SECTION 2

ADVANCED
PRACTICAL
RADIO ENGINEERING

TECHNICAL ASSIGNMENT

CLASS C AND CLASS B AMPLIFIERS

Capitol Radio Engineering Institute
Washington, D. C.

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CLASS C AND CLASS B AMPLIFIERS

TUBE NOMENCLATURE

PLATE VALUES

i_b = total instantaneous plate current.

I_b = quiescent (d-c) value of plate current.

i_p = instantaneous value of the a-c (sinusoidal fundamental) component.

I_p = r.m.s. value of the a-c (sinusoidal fundamental) component.

I_{pm} = crest or peak value of the a-c (sinusoidal fundamental) component.

i_{bmax} = peak value of total plate current.

i_{bmin} = minimum value of total plate current.

E_{bb} = power supply (d-c) voltage.

E_b = d-c *plate* voltage.

e_b = instantaneous value of plate voltage.

e_{bmax} = peak value of plate voltage.

e_{bmin} = minimum value of plate voltage.

e_p = instantaneous value of the a-c (sinusoidal fundamental) component.

E_p = r.m.s. value of the a-c (sinusoidal fundamental) component.

E_{pm} = peak value of the a-c (sinusoidal fundamental) component.

GRID VALUES

E_{cc} = d-c bias source applied to grid.

E_c = d-c grid bias.

e_c = instantaneous grid voltage.

$+e_{cmax}$ = maximum positive or negative instantaneous grid voltage.

e_g = instantaneous value of the a-c (sinusoidal fundamental) component.

E_g = r.m.s. value of the a-c (sinusoidal fundamental) component.

E_{gm} = peak value of the a-c (sinusoidal fundamental) component.

i_c = instantaneous value of grid current.

I_c = d-c grid current.

i_{cmax} = maximum value of grid current.

i_{cmin} = minimum value of grid current.

i_g = instantaneous value of a-c (sinusoidal fundamental) component.

I_g = r.m.s. value of a-c (sinusoidal fundamental) component.

I_{gm} = peak value of a-c (sinusoidal fundamental) component.

SCOPE OF ASSIGNMENT

This assignment will take up the subject of Class C and Class B amplifiers. It will first discuss the advantages of such amplifiers, and then show how they are designed, whether for CW or pulse operation.

One important feature will be the sets of curves that will enable the student to take the manufacturer's rating for a tube, and work backwards to find what peak plate current he used, in order to modify the design to meet other operating conditions, such as lower plate voltage, or pulse operation, and the like.

Push-pull amplifiers will also be covered, with particular reference to tank circuit impedances as compared to single-ended operation. This is often a puzzling matter to the student and even engineer.

The final topic will be the linear amplifier. This is really a special case of the Class C amplifier, in which the angle of plate-current flow is 180°, so that Class B operation is obtained. The operation, adjustment, and measurement of distortion will conclude this topic.

GENERAL CONSIDERATIONS

NARROW AND BROAD BAND AMPLIFIERS.—The amplifiers discussed up till now are of the broad-band type; they are capable of amplifying more than one frequency SIMULTANEOUSLY. The reason is that the plate current output is arranged to be a replica of the signal voltage input applied to the control grid, so that in order to develop an output voltage of similar wave shape, the output plate current merely is made to flow through an ordinary resistor or other impedance that is reasonably constant in magnitude over a broad band.

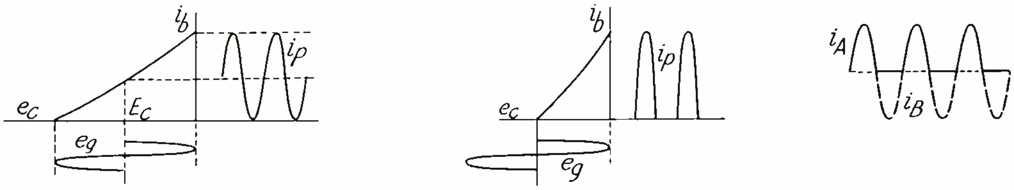
If, on the other hand; the current is permitted to be a distorted copy of the input voltage, then a selective plate load impedance is required, such as a resonant circuit, in order to eliminate the unwanted distortion products. Such a circuit can function, however, at only one frequency or narrow band of frequencies at a time, and cannot therefore amplify a broad band of frequencies, such as is required in audio and video work.

Hence, if it is desired to amplify a broad band of frequencies simultaneously, distortionless amplification is required in order to avoid having the distortion products occur within the band of operation. This in turn implies Class A, or at most Class B push-pull amplification.

In Class A amplifiers, the grid is biased halfway between cutoff and zero volts, Fig. 1(A). This means that plate current flows for the entire 360° of the signal cycle, and is therefore a fairly faithful copy of the signal wave shape, so long as the tube characteristics are reasonably straight.

In Class B operation the grid is biased at or near cutoff, and plate current flows for only the positive half cycle of the signal voltage. It is therefore clearly a distorted copy of the grid signal voltage, as is indicated in (B), but since in push-pull operation two tubes are used, and the signal is applied to the control grids 180° out of phase, distortionless output can be obtained from the circuit as a whole.

Thus, as shown in Fig. 1(C), the output of one tube is i_A, a series of half sine waves; and the output of the other tube is i_B, also a series of half sine waves. The output circuit combines the two waves, as shown in (C) in solid and dotted lines, to provide a complete sine wave having no distortion.



(A) (B) (C)

Fig. 1.—Class A and Class B push-pull operation results in essentially distortionless output.

Although such operation is practically distortionless, it does limit the output of the tube to a value considerably less than can be obtained if distortion were permissible. If, however, we wish to amplify but one frequency or at most a narrow band at any one time, then the tube can be permitted to produce distortion products, with the plate load impedance designed to filter out these products and leave just the single sine wave or narrow band of frequencies in the output.

This is the case in a transmitter, where the carrier frequency is to be amplified and modulated. The latter process does produce sidebands, but these are so close in frequency to that of the carrier that they can also readily affect the tuned plate impedance and thus register at the output.

Of course the distortion products are not generated merely to be filtered out. They are generated because they are inherent in a process that produces considerably more output than is obtained in Class A or Class B push-pull operation; the increased output and efficiency is the real reason for the distorted operation.

It is obtained by overbiasing the grid to from two to five times cutoff. This permits the plate current to flow for but a small portion of the cycle: less than 180°, which would be Class B operation. Thus, as indicated in Fig. 2 the grid swing e_g is such that from cutoff to the positive peak of the cycle occupies a time equivalent to from 120° to 150° of the entire grid cycle.

This then indicates that the plate current will flow for this period of time, too. The grid swing is sufficient to actually drive the grid positive with respect to the cathode. As a result, grid current is also drawn, but over an even smaller fraction of the cycle, as is evident from Fig. 2. The result is also a pulse of grid current i_g, of even shorter duration than the plate current i_b.

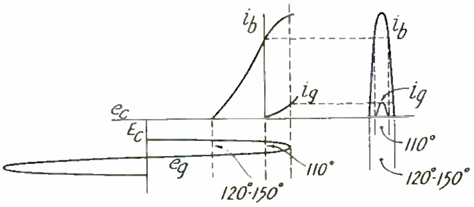


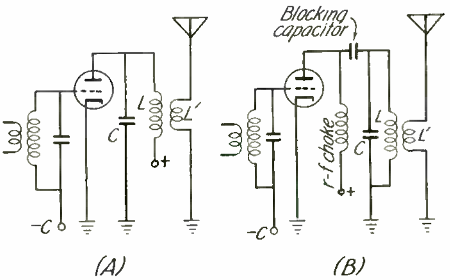
Fig. 2. — **Current-voltage relations in a Class C amplifier stage.**

The plate current pulses are smoothed out or filtered by means of a parallel resonant circuit, L, C, called a tank circuit, as shown in Fig. 3. The impedance of L and C is a maximum at resonance, which is chosen to be that of the incoming grid signal. Therefore the fundamental component of the plate current pulse produces the maximum voltage across the tank and the harmonic components are practically short-circuited by C. As a result, the tank voltage is essentially sinusoidal in wave form, and of the same frequency as the incoming signal.

In Fig. 3(A) the tank circuit is directly connected to the plate, and the d-c component of the tube current flows through L. The coupled coil L' transmits the r-f energy to the antenna; in effect it acts to insert a resistance in series with L.

In (B) is shown what is known as shunt coupling. The r-f choke coil carries the d.c., but has too high an impedance to permit appreciable r-f to flow through it. Instead, the r-f component flows through the d-c blocking capacitor to the L-C tank circuit shunting the r-f choke, and thence to L' and the antenna. The advantage of this circuit is that both L and C are at d-c ground potential.

Note in either case that the grid is driven from a tuned circuit coupled to a previous stage. The Q of the tuned circuit is chosen sufficiently high so that even when grid current flows at the positive peaks of the cycle, the grid-signal voltage is not materially flattened from a sinusoidal wave shape.



(A) (B)

Fig. 3. — **Series-and Shunt-fed tank circuits.**

CLASS C OPERATION.—When plate current flows through the tank circuit, it produces a sinusoidal voltage drop which is subtracted from the impressed d-c supply voltage. In other words, the plate voltage decreases as the grid swings in a positive direction, in a manner similar to that taking place in an ordinary audio amplifier.

Fig. 4 shows the various relations between plate current, grid voltage, and plate voltage. The bias is arranged to be from two to five times the plate-current cutoff value, and the grid swing is made so large that in spite of this high bias the grid actually goes positive by the amount e_{cmax}, as shown. The plate current i_b flows during the portion of time when the grid voltage is above cutoff, as was also shown in Fig. 2; this is denoted by θ_p. The grid current i_c flows when the grid is positive; its angle of flow is denoted by θ_g.

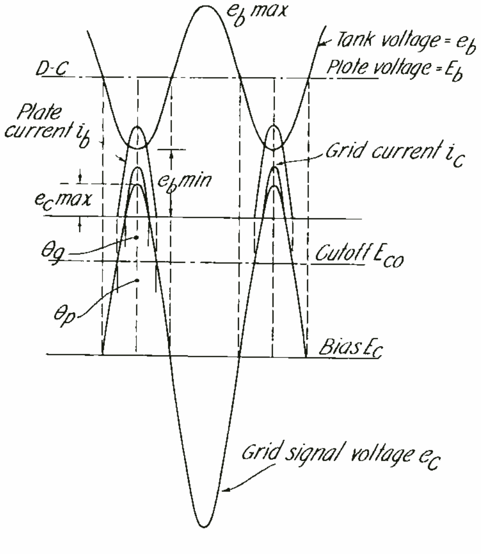


Fig. 4.—Current and voltage relations in a Class C amplifier.

Fig. 4, however, goes further than Fig. 2 in that it also shows the plate voltage. As was mentioned previously, this voltage is practically sinusoidal in shape owing to the "flywheel" effect of the parallel-resonant tank circuit. Note further, however, that it is 180° out of phase with the grid voltage. This is the expected relationship for a Class A amplifier; the only reason that it might appear unusual here is simply that the plate current consists of a series of pulses, and hence how it excites the tank circuit and what voltage it produces across it are not obvious.

It turns out, however, that the *fundamental* component of the plate-current pulse has its positive peak occurring at the same time as the peak in the pulse, whereupon the peak of the plate *voltage*, if the tank circuit is resonant at the excitation frequency, will be in *phase* opposition to the fundamental component, and hence will be 180° out of phase with the grid voltage, as shown.

POWER RELATIONS.—This has important consequences. In the first place, when the plate *voltage* is high, the plate current is zero, and so the power expended on the plate, or plate dissipation, at such times is zero, since it is the product of the two quantities. On the other hand, when the plate *current* is high, the plate voltage is low (reaching e_{bmin} when i_b is a maximum). The product of the two, or plate dissipation is now greater than zero, but it is still rather low.

As a result, the plate dissipation, when averaged over the entire grid cycle, is very small. This means, in turn, a very efficient mode of operation. To summarize, in Class C operation the plate voltage is low during the interval of time when plate current flows, so that the power dissipated on the plate of the tube is particularly low. Hence a relatively small tube can be employed to furnish comparatively large amounts of power output without becoming excessively hot. Furthermore, the efficiency of operation is very high, — in the range from 60 to 80 per cent.

From Fig. 4 it can be seen that as the angle of flow θ_p is decreased, the plate-current pulses become narrower, and therefore center more closely under the minimum point of the plate voltage excursion. This is further clarified in Fig. 5, (A) and (B).

This is Class B operation; but push-pull is not considered here, instead a resonant tank circuit is assumed to filter out the distortion products, just as in Class C. In fact, Class B is merely a special case of Class C for which $\theta_p = 180°$.

The various power relationships can be readily brought out in this diagram, or rather, the INSTANTANEOUS power relationships. Consider a moment in the cycle denoted by A. The instantaneous plate current is AB; the instantaneous plate voltage (voltage between cathode and plate) is AC; the instantaneous TANK voltage is DC; and the applied d-c voltage is AD, regardless of course of what moment in the cycle is under consideration.

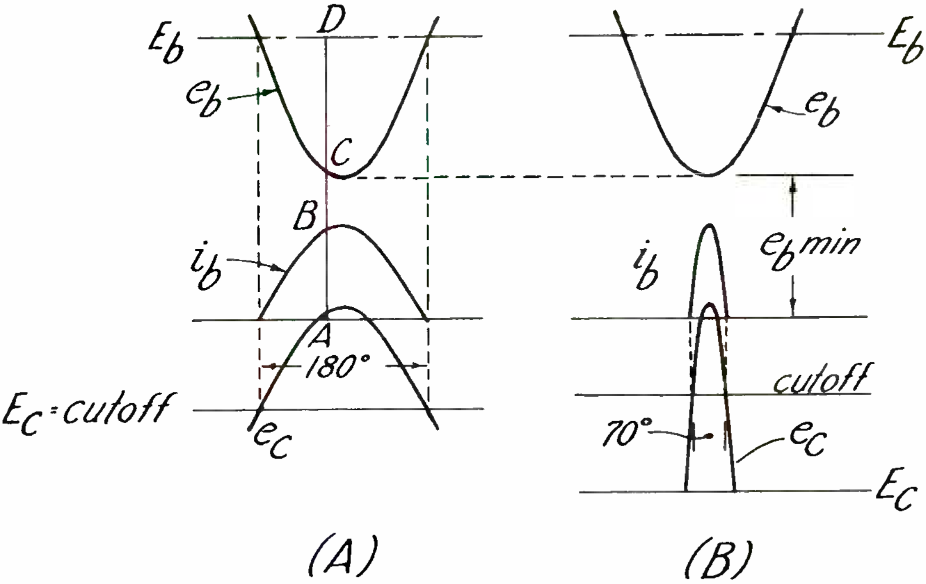


Fig. 5. — Class B and extreme Class C operation, showing difference in width of plate-current pulses.

In (A), the bias E_c is shown coinciding with plate-current cutoff. This means that plate current flows during the entire positive half cycle of the grid swing, or the angle of flow $\theta_p = 180°$.

The plate dissipation AT THAT INSTANT is AB × AC. The total input power is AB × DA. This comprises both the plate dissipation and the power fed into the tank circuit. The latter power is represented at that instant by DC × AB, and in itself comprises power going out into the load and power to provide energy that is being stored in the tank inductance.

At every instant in the cycle WHILE PLATE CURRENT IS FLOWING, there is power coming into the entire tube circuit, power dissipated on the plate, and power flowing into the tank circuit. When no plate current flows, there is no power going into the entire tube circuit, and there is no plate dissipation, but there is still power flowing *from* the tank circuit into the output load. This comes from the energy stored in the tank coil during the time that the plate current was flowing.

Let us concentrate our attention on the plate dissipation. It is AB × AC. If this is averaged out over the cycle, it will represent a certain number of watts, so many joules every second.

Since the plate current flows for half a cycle, some of its instantaneous values will be multiplied by values of e_b close to its minimum value e_{bmin}.

Now refer to Fig. 5(B). The plate current flows for a much shorter period of time, as is suggested by $\theta_p = 70°$. This means that both the plate dissipation and power input will be less. But the plate dissipation will be particularly low because the current at any instant is multiplied by a voltage hardly any greater than e_{bmin}.

On the other hand, the power input is the product of the instantaneous values of the current by the constant or d-c voltage E_b, and therefore is not so low. This means that the power going into the tank circuit will be a relatively large portion of the power input, or the EFFICIENCY will be high. On the other hand, the efficiency for the larger angle of flow of Fig. 5(A) will be relatively low.

It would therefore appear desirable to operate a Class C stage with a maximum of bias and a minimum of angle of flow. Unfortunately, however, although as the angle of flow is decreased the power output approaches the power input, the efficiency increases, and the plate dissipation decreases, the actual number of watts output nevertheless becomes very small, and we could end up in using a huge expensive tube to furnish a few watts of output power.

Hence, a compromise is effected between operating efficiency and first cost of the tube, and an angle of flow in the neighborhood of 120° is normally used. In a tube properly designed to withstand the optimum value of power-supply voltage, the power output will be large, yet the plate efficiency will be fairly high (in the neighborhood of 80 per cent if the frequency is not too high), and the plate dissipation will not exceed the permissible limits set by the manufacturer.

PLATE LOAD IMPEDANCE.—The angle of flow θ_p depends upon the relative values of the bias and grid swing, and normally the latter is sufficient to drive the grid positive at its peak. It was just shown that the plate dissipation decreases as θ_p decreases, and the efficiency increases. There is, however, another factor that affects the efficiency and plate dissipation, and that is the magnitude of the plate load impedance.

In Fig. 5, e_{bmin} was the same for either angle of flow. The reason was that it was tacitly assumed that the load impedance was the same in either case, so that the same voltage drop occurred across the tank in either case. As in the case of any other type of amplifying circuit, the voltage E_L across the tank is algebraically subtracted from the d-c input voltage E_{bb}, as indicated in Fig. 6. Here E_{bb} is the applied d-c voltage; it is practically the same as the d-c voltage E_b measured at the plate of the tube, since there is a negligible d-c voltage drop in the tank coil.

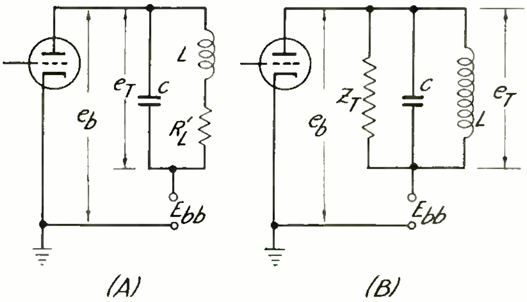


Fig. 6.—Equivalent circuits for the tank load.

The tank capacitor C is shown connected to the positive terminal of the power supply instead of to ground as is normally the case, merely to make the voltage relations more obvious. Electrically the two connections are practically identical so far as the tube's behavior is concerned.

The voltage developed across the tank is denoted by e_T. This is a negative voltage when i_b increases, as occurs when the grid swings in a positive direction. Hence the net instantaneous voltage between the plate and cathode (ground) at such time is $E_{bb}-e_T$. A half cycle later, when the grid swings in a negative direction and cuts off the tube, the tank coil current is forced to flow into C, charging it up until the voltage e_T reverses (becomes positive) and now ADDS to E_{bb}. The plate voltage is now $E_{bb} + e_T$; actually this is indicated in Fig. 5.

The tank load resistance may be the radiation resistance of an antenna that is coupled to the tank coil. In effect, over the narrow band of frequencies involved, it acts as if it were a resistance R'_L in series with the tank coil L, as is shown in Fig. 6(A). By a simple network theorem, it can be shown that R'_L in series with L is equivalent (at and around the resonant frequency of L and C) to a SHUNT resistance Z_T, as shown in Fig. 6(B). The relation between the two is

$$Z_T = \frac{L}{C R'_L} \qquad (1)$$

provided R'_L is small compared to $\omega_r L$, where ω_r is the resonant angular frequency of L and C.

In the discussion to follow Z_T, the equivalent shunt resistance, will be the one considered at all times, regardless of where the actual resistance is located. The tube may be said to face the load resistance Z_T, and the ideal or resistanceless shunt L and C provide the so-called "flywheel" effect that converts the tube's current pulses into a sinusoidal current in L, C, and Z_T.

The ideal shunt L and C in themselves can be assumed to draw no current from the tube; i.e., they appear in the neighborhood of parallel resonance as an infinite impedance to the tube. Hence the only finite impedance presented to the tube is Z_T. If Z_T is high, then the sinusoidal tank voltage e_T developed across it is high; if Z_T is low, e_T is low.

This in turn means that if Z_T and e_T are large, the instantaneous plate voltage $e_b = E_{bb} - e_T$ is small, particularly at the negative peak value of e_T, at which moment e_b assumes its minimum value e_{bmin}. In other words, if the plate voltage is to dip down to a very low minimum value, Z_T must be high. But it will be recalled that if e_{bmin} is small, the plate dissipation will be small, because the peak plate current occurring at this moment will be multiplied by a small value of e_{bmin}.

Hence, for high efficiency and low plate dissipation, not only should the angle of flow θ_p be small, but the tank impedance Z_T should be high: θ_p should be small to narrow the plate current pulse to the time at and around that when e_{bmin} occurs, and Z_T should be high to make e_{bmin} as small as possible.

It was shown previously, however, that if θ_p is made too small, the plate dissipation will be low and the efficiency will be high, but unfortunately the power output will be small considering the size tube employed. The question arises, "Is there a limitation as to how low e_{bmin} can be, and hence as to how great Z_T can be?" The answer is, "Yes, there are limitations with regard to these two quantities."

To show this, refer to Fig. 4, which is repeated here for convenience. Note again that as e_c rises to its maximum value e_{cmax}, e_b drops simultaneously to its minimum value e_{bmin}. So long as e_{bmin} exceeds e_{cmax}, very little space current is diverted to the grid, and most of it flows to the plate and therefore represents plate current.

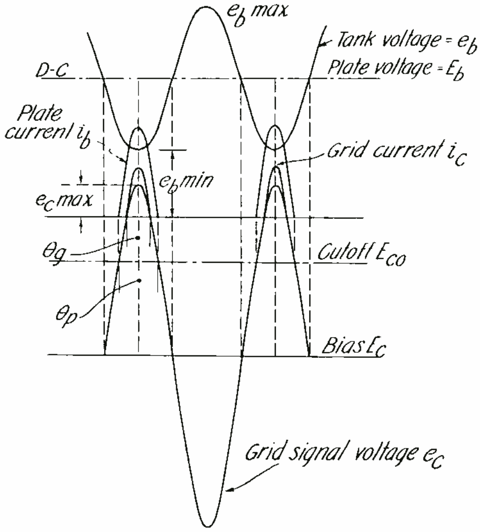


Fig. 4.—Current and voltage relations in a Class C amplifier.

Should, however, e_{cmax} approach e_{bmin}, and particularly should it exceed the latter, the grid will rob the plate of current, so that the i_b pulse will show a crater at its center instead of a peak, and the grid current i_c will become excessive. This in turn will mean that the output power will be reduced, and the input grid driving power will simultaneously become excessive, so that the grid will overheat and also require an excessively large driver stage preceding it.

Even if the requirement that e_{bmin} exceed e_{cmax} could be eliminated, there would still be a limitation as to how large Z_T can be. This further limitation is that as Z_T is increased, the peak value of i_b, the plate current, decreases, and hence the power output goes down. There is therefore an optimum value of Z_T, just as in the case of Class A audio amplifiers, for example. Too large or too small a value of Z_T results in insufficient power output from the size tube chosen; this is in addition to the consideration that too large a value of Z_T causes e_{bmin} to equal or be less than e_{cmax}, with resulting excessive grid current flow, and too small a value of Z_T causes e_{bmin} to be too high, with resulting excessive plate dissipation.

It is for this reason that the plate-supply voltage E_{bb}, the tank load impedance Z_T, the grid bias E_c, and the grid drive should all be coordinated so that e_{cmax} never exceeds e_{bmin}. In fact, in actual practice e_{bmin} is generally arranged to be from 1.5 to 5 times e_{cmax}. For small tubes it may be somewhat less than twice; the factor five is used for very large tubes.

DYNATRON ACTION.—There is one effect that must be guarded against in the grid circuit, and that is a negative resistance phenomenon that occurs owing to secondary emission. It is more apt to be encountered in large tubes whose electrode voltages are high.

Fig. 7 illustrates this effect. As the grid voltage e_c increases, the grid current i_c rises, too, along curve OA. But as the grid goes further positive, the electrons arriving at the grid strike it so hard as to knock out secondary electrons from it. In general these range from two to four or more for each primary electron.

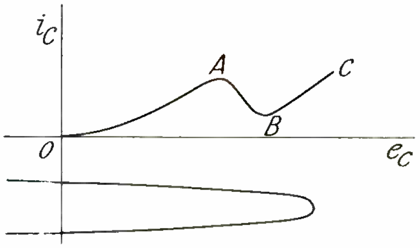


Fig. 7.—Negative resistance characteristic that may occur in the grid circuit.

Since there is a highly positive plate in the vicinity, it attracts the secondary electrons to itself. As a result the grid begins to lose more electrons than it receives from the cathode, and so the grid current begins to fall along path AB. In extreme cases the grid current can even go negative.

As the grid swings further positive, the rising plate current causes the plate voltage to drop still further, until finally the dropping plate voltage may become less than the rising grid voltage. Now it is the grid that may start robbing the plate of secondary electrons, so that the plate current may begin to show a dip. The transition from the one effect to the other is indicated in Fig. 7 by the portion BC, where the grid current starts to rise once more.

However, it is the portion AB that will cause trouble. This is because it has a NEGATIVE slope, which means that as the voltage INCREASES, the current DECREASES. Hence, for variations in voltage in this region, the current varies in the opposite rather than in the same manner, and this is after all what one means by a NEGATIVE resistance.

Since the grid is driven by a tuned circuit connected to the plate of the preceding stage, it is evident that in conjunction with this negative resistance we have a mechanism capable of oscillating. This is of course highly undesirable; the grid should be driven solely by the preceding stage, and not by its own regenerative feedback.

The circuit becomes what is known as a DYNATRON oscillator. To suppress such oscillation is not easy; it may require resistive damping in the grid circuit, or in the tuned driving circuit, such as by connecting a resistor across the preceding tuning capacitor. Fortunately, such dynatron action is not too common, but it is well to be on the lookout for it in order to be able to eliminate this phenomenon if it should arise.

CLASS C AMPLIFIER DESIGN

CURRENT COMPONENTS.—In Fig. 8 are shown the current pulses and their d-c and fundamental components. These are obtained by a Fourier analysis; their amplitudes are related to the shape, peak value, and angle of flow of the pulses.

If the tube is exactly linear above cutoff, then the plate current i_b will be an exact copy of the grid voltage projecting above cutoff, and hence will be a segment of a sine wave. Under these conditions an exact Fourier analysis of the d-c and fundamental components is possible for each angle of flow θ_p. These components can than be plotted as a function of θ_p, as has been done in Fig. 10.

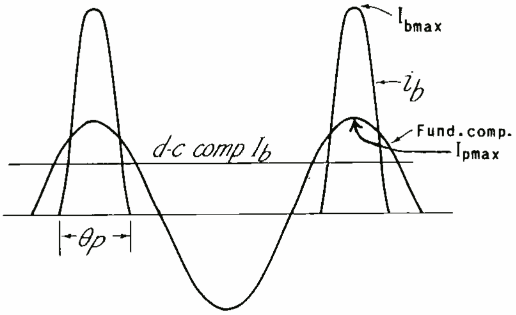


Fig. 8.—Class C current pulses and their d-c and fundamental components.

In actual tubes the SPACE current is more nearly a three-halves power function of the grid and plate voltages. What this means is as follows: let i_b be the current that flows to the plate, and i_c that which flows to the grid. Then the space current flowing from the cathode is $i_s = (i_b + i_c)$. The relationship between the space current and the instantaneous grid and plate voltages, e_c and e_b, respectively, is

$$i_s = (i_b + i_c) = K\,(e_c + e_b/\mu)^{\alpha} \qquad (2)$$

where μ is the amplification factor of the tube (assumed constant), K is a constant of proportionality, and α is an exponent. If the tube obeys Child's law, α has the value of 3/2 or 1.5.

In this case, the shape of the space current pulse leaving the cathode will be more peaked than a segment of a sine wave, as is indicated in Fig. 9(A). The waves are plotted under the assumption that the grid swing is the same in all cases. The α = 1.5-curve is more peaked and gives a higher maximum value than the curve for $\alpha = 1$, and the curve for $\alpha = 2$ is the most peaked of all. This is even more strikingly brought out in Fig. 9(B), where the three pulses are plotted so as to have the same peak value.

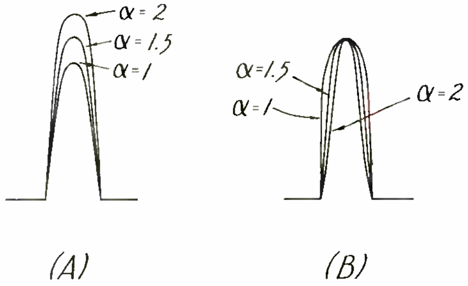


Fig. 9.—Difference in pulse shape for α = 1, 1.5, and 2.

The d-c and fundamental components will vary somewhat for all three pulse shapes, but for the same peak value, the variation is not very marked for a given angle of flow. Nevertheless, the curves of Fig. 10 indicate the differences in these components for the three values of α.

The reader may wonder why a value of $\alpha = 2$ is included. The reason is that the grid current, during its small angle of flow, obeys approximately the *square* law ($\alpha = 2$) with regard to positive grid voltage. From this follows a rough but reasonable approximation with regard to the plate current i_b.

Since $i_b = i_s - i_c$, and since i_s follows approximately the 3/2-power law, and i_c the square law, it turns out that i_b follows approximately a linear relationship. In other words, with respect to i_b, Eq. (2) can be replaced by

$$i_b = K\,(e_c + e_b/\mu) \qquad (3)$$

In one Class C design method, the plate current is used as the starting point; in another method, the space current is used as the starting point. Which method is to be used depends upon the data furnished. If the tube curves or similar information gives the maximum plate current that the tube can supply, then the plate-current method can be employed.

But if the information is given in the form of maximum filament emission, as is sometimes the case, then the space-current method is to be employed. Very often neither value is given, but it is possible from the manufacturer's operating values to deduce one or the other magnitudes. The proper design procedure can then be followed.

PEAK CURRENT ESTIMATE.—The exponent α in Eq. (1) is theoretically 3/2 for the SPACE current. It would be exactly this value if the tube were perfectly symmetrical and had infinite emission and hence full space saturation. Checks on a number of tubes seem to indicate that a value of $\alpha = 1.2$ instead of 1.5 is closer to the correct value for actual tubes, and hence will be employed here where necessary. A value of $\alpha = 1$ will still be used for the PLATE-current component of the space current; and $\alpha = 2$ for the grid-current component of the space current. The fundamental and d-c components for the value of $\alpha = 1.2$ can be interpolated in Fig. 10 from the curves marked $\alpha = 1$ and $\alpha = 1.25$.

In designing a Class C amplifier the first step is to choose a suitable value of maximum space current I_s. The maximum value permissible is determined by the electron emission which the filament is capable of producing, and in order to use the full possibilities of the tube it is usually desirable to select the highest possible value of I_s which will not shorten the life of the tube. With tungsten filaments full emission is usually selected for Class C amplifiers and 2/3 of this value for Class B amplifiers where linearity is important.

With thoriated tungsten filaments the deterioration during life is such that a factor of safety of from three to seven is common, depending upon how well the tube is evacuated. However in pulse work **or where the life of the tube is not important, such as in a VT fuse, full emission may be used.** For oxide-coated filaments the characteristics are variable, hence larger factors of safety must be employed.

After an appropriate value of maximum space current has been determined one next selects a combination of maximum grid voltage e_{cmax}, and minimum plate voltage e_{bmin} that will draw the total space current. As explained previously, e_{cmax} must not exceed e_{bmin} if excessive grid current is to be avoided, hence in practice e_{bmin} is made approximately twice e_{cmax}, for smaller tubes it will be somewhat less and for larger tubes it may be increased to as high as five times e_{cmax}, depending upon the desired power output and efficiency.

A complete set of tube characteristic curves is usually published by the manufacturer along with other data for the tube. This can be used to determine I_{smax}. On the other hand, some manufacturers publish a curve that has filament emission plotted as a function of filament current or power; in this case a value of emission can be chosen for a filament current or power that is consistent with satisfactorily long life of this element.

However, not all manufacturers give such information, and not on all tubes. They do, however, furnish operating values, such as plate-supply voltage, bias, grid drive, d-c input, r-f output, and hence indirectly the plate dissipation and efficiency. This information, even more indirectly, indicates the peak space current the manufacturer is using in his suggested operating values. This is obtained by working the design backwards; that is, by calculating from the power output, etc., what peak space current the tube has to draw to provide this power output.

"But," the student may ask, "what need is there to calculate the peak space current, if the answers are already furnished by the manufacturer?" The answer is that there is no need for such work so far as *those operating conditions* are concerned. But suppose it is desired to operate the tube at a lower plate voltage for some special application, or it is desired to operate the tube as a pulsed r-f amplifier. Then, if the peak space current can be ascertained from the usual operating conditions, the proper design for the particular application at hand can be made.

Indeed, it may be found that more output can be obtained at a reduced voltage rating than the manufacturer indicates at this rating, without exceeding the plate dissipation or grid losses, by employing a higher peak space current, or greater angle of flow, or suitable combination of the factors mentioned previously. It is such considerations that justify this assignment on the design of Class B and C amplifiers.

The procedure for determining the peak space current employed by the manufacturer in his ratings; that is, the procedure for working the design *backwards* to this value, is best summarized as follows:

STEPS IN CHECKING CLASS C DESIGN

1. First choose a value for the ratio $m = e_{bmin}/e_{cmax}$. As was indicated previously, this ratio m may vary anywhere from 1.5 to 5, depending upon the size of the tube. For small tubes, a value of from 1.0 to 3 can be chosen; for medium-sized tubes a value in the neighborhood of 3 is advisable; and for large tubes values up to 5 may be used. If the first trial leads to results inconsistent with the manufacturer's values for output power, etc., a suitably altered value of m can be tried as a second approximation.
2. Since the grid bias E_c and peak grid swing E_{gm} are given by the manufacturer in the Tube Manual, the peak positive grid swing can be found. Thus,

$$e_{cmax} = E_{gm} - E_c \tag{4}$$

Then

$$e_{bmin} = me_{cmax} \tag{5}$$

3. With the values of e_{cmax} and e_{bmin} and the tube curves found in the Manual, the peak plate current i_{bmax} and the peak grid current i_{cmax} can be found. Either the i_b - e_b and i_c - e_b curves can be used, or the so-called constant-current curves. The latter will be explained subsequently.
4. Refer now to Fig. 10. The ratio $r_1 = I_b/i_{bmax}$ and the ratio $r_2 = I_{pm}/i_{bmax}$ is plotted there for various values of the exponent α. The ratio r_1 is that of the d-c component of the plate current to its peak value, and the curve for which $\alpha = 1$ should be used. Since I_b is given in the Tube Manual, and i_{bmax} has just been determined in Step 3, r_1 can be calculated. Then this value can be located on the $\alpha = 1$ curve in Fig. 10, and the corresponding value of the angle of flow θ_p determined.
5. The ratio r_2 is that of the fundamental component I_{pm} of the plate current to the peak value. It can now be found once θ_p has been determined in Step 4. From this, the fundamental component itself can be found:

$$I_{pm} = r_2 \, i_{bmax} \tag{6}$$

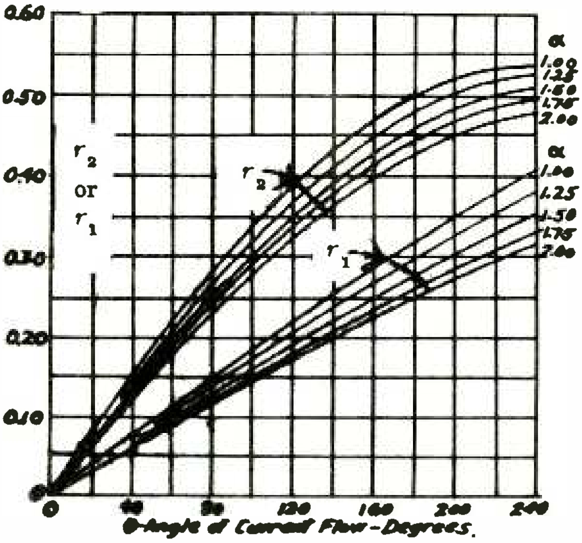
6. The power output P_o can next be determined.

$$P_o = \frac{(E_b - e_{bmin})I_{pm}}{2} \tag{7}$$

This can be compared with the value given in the Tube Manual. If the discrepancy is small, say not more than 5%, the rest of the calculations can be performed; if not, a new value of m should be chosen. If the calculated value of P_o is too high, a smaller value of m should be tried; if too small, a larger value of m. Usually a second trial is sufficient.

7. Calculate the d-c plate input power. This is simply

$$P_{dc} = E_bI_b \tag{8}$$



Courtesy Terman Hdbk.

Fig. 10.—Relation between peak pulse current, d-c component, and fundamental component for a Class C amplifier for various angles of flow and for various values of α.

Then the plate dissipation can be checked. It is

$$W_{pd} = P_{dc} - P_o$$

$$= E_b I_b - \frac{(E_b - e_{bmin}) I_{pm}}{2} \qquad (9)$$

8. The grid angle of flow θ_g can now be determined. This is given by the formula

$$\cos(\theta_g/2) = E_c/E_{gm} \qquad (10)$$

Fig. 11 shown how these quantities are related. The half angle $\theta_g/2$ is measured from the peak of the grid wave, so that the cosine rather than the sine of the angle is involved.

Alternately, θ_g may be found from Fig. 10. Calculate the ratio I_c/i_{cmax} and then for $\alpha = 2$, find from Fig. 10 the corresponding value of θ_g. Compare this value with the one just obtained. The discrepancy should not exceed perhaps 10%, although the grid-circuit values will not in general check as closely as the plate-circuit values.

9. Assuming the discrepancy is not too great, we can now find the ratio of the findamental component I_{gm} of the grid current to its maximum value i_{cmax}' from Fig. 10 for α - 2. Then I_{gm} can be calculated since I_{cmax} is known.

10. Finally check the grid driving power. This is

$$P_g = \frac{E_{gm} I_{gm}}{2}$$

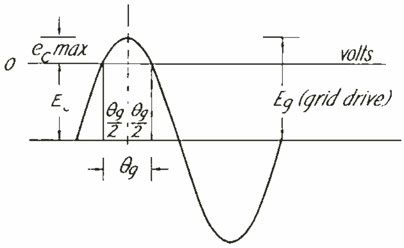


Fig. 11.—The grid current angle of flow is computed from E_c and E_g.

and should compare within perhaps 10% with that given in the Manual. If it is too small, try a smaller initial value of m so as to obtain a somewhat higher value of I_{gm}, and of course if it is too large, try a larger value of m.

If all quantities check reasonably well, then the values of i_{bmax} and i_{cmax} are satisfactory, as is their sum i_{sm}, the peak space current. This value can now be used for any further calculations on the tube, such as at reduced plate voltage, pulse operation, etc.

DESIGN PROCEDURE.—Hence, suppose i_{sm} is found or given by the manufacturer. What are the steps in designing a Class C Amplifier? First note that besides knowing i_{sm}, we also know the allowable plate and grid dissipations, and the plate supply voltage E_{bb}, as well as the tube characteristics.

It will be of value to discuss the constant-current type of tube characteristics before putting down the steps in the design procedure, since this type of characteristic has not been discussed previously in these texts. The constant-current curves differ from the characteristic curves previously mentioned in that the plate current i_b is kept constant for any one curve, and the relationship between e_c and e_b plotted that keeps i_b constant.

To make this clearer, some fundamental considerations will have to be taken up first. In the case of a triode tube, three variables are involved: i_b, e_c, and e_b. In order to plot these properly, a three-dimensional graph is required. However, they can be plotted on an ordinary flat sheet of paper if one of the variables is kept constant at one or other of a set of values, and for each constant value, the other two variables are plotted in the form of a curve, (one being chosen as the independent variable and the other as the dependent variable). For each fixed value of the first-mentioned variable (called a PARAMETER), a curve is obtained for the relationship between the other two. The totality of fixed values assigned to the parameter gives rise to a whole set or FAMILY of curves.

If the grid voltage e_c is made the parameter, and assigned successive fixed values, the curves give the relationship between e_b and i_b. The family of curves is known as the PLATE family. If the plate voltage e_b is made the parameter and i_b plotted against e_c, a family of curves usually known as the TRANSFER CHARACTERISTIC is obtained. The third possibility is to make i_b the parameter, and then plot e_c versus e_b. The result is the CONSTANT-CURRENT family of curves, because the plate current i_b is being kept constant at one value or another.

This family of curves has an advantage over the other two for Class C calculations. The reason is that owing to the tank circuit's flywheel action, the tank voltage e_T is a sine wave 180° out of phase with the grid drive voltage e_g. Hence if one is plotted against the other, a Lissajous figure in the form of a straight line is obtained on the family of curves, as is illustrated in Fig.12 in solid lines for some hypothetical tube. It is obviously easier to draw a straight line than some unknown curved line.

Point A corresponds to e_{cmax} and e_{bmin}, and gives the peak plate current i_{bmax}, (as well as peak grid current). As the grid swings in a negative direction, the plate voltage simultaneously rises, and the path of operation is along AB, which cuts across the various curves corresponding to the various values of i_b from 35 amperes down to 0 amperes.

Note one curious feature is that the region below the curve for which $i_b = 0$ corresponds to various combinations of e_c and e_b for which i_b is at all times zero (beyond cutoff). In other words, for $i_b = 0$ the graph is not a single curve but a whole area, for which the $(i_b = 0)$-curve is the upper boundary.

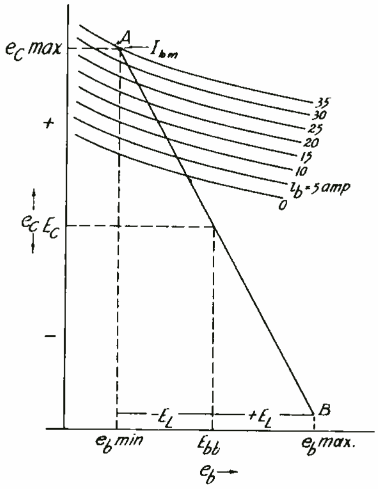


Fig. 12.—Load line on constant-current family of curves.

One further point to note is that E_b is halfway between e_{bmin} and e_{bmax}; the excursions from E_b to e_{bmin} and e_{bmax} represent the negative and positive half-cycles of the sinusoidal a-c tank voltage e_T. Thus this set of curves provides a convenient means for presenting information, as well as for graphical constructions. However, algebraic (analytical) computations will be employed in this assignment in the design procedure.

In similar fashion the grid current can be made the parameter, and the grid and plate voltages plotted against one another. For each fixed value of grid current there is obtained an e_c - e_b curve, and the collection of curves constitutes a constant-grid-current family, as shown in dotted lines in Fig. 13.

With this in mind, we can proceed with the design:

STEPS IN DESIGNING A CLASS C AMPLIFIER

1. Choose a reasonable value of $m = e_{bmin}/e_{cmax}$, and an angle of plate-current flow θ_p, in the range from 110° to 160° or thereabouts.
2. Use the constant-current family of curves, if available in order to save time. Draw a line through the origin at a slope m (to scale). Thus, as indicated in Fig. 13 OA is drawn at a slope $m = 3$. At point A, for example, $e_c = +1000$ volts and $e_b = 3000$ volts. A line joining A to the origin has the desired slope.

It crosses the constant-plate- and constant-grid-current families as shown. As one proceeds from 0 to A, the plate-current and the grid-current "labels" on the two sets of curves become larger and larger. Suppose at point B, a plate current i_{bmax} is found, together with a grid current i_{cmax}, such that $i_{bmax} + i_{cmax}$ is just equal to the peak space current i_{sm} given initially.

Then the corresponding values of e_c and e_b for this point are the desired magnitudes of e_{cmax} and e_{bmin}. In other words, these two values of voltage will draw just the right amount of i_{bmax} and i_{cmax} to total to the given value of i_{sm}. We have therefore actually determined four quantities, the peak plate current, the peak grid current, the peak positive grid swing, and the corresponding minimum plate voltage.

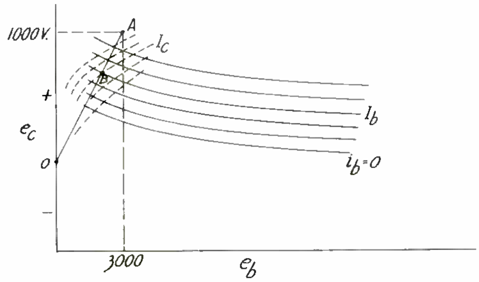


Fig. 13.—Use of constant-current curves to determine peak plate and grid currents.

3. Since a value of θ_p was assumed, use this in conjunction with Fig. 10 and $\alpha = 1$, to determine the ratios $r_1 = I_b/i_{bmax}$ and $r_2 = I_{pm}/i_{bmax}$ and thus I_b and I_{pm}.

4. Calculate the r-f output power

$$P_o = \frac{(E_b - e_{bmin})I_{pm}}{2} \qquad (7)$$

5. Calculate the d-c input power

$$P_{dc} = E_b I_b \qquad (8)$$

6. Calculate the plate dissipation

$$W_{pd} = P_{dc} - P_o = E_b I_b - \frac{(E_b - e_{bmin})I_{pm}}{2} \qquad (9)$$

Check to see that it does not exceed the manufacturer's permissible value. If it does, decrease θ_p. This also decreases the power output.

7. Now calculate the grid bias. To facilitate this computation, Fig. 14 has been prepared. Use the value of μ given in the Manual for the tube, and add to it the value of m chosen in Step 1. Then enter Fig. 14 with the value of $(\mu + m)$, proceed upward until the curve is met which has the θ_p chosen in Step 1. The corresponding ordinate is a quantity s from which E_c can be calculated. Thus:

$$E_c = \frac{se_{cmax} + E_b}{\mu} \qquad (12)$$

8. Calculate the peak r-f voltage. This is

$$E_{gm} = E_c + e_{cmax} \qquad (13)$$

9. Calculate θ_g from the formula:

$$\cos \theta_g/2 = E_c/E_{gm} = E_c/(E_c + e_{cmax}) \qquad (10)$$

10. Now, from Fig. 10, for $\alpha = 2$ and the value of θ_g determined in Step 9. find the d-c and fundamental grid-current ratios, and calculate I_c and I_{gm}.

11. Calculate the grid driving power

$$P_g = E_{gm} I_{gm}/2 \qquad (11)$$

12. Calculate the portion of this power (coming from the preceding r-f driver stage) that is consumed in the bias source. This is

$$P_c = E_c I_c \qquad (14)$$

13. Calculate the power dissipated on the grid. This is

$$W_{gd} = P_g - P_c = (E_{gm} I_{gm}/2) - E_c I_c \qquad (15)$$

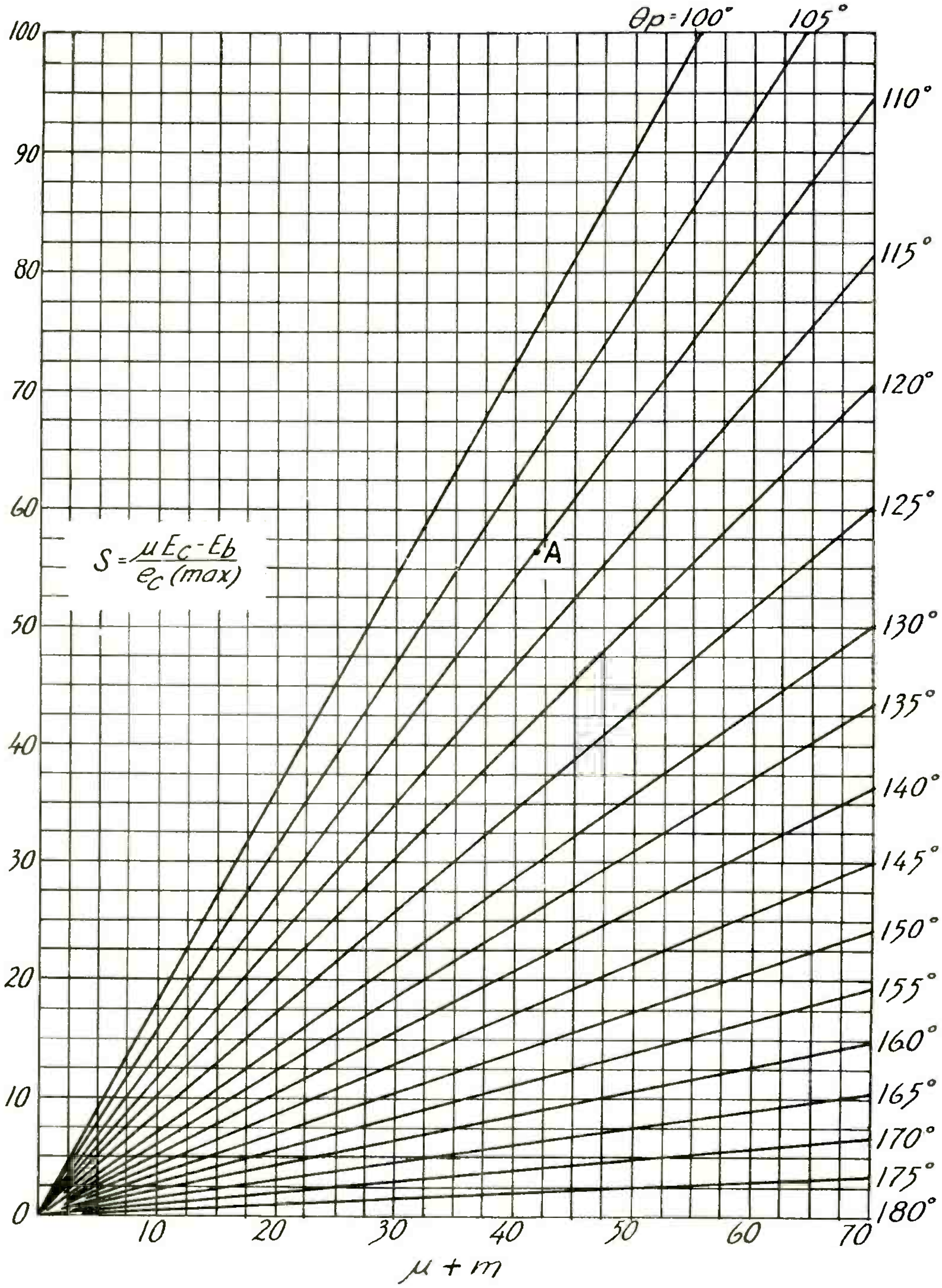


Fig. 14.—Plot of two factors used in Class C Amplifier design with the angle of flow as a parameter.

14. Calculate the tank load impedance:

$$Z_T = \frac{E_b - e_{bmin}}{I_{pm}} \qquad (16)$$

15. Calculate the plate-circuit efficiency. This is

$$Eff = P_o/P_{dc} \qquad (17)$$

ILLUSTRATIVE EXAMPLE.—The above procedure will be clearer after the following illustrative example has been presented. Assume a Type 826 tube. The manufacturer furnishes a top rating employing E_b = 1,250 volts, E_c = 125 volts, and forced-air cooling under ICAS (Intermittent Commercial and Amateur Service). An r-f power output of approximately 120 watts can be obtained, with a driving power of approximately 7.7 watts. The peak grid drive E_{gm} is 245 volts; the d-c plate current I_b = 125 ma.; the d-c grid current is approximately 35 ma, and the permissible plate dissipation is W_{pd} = 75 watts maximum under ICAS conditions, and 60 watts maximum under CCS (continuous commercial service) operation.

It will now be of interest to find the peak space current employed by the manufacturer to obtain the output, etc. Step 1. Since the tube is a small one, a factor of m = 1.5 will be tried first.

Step 2. Then $e_{bmin} = 1.5\, e_{cmax} = 1.5 \times 120 = 180$ volts. In Fig. 15 are shown the plate and grid current characteristics for the tube. Unfortunately, the Tube Manual used (RCA) does not furnish constant-current characteristics, but those shown in Fig. 15 will do almost as well.

Step 3. For e_{bmin} = 180 volts and e_{cmax} = 120 volts, the peak plate and grid currents are, from Fig. 15, i_{bmax} = 482 ma. and i_{cmax} = 184 ma. respectively.

Step 4. Since I_b = 125 ma., and i_{bmax} = 482 ma., the ratio $r_1 = I_b/i_{bmax}$ is equal to

$$r_1 = 125/482 = 0.259$$

From Fig. 10, for $\alpha = 1$, θ_p comes out to be 141°.

Step 5. Now the ratio $r_2 = I_{pm}/i_{bmax}$ can be found from Fig. 10 for $\alpha = 1$ and $\theta_p = 141°$. It is $r_2 = 0.44$, so that by Eq. (6)

$$I_{pm} = 482 \times 0.44 = 212 \text{ ma.}$$

$$= 0.212 \text{ ampere.}$$

Step 6. The power output is therefore, by Eq. (7),

$$P_o = \frac{(1250 - 180)(.212)}{2}$$

$$= 113.5 \text{ watts.}$$

This is lower than the 120 watts specified in the Manual; but the grid-circuit conditions will be checked first before trying another value of m.

Step 7. The plate d-c input power is, by Eq. (8)

$$P_{dc} = 1250 \times .125 = 156.3 \text{ watts.}$$

The plate dissipation is

$$156.3 - 113.5 = 42.8 \text{ watts}$$

which is less than the permissible amount under the ICAS rating of 75 watts. If the manufacturer's value of 120 watts is used, the plate dissipation is even less, or 36.3 watts.

Step 8. From Eq. (10),

$$\cos \theta_g/2 = 125/245 = 0.51$$

$$\theta_g/2 = 59°20' \text{ or } \theta_g = 118°40'$$

Alternatively, I_c/i_{cmax} = 35/184 = 0.1902, and for α = 2, Fig.10 indicates that θ_g must be 135°. This is of course much larger than the value of 118°40' found in Step 8, and indicates that the constants chosen were not quite correct. If m is chosen smaller, e_{bmin} will be less, and this in turn, for the given value of e_{cmax}, will allow i_{cmax} to be larger, as is evident from an inspection of the grid curves of Fig.15.

At the same time, i_{bmax} will be smaller, but to counteract this, θ_p will be larger and this, together with the lower value of e_{bmin}, will permit the r-f power output P_o to be larger. Hence the proper procedure is to use a smaller value of m. After several trials, a value of m = 1 was found acceptable. This is very small, but presumably is permissible in view of the ICAS operation.

For m = 1.0, $e_{bmin} = e_{cmax}$ = 120 volts, i_{bmax} = 445 ma, i_{cmax} = 202 ma., θ_p = 163°, which is large, and P_p = 120.4 watts, which checks the manufacturer's value. Furthermore, I_c/i_{cmax} = 35/202 = 0.1733, for which ratio and α = 2, Fig.10 shows θ_g to be equal to 119°, which is a very close check of the previous value of 118°40' found by use of Eq.(10). Also, incidentally, the plate-circuit efficiency is 120.4/156.3 = 77%, which is acceptably high.

It can therefore be assumed that the manufacturer employed a peak space current of $i_{bmax} + i_{cmax}$ = 445 + 202 = 647 ma. This can be compared with the following rule for a *thoriated* filament:

Suppose the available emission is 80 ma. per watt of heating power. Since the heating power is here 7.5 volts × 4 amperes = 30 watts; 30 × .08 = 2.4 amperes emission. However, a factor of safety of anywhere from 3 to 10 is employed; here the factor is 2.4/.647 ≈ 3.71, which is within the range mentioned. In passing, it is to be noted that a 10 per cent increase in heating power produces a two fold increase in emission, or 4.8 amperes maximum, and at least 2 × .647 = 1.3 amperes usable. This will be further discussed in the section on pulse operation.

FURTHER ILLUSTRATION.—Now consider the operation of the tube at a lower plate potential of 1,000 volts, using forced-air cooling. This will be a CCS rating. Using the cue that m = 1 and θ_p = 163° for ICAS rating, we shall employ somewhat more conservative values now. Hence, Step 1. choose m = 1.5 and θ_p = 140°.

Step 2. Since the constant-current curves are lacking here, recourse will have to be made to the curves of Fig.15, and a series of trials will be necessary. Choose as a first trial, e_{cmax} = 120 volts. Then e_{bmin} = 1.5 × 120 = 180 v. From Fig.15, i_{bmax} = 481 ma and i_{cmax} = 187 ma. Hence the total space current comes out to be i_{sm} = 481 + 187 = 668 ma. which is greater than the value of 647 ma determined in the preceding section.

Hence try a lower value of e_{cmax} = 100 v., and e_{bmin} = 1.5 × 100 = 150 volts. These yield i_{bmax} = 401 ma., i_{cmax} = 155 ma., and i_{sm} = 566 ma, by interpolating between the e = +90-volt and e = +120-volt curves. Now i_{sm} = 556 ma is too low, hence the values of e_{cmax} and e_{bmin} must be somewhere in between the values chosen.

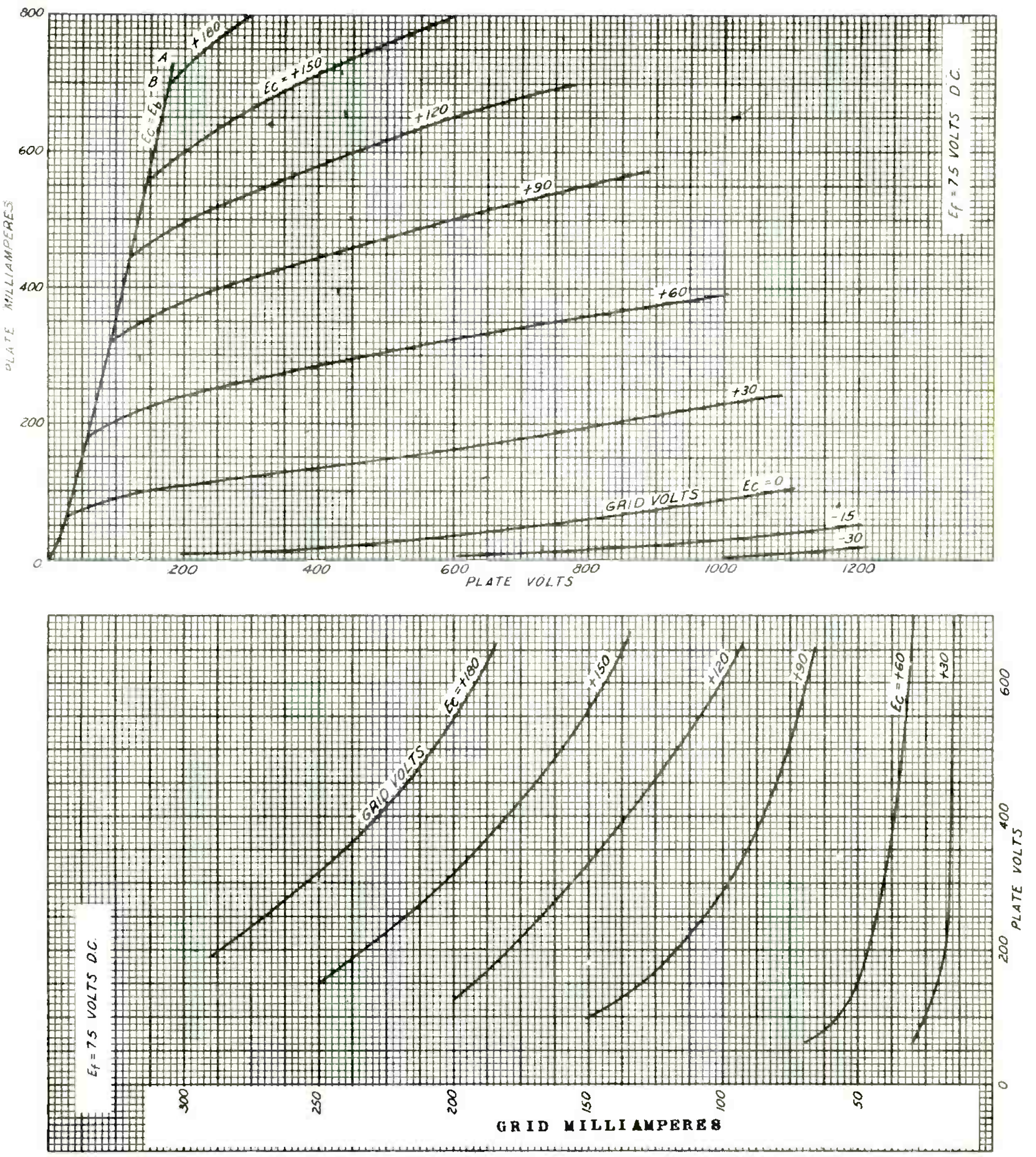


Fig. 15.—Plate-current and grid-current characteristics for a Type 826 tube.

After perhaps two or three trials, e_{cmax} = 115 volts and e_{bmin} = 172.5 volts are found to be suitable, in that i_{bmax} = 460 ma., i_{cmax} = 172.5 ma., and i_{sm} = 632.5 ma. which is reasonably close to 647 ma. (It is to be appreciated that one is not forced to use the peak value of i_{sm} if one does not choose to do so.)

Step 3. From Fig. 10, for $\alpha = 1$, $r_1 = 0.26$ and $r_2 = 0.44$. Then I_b = 460 × .26 = 119.8 ma., and I_{pm} = 460 × .44 = 203 ma.

Step 4. From Eq. (7),

$$P_o = \frac{(1000 - 172.5)(.203)}{2}$$

$$= 84 \text{ watts.}$$

Step 5. From Eq. (8),

$$P_{dc} = (.1198)(1000) = 119.8 \text{ watts.}$$

Step 6. From Eq. (9), W_{pd} = 119.8 - 84 = 35.8 watts, which is well within the limit of 60 watts.

Step 7. The value of mu is 31, and m = 1.5, so that $(\mu + m)$ = 31 + 1.5 = 32.5.

For this value of $(\mu + m)$, and $\theta_p = 140°$, Fig. 14 yields a value of s = 16.8. Then, from Eq. (12),

$$E_c = \frac{16.8 \times 115 + 1000}{31} = 94.6 \text{ volts}$$

Step 8. The peak r-f voltage is, by Eq. (13),

$$E_{gm} = 115 + 94.6 = 209.6 \text{ or } 210 \text{ volts.}$$

Step 9. From Eq. (10)

$$\cos \theta_g/2 = \frac{94.6}{210} = 0.451,$$

from which $\theta_g/2 = 63°10'$, and $\theta_g = 126°20'$.

Step 10. From Fig. 10, for $\alpha = 2$ and $\theta_g = 126°20'$, we find $I_c/i_{cmax} = 0.175$ and $I_{gm}/i_{cmax} = 0.33$. Then I_c = 172.5 × .175 = 30.2 ma., and I_{gm} = 172.5 × .33 = 56.9 ma.

Step 11. The grid driving power is then, by Eq. (11),

$$P_g = 210 \times .0569/2 = 5.96 \text{ watts.}$$

Step 12. From Eq. (14), the amount of the above power consumed in the bias source is

$$P_c = (94.6)(.0301) = 2.86 \text{ watts.}$$

Step 13. Hence, from Eq. (15), the driver power dissipated in the grid is

$$W_{gd} = 5.96 - 2.86 = 3.10 \text{ watts.}$$

Step 14. Finally, from Eq. (16), the tank circuit impedance, as presented to the tube, is

$$Z_T = \frac{(1000 - 172.5)}{.203} = 4075 \text{ ohms}$$

It will be of interest to compare these results with those furnished by the manufacturer for 1000-volt operation using forced-air cooling of the tube. These are summarized in the following table.

COMPARISON OF RESULTS

	TEXT DESIGN		MANUFACTURER'S VALUES	
I_b	119.8	ma.	125	ma
P_o	84	watts	86	watts
P_{dc}	119.8	watts	125	watts
W_{pd}	35.8	watts	39	
E_c	-94.6	volts	-70	volts
E_{gm}	209.6	volts	183	volts
I_c	30.2	ma	35	ma
P_g	5.96	watts	5.8	watts
P_c	2.86	watts	2.45	watts
W_{gd}	3.10	watts	3.35	watts
Eff.	70.2	%	68.8	%

It will be observed that the values in the text design are in all cases lower than the manufacturer's values, although in most cases the values are quite close. For example, the power output is within two watts of that given by the manufacturer.

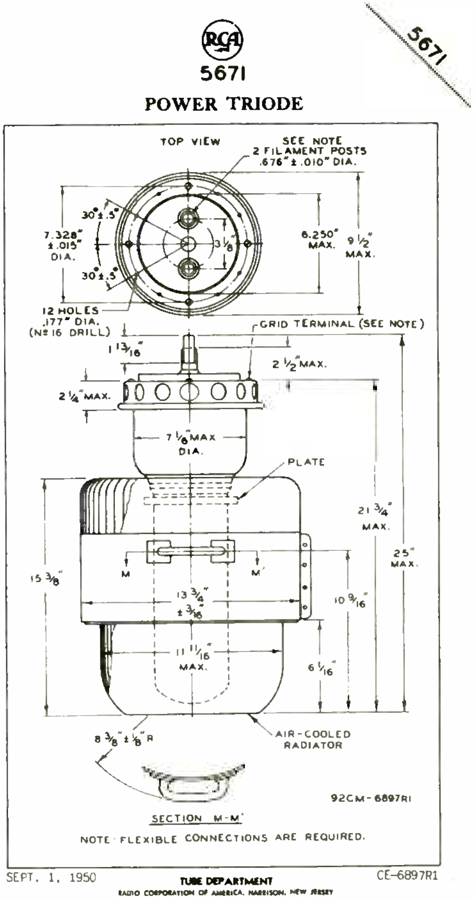
Apparently a smaller angle of flow was used in the text than that employed by the manufacturer. This shows up in the fact that the efficiency is somewhat higher, the power output is slightly less, as is also the d-c power input. As a result, the grid bias is higher and the peak grid swing is greater, yet the driving power is but slightly higher because the d-c grid current is less, and the grid dissipation is actually lower, because most of the driving power is absorbed in the bias supply.

It is to be appreciated that there is no unique solution to a Class C amplifier design, and that a different choice for the variables can produce results quite close to one another. No attempt was made to make the text design fit that indicated by the manufacturer, since it appeared to be just as satisfactory.

SECOND EXAMPLE.—It will be of interest to go through the design of a larger tube, namely the Type 5671 power triode. This can furnish an output of 70 KW for a plate potential of 15,000 volts (Class C Telegraphy); it employs forced-air rather than water cooling. Fig. 16 is an outline drawing showing its shape and dimensions. For this tube the manufacturer states that the maximum peak cathode or space current is i_{sm} = 50 amperes. Working backwards from the operating data, it will be found that the peak value used for E_b = 15,000 volts is only about 37.5 amperes.

This indicates that only about 75% of the maximum value of i_{sm} has been used for Class C Telegraphy operation; this is a useful fact to remember in Class C design. In the design to follow, 37.5 amperes rather than 50 amperes will be used.

A design employing 10,000 volts on the plate will now be worked out:


5671

POWER TRIODE

SEPT. 1, 1950

TUBE DEPARTMENT

RADIO CORPORATION OF AMERICA, HARRISON, NEW JERSEY

CE-6897R1

Fig. 16.—Outline drawing of the Type 5671 Power Triode, showing its outline and dimensions.

Step 1. Choose $m = 3$, $\theta_p = 120°$ as reasonable values for a large tube.

Step 2. Fig. 17 gives the constant-current curves for this tube. On these curves a line with a slope corresponding to $m = 3$ is drawn as shown. One point is $e_c = e_b = 0$, another point is $e_c = 1000$ v., $e_b = 3 \times 1000 = 3000$ volts. Choose a point along this line for which $e_c = 700$ volts, and $e_b = 3 \times 700 = 2100$ volts. The plate current is 27.8 amperes; the grid current is 6.05 amperes; and the total space current is therefore $27.8 + 6.05 = 33.85$ amperes, which is less than 37.5 amperes and hence too low.

Consequently, a higher point must be chosen along this line. After one or two trials, a point is found for which $e_c = 770$ volts, $e_b = 2310$ volts, $i_b = 30.7$ amperes, and $i_c = 6.75$ amperes. The space current is $30.7 + 6.75 = 37.45$ amperes, which is practically the desired value. Hence e_{cmax} will be taken as 770 volts, e_{bmin} as 2310 volts, $i_{bmax} = 30.7$ amperes, and $i_{gmax} = 6.75$ amperes.

Step 3. From Fig. 10, for $\alpha = 1$, $r_1 = 0.22$ and $r_2 = 0.39$. Hence

$$I_b = 30.7 \times .22 = 6.76 \text{ amperes,}$$

and

$$I_{pm} = 30.7 \times .39 = 11.98 \text{ amperes.}$$

Step 4.

$$P_o = \frac{(10000 - 2310)(11.98)}{2} = 46.1\text{KW.}$$

This compares favorably with 55KW at 12,500 volts operation, as given in the Tube Manual.

Step 5. $P_{dc} = 10000 \times 6.75 = 67.6$KW.

Step 6. $W_{pd} = 67.6 - 46.1 = 21.5$KW, which is less than the permissible value of 25KW as given by the manufacturer.

Step 7. $\mu = 39$, $m = 3$, $(\mu + m) = 42$. From Fig. 14, for $\theta_p = 120°$, $s = 42$ (it will be observed that for the 120° curve, $s = \mu + m$). Then

$$E_c = \frac{42 \times 770 + 10000}{39} = 1088 \text{ volts}$$

Step 8. $E_{gm} = 1088 + 770 = 1858$ volts.

Step 9. $\cos \theta_g/2 = 1088/1858 = 0.585$; $\theta_g/2 = 54°10'$, and $\theta_g = 108°20'$.

Step 10. From Fig. 10, for $\alpha = 2$ and $\theta_g = 108°20'$, $I_c/i_{cmax} = 0.155$, and $I_{gm}/i_{cmax} = 0.29$. Then $I_c = 6.75 \times .155 = 1.047$ amperes, and $I_{gm} = 6.75 \times .29 = 1.958$ amperes.

Step 11. $P_g = 1858 \times 1.958/2 = 1.82$KW.

Step 12. $P_c = 1088 \times 1.047 = 1.14$KW.

Step 13. $W_{gd} = 1820 - 1140 = 680$ watts. This is somewhat greater than the 540 watts dissipation incurred at 15,000 volts operation; in the absence of any restriction given by the manufacturer, this can be regarded as satisfactory. However, it will be left as a problem in the examination to work out the design for $m = 3.5$ and $\theta_p = 120°$, in which case it will be found that the grid dissipation will be lower.

The reason is that primarily a higher m means a higher e_{bmin} and lower e_{cmax}, which in turn means a lower grid current i_{cmax} for the same i_{bmax}. The lower grid current will be found to yield a lower driving power and grid dissipation.

Step 14. The plate tank impedance is

$$Z_T = \frac{10000 - 2310}{11.98} = 642 \text{ ohms.}$$

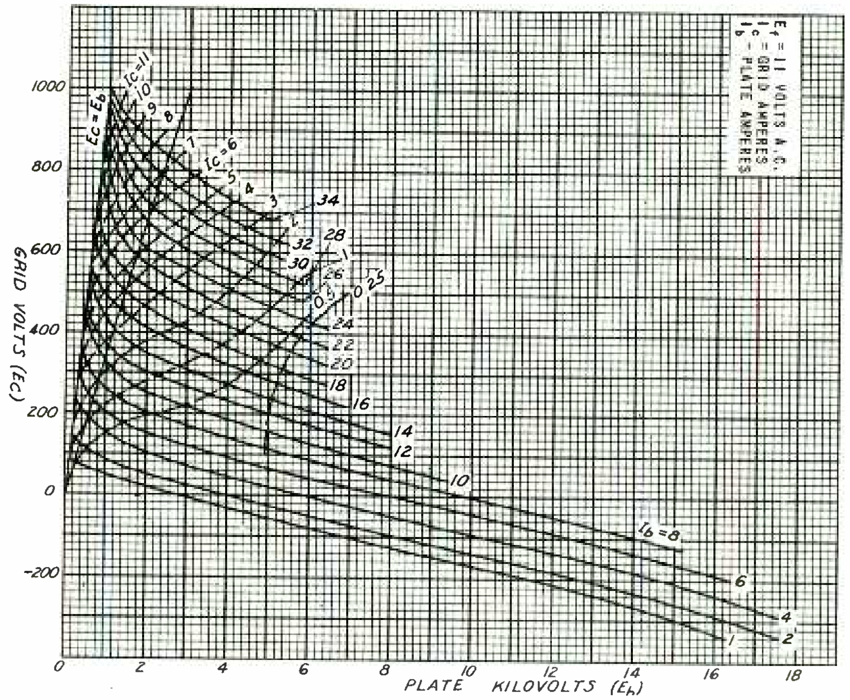


Fig. 17.—Constant-current characteristics for the Type 5671 tube.

Step. 15. The plate-circuit efficiency is 46.1/67.6 = 68.3%, which is satisfactory.

The values all compare favorably with those given by the manufacturer for 12,500-volt operation.

PULSED OPERATION

GENERAL CONSIDERATIONS.—There are many applications of Class C amplifiers in which the modulation or intelligence, as it is called, consists of a series of pulses. By this is meant that the amplifier is "turned on" or energized for a given period of time involving a number of r-f cycles, then it is shut off for another fixed period of time, and this sequence is repeated over and over again.

Fig. 18 illustrates this process. A group or train of pulses occuring for a period of say T_1 milliseconds is followed by a quiescent period of T_2 milliseconds. The entire time for the pulse cycle is $T = T_1 + T_2$. The envelope of the r-f wave has the required pulse shape; after detection this is the output obtained.

Such pulsed operation is employed in radar, loran, shoran, pulse-code and pulse-time modulation, distance-measuring techniques in aeronautical radio applications, etc. In the u-h-f bands special tubes such as klystrons and magnetrons are employed, but in the lower portions of the spectrum ordinary triodes and pentodes are used, although they may be of special construction to operate properly in the ultra high frequency band.

There is a special type of pulse operation in which the tube is expendable, and is to be operated at maximum possible output for at most a day or two, or perhaps for even a few hours. An example might be portable transmitters dropped behind the enemy's lines to jam their radar transmitters; other military tactics also have need for such operation.

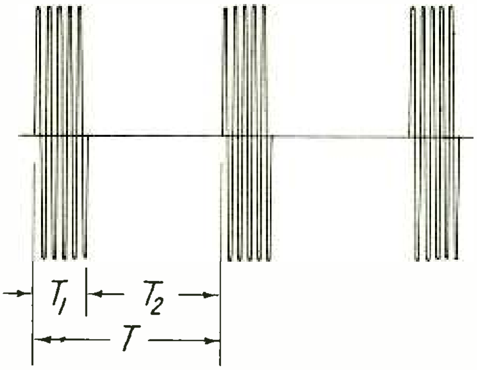


Fig. 18.—Pulsed operation of a Class C amplifier, showing the groups of waves comprising the pulses.

Although for such applications it may pay to develop special tubes, often the urgency of the situation or other factors necessitate using standard available tubes. In such cases it is desirable to know the maximum emission possible, perhaps with over-voltage on the cathode, and perhaps with the plate or grid dissipation somewhat in excess of the value normally permitted by the manufacturer.

Indeed, in many cases it has been found that under u-h-f operation some particular part of the tube may fail, such as the grid seal in the glass envelope, and special air-cooling will be required for this member. Life tests must normally be made before the design can be released.

The reason why maximum emission is so important in pulsed operation is that this, rather than plate-dissipation considerations, limit the output of the tube. Owing to the intermittent nature of pulse operation, the plate dissipation tends to be low in spite of the large momentary output when the tube is pulsed, and the momentary output is limited practically entirely by the emission from the cathode. This brings up first the question of the duty cycle, which will now be discussed.

DUTY CYCLE.—From an ordinary common sense viewpoint it is evident that if the pulses have 50 per cent of the on-off width, so that the transmitter is on only half the time, the power input, power output, and the plate dissipation will be only half of that for continuous operation. In Fig. 18, if $T_1 = T_2 = T/2$, then the various powers calculated by the methods described in the preceding sections, and which refer to continuous operation, must be modified to give the actual, average powers, which in this case will be but half of these values. The duty cycle is then said to be fifty per cent; the *average* power is but half of the *peak* power.

In the more general case, where T_1 and T_2 are unequal, (and in general T_1 is less than T_2), the duty cycle can be calculated as follows. Let P_m be the peak power while the tube is operative. Since power is the time rate of producing energy, the energy developed during the pulse cycle will be

$$E_n = P_m T_1 \qquad (17)$$

This amount of energy is then averaged over the entire cycle by dividing by T to give the **AVERAGE RATE OF ENERGY PRODUCTION** or **AVERAGE POWER.**

Thus,

$$P_{avg} = \frac{P_m T_1}{T} \qquad (18)$$

and the duty cycle can be defined as

$$\text{Duty cycle} = T_1/T \qquad (19)$$

For example, suppose a pulse of 100 μsecs. occurs at the rate of 1000 times per second. Then $T_1 = 100$ μsecs., and $T = 1/1000 = 0.001$ sec. $= 0.001 \times 10^6 = 1000$ μsecs. The duty cycle is then 100/1000 = 0.1 or 10 per cent. The average power is then one-tenth of the peak power of the tube.

Suppose the tube has an allowable plate dissipation of 75 watts. This means an AVERAGE plate dissipation of 75 watts. The plate dissipation during the time the tube is pulsed into operation can be 1/0.1 = 10 times as great or 75 × 10 = 750 watts for a duty cycle of ten per cent.

The significance of this is that ordinarily tubes are designed in such manner that the various characteristics are fairly well coordinated. For example, if the allowable plate dissipation is 75 watts, then the peak emission and plate voltage are usually such that not very much more than this dissipation will be incurred in anywhere near normal operation with reasonable angle of flow, etc.

Hence, if in pulsed operation, 750 watts instantaneous plate dissipation is permissible during the intervals when the tube is operative, it may be that such dissipation cannot be attained by the tube simply because the plate voltage cannot be made high enough, or the emission cannot be made large enough to reach such momentary high levels of operation.

In such a case, for small increases in the momentary plate dissipation and power output, the tube will run unnecessarily cool. Means must be found to work the tube harder. Perhaps the plate voltage can be greatly increased without glass seals breaking down prematurely, where prematurely may mean before a few hours operation in an expendable unit.

Perhaps a blower can be used to direct air principally against glass seals needing this extra cooling, in which case continuous and extended operation may be possible. Or perhaps, in an expendable application, the filament power may be increased with a resulting large increase in filament emission and peak power output, etc. It should be recognized, however, that duty cycle considerations hold only for "on" intervals that are relatively short, say 0.1 second or less. If the tube is operative for more than 0.1 second continuously, then its small heat storage capacity, particularly that of the grid wires, will make that electrode overheat. Consequently a suitable correction factor must be applied that can be perhaps best determined experimentally, whether by the designer or the tube manufacturer.

If, in some special pulse application, the pulses have each a duration exceeding 2.5 seconds, the tube must be considered as being in continuous service; i.e., the duty cycle must be considered as being 100 per cent. However, these are special and rare cases; most pulse operations require pulses less than 0.1 second each in duration. The following example will make these more usual operating considerations clearer to the reader.

EXAMPLE OF PULSED OPERATIONS.— In a preceding section the c-w (continuous-wave) operation of a Type 826 tube was analyzed, and at that time it was pointed out that the peak space current value of 647 ma presumably employed by the manufacturer was considerably less than the 2.4 amperes emission available from a thoriated filament consuming 30 watts of power.

It will be of interest to study the behavior of this tube under pulsed operation. For convenience, assume a 10 per cent duty cycle; this is a representative value. Previously it was found that if E_b = 1250 volts, 120 watts output could be obtained under ICAS operation, and the plate dissipation would be 42.8 watts and hence considerably less than the 75 watts permitted by the manufacture.

If the tube is pulsed to these same values with a 10 per cent duty cycle, the output and plate dissipation will be reduced to 12 and 4.28 watts respectively. Obviously, the tube should be "worked harder" in order to obtain pulsed results somewhere comparable to the previous c-w operation.

It may be argued that even though the duty cycle is low the tube, when operating, is still delivering a large amount of power which can overide the attendent noise just as well as during c-w operation. For example, in radar it may be felt that a given peak power will produce a pulse height on the cathode ray tube screen which will stick up above the noise regardless of how long the pulse is on; i.e., regardless of the duty cycle.

A careful analysis of radar operation reveals, however, that the ability to detect a target depends upon the average rather than the peak power in the pulse. Much the same results are found to be true in other pulse operations. This means that a tube operating under pulsed conditions should be worked as hard as in c-w operation; that is, the plate dissipation, etc., should be comparable if this is possible to attain.

One way to increase the output is to increase the plate angle of flow θ_p. This has the disadvantage of reducing the efficiency; i.e., the input power goes up faster than the output power, so that the plate dissipation rises rapidly, too. To put it another way, increasing θ_p increases the input power and plate dissipation more markedly than it does the output power, which is what it is desired to increase. Moreover, in the case of the 826 tube, the value of θ_p presumably employed by the manufacturer is 163° and therefore on the large side, so that not much further increase can be had. Indeed, perhaps a smaller value had better be employed to avoid excessive grid dissipation.

This all points to the fact that to obtain more output, a higher peak space current must be obtained. Also, if the plate voltage can be raised say to 1500 volts, more output and at a higher efficiency can be obtained. It was mentioned previously that a thoriated filament can emit 80 ma. per watt of heating, so that for 30 watts heating as in the case of the 826 tube, 30 × .08 = 2.4 amperes emission can be expected.

Note that this is the amount of emission that can be expected over the life of the tube, not just when the tube is new. The 647 ma. used previously for this tube represents a large factor of safety that is not needed for expendable operation.

Furthermore, if the filament heating power is increased 10% to 33 watts, DOUBLE the emission can be expected, or 2 × 2.4 = 4.8 amperes. Assume therefore that the filament heating power is increased 10 per cent, and that the peak space current will be at least 3.5 amperes. This will represent a factor of safety that may not be necessary in expendable operation, but takes care perhaps of variations in tubes.

Assume further that 1500 volts can be applied to the plate. This may require either the sanction of the manufacturer or, in the event he does not know whether or not such operation is feasible, actual tests on several tubes to see if this voltage can be applied. In the event that one particular tube seal breaks down, perhaps additional forced-air cooling of this part of the tube may eliminate this difficulty.

EXTRAPOLATION TO HIGHER PEAK CURRENTS.—In proceeding with the design, it is immediately discovered that the tube curves do not extend to such high values of plate and grid currents. This means that the design will be approximate and merely indicate the possible power output etc. Experimental tests will then be necessary to indicate whether or not the initial assumptions were correct.

A series of estimates will therefore have to be made, and if the results are not particularly accurate, they at least point the way in an uncharted area of operation. Experimental checks can then be made to test the accuracy of the design and to indicate what modifications, if any, are required.

It was stated previously that the space current i_s varies as the 1.2 power of the grid and plate voltages, or more explicitly,

$$i_s = k \left(e_c + e_{b/\mu}\right)^{1.2} \qquad (20)$$

Child's law gives a value of 1.5 for the exponent, but checks on actual tubes indicate that α = 1.2 is more accurate. For any given tube this relationship can be checked, if desired, but the value of 1.2 will be used in the text as sufficiently accurate for most purposes.

In Fig. 19 are shown the $e_b - i_b$ and $e_b - i_c$ characteristics for the 826 tube once more. The line marked OBA is known as the diode line; inspection will show that the plate and grid voltages are approximately equal along this line. It represents the "knee" of the characteristics just as in the case of a screen-grid tube, where such "knees" are present even for negative control-grid voltages, owing to the presence of a positive screen grid. Here, in the case of a triode, the knee shows up only where the control grid is positive.

The reason in every case is that for values of e_b less than the positive grid (whichever grid is positive) the grid robs the plate of electrons, thereby causing the plate current to drop precipitously and thus produce a knee in the curve.

Along the diode line m = 1 since $e_b = e_c$. Consider point B, where $e_b = e_c$ = 180 volts. The plate current i_b = 700 ma. From the $e_b - i_c$ curves, i_c = 292.5 ma for $e_b = e_c$ = 180 volts. Hence $i_s = i_b + i_c$ = 993 ma. To reach 3.5 amperes (= 3500 ma) along the diode curve, one would have to move up a distance that comes out to be e_b

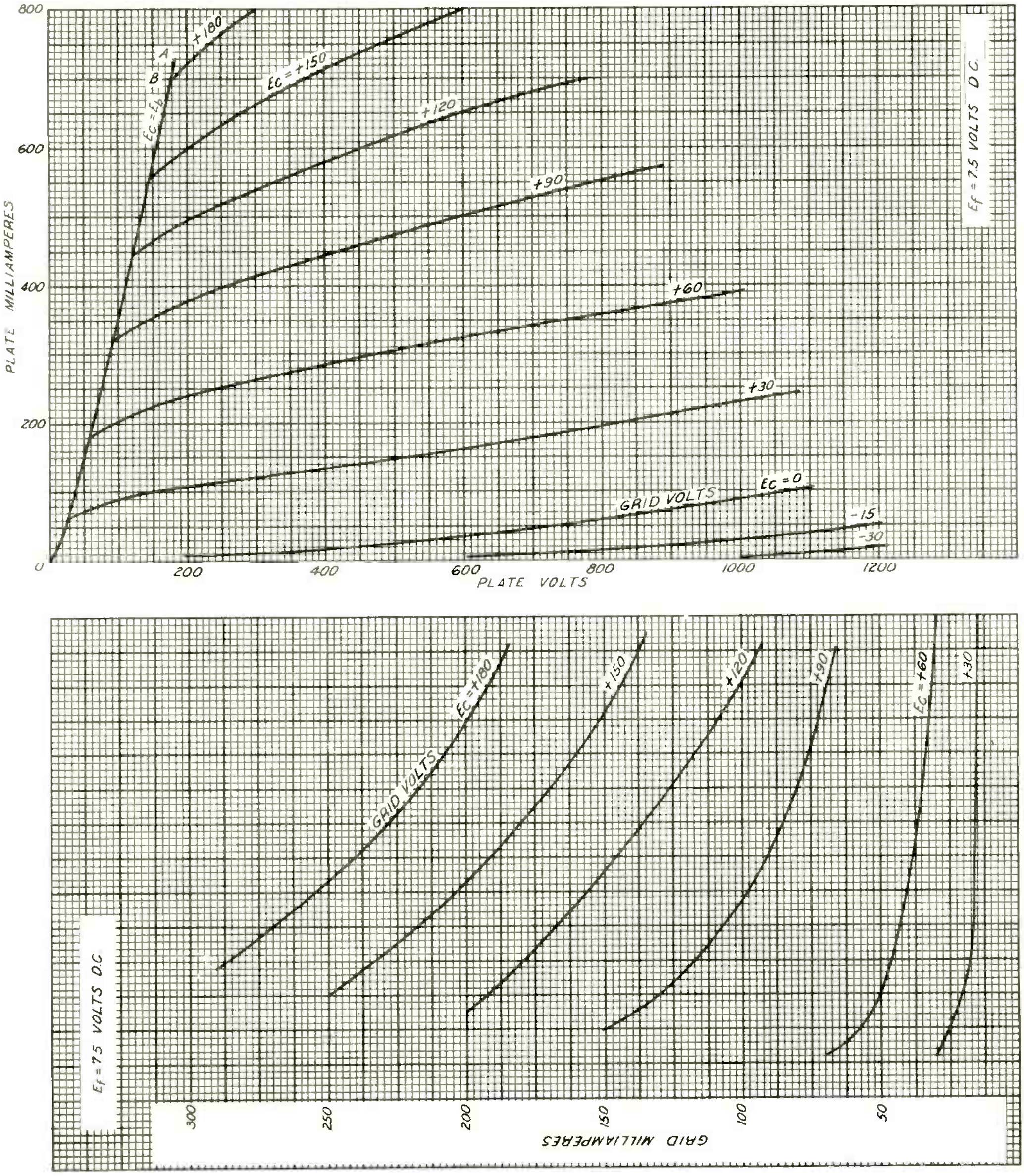


Fig. 19.—Characteristics for the Type 826 tube.

$= e_c = 515$ volts.

This can be found from the 1.2-power law as follows. Since the grid and plate voltages are equal along the diode curve, call their common value e. Then

$$\left(\frac{e}{180}\right)^{1.2} \times 993 \text{ ma} = 3500 \text{ ma.}$$

or

$$e^{1.2} = (180)^{1.2} \times 3500/993$$
$$= (180)^{1.2}(3.53)$$

Taking logarithms of both sides, there is obtained

$$1.2 \log e = 1.2 \log 180 + \log 3.53$$

(remembering that the logarithm of a product is equal to the sum of the logarithms of the factors).

$$\log e = [(1.2)(2.2553) + 0.5478]/1.2$$
$$= 2.7118$$

$$e = \text{anlg } 2.7118 = 515 \text{ volts.}$$

This means that to draw a space current of 3.5 amperes, the grid and plate voltages, if maintained equal, will each have to be 515 volts. Ordinarily, the plate voltage is made m times the grid voltage, where m varies from one for smaller tubes to three for larger tubes. The 826 may be regarded as a smaller tube, and a value of $m = 1$ will be employed. It will be recalled that this was the value used by the manufacturer in c-w operation).

If it is desired that $m = 1$, then $e_b = e_c = 515$ volts will be the correct values to be used. However, assume that a value of $m = 3$ is desired. This will indicate the procedure to be followed for larger tubes, and will also bring out in this example why $m = 1$ is a better value to be used here.

DETERMINATION OF TUBE MU.—Before proceeding any further, the actual mu in the positive-grid region will have to be ascertained. It very often is half the value obtained in the negative-grid region, which is the value normally given in the tube manual. However, the mu refers to the change in plate voltage that just balances an opposite change in grid voltage and leaves the SPACE current unchanged.

In the negative-grid region, the space and plate currents are identical; $i_b = i_s$. But in the positive-grid region, the space current exceeds the plate current by the grid current; $i_s = i_b + i_c$. Hence care must be exercised in determining the mu on the plate current curves.

The procedure is as follows. In Fig. 20 are shown the $e_b - i_b$ characteristics for the 826 tube. The +150-volt and +120-volt curves are used. Refer back to Fig. 19 for a moment and inspect the grid-current curves. It will be noted that the grid current drops rapidly as the plate voltage increases, and from about 400 volts and up, the grid current is a relatively small fraction of the space current.

Hence, determine the mu of the tube in this range of plate voltage. As shown in Fig. 20, the 700-ma abscissa is used; i.e., the plate current will be assumed constant at a value of 700 ma. for various plate and grid voltages. For a grid potential of +150 volts, 375 volts are required on the plate. If the grid potential is lowered to +120 volts, then the plate potential must be raised to 780 volts in order to maintain the plate current at 700 ma.

The mu of the tube in this region of operation is then

$$\mu = \frac{780 - 375}{150 - 120} = 13.5$$

This is slightly less than half of the value of 31 given in the Manual; the latter value will be obtained if one performs a similar measurement in the negative grid region.

The value of μ = 13.5 can be used; however, a value of 31/2 = 15.5 or half of the value given in the manual is satisfactory. The value of the mu to be used in determining $e_{b\,min}$ and $e_{c\,max}$ should be either that given in the manual or half that value. The procedure just described is merely to see if half or the full value should be used,

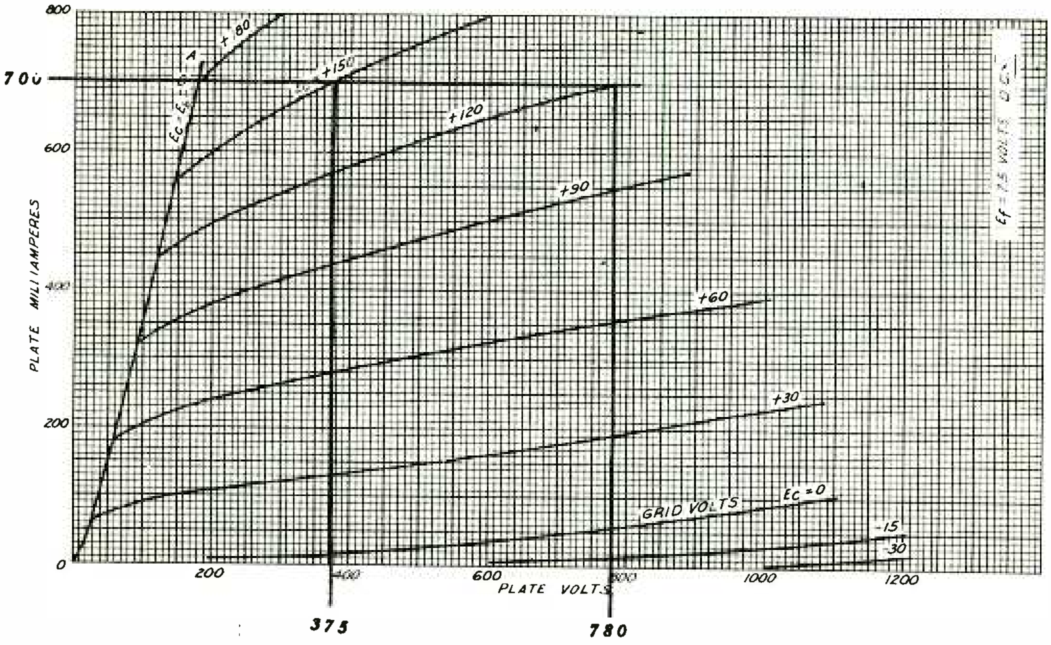


Fig. 20.—Method of graphically determining the mu of a tube in the positive-grid region.

and the determination should be made at plate voltages where the grid current begins to level off; which means at plate voltages that are to the right of the diode line.

Hence a value of mu = 15.5 will be employed. We can say that we have an equivalent single voltage $E = (\mu e_c + e_b)$ which acting at the plate of the tube in the absence of the grid, causes the same space current to flow as e_c applied to the grid and e_b applied to the plate of the tube.

For $m = 1$, and $e_c = e_b = 515$ volts, we have

$$E = (15.5)(515) + (515) = 8498 \text{ volts.}$$

If m is different from unity, the same value of E must be obtained to draw the same space current of 3.5 amperes. That is, in general

$$E = \mu e_c + m e_c = (\mu + m)\, e_c \qquad (21)$$

We just determined E to be 8498 volts in the case of $m = 1$, by use of the diode line. If m is to be three, then from Eq.(21)

$$8498 = (15.5 + 3)\, e_c$$

or

$$e_c = 8498/18.5 = 460 \text{ volts}$$

or less than the previous value of 515 volts. But now e_{bmin} must be $3 \times 460 = 1380$ volts, or too uncomfortably close to the applied "B" supply potential of 1500 volts! This is of course undesirable, and means that where both e_{cmax} and e_{bmin} must be high in order to draw maximum emission current, any attempt to make e_{bmin} many times e_{cmax} $(m>>1)$ runs into the difficulty that e_{bmin} may be too close to or even exceed the applied "B" potential.

It may be that a value of $m = 1.5$ will be satisfactory, and even $m = 3$ for larger tubes, but the values must be checked as above in order to avoid impossible operating conditions. In the case of the 826 tube a value of $m = 1$ will be used, since this value was also presumably used by the manufacturer in ordinary c-w operation. This means that no determination of the mu in the positive-grid region is necessary; the initial value of $e_{cmax} = e_{bmin} = 515$ volts, as determined from the diode line, will be satisfactory.

CONTINUATION OF DESIGN PROCEDURE.—Hence the design starts with $E_b = 1500$ volts, $i_{sm} = 3.5$ amperes, $m = 1$, and $e_{cmax} = e_{bmin} = 515$ volts. Let $\theta_p = 150°$. Then, from Fig. 10, $r_1 = 0.27$; $r_2 = 0.455$. It now becomes necessary to find i_{bmax} and i_{cmax}. A clue to the ratio of i_{cmax} and i_{bmax} to i_{sm} can be found from their relative values at lower positive grid swings.

Thus, an examination of Fig. 19 shows that when $e_c = e_b = +180$ volts, $(m = 1)$, $i_b = 700$ ma and $i_c = 292.5$ ma., so that $i_s = 700 + 292.5 = 992.5$ ma. Then $i_b/i_s = 700/992.5 = 0.705$ and $i_c/i_s = 280/992.5 = .282$. Accordingly, when $i_{sm} = 3500$ ma, $i_{bmax} = 3500 \times .705 = 2465$ ma, and $i_{cmax} = 3500 \times .282 = 986$ ma. We can now proceed with the design.

$I_b = r_1 i_{bmax} = 2465 \times .27 = 675$ ma; $I_{pm} = r_2 i_{bmax} = 2465 \times .445 = 1120$ ma. Then

$$P_o = \frac{(1500 - 515)\ (1.12)}{2} = 550 \text{ watts}$$

while the tube is being pulsed. On a 10 per cent duty cycle, P_o (avg.) $= 550 \times 0.1 = 55.0$ watts, which is a fairly high average r-f output for pulse operation.

The d-c power input is $P_{dc} = 1500 \times .675 = 1013$ watts; on a 10% duty cycle this becomes P_{dc} (avg) $= 1013 \times 0.1 = 101.3$ watts. Note that this latter figure indicates the actual load on the plate power supply.

The plate dissipation is therefore $W_{pd} = 101.3 - 55.0 = 46.3$ watts, which is far below the 75 watts permissible under ICAS operation using forced air cooling. This is to be expected, since generally emission rather than plate dissipation limits the output of the tube.

The grid bias E_c and peak grid swing E_{gm} are next to be evaluated. First $(\mu + m) = 31 + 1 = 32$. Note that here the value for μ is that taken from the tube manual rather than half (15.5), because it represents an average value from cutoff up to the peak swing. From Fig. 14, for $\theta_p = 150°$, $s = 10.6$. Then

$$E_c = \frac{10.6 \times 515 + 1500}{31}$$

$= 225$ volts negative bias.

$E_g = E_c + e_{cmax} = 225 + 515 = 740$ volts.

The grid angle of flow is found from

$\cos \theta_g/2 = 225/740$ or $\theta_g/2 = 72°$

so that $\theta_g = 144°40'$.

Next, from Fig. 11 for $\alpha = 2$, $I_c/i_{gmax} = 0.205$, and $I_{gm}/i_{cmax} = 0.37$, whereupon $I_c = 1000 \times .205 = 205$ ma., and $I_{gm} = 1000 \times 0.37 = 370$ ma. The grid input power from the driver stage is therefore $740 \times .370/2 = 137$ watts, or 13.7 watts on a 10% duty cycle. The power expended by the driver in the bias supply is $P_c = 225 \times .205 = 46.1$ watts, or 4.61 on a 10% duty cycle. Hence the grid dissipation is $W_{gd} = 13.7 - 4.61 = 9.09$ watts. This appears high, since the greatest value computed from the Tube Manual is only 3.3 watts. However, the manufacturer does not state any limit, so that there is no definite reason for assuming 9.09 watts as being excessive.

Certainly experimental runs should be made on several tubes to see if the tubes overheat for any cause and on any electrode. If the grid does overheat, a value of m greater than unity will have to be chosen, say $m = 1.5$. This will decrease the power output and increase the plate dissipation, but will decrease the grid current and grid dissipation. In this case the ratio for i_c/i_s and i_b/i_s will have to be found for the value of m chosen rather than along the diode curve for which $m = 1$.

The above analysis, it is stressed once again, is approximate owing to lack of information on the part of the manufacturer for high values of emission. Nevertheless, the procedure described should lead to reasonable values and act as a guide in the design and operation of the stage. This is a great help since it is difficult enough to know exactly what load impedance is being coupled into the tank circuit, and hence what e_{bmin} and e_{cmax} are, without having to juggle these quantities in an experimental setup in order to arrive at a satisfactory design.

"PENCIL-TRIODE" TUBE.—Although u.h.f. tubes will be taken up at a later point in the course, mention will be made here of a "pencil-type" triode tube put out by RCA for pulse operation at carrier frequencies as high as 3300 mc. It is a medium-mu

type of tube capable of producing a peak output of more than 1000 watts in plate-pulsed service at such a high frequency.

It can be used as a pulsed oscillator, power amplifier, and for cw as well as pulse operation. It is shown in Fig. 21, where some idea of its construction can be had. It measures only 2 5/16 inches in overall length, and has a double-ended, metal glass coaxial-electrode structure. The plate and cathode cylinders are each only 1/4 inch in diameter, and jut out from either side of the grid flange located at the midsection of the tube. The flange, incidentally, serves to isolate the plate and cathode circuits from one another when the tube is used in grounded-grid service.

Fig. 21.—RCA-5893 "pencil-type" triode for u-h-f pulse and c-w operation up to 3300 mc.

The "pencil-type" construction leads to low transit time, low lead inductances, and low interelectrode capacitances. This facilitates u-h-f operation, as will be explained in a later assignment.

The interesting features here are its operating voltages and power outputs in pulse and in c-w operation. As a c-w amplifier, it can deliver 6 watts at a plate potential of 300 volts and a frequency of 1000 mc.

As a pulse oscillator, the plate potential can be increased to 1750 volts! whereupon it is capable of furnishing 1000 watts up to 3300 mc., although it may be operated at pulse voltages as low as 800 volts and still maintain stable oscillations. It is specifically designed for service in low-power pulse equipment such as transponders, navigation beams, telemeters, and pulse altimeters, although it is also adaptable for use in signal generators and mobile transmitters as a c-w oscillator and a power amplifier in the UHF region.

MISCELLANEOUS CONSIDERATIONS

PUSH-PULL OPERATION.—The push-pull operation of a pair of tubes involves no particular complications. The tank circuit design will be taken up in a following assignment; here considerations of load impedance and similar matters will be discussed.

The tubes act essentially like two generators in series. Hence the load resistance that they have to face is exactly twice that either has to face by itself; i.e., if the load impedance for a single-ended Class-C stage is Z_T, that for a push-pull stage is $2Z_T$.

For example, it was found that for a single Type 5671 tube operating at 10,000 volts plate potential, Z_T had to be 642 ohms. For two tubes in push pull, it will have to be 2 × 642 = 1284 ohms.

It is often thought by some that although 2 Z_T is reflected across the entire tank coil, (see Fig. 22) the impedance seen by either tube "looking into" half the tank coil is $2Z_T/(2)^2 = Z_T/2$ owing to the 4 : 1 impedance stepdown ratio.

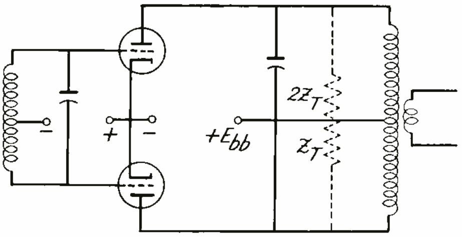


Fig. 22.—Impedance considerations in a push-pull stage.

This, however, is incorrect because it overlooks the action of the other tube upon the one under consideration. Both tubes are sharing the load $2Z_T$. If one tube alone were present, it would have to supply all the load current, but if another tube is present, it need supply only half as much load current. This in turn means that the impedance seems twice as high as it otherwise would.

Thus, if the other tube is pulled out, the remaining tube does see an impedance of $2Z_T/(2)^2 = Z_T/2$ as predicted. But if the other tube is left in the circuit, the tube just mentioned sees an impedance twice as great, or Z_T. This is the correct value for it to deliver the desired output, etc.

The bias for two tubes is of course the same as for a single tube, but the excitation voltage is doubled, and the required driver power is doubled, as well as the power expended in the bias supply. The power output is doubled, and the even harmonics cancel out, which is an advantage of this circuit. The push-pull stage also has advantages at ultra-high frequencies, but this will be covered in that section of the course.

It must be noted, however, that aside from the elimination of even harmonics, the decrease in distortion obtained in push-pull operation is not of any consequence, since the tank circuit performs this function. Moreover, the components, particularly in the case of a pi-tank circuit, are more complicated; the tank capacitor is often made in the form of two sets of rotor plates in order to maintain circuit symmetry.

For this reason parallel operation of two tubes is at least as popular as push-pull operation in the case of Class-C amplifiers. In parallel operation, the load impedance faced must be $Z_T/2$; owing to the sharing of the load between the two tubes, it appears as Z_T to either one.

The driving voltage remains unchanged, but the driving current is doubled, so that the driver power is doubled and the power expended in the bias supply is doubled, just as in the case of push-pull operation. Similarly, the plate and bias voltages are the same as for single-tube operation.

CLASS B OPERATION.—Class B operation is but a special case of

Class C operation; one for which the plate angle of flow θ_p is 180°. It has, however, certain interesting characteristics that make it of value in practical applications.

As is illustrated in Fig. 23, the plate current flows in half-cycle pulses; the bias required is evidently the cutoff value. Since the tube characteristics curve sharply near cutoff, it is necessary to use the projected cutoff value.

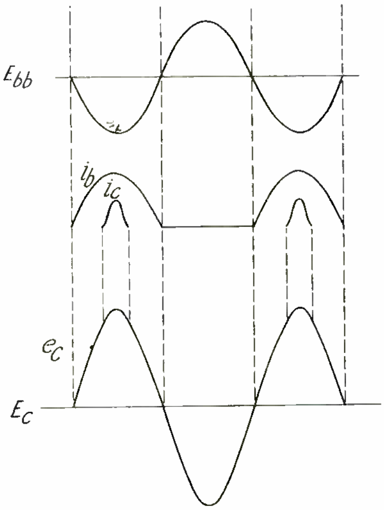


Fig. 23.—**Class-B current and voltage relations.**

This is found as shown in Fig. 24. The straight-line portion of the tube curve is prolonged until it meets the plate-voltage axis, as is indicated by the dotted-line extension in the figure. The bias value e_{co} is that for the plate-supply voltage E_{bb}. This means that the proper tube curve must be chosen so that its straight-line projection meets the axis in E_{bb}, since the latter point is specified initially.

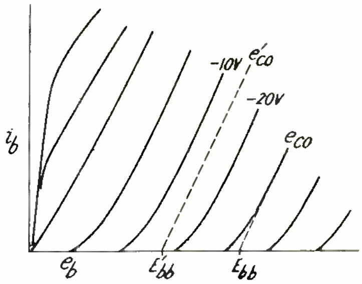


Fig. 24.—**Method of obtaining projected cutoff.**

In case no tube curve happens to line up with E_{bb}, then an estimate or interpolation must be made, such as by drawing a line through E_{bb} parallel to the upper straight portions of the adjacent plate curves, and then estimating its bias value from those of the adjacent curves.

This is shown in Fig. 24 for the plate-supply voltage E'_{bb}. A straight line (dotted) is drawn through E'_{bb} as nearly parallel to the -10-volt and -20-volt plate-current curves as is possible. In the figure this line is shown about midway between the other two curves. It therefore corresponds to a bias approximately midway between -10 and -20 volts, or -15 volts. If it were closer to the -20-volt curve, its bias value would be correspondingly closer to -20 volts.

An important fact to notice is that if the grid drive varies the plate angle of flow θ_p remains constant at 180°. Since the peak value of the plate current tends to be in proportion to the peak grid swing, and since the plate-current wave shape remains essentially a half sine wave throughout such a variation, it can be expected that the d-c and fundamental components of the plate current will also tend to be in proportion to the grid swing. Hence the output voltage or current will be in proportion to the grid swing.

The significance of this is that the r-f output is practically directly proportional to the driver input; if the latter is a modulated wave instead of one of constant amplitude, the output wave will be similarly modulated, that is, a copy of the input. Such an amplifier is known as a LINEAR AMPLIFIER.

It is used in many practical designs. For example, a G.E. television transmitter will use a low-level stage as a modulator stage, and a small video-amplifier power stage to grid-modulate it. Then will follow a succession of linear amplifiers, which amplify this low-level modulated carrier to the final desired power output, even if most of one sideband is removed, as in vestigial sideband transmission used in television.

The advantage is that the modulating video amplifier can be one of low level, which is much easier to build than a high-level stage. The same is true (although to a lesser extent) of audio amplifiers. The disadvantage is that whatever is saved in the way of audio power is counteracted by the lower efficiency of a Class B or linear amplifier compared to that of a Class-C stage. Another disadvantage is in maintaining linearity over a succession of stages, although inverse feedback is of great assistance here.

Another application is where a broadcast station has say a 1 kw transmitter, and wishes to increase the power to 10 kw. By adding a 10 kw linear amplifier to the existing station, the desired output is obtained without disturbing the modulation system or indeed any of the existing equipment. Moreover, reduced output at 1 kw is available in the case of failure of the 10 kw stage.

DESIGN CONSIDERATIONS.—The foregoing discussion indicated that the output is directly proportional to the input. This, however, is not always the case, and depends upon various factors, principally the load impedance Z_T. It will be of interest to examine the design considerations in detail.

The basic design of a Class B stage is exactly the same as that of the ordinary Class C stage, for it is after all nothing but a Class C stage with $\theta_p = 180°$. However, since the excitation is amplitude modulated, it is necessary to study the relationship between the input voltage and the load impedance, with a view to ascertaining how linear the input-output relationship is.

Suppose a certain value of tank load impedance Z_T is employed. As the grid swings positive, the plate voltage drops to a minimum value $e_{b\,min}$ which depends upon the grid swing and consequent fundamental peak current amplitude I_{pm} and the load impedance Z_T through which it flows. Specifically, $e_{b\,min} = E_b - I_{pm}Z_T$.

Since $e_{b\,min}$ cannot be less than zero, $I_{pm}Z_T$ cannot exceed E_b. The greater Z_T is, the smaller I_{pm} must be, and no matter how large the grid swing is, I_{pm} cannot exceed a peak value such that $I_{pm}Z_T = E_b$. Hence, if $I_{pm}Z_T$, which is the peak output or tank voltage, is plotted against E_{gm}, the peak value of the grid exciting voltage, a graph such as that shown in Fig. 25 is obtained.

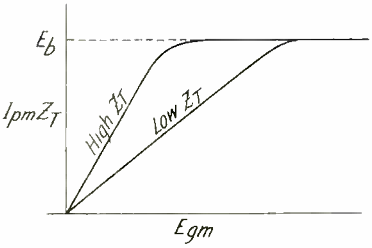


Fig. 25.—**Relation between tank output and input grid excitation voltage, for high and low values of tank impedance.**

Here it will be observed that there is an upper limit to $I_{pm}Z_T$, namely E_b, and excitation voltages greater than E_{gm} cannot increase $I_{pm}Z_T$; the curve flattens out and shows a saturation characteristic. Naturally, if the tank impedance Z_T is high, saturation is reached at a lower grid swing, as is clear from the figure.

If the exciting voltage is too great, so that saturation is incurred, the peaks of the envelope will be flattened, as is illustrated in Fig. 26. On the other hand, even if saturation is not incurred, non-linearity may be present, merely because even in this region the output is not quite proportional to the input.

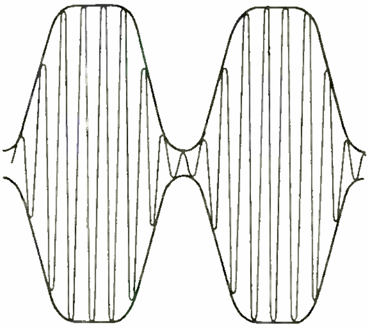


Fig. 26.—**Showing how the peaks of the envelope of the modulated output wave are flattened by saturation of the linear amplifier.**

Another factor may be that as the grid peaks swing into the positive region at maximum outward modulation, grid current is drawn and the driver stage is loaded. On the other hand, during periods of inward modulation, the grid drive is small and the grid peaks do not reach the positive grid region. In this case no grid current is drawn and the driver stage is not loading.

The net result is flattening on the peaks of modulation for exactly the same reason that a Class AB_2 audio push-pull amplifier may distort if the driver stage cannot accomodate the grid current drawn by the power tubes. A similar remedy is available: make the driver stage sufficiently large so that it appears as a low-impedance source and the momentary loads during peak outward modulation do not produce appreciable regulation in it. In the case of the linear amplifier, inverse feedback is also very helpful in minimizing this form of distortion.

The current drawn from the plate supply varies with the amplitude of the grid excitation, as was pointed out previously. This means that it is a more or less faithful copy of the modulation envelope. Since, in sound broadcasting, the envelope wave is pure a.c., which means that the average carrier amplitude is constant, the current drawn from the plate supply will have a constant d-c component, about which will occur the modulation a-c fluctuation.

This is shown in Fig. 27. When no modulation occurs, the grid excitation voltage assumes a constant amplitude corresponding to carrier conditions. The output tank voltage thereupon assumes its constant carrier value, and the current drawn from the plate supply assumes a constant d-c value.

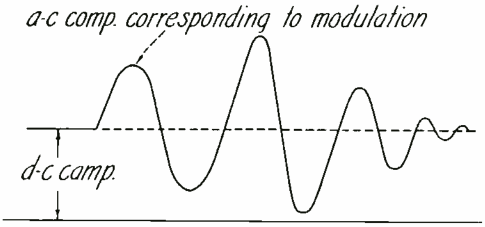


Fig. 27.—Plate supply current variations are such that the average or d-c value remains the same whether modulation is occurring or not.

When modulation occurs (someone speaks into the microphone), the grid excitation voltage begins to fluctuate in amplitude, as does also the output tank voltage, and the plate supply current acquires an a-c component that is a copy of the microphone current and also of the r-f envelope.

But, as is indicated by the dotted line in Fig. 27, the *average* value of the plate current, I_b, remains unchanged. The d-c power input to the linear amplifier stage is $P_{dc} = I_b E_b$, and is independent of variations in I_b, so long as these are a-c in nature. This means that the power input to a linear amplifier is CONSTANT, and does not change with modulation.

The r-f power output, however, does increase when modulation occurs. For sinusoidal 100% modulation, the power output increases by 50%, which represents the additional energy going into the sidebands. Whence comes this additional power?

The answer is, "From the increased efficiency of operation of a linear amplifier when it is modulated." For example, for 100 per cent modulation, the peak amplitude is twice the carrier amplitude, and it turns out that the efficiency is also doubled. For full output the plate efficiency is from 50 to 65 per cent, hence when no modulation occurs, the efficiency is on the order of 30 per cent.

In designing a Class-B linear amplifier, it will be found that the *peak* power is about the same as for an ordinary Class-C amplifier (θ_p less than 180°). Since the peak power at 100 per cent outward modulation is four times that at carrier level, it follows that the maximum *carrier* level of a linear amplifier is about one-fourth that of a Class-C amplifier operating under c-w conditions.

Another point is that the bias must at all times remain fixed at its cutoff value. This immediately precludes the use of a grid-leak resistor for bias purposes, in view of the way in which the grid current varies with the degree of modulation.

Hence fixed bias is required. However, in view of the fact that the plate-supply current has a fixed d-c component, cathode self-bias may be employed provided the cathode resistor is adequately by-passed for the modulation components.

LINEAR AMPLIFIER ADJUSTMENTS.— In adjusting a linear stage, the grid excitation is preferably varied in steps from a low value to a value producing saturation, and the output noted at each point. The relationship between output and input should be one of direct proportionality, or linear. Of course the d-c component of the plate supply will in such a case vary with the degree of excitation, in contrast to the case where the fluctuations are rapid, as in normal modulation.

A combination of excitation voltage and load impedance is found which provides the desired peak output together with satisfactory linearity. Note that if the plate dissipation is not excessive at normal carrier levels, it will not be excessive under modulation conditions, for then the output goes up while the d-c input remains unchanged, so that the plate dissipation actually decreases. This is a result of the increased efficiency of operation under modulation conditions.

Another method is to apply modulation to a fixed carrier value. This corresponds to the preceding test performed at a more rapid rate. As the modulation is varied, the d-c component of the plate current should remain unchanged; otherwise distortion or carrier shift (change in carrier amplitude) is present. However, constancy of the d-c component does not insure that distortion is absent, as will be seen.

A relatively simple test set-up for checking linearity is shown in Fig. 28. The output of the driver and of the linear power stage are suitably rectified and applied to the horizontal and vertical plates of a cathode-ray oscilloscope. The resulting Lissajous figure shows the relationship between the input and output envelopes i.e., between the input and output amplitudes.

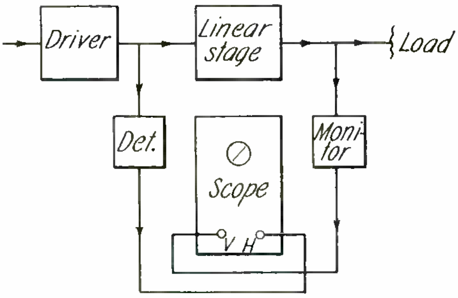


Fig. 28.—Use of a cathode-ray oscilloscope to check the linearity of a linear amplifier.

If the Lissajous figure is a straight line, the relationship is linear. If it bends over horizontally, it indicates saturation is taking place. The modulation and/or the tank load resistance should be suitably altered. If then the figure shows appreciable curvature, distortion is present. If the curvature is in one direction, even harmonics of the modulation are being produced. This may come about from driver distortion owing to grid current, as explained previously. In general, such distortion is accompanied by a change in carrier level (usually downward) as well as a change in the d-c plate current.

On the other hand, if an S-shaped Lissajous figure is obtained, it indicates distortion of the odd-harmonic type, but usually no change occurs in the carrier level or d-c plate current. The scope presents the information immediately in the form of a graph (Lissajous figure) similar to that plotted in the first type of test described.

RESUME'

We have reached the end of another assignment. The extremely important subject of Class-C amplifiers has been covered, and the fundamental principles governing such distorted operation have been developed. It was seen how a pure sine wave is obtained by the action of the tank circuit, even though the plate current is highly distorted, and how large outputs can be obtained without exceeding the permissible plate dissipation.

Of particular interest is the discussion of pulse performance, with the possibility of extreme stressing of the tube electrically if expendable operation is contemplated. By using higher plate and filament voltages, greater peak currents can be obtained, and with this of course increased output.

The concluding section on linear (Class B) amplifiers covers a type of amplifier stage that is not only of importance in broadcasting, but in television as well, where the problems of wide-band modulation and vestigial sideband transmission make this mode of operation attractive.

CLASS C AND CLASS B AMPLIFIERS

EXAMINATION

1. (A) Explain briefly why the plate losses are inherently low in a Class-C stage.

(B) What is the objection to operating a Class-C stage with a very small angle of flow?

2. (A) How does the positive peak I_{pm} of the fundamental component of the plate current compare in timing with the peak i_{bmax} of the plate current?

(B) How does the peak i_{cmax} of the grid current compare with i_{bmax} in timing?

3. Consider the Type 5671 tube treated in the text. Take the peak current as equal to 37.2 amperes, $\theta_p = 120°$, and $m = 3.5$. The plate-supply potential is 10,000 volts, $\mu = 39$.

(A) Find e_{cmax}, e_{bmin}.

(B) Find i_{bmax}, i_{cmax}.

(C) Calculate the crest fundamental component I_{pm} of the plate current, and the d-c component I_b.

3. (D) Calculate the power output, power input, plate dissipation, and efficiency.

(E) Calculate the plate tank impedance Z_T.

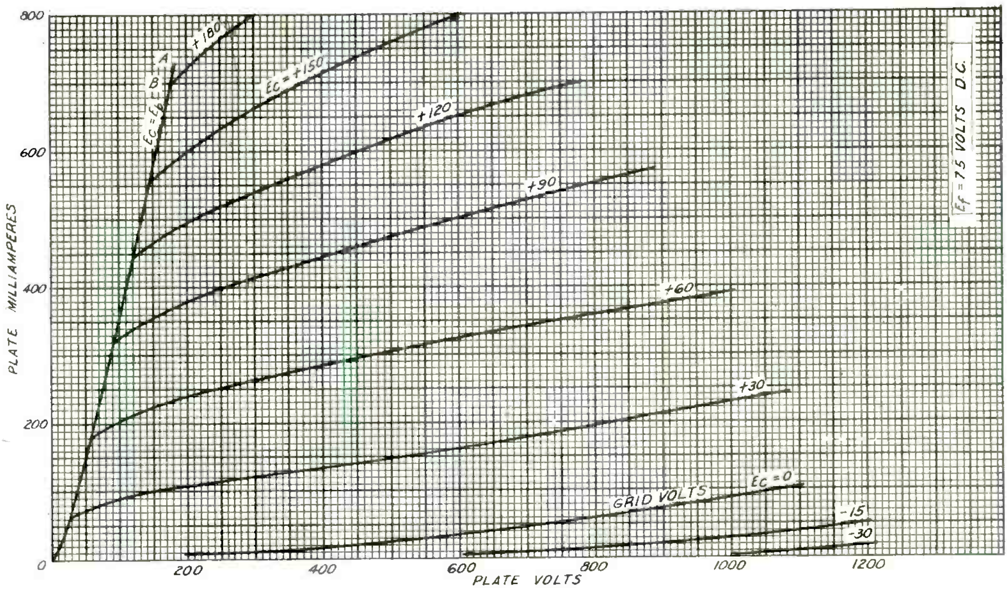
4. For the same tube and operation conditions,

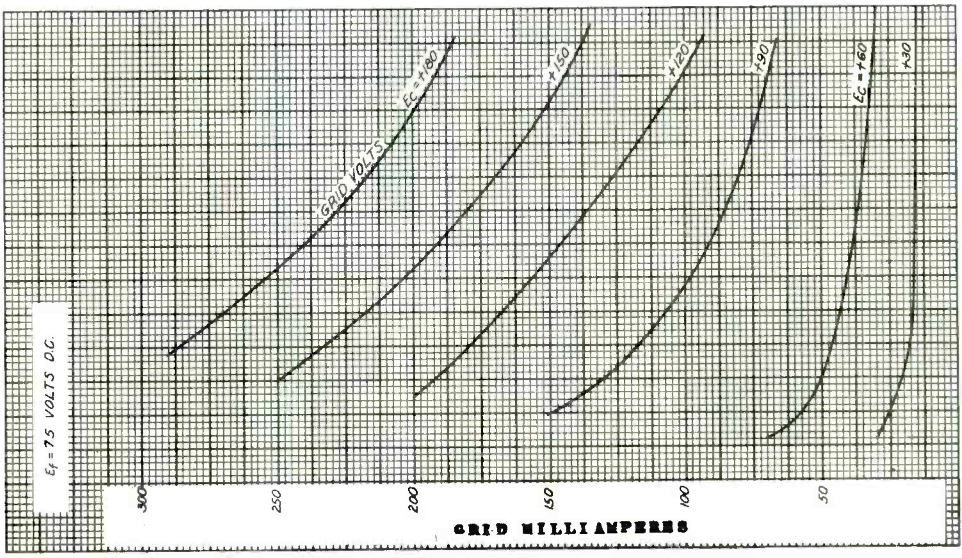
(A) Calculate the grid bias E_c, and peak grid swing E_{gmax}.

(B) Calculate the grid angle of flow θ_g, the crest fundamental component of the grid current I_{gm} and the d-c component I_c.

(C) Calculate the grid input power, the power expended in the bias supply, and the power dissipated at the grid.

5. Calculate the Class-C design of an 826 tube, operating at 1000 volts plate potential, forced-air cooling. Use the curves furnished here. The peak space current is 647 ma. Let m = 1.5, and θ_p = 130°.





5. *(Continued)*

6. An 826 tube is to be operated as an expendable pulsed amplifier with a duty cycle of 10%, and with a plate potential of $E_b = 2000$ volts. In order to obtain uniformity in results, certain values and constants will be furnished the student. Thus, let $i_{sm} = 3{,}500$ ma., $m = 1.5$, $\mu = 15.5$ in the positive grid region and 31 in the negative grid region, $E = [(\mu + m)\, e_{cmax}] = 8{,}500$ volts. Furthermore, let $i_{bm}/i_{sm} = 0.85$ and $i_{cm}/i_{sm} = 0.15$, and the plate angle of flow $\theta_p = 160°$.

(A) Calculate the peak plate and peak grid currents.

(B) Calculate the peak fundamental and d-c components of plate current.

(C) Calculate the peak and average power outputs.

(D) Calculate the d-c power input.

(E) Calculate the plate dissipation, and compare with the ICAS operation under forced air cooling.

(F) Calculate the plate efficiency.

(G) Calculate the tank-circuit impedance.

7. In the preceding problem, continue the design by calculating:

(A) The grid bias E_c.

(B) The peak grid swing E_{gm}.

(C) The grid-current angle of flow.

(D) The d-c and fundamental components I_c and I_{gm} of the grid current.

(E) The driver input power.

(F) The power expended in the bias circuit.

(G) The grid dissipation.

8. Two 826 tubes are to be employed in push-pull in pulsed operation as calculated in Problems 6 and 7.

(A) What is the magnitude of the tank impedance Z_T and how does it compare with the previous value for a single tube

(B) What is the power output and how does it compare with the previous value?

(C) What is the plate dissipation per tube and how does it compare with the previous value?

(D) What is the driver input power and how does it compare with the previous value?

(E) What is the power expended in the grid-bias circuit and how does it compare with the previous value?

(F) What is the grid dissipation per tube and how does it compare with the previous value?

9. The two 826 tubes are to be operated in parallel. Answer questions (A) to (F) of the preceding problem for this mode of operation.

(A)

(B)

(C)

(D)

(E)

(F)

10. In a Class B stage:

(A) Why does the output "saturate" as the grid excitation is increased?

(B) Will this show up on outward or inward modulation?

(C) Will this show up sooner if the tank impedance Z_T is low or high?

(D) Does the instantaneous current drawn from the plate supply under distortionless conditions vary, or is it constant?

(E) Does the instantaneous power drawn from the plate supply vary, or is it constant?