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ANALYSIS OF THE OPERATION OF VACUUM TUBES AS CLASS C AMPLIFIERS*

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Summary—*The operation of class C amplifiers under carrier and modulated conditions is analyzed with the aid of constant-current charts. With these charts one can precalculate all operating factors such as output, efficiency, and grid driving power. The analysis discloses certain fundamental differences in the behavior of modulated amplifiers connected with self-bias and fixed, or generator bias operation. Audio harmonic distortion traceable directly to the amplifier is discussed in detail, together with methods for "compensating" the grid excitation to eliminate this distortion and to increase the operating efficiency. Oscillograms of the audio relations in modulated class C amplifiers experimentally verify the theoretical conclusions. The problems of grid excitation power, "true" grid dissipation, and "effective" plate dissipation for modulated amplifiers are treated for three tubes differing only in their amplification factors.*

Broadcast transmitters in which vacuum tubes are used in the output stage as class C amplifiers, in combination with class B plate modulators,[1] because of their high over-all efficiency, are particularly suitable for high power installations.

Historically, class C amplifiers have evolved from the classical self-oscillator as frequency stability became a paramount requirement for broadcast transmitters. In both cases plate modulation was effected by means of very inefficient class A audio amplifiers. The necessity of using too great a number of modulator tubes augmented by the practical impossibility of the application of more than sixty or seventy per cent modulation subsequently forced radio engineers to give preference to the class B radio amplifier scheme. Here, modulation is applied to one of the earlier stages of power amplification and the output stage has only to reproduce faithfully the modulated wave. This scheme soon became standard in designing larger transmitters although the efficiency of the output stage for an average depth of modulation is in this case relatively low.

Quite recently, the advance in the art of designing high power audio transformers[2] made possible the application of high efficiency class B audio modulators and also permitted the realization of 100 per cent modulation in class C transmitters. As a consequence the latter have

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[1] J. A. Hutcheson, Proc. I.R.E., vol. 21, p. 944; July, (1933).

[2] J. A. Chambers, et al., Proc. I.R.E., vol. 22, p. 1158; October, (1934).

reappeared in the limelight. Therefore, a thorough study of this mode of operation of vacuum tubes has acquired a new importance as shown by numerous technical papers of recent times. The necessity of such a study is further emphasized by these two facts: (1) With the ever-increasing size of transmitters the economic side of operation begins to play a prominent rôle; hence, a thorough investigation of the actual limitations of transmitting tubes is highly desirable; (2) high modulation, up to 100 per cent, and occasional overmodulation bring about complications in tube performance which must be fully recognized both by the designer of transmitters and the tube engineer.

Problems Outlined

In this analysis, the first problem to be solved is: By what means can one accurately precalculate output power, efficiency, grid excitation power—in a word, all necesssary data for any assumed operating condition of a tube used as a class C amplifier?

The second problem is the application of the adopted method to a 100 per cent modulated amplifier with the purpose of investigating tube behavior during the entire audio modulation cycle.

Finally, the third problem involves the consideration of means and methods by which some inherent weak points of modulated class C operation can be improved.

During the investigation one must keep in mind that, by definition, the basic characteristic feature of a class C amplifier is the application of such a high negative bias that electronic current to the plate is allowed to flow during only a fraction of the half cycle corresponding to the positive grid swing. This enables the tube to deliver into the oscillating circuit large high-frequency power at high efficiency. The narrower the angle of the plate current the greater is the efficiency, all other conditions being the same. In this respect class C amplifiers and self-oscillators are alike. The main difference between a class C amplifier and a self-oscillator is in the grid excitation: *it is constant with the class C amplifier and strictly proportional to the radio-frequency plate voltage with the self-oscillator.*

Choice of Methods for Precalculation of Class C Performance

By virtue of the very character of class C operation the performance of a tube can be predicted accurately only in the case when one possesses a complete knowledge of tube characteristics, up to the highest feasible values of plate and grid currents. Unfortunately, no simple analytical expression is apt to supply this information. Thus, the basic 3/2-power law for static characteristics is valid only over a very limited portion of the current-voltage curves; it does not hold either for very low plate currents, or for currents greater than half of the value of the available filament emission where saturation effects come to light. Yet, the greatest handicap in applying analytical methods to class C amplifiers is connected with the region of "quasi saturation" at high positive grid potentials: there, grid current becomes prominent, and the plate-current wave highly flattened, or even saddled-in. But just this region is the most interesting with class C amplifiers if high outputs and efficiencies are to be secured from the tube. In addition, one may point out that the region of reversed grid current, which is even harder to handle analytically, must also be explored if an exhaustive study of class C performance is to be considered.

In short, in the absence of a complete chart of tube characterists, one certainly is forced to look for suitable, even if approximate, analytical methods for precalculation of class C operation. But if such charts are available, results can be obtained more easily and accurately by a graphical treatment of this problem. A graphical method can be applied to any region of tube characteristics without restriction; it is independent of the shape of static characteristics. In addition, by a mere glance at a chart, one can better define tube limitations and preview the influence of various factors on tube operation.

Graphical Method for Studying Class C Performance

Dynamic characteristics for any mode of operation can be plotted on complete charts of the conventional type in which plate current is given as a function either of plate potential with grid voltage as parameter, or vice versa. However, in studying class C performance it proves to be much more convenient to employ different types of charts, occasionally mentioned in technical literature, but apparently seldom, if ever, used in engineering practice. These are *constant-current charts* with plate and grid potentials plotted on the two coördinate axes, respectively. These charts contain two families of curves, each curve drawn either for a constant plate, or a constant grid current (Fig. 1). The advantages of such a representation are evident:

(1) Plate and grid characteristics are conveniently combined in the same chart, in spite of the substantial difference in the magnitude of the two quantities.

(2) The operating point, for example, A, is *definitely located* on the chart as function of the operating direct plate voltage, E_p, and grid bias, e_c; this is not the case with any conventional chart.

(3) Every dynamic characteristic for class C operation is represented by *a straight line,* such as AB; this is true since the variation of both plate and grid potentials during oscillation can be considered synchronous and sinusoidal.

It may be noted in passing that for the same reason dynamic characteristics for class B and class A radio-frequency amplifiers are also represented in the adopted charts by straight lines. Therefore, the method which is outlined here is also applicable to these cases.

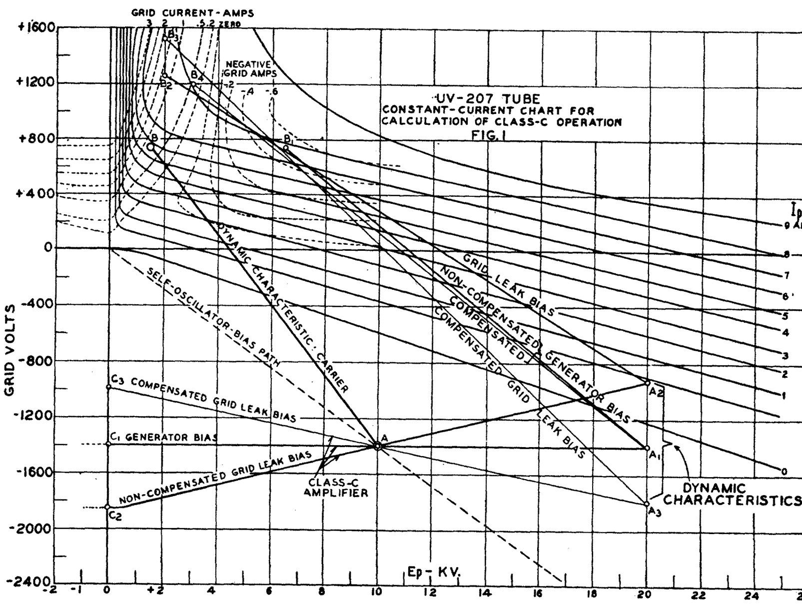


Fig. 1

Application of the Constant-Current Charts to the Calculation of Carrier Performance

The chart shown in Fig. 1 belongs to an individual tube of the UV-207 type having μ equal to 20. The chart has been prepared by the oscillographic method.[3] It may be noted that the inverted slope of the constant plate-current curve at any point of this chart gives the measure of the amplification factor, μ. This follows directly from the definition, $\mu = dE_p/dE_g$.

In order to describe better the method of application of the constant-current charts we shall proceed with the calculation of performance of the UV-207 tube for an arbitrarily chosen operating condition.

[3] H. N. Kozanowski and I. E. Mouromtseff, Proc. I.R.E., vol. 21, p. 1082; August, (1933).

Suppose the operating point is given by the direct plate voltage, $E_p = 10{,}000$ volts, and grid bias, $e_c = -1400$ volts. Let us assume that during oscillation the plate voltage on its downward swing reaches a minimum, $E_{\min} = 1500$ volts, so that the voltage amplitude is $E_0 = E_p - E_{\min}$ or 8500 volts. Let us further assume that grid excitation is such that maximum positive grid potential during oscillation reaches the value, $e_{\max} = +740$ volts. The grid voltage amplitude is then $e_0 = -e_c + e_{\max} = 2140$ volts. We draw a straight line AB through the operating point A and the end point of the operating characteristic B with coördinates $E_{\min} = 1500$ and $e_{\max} = +740$ volts. From this straight line dynamic characteristic we can easily plot a plate-current time curve by computing the electric angles corresponding to each point of intersection of the dynamic line with the individual plate-current curves. The values of electrical angles, which are proportional to time, will be obtained from the ratios of instantaneous plate voltages at each point found in the chart to the chosen amplitude, E_0, these ratios being sines of the respective angles. By virtue of the symmetry of the current-time curve with respect to its mid-ordinate, only one half of the actual curve is needed for calculation (Fig. 2). The current-time curve averaged over the entire cycle gives the value of the average or direct plate current, $I = 1.11$ amperes. This result is conveniently obtained from Fig. 2 by dividing the area of the time curve into nine narrow strips, each ten electrical degrees wide, measuring of the middle ordinates of each strip, summing up the middle ordinates and dividing the sum by $2 \times 9 = 18$; the factor 2 is necessary for averaging over the entire radio-frequency cycle.

Power output, P_0, can be determined graphically on the basis of the expression

$$P_0 = \frac{1}{2n} \sum_{n=1}^{n=9} i_n E_0 \sin \phi_n = \frac{E_0}{2n} \sum_{1}^{9} i_n \sin \phi_n \qquad (1)$$

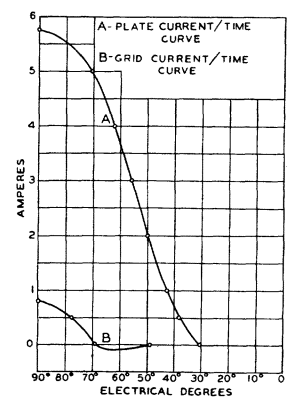
where i_n is the instantaneous value of plate current in the middle of each strip, and E_0 is the plate voltage amplitude. Hence, multiplication of the measured middle ordinates of the strips by their respective sines summing the products, a further multiplication of the sum by the value of radio-frequency voltage amplitude, 8500 volts, and averaging of the result over the entire cycle by dividing by 18, will yield us the value of power output $P_0 = 8.5$ kilowatts. The plate input power and efficiency can be computed from $P_i = E_p I_p$ and $\eta = P_0/P_i$. They are: $P_i = 11.1$ kilowatts and $\eta = 77$ per cent, respectively. The entire calculation is tabulated in the table of Fig. 2.

Knowing E_0 and P_0 one can compute the value of the effective load resistance, R_L, which is to be connected across the tube on the output side from the expression

$$R_L = E_0^2/2P_0 = 4250 \text{ ohms.} \tag{2}$$

Proceeding in a similar manner with the grid-current time curve (Fig. 2) we shall find

Average grid current, $I_g = 57$ milliamperes
Grid input power, $p_{gi} = 120$ watts
Bias loss, $p_c = 80$ watts



Values of Mid-Ordinates

5.87	amperes ×0.996	which is sin 85°	=5.65
5.27	.966	sin 75°	5.08
4.37	.906	sin 65°	3.96
2.87	.819	sin 55°	2.35
1.32	.707	sin 45°	0.93
0.28	.573	sin 35°	0.16
19.98			18.13

$I_p = 19.98/18 = 1.11$ amperes
$P_0 = 18.13/18 \times 8.5$ kilovolts $= 8.5$ killowatts
$P_i = 11.1$ killowatts
$\eta = 77$ per cent

Fig. 2

The power loss, p_{gh}, converted into heat in the grid itself might, at first thought, be calculated as the difference between the total grid input and the bias loss, $p_{gi} - p_c$. In reality, it can be shown that, generally

$$p_{gh} \gg p_{gi} - p_c.$$

However, we shall postpone the discussion of this statement to a later section.

