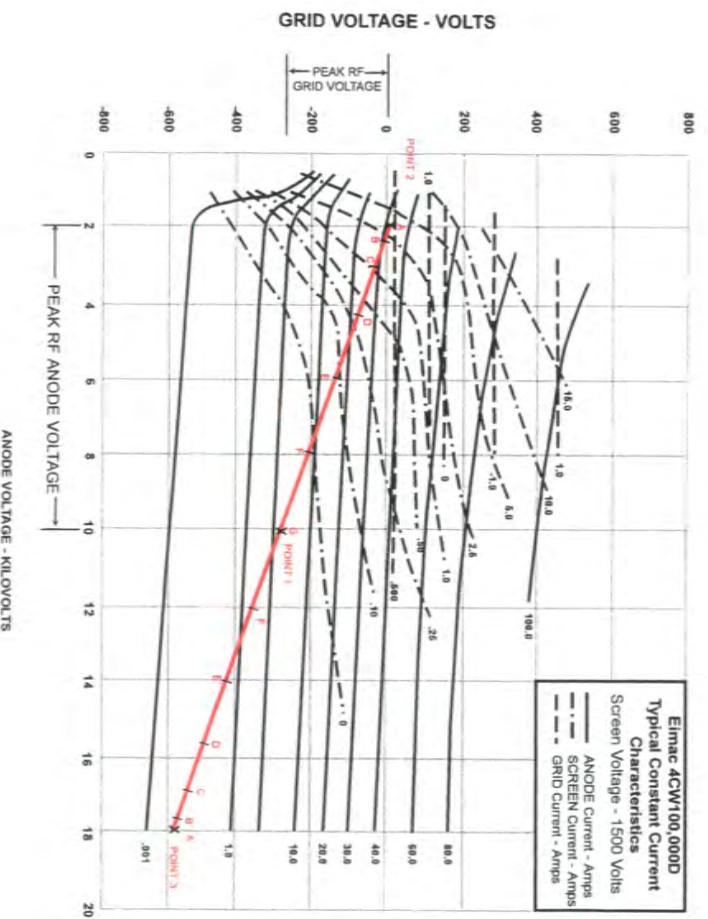


Figure 5

B, C, D, E, F and G, the second (inverted) set of Figures may be termed A', B', C', D', E', and F', with the sets used in the following formulae, which are modifications of Chaffee's permitting the use of current values directly from the constant current curves:

### An Example: Using the Computer for Class AB1, Service

Operating data is to be derived for an EIMAC 4CW100,000D tetrode operating at a anode potential of 10 kV with a screen potential of 1.5 kV. Assume that power output design goal for this particular application is about 60 kW. Grid current is zero; that is, the tube is operated in the Class AB1 mode, with the grid never being driven positive.

Within frequency limits, an anode circuit efficiency of about 55-60% may be assumed for Class AB1 operation. Maximum dc anode input is therefore 2.2 to 2.75 times the anode dissipation. A maximum power input of  $2.2 \times 50,000 = 110$  kW is chosen. At 10 kV, the maximum dc anode current is then 11.0 A. This is within the maximum rated anode current of 15 A for Class AB1 service as specified on the data sheet.

For Class AB1 service the tube does not operate in a cut-off condition, but rather a certain value of idling anode current exists. This must be taken into account when choosing Point 1 on the constant current curve. Generally speaking, high levels of resting anode current provide reduced levels of intermodulation distortion products and somewhat lower anode efficiency. Idling anode current is usually chosen so that anode dissipation under quiescent conditions is about 50-70% of the maximum dissipation rating. In the following example, idling anode current is chosen to be 4.5 amperes. From Figure 5, it may be determined that a grid potential of about -295 volts is required to produce the desired anode current at the chosen screen and anode potentials. The intersection of the -295 volt bias line and the 10 kV anode line determines the idling point on the operating line (Point No. 1).

Next, the peak value of anode current must be determined, and the minimum amount of instantaneous anode voltage chosen to pass this amount of current. Determination of these values will locate Point No. 2 and will thus define the operating line.

Class AB1 service limits grid voltage excursions to negative grid regions on the constant current graph. Point No. 2 therefore may never be located above the zero grid voltage line. In addition, the minimum instantaneous anode voltage is usually not allowed to swing as low as the dc screen potential, since screen dissipation tends to become abnormally high. The location of Point No. 2 thus has certain restrictive limits defined by screen dissipation and the maximum positive grid signal voltage. In this case, for the 4CW100,000D, minimum instantaneous anode voltage is about 2 kV. Peak RF voltage is thus  $10,000 - 2,000 = 8,000$  volts.

Peak RF anode current in a Class AB1 amplifier usually runs about 2.5 to 3.0 times the average dc anode current. In this case, a maximum peak anode current of about 2.9 times the maximum signal dc anode current of 11.0 A, or 32 amperes, is chosen. This defines Point No. 2, which is at the intersection of the 2 kV minimum anode voltage line and thus falls within the limits discussed in the preceding paragraph. A straight line is drawn between Point No. 1 and Point No. 2 which is the negative anode cycle portion of the

operating line.

When the operating line is extended to the right of Point No. 1, it can be observed that the tube conducts over the rest of the cycle where (by virtue of the "flywheel" effect of the resonant tank circuit) the instantaneous anode voltage swings as far above the normal dc value as it swings below. It is important to note that operation with less than cutoff bias requires that the EIMAC Tube Performance Computer employ points on the operating line failing to the right of Point No. 1. The operating line is accordingly extended and the computer is used in a two-part operation, as shown in the following example:

### 4CW100,000D COMPUTATIONS

d-c Plate Voltage = 10 kV	Power Input = 110 kW
d-c Screen Voltage = 1.5 kV	Max. d-c Plate Current = 11 amp.
	Zero-Signal Plate Current = 4.5 amp.
	d-c Grid Voltage = -295 volts
Constant Current Graph and	Peak Plate Current = 32 amp.
Operating Line determine:	Peak RF Voltage = 8,000

Step One			Step Two		
EIMAC Computer Readings			Inverted Computer Readings		
Instantaneous Peak Current (amps)			Instantaneous Peak Current (amps)		
Ordinate	Crossing	Plate Screen	Ordinate	Crossing	Plate Screen
A	32	3	A'	0.20	—
B	31	2	B'	0.25	—
C	28	1.2	C'	0.30	—
D	22	0.25	D'	0.50	—
E	15	0.07	E'	0.80	—
F	9	—	F'	1.50	—
G	4.5	—			

$$\begin{aligned}
 \text{d-c Plate Current} &= \frac{1}{12} \left[ \frac{32^2}{2} + 31.25 + 28.3 + 22.5 + 15.8 + 10.5 + 4.5 \right] = 10.75 \text{ amp} \\
 \text{Plate Power Input} &= 10 \text{ kV} \times 10.75 \text{ A} = 107,500 \text{ watts} \\
 \text{Peak Fundamental RF Current} &= \frac{1}{12} [31.8 + 59.4 + 47.7 + 30.3 + 14.2 + 3.9] = 15.6 \text{ amp} \\
 \text{Power Output} &= \frac{15.6 \times 8000}{2} = 62,500 \text{ watts} \\
 \text{Plate Dissipation} &= 45,000 \text{ watts} \\
 \text{Efficiency} &= \frac{62,500}{107,500} \times 100 = 58.2\% \\
 \text{Resonant Load Impedance} &= \frac{8000}{15.6} = 512 \text{ ohms} \\
 \text{d-c Screen Current} &= \frac{1}{12} \left[ \frac{3}{2} + 2 + 1.2 + 0.25 + 0.07 \right] = 417 \text{ mA}
 \end{aligned}$$

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*The Tube Performance Computer on the next page can be printed on any computer printer using transparency material instead of paper. Just display the page and then print the current page. Select 'fit to page' for printers that require margins.*





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**TUBE PERFORMANCE COMPUTER**  
**Application Bulletin No. 5**  
For RF Amplifiers (Class B, C and Frequency Multipliers)

Use with constant current curves to obtain plate, grid and screen current values; also output and driving power.

DC Current (meter reading)	$1/12 (0.5A+B+C+D+E+F)$
Peak Fundamental RF	$1/12 (A+1.93B+1.73C+1.41D+E+0.52F)$
Peak 2 <sup>nd</sup> Harmonic RF (Approx.)*	$1/12 (A+1.73B+C-E-1.73F)$
Peak 3 <sup>rd</sup> Harmonic RF (Approx.)*	$1/12 (A+1.4B-1.41D-2E-1.41F)$

Output Power =  $\frac{1}{2}$  Peak RF plate current x Peak RF Plate Voltage  
Driving Power = DC Grid Current x Peak RF Grid Voltage

\*Use only for tetrodes or pentodes – Approximate Only.

**INSTRUCTIONS**

1. Mark *point* of DC plate voltage and DC Grid Bias.
2. Mark *point* of peak plate current in low plate voltage region. (This is about four times DC plate current.)
3. Draw straight line between points selected in No. 1 and No. 2. This is "Operating Line."
4. Place computer on curve sheet with guide lines parallel to "Operating Line." Make OG line of computer go through point of Step No. 1. Make OA line of computer go through point of Step No. 2.
5. Read current values where "Operating Line" crosses OA, OB, OC, OD, OE and OF.
6. Put values in formulas as A, B, C, D, E & F.

For detailed instructions see *Eimac Application Bulletin No.5*

← **GUIDE LINES**