It may be noted that the whole outlined procedure can be greatly helped by using a simple instrument, the *sine scale*, described elsewhere.[4]

Modulated Class C Operation

Choice of Carrier Conditions

In all practical cases, one may consider that the direct plate voltage, grid bias, and carrier output per tube are prescribed by the general design of a transmitter, in which the economic side plays no small part. Just for this reason, tubes are not always operated at their best ratings. Thus, for instance, the choice of the bias is often governed by the desire of reducing to a minimum the size and cost of the excitation stage and bias supply; thus, the use of sufficiently high biases required by ideal class C operation is precluded. Also, there is always a tendency to boost power output per tube in order to reduce as far as possible the number of tubes employed. In our further discussion we shall consider an actual case of a transmitter, with several UV-207 tubes in the output stage, operated as 100 per cent plate modulated class C amplifier with an output of 8.5 kilowatts per tube. This is somewhat in excess of the conservative tube rating, but through such a choice of a practical example some interesting facts regarding class C operation and its limitations will come to light more conspicuously.

With the assumption of $E_p = 10{,}000$ volts and $e_c = -1400$ volts the operating point in Fig. 1 is fixed at point A. We shall temporarily omit any consideration of the manner in which the bias is supplied. Now, we have to decide what grid excitation must be applied to the tube in order to obtain the desired output. For this, we shall first explore the variation of power output physically obtainable from the tube along several vertical lines in the chart, corresponding to $E_{min} = 1000$, 1500, 2000 volts, and so on. In each case we assume e_{max} equal in turn to +400, +800, +1000, and +1200 volts. For every combination of E_{min} and e_{max} we plot a straight line dynamic characteristic and proceed with calculation of all necessary quantities in the manner outlined in the previous section. Four points for each vertical line are in this case sufficient for shaping a smooth curve representing output power as a function of grid excitation for any assumed E_{min}. The calculated curves are plotted in Fig. 3. One can notice that:

(1) For low and medium grid excitation, all curves almost coincide.

(2) With higher grid excitation, there is an optimum for power output, at $E_{min} = 1500$ volts; below and above this value of E_{min}, power output decreases for any given grid excitation.

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[4] This sine scale consists of a celluloid right-angled triangle on which are scribed slant lines corresponding to five-degree angle intervals from zero to ninety degrees. Any angle to be used in plotting the current-time curve can be read directly from the triangle. A detailed description of this scale is to be published in the *Electric Journal.*

(3) For higher grid excitation with the potential swinging to somewhat above +1200 volts, the output curves flatten and may even sink due to quasi saturation, which one may designate as grid saturation.

(4) Throughout the explored region, the output of 8.5 kilowatts can be obtained only with positive peak grid voltages definitely fixed within very narrow limits in the vicinity of 740 volts irrespective of the minimum plate voltage reached during oscillation.

Of course, for the realization of any particular value of $E_{\min} = E_p - E_0$ the load resistance, R_L, must be appropriately chosen, as follows from equation (2). In each case the efficiency, η per cent, and average plate and grid currents will be different: the lower is $E_{\min}$, the higher is

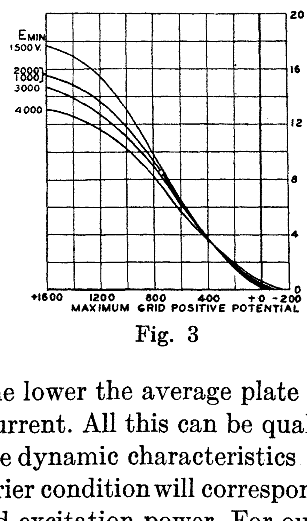


Fig. 3

the efficiency, and the lower the average plate current, but the higher is the average grid current. All this can be qualitatively foreseen from the direct plots of the dynamic characteristics in the chart. A compromise choice of the carrier condition will correspond to good efficiency and not too excessive grid excitation power. For our further discussion we shall choose $E_{\min} = 1500$ volts, for which everything has been calculated in the above numerical example.

Tube Behavior During Modulation

With 100 per cent modulation applied to the plate of the tube, the average or input plate voltage swings at audio frequency down to zero and up to twice the original carrier voltage. With this, the output power varies down to zero and up to a certain maximum. In an ideal class C amplifier the maximum power is expected to be exactly four times the carrier output. Yet, as a rule, this never happens. The results of the present graphical investigation and of an oscillographic study corroborate the fact that even with a strictly sinusoidal modulation wave applied to the plate of a tube the output wave in a great many cases is distorted. This is not necessarily due to the lack of filament emission: it is inherent in the tube characteristics and may occur even with a large margin of electron emission left unused. It will be more clearly understood in the course of the analysis of the two following specific cases.

Case 1: Bias is Supplied by a Generator

At the crest of modulation in our numerical example the operating point in Fig. 1 will be at A_1 with $E_p = 20{,}000$ volts and $e_c = -1400$ volts. First, we shall calculate the output power for several dynamic characteristics plotted through the operating point and terminating on the horizontal line corresponding to the assumed grid excitation with $e_{max} = +740$ volts. Generally, for each of these dynamic lines the output power will have a different value. Then, in order to decide which line

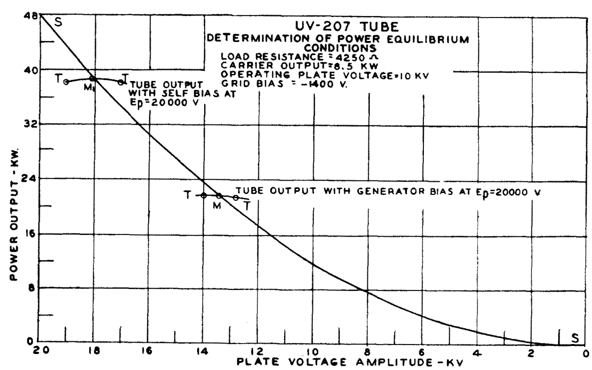


Fig. 4

will be followed in actual tube operation, we must keep in mind that the power output calculated for any dynamic characteristic is the output which the tube is able to supply when the correct load resistance, different for each line, is connected across the tube (see equation (1)). But in the present case one has to consider the resistance, R_L, *which has already been chosen in the adjustment of carrier conditions.* Therefore, we may proceed in the following manner.

Fig. 4 contains a curve, SS, showing amount of power which is consumed in the resistance, $R_L = 4250$ ohms, at different values of radio-frequency voltage amplitude, from zero to 20,000 volts, across the resistance. In the same drawing, another curve, TT, is plotted connecting several calculated points giving the power which *the tube is able to deliver* into the resistance correctly matched for each value of radio-frequency plate voltage. Hence, the intersection of the two curves at point M with $E_{min} = 6500$ volts indicates the dynamic characteristic along which the equilibrium between power delivered into the oscillating circuit and the power consumed in the load is established. Therefore, point M gives the only possible operating conditions for stable performance of the tube. The corresponding dynamic characteristic A_1B_1 is plotted in Fig. 1.

The calculation for this line yields the following figures:

Output power	$P_0 = 21.75$ kilowatts
Input power	$P_i = 37.1$ kilowatts
Efficiency	$\eta = 58.8$ per cent
Plate dissipation	$P_h = 15.35$ kilowatts
Direct grid current	$I_c = -100$ milliamperes

At a glance, one can notice the following shortcomings of such an operation:

(1) Power output at the crest of modulation instead of being 34 kilowatts as required for distortionless modulation, is only 21.75 kilowatts. This produces a strong second harmonic component in the output wave, approximately 10 per cent in magnitude.

(2) Efficiency at the crest of modulation drops enormously, from 77 to 58.8 per cent, thus minimizing the main advantage of class C operation.

(3) Plate dissipation increases disproportionately; in ideal class C operation it should not exceed four times the carrier loss, or 12 kilowatts. Although unfavorably affecting the average over an audio cycle the calculated dissipation, 15.35 kilowatts does not appear too excessive *per se* since it shows the plate dissipation only at the positive crest of an audio cycle; yet, one will note that the dynamic characteristic at this condition runs decidedly through the negative grid region. Under these circumstances, the "effective" plate dissipation is much higher than calculated and eventually may cause the cooling water to boil although the actually measured average loss does not exceed the rated 10 kilowatts. The discussion of the "effective" plate dissipation will be the subject of one of the later sections.

(4) The high negative average of direct grid current is due to the strongly emphasized portion of reversed grid current in the grid-current time curve. With this, the grid may easily become a generator of parasitic oscillations.

The enumerated defects of operation at or near the crest of audio modulation become greatly emphasized when over modulation is occasionally allowed to occur. For example, with 20 per cent overmodulation, which not so infrequently happens in real operation, the maximum effective plate dissipation in our case becomes 40 kilowatts; with this the average dissipation becomes quite prohibitive.

The above calculations and deductions are corroborated by an oscillographic study. Fig. 5 contains oscillographic records of the audio-frequency envelopes for grid current, plate current, and rectified radio-frequency current of the output wave, all taken simultaneously with sixty-cycle modulation of 100 per cent applied to the plate of a UV-207 tube operated under conditions similar to those of the above numerical example. Without paying attention, at this time, to the record at the extreme right, one can notice that the plate current on the positive swing of modulation distinctly exceeds its theoretical two-times-carrier value; at the same time, the output current is less than twice its carrier value. This is interpreted to mean that there is a "shortage" in output and that the efficiency is poorer at the crest of modulation than is appropriate for ideal class C operation. The phenomenon becomes intensified with reduced filament voltage and hence may become of more consequence when one considers worn-out tubes approaching the end of their career.

Another critical point in operation to be considered is the trough of audio modulation when the plate voltage becomes zero. Power input and output at this moment are both zero. Yet, it is obvious that with fixed grid excitation the grid current rises at this point to a very high value. Calculation gives the following figures:

Average grid current	$I_c=$	485 milliamperes
Average input power	$p_{gi}=$	1000 watts
Bias loss	$p_c=$	675 watts

Case 2: Operation with Self-Bias

In order to reproduce exactly carrier conditions adopted in the previous discussion one must choose the proper value of grid-leak resistance so that the following relation is fulfilled:

$$R_g = e_c/I_c. \tag{3}$$

With an average grid current of 57 millamperes in our case and $e_c = -1400$ volts, R_g must be 24,600 ohms.

With modulation applied, a self-biased tube behaves in a manner entirely different from a tube operated with generator bias. Indeed, with grid-leak bias there is no way to keep bias constant because the variation of average grid current during modulation is beyond our control. One may point out that in contrast to the case of a self-oscillator, the grid current and hence the grid bias of a class C amplifier during modulation *always decreases with increasing plate voltage, and vice versa.* This conclusion can be reached by a simple inspection of the chart of Fig. 1. Indeed, at higher voltages, dynamic characteristics are necessarily shifted toward and into the region of reversed grid currents which brings down the average grid current and bias. Graphical calculation as well as oscillographic recording confirm this.

The actual value of grid current and bias at every particular instant of the modulation cycle depends on the actual position of the dynamic characteristic; its exact location is forcibly established by the simultaneous fulfilment of *two equilibrium conditions:* (1) The average grid current calculated along any dynamic characteristic plotted in the chart multiplied by the value of the adopted grid-leak resistance must be exactly equal to the bias assumed in plotting; and (2) as pointed out before, the tube output along the same dynamic characteristic must be balanced by the power consumed in the load resistance. One must keep in mind that both the grid-leak and the load resistances have been originally established by the carrier condition. The actual location of the dynamic characteristic at the crest of modulation for our numerical example is given in Fig. 1 as the line A_2B_2. In the same chart, the path AA_2AC_2A is also plotted, along which the operating point travels back and forth when 100 per cent modulation is applied to the carrier.

The inherent variation of self-bias in a certain sense constitutes self-adjustment of the tube. Thus, due to the lower bias at higher plate voltages the grid, being excited with the constant radio-frequency voltage, swings to higher positive potentials. Therefore, the power output at the crest of modulation is greater than in operation with generator bias. In fact, the output power can even exceed the "four-times-carrier" value with a resulting "negative" second harmonic component in the output wave. However, such self-adjustment is not without its drawbacks. These can be discussed more concisely after a glance at the following results of calculation:

Average plate current, I_p	2.82 amperes
Output power, P_0	38.8 kilowatts
Input power, P_i	56.4 kilowatts
Plate dissipation, P_h	17.6 kilowatts
Efficiency, η	69 per cent
Direct grid current, I_c	40 milliamperes
Grid bias, e_c	−930 volts
Grid excitation power, p_{gi}	85 watts
Grid bias dissipation, p_c	36 watts

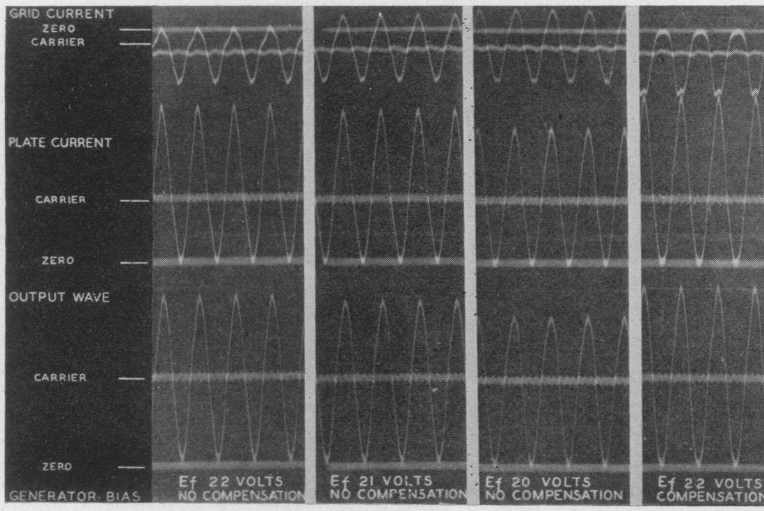
This calculation actually confirms the statement that the output in this case is greater than the 34 kilowatts required for distortionless modulation. The ensuing second harmonic component amounts to 3.4 per cent. Then, efficiency, though higher than with generator bias, still is much lower than in the initial condition of the carrier. Yet, the most important fact revealed by the calculation is the disproportionate increase in power input and in plate dissipation. This is a direct consequence of the loss of bias, which has dropped from −1400 to −930 volts. By going back to the chart of Fig. 1 one can perceive that the operating point at high modulation trespasses the zero plate-current line so that the tube ceases to be a class C amplifier: it shifts through the class B condition into nearly class A operation. Thus, in contradiction to the basic conception of class C operation, the current angle grows larger than 180 degrees; in our case it reaches 220 degrees. Hence, plate current flows at high instantaneous voltages and high negative grid potentials. As a result, due to the focusing action of the grid on the electron current to the plate, the "effective" plate dissipation increases more rapidly than the computed loss.

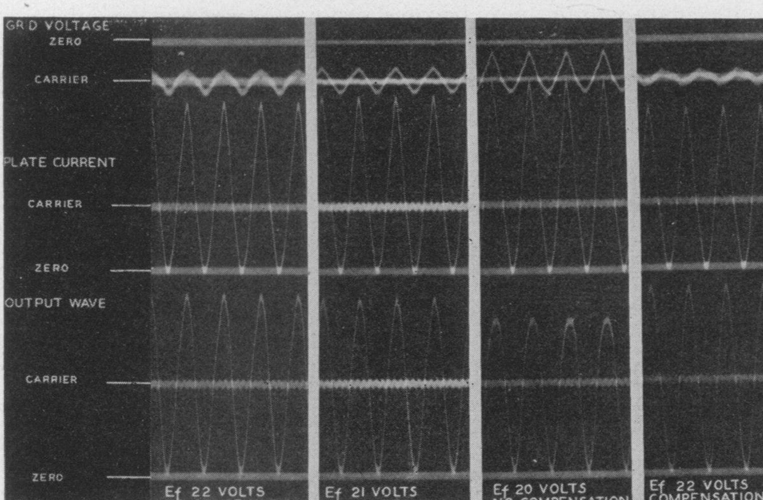
With heavy overmodulation the situation grows more serious in every respect: the bias drops further, input increases, the efficiency decreases so that finally the tube may run away. But even prior to such an extreme condition, the effective plate dissipation may reach quite a prohibitive value, causing the tube to boil; in our example, for instance, with 20 per cent overmodulation the effective plate dissipation at the highest point reaches a figure close to 50 kilowatts. In such a circumstance the electrons impinge on the plate at high instantaneous plate potentials so that X-rays may be generated abundantly within the tube. All such factors may contribute to the production of flashbacks, a very bothersome phenomenon in the operation of high power tubes.

At the negative swing of the plate modulation voltage bias self-adjustment becomes rather a beneficial factor in the respect that a heavier grid current builds up a higher bias, thus automatically preventing the radio-frequency potential from reaching as high positive grid values as in the case of the bias generator. Hence, lower grid current and grid excitation power ensue. The results of graphical calculation of the explored case are:

Average grid current, I_c	74 milliamperes
Grid bias, e_c	−1850 volts
Grid excitation power, p_{gi}	158 watts
Grid bias dissipation, p_c	136 watts

All conclusions regarding the operation of a self-biased class C amplifier, derived from the foregoing graphical calculation were also confirmed by oscillographic recording. A few typical records pertaining to this case are shown in Fig. 6. Temporarily, we shall again leave out of consideration the curves on the extreme right. In the records of the first panel on the left, the output wave of a 100 per cent modulated tube with self-bias, the wave is designated as "output," proves to be





Figs. 5 and 6—UV-207 class C amplifier, 100 per cent modulated
Carrier:
E_p 10 kilovolts — I_p 1.1 ampere
E_g −1400 volts — I_g 0.100 ampere

essentially symmetrical with respect to the carrier, although more precise measurement can detect a slight overshooting on the positive half cycle. It implies that in this case the power output actually varies from zero to approximately four times the carrier output, which is in a good agreement with our calculation.

The records of panels 2 and 3 are especially interesting. They reveal that with filament voltage reduced below normal the output wave loses its symmetry to a great degree, thus indicating a distinct "shortage" in power output at higher plate voltages just as in the case of generator bias. Again, one cannot ascribe this effect directly to a lack of filament emission, as might seem logical at first sight. Indeed, the plate-current amplitude should be directly affected by insufficient emission; yet, in this case it even goes up as the output drops. The coexistence of these two factors points to a reduced efficiency. The phenomenon is due rather to a more pronounced reversed grid current and to the redistribution of plate and grid characteristics compelling the establishment of a new and rather adverse state of "double equilibrium."

The same oscillograms distinctly show that the grid current and hence the tube bias in the case under consideration do not stay constant during an audio cycle; both vary in a sense opposite to the variation of the modulated plate voltage. Under special conditions, such as are met with during heavy overmodulation, the grid bias at the apex of audio plate voltage may become so low as to cause the tube to run away.

It is important to note that this variation of the grid bias during modulation with a self-biased class C amplifier occurs in just the opposite sense to that in a self-oscillator.

Comparison of Tubes Having Different Values of μ

Knowledge of class C operation is incomplete without an understanding of the manner in which this is affected by the amplification factor, μ, of a tube. A direct way to answer this question is to carry out a comparative analysis of the performance of tubes having structure similar in every respect except for the number of turns on their grids, determining their voltage factors. Such tubes are available: they are standard water-cooled sister tubes UV-863, UV-207, and UV-848, with respective values of μ 50, 20, and 8. The constant-current charts for the UV-863 and UV-848 are plotted in Figs. 7 and 8. Similar to the UV-207 chart of Fig. 1, they are mapped from oscillographic records. Once these charts are available one can pursue parallel calculations of class C operation for all three tubes with the assumption of comparable operating conditions. In our case, let them be determined primarily by the operating plate voltage $E_p = 10{,}000$ volts and the prescribed output power, 6 kilowatts, which is the rated carrier output. In addition, the

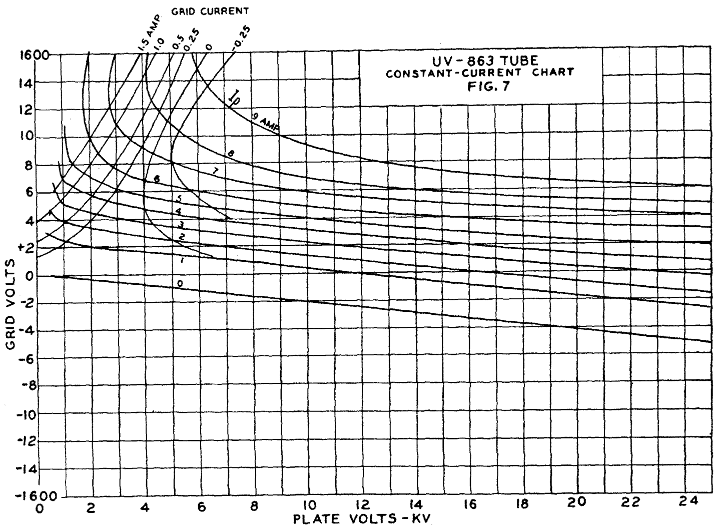


Fig. 7

biases are so selected that the plate-current angle, ϕ, is consistent with good class C operation and is approximately the same with each tube. After a preliminary computation it was found that with the respective

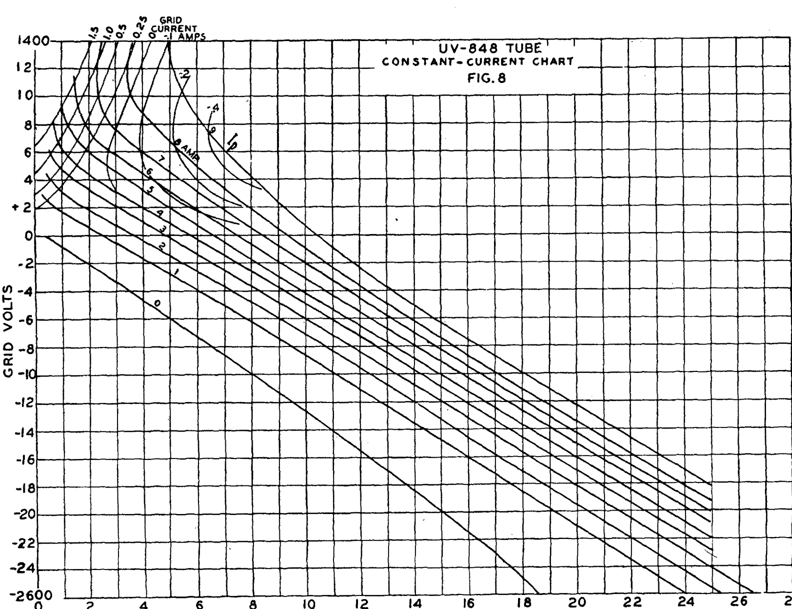


Fig. 8

biases of −2300, −2800, and −3700 volts the current angle with each tube is nearly 85 degrees. Incidentally, the −2800-volt bias on the UV-207 tube is twice as high as that used in the first example. With this the comparative effect on operation of low and high bias will come to light.

By the method outlined in the earlier sections the necessary grid excitation voltage is determined for each type of tube. The minimum plate voltage during oscillation was assumed to be $E_{min}=1500$ volts with all tubes, which is equivalent to the assumption of the same load resistance, 6020 ohms, for all three tubes.

The calculated operating data, for a *constant grid bias* such as supplied by a generator, are assembled in Table I.

TABLE I

Tube Type	Plate Volts E_p	Grid Bias e_c	Plate Volts Min. E_{min}	+Grid Volts Max. $+e_{max}$	Plate Current amps. I_p	Output Power kw P_0	Input Power kw P_i	Eff. % η	Grid Current ma I_c	Excit. Power watts p_{gi}
					Carrier Conditions					
UV-863	10 kv	−2300	1500	+765	0.760	6	7.6	79%	149	460
UV-207	10	−2800	1500	+720	0.760	6	7.6	79	60	190
UV-848	10	−3700	1500	+690	0.760	6	7.6	79	55	242
					Positive Crest of Modulation Generator Bias					
UV-863	20 kv	−2300	6400	+765	1.21	15.4	24.2	63%	−93	0
UV-207	20	−2800	4000	+720	1.15	17.2	22.9	75	−25	0
UV-848	20	−3700	3750	+690	1.45	21.8	29.0	74	−19	0
					Self-Bias					
UV-863	20 kv	−1880	2400	+1185	1.63	25.7	32.6	79%	121	370
UV-207	20	−2440	2100	+1080	1.63	26.5	32.6	82	60	213
UV-848	20	−3300	1870	+1060	1.64	27.3	32.8	83	49	214

Analyzing the carrier conditions one will note that in order to secure the same amount of output power from any of the explored tubes the grid must be swung to approximately the same positive grid potential in spite of a wide difference in values of μ and in the biases applied. However, the grid current goes down rapidly as the μ of the tube decreases. As the required grid excitation depends on the product of grid current and bias, medium-μ tubes such as the UV-207 are most apt to give the optimum solution for lowest excitation.

With 20,000 volts on the plate, twice the carrier voltage, none of the tubes satisfies the condition of distortionless modulation which requires the crest power output of 24 kilowatts. This only corroborates our previous conclusion. The largest distortion due to the "shortage" in power output is inherent in high-μ tubes and decreases as μ decreases. Expressed in percentage of second harmonic, distortions introduced by the class C amplifier in the analyzed case are 10 per cent, 7.6 per cent, and 2.4 per cent, respectively.

The results of similar calculation for *self-biased operation* of the same tubes are also shown in Table I: Carrier conditions are the same as for generator bias.

In this case, the output power with all three tubes is *greater* than four times the carrier output with resulting second harmonic components, 1.7 per cent, 2.6 per cent, and 3.4 per cent, respectively, for the UV-863, UV-207, and UV-848 tubes. Thus, from the viewpoint of second harmonic distortion the last series of calculations distinctly exhibits the merits of the self-biased scheme and also of the application of high biases in class C operation. Self-biased operation also proves to be superior to that with generator bias with respect to the efficiency at the crest of the modulation voltage and the smaller grid loss on its negative swing. However, the action of self-bias on the negative swing of modulation voltage is such that harmonics of higher order can be introduced by the amplifier more readily than in fixed bias operation.

Before going into a general discussion of the foregoing results, we shall examine in greater detail the role of plate dissipation and grid losses from the viewpoint of limitations inherent in vacuum tubes.

Plate Dissipation

With all three types of tubes under investigation, 10-kilowatt plate dissipation has been experimentally established as a permissible limit for unmodulated class C operation. The associated rate of water flow is three gallons per minute. However, the 10-kilowatt maximum rating cannot be indiscriminately applied to all cases of modulated class C operation. This can be substantiated by the following discussion.

With 100 per cent modulation applied to the carrier the plate dissipation averaged over an audio cycle is theoretically equal to 1.5 P_{hc} if by P_{hc} we designate carrier plate loss. But this relation holds only in the case of "ideal" class C operation with constant efficiency throughout the audio cycle. In actual practice, one can express the average plate dissipation with good approximation as

$$P_{h\,\mathrm{av}} = 1/2\left(\frac{P_{hc} + P_{h\,\mathrm{max}}}{2} + \frac{P_{hc} + P_{h\,\mathrm{min}}}{2}\right) \tag{4}$$

where $P_{h\,\mathrm{max}}$ and $P_{h\,\mathrm{min}}$ are dissipation rates at the positive and negative crests of modulation, respectively. With 100 per cent modulation this expression turns out to be

$$P_{h\,\mathrm{av}} = 1/2P_{hc} + 1/4P_{h\,\mathrm{max}}. \tag{5}$$

Hence, $P_{h\ av}$ is equal to 1.5 P_{hc} only in the exceptional case when $P_{h\ max} = 4\ P_{hc}$. Yet, in the foregoing numerical examples we have seen that $P_{h\ max}$ may, and often does, depart considerably from the theoretical figure of 4 P_{hc}, thus affecting the average, $P_{h\ av}$.

The difference in plate dissipation between unmodulated and modulated operation may be further augmented by the focusing effect of the grid. This comes to light during a modulation cycle at higher plate voltages whenever appreciable instantaneous plate currents flow while the grid potential sweeps through its negative and low positive values. In this condition the heat generation is confined to narrow areas of the anode, formed as patterns of the grid mesh. Hence, local steam bubble

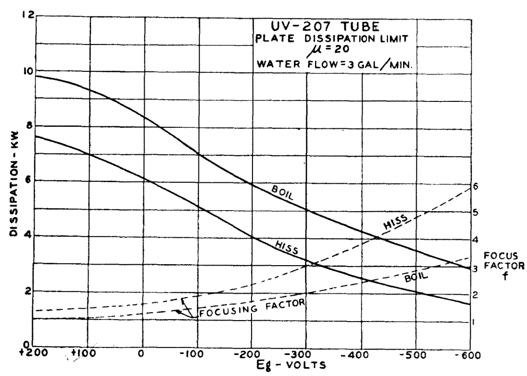


Fig. 9

formation may be started long before the average temperature of the cooling water warrants such a phenomenon. In order conveniently to take the focusing effect of the grid into consideration one may introduce conceptions of "focusing factor" and "effective plate dissipation." The focusing factor can be described as the ratio of the total available area of the active part of the anode to the actual area into which the impinging electrons are crowded in each specific case. The curve 1 of Fig. 9, taken experimentally on a UV-207 tube under static conditions, shows plate dissipation in kilowatts at different grid potentials; at each point this dissipation cannot be exceeded without producing steam bubbles at the anode accompanied by a hissing noise. Each ordinate of this curve divided into 10 kilowatts gives, then, the focusing factor, f, for the corresponding grid potential.

Thus, in calculation of plate dissipation along a dynamic characteristic one has to determine the factor f for each elementary strip of a current-time curve such as is dealt with in Fig. 2. Then the value of actual elementary dissipation, computed for each strip, is to be multiplied by the related value of f. The average of the sum of all such weighted elementary dissipations over a radio-frequency cycle will be the average "effective" dissipation for the explored dynamic characteristic. The effective dissipation may in some cases affect modulated class C operation strongly, and must hence be taken into account. This is particularly true in the following specific cases: (1) If a relatively low bias is used; (2) if bias is strictly constant during a modulation cycle, such as is the case with a bias generator; and (3) if the tube has a low amplification factor, μ.

As an illustration of the importance of "effective" dissipation, it may be mentioned that in one particular case of operation of a UV-848 tube the cooling water was decidedly "boiling," while the temperature of the outgoing water was only 7 degrees centigrade.

Grid Excitation

The knowledge of grid excitation necessary to secure the desired output from the modulated stage is primarily important from the economic viewpoint. Indeed, the radio-frequency excitation voltage and power govern the construction of the exciter stage. The numerical value of grid excitation power in each case of operation can be computed conveniently and with a sufficient degree of accuracy as the product of the direct current and of the crest value of grid excitation voltage,[5] that is,

$$p_{exc} = i_c(e_c + e_{\max}). \tag{6}$$

During modulation the average direct grid current and the excitation power both vary. They decrease as the positive peak of modulation is approached and may even become negative if generator bias is used. As the plate voltage falls to zero on the negative swing of modulation both quantities increase considerably.

In addition to economic considerations, one must realize how and in what degree the grid excitation can affect the tube itself. Grid-excitation power is consumed partly in the bias supplying source, grid-leak resistors, or bias generator, and partly in the grid itself, where it is converted into heat. The grid temperature therefore rises and eventually may reach a level where the grid starts emitting primary electrons of its own. With this, the grid loses its controlling action and may cause heavy overloading of the tube. In this manner the grid excitation may become a limiting factor in class C operation of a tube. Therefore, in each particular case, both carrier conditions and modulated operation must undergo scrutiny in this respect.

The amount of power which a grid can absorb without being heated

[5] H. P. Thomas, Proc. I.R.E., vol. 21, p. 1134; August, (1933).

to the emission point can be measured directly by a simple scheme.[6] A detailed consideration of the method is, however, out of the scope of this investigation. It has been found that appreciable emission of primary or thermionic electrons from the grid starts at the following conditions of dissipation:

With	UV-863 tube at	450 watts
	UV-207	350
	UV-848	250

From completely undisturbed operation of these tubes these limits must be reduced; thus one may with safety assume permissible grid dissipation limits at 350, 250, and 175 watts, respectively.

The amount of power actually supplied to a grid by the excitation stage is found by simple calculation to be the difference between the total input power and the power lost in the bias device:

$$p_i = i_c(e_c + e_{\max}) - e_c i_c = i_c \, e_{\max}. \tag{7}$$

However, this is not the true total power converted into heat at the grid during oscillation. Actually the measured grid current at any instant represents the difference between the total incident grid current and the secondary emission current from the grid to the plate. In other words, at any instant the actual flow of electrons emitted from the filament and impinging on the grid is greater than the grid current recorded on a meter by the amount of the secondary emission current. Hence the total electronic flow to the grid can be viewed as though divided into two parallel streams with different external paths. One stream constitutes the current flowing into the grid circuit; the other component, being exactly equal in magnitude to the secondary emission current, is linked through this secondary emission current with the external plate circuit. Both primary electron streams physically end their career at the grid and contribute to its heating in proportion to their respective magnitudes. The comparatively small cooling effect due to the emission of secondary electrons can safely be neglected.

The amount of energy supplied to the grid by the exciter stage is, as we have seen, easily calculated from (7). The computation of the heat due to the primary grid current linked with and energized by the plate circuit is not so simple as this current blends completely with the main plate current in the external circuit. Fortunately the sum total of the electron current impinging on the grid is accessible by an indirect calculation. Some study carried out in our laboratory has

[6] Described in "Grid dissipation as a limiting factor in vacuum tube operation," presented before joint I.R.E.-U.R.S.I. meeting, Washington, D.C., April 26, 1935.

shown that one will not be far from the true value of actual grid dissipation if, in calculation along any given dynamic characteristic, one proceeds in the following manner:

(a) For instantaneous grid voltages above the diode line, or for $e_g \geqq E_p$ one can safely take the grid current values indicated in the chart.

(b) For all voltages such that $e_g \leqq E_p$ one can assume the *same instantaneous values of grid current as for the diode line,* $E_p = e_g$. By plotting such a "true" primary grid current as function of time, or of electrical angle, computing the grid dissipation for the narrow strips into which the time curve is divided, and then averaging the grand total over

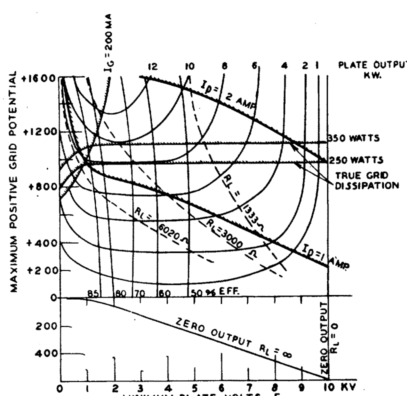


Fig. 10—Lines of equal output and efficiency for carrier conditions UV-207 tube E_p=10000 v. e_c=-2800 v.

the entire radio-frequency cycle, one arrives at a more correct value of grid dissipation than is indicated by the externally recorded grid current alone. The final result will then contain a certain margin of safety.

General Discussion

In general, there is no rigorous common rule concerning the choice of tubes and grid excitation arrangements for modulated class C operation. Hence, in practice one encounters a great variety of independent solutions of these problems, sometimes differing basically from each other. Now, in the light of the foregoing analysis one can make a few statements which contribute to the general knowledge of modulated class C operation and which will help in the design of the output stage and in the proper selection of vacuum tubes.

(1) We have seen that with strictly constant grid bias, such as supplied by a bias generator, it is impossible to realize distortionless 100 per cent plate modulation with any type of tube unless the amplifica-

tion factor, μ, is extremely low; but then the other limitations come to the foreground. Therefore, the bias generator, or any other method supplying an essentially constant bias, must be generally considered unsuitable for modulated class C operation.

(2) Distortion of the output wave is also inherent in self-biased operation. Only here, in contrast to the previous case, distortion is due to an excess in power output at the crest of modulation. Yet, if one can tolerate some distortion introduced by the output stage, high-μ tubes are the most suitable for the purpose, giving the least distortion.

(3) A more flexible method of supplying bias is the simultaneous use of generator and grid leak in series. By combining the two methods exercising opposite effects on distortion one may adjust the output stage to a lower distortion than is possible with either method alone.

(4) Distortion changes greatly to the disadvantage of operation as the tubes in service become older. Hence, a periodical readjustmentof the bias and excitation is expedient.

(5) Distortion of the output wave inherent in class C operation is to some degree affected by the choice of the load resistance. From the very technique of the outlined graphical method one may arrive at the conclusion that the load resistance is to be chosen as high as possible in the case of constant bias and as low as possible in a self-biasing scheme. Nevertheless in either case the choice will be restricted by other factors such as grid excitation or tube efficiency.

(6) It is known that good class C operation requires the application of higher biases. On the other hand, from the economy viewpoint lower biases are advantageous. In addition too high a bias, necessitating high grid-excitation voltage, causes high dielectric loss in the press and other insulating parts of the tube; this may result in puncture of the tube. A compromise choice of the bias must be governed by the operating conditions at the apex of modulation rather than by the carrier.

(7) Plate dissipation at carrier conditions can hardly be a cause of concern to the designer. But when the tube may run into class B or even into class A operation during modulation, dissipation may become a limiting factor in choosing the best type of tube and appropriate operating conditions. In this respect low-μ tubes are particularly bad as their 100 per cent modulated operation is inherently accompanied by high "effective" plate dissipation.

(8) Grid excitation for producing a desired output is generally the highest with high-mu tubes and the lowest with tubes of medium μ, but power dissipation in the grid may become a limiting factor almost in the same measure with any of these tubes irrespective of the value of mu. This is because high-μ grids are usually built more massively,

have a larger cooling surface, and hence, can stand more dissipation without overheating.

With any tube, the grid excitation power increases rapidly as the minimum plate voltage touched during oscillation decreases; in other words, as the chosen load resistance increases. But this is not true with respect to grid dissipation. Indeed, we have seen that the true grid dissipation depends merely on the maximum grid excitation voltage, and this varies but little with different chosen values of $E_{\min}$, or of the load resistance.

(9) Correlating all results of the previous discussion one arrives at the verdict that the most suitable tubes for modulated class C operation are those of medium μ. Also, there appears to be no justification whatsoever in the application of low-μ tubes for this class of service. Nevertheless, if, for some reason, a low-μ tube is to be used as a class C amplifier, its rating must be decidedly lower than that of its sister tubes of higher μ. A bias generator in this case will be more suitable than a self-biasing scheme.

A general idea regarding the mutual relation of various factors in class C operation can be conveniently obtained from a map such as plotted in Fig. 10 for the UV-207 tube. In the map, lines of equal output are plotted for $E_p = 10{,}000$ volts and $e_c = -2800$ volts, which is the carrier condition in one of our numerical examples. The coördinates here are the same as used in the constant current charts, so that the two kinds of charts can be superimposed on each other. Any point of the new map represents the termination of a dynamic characteristic to which the inscribed values belong. The map also contains the curves of the conventional limits, $i_g = 0.200$ ampere and $I_p = 1.0$ and 2.0 amperes. The lines of true grid dissipation, $p_{gh} = 250$ watts and $p_{gh} = 350$ watts are also shown. In addition, the loci of the end-points of dynamic characteristics for three different load resistances are traced.

It may be of interest to mention the following relation between the instantaneous and average values of plate current in a modulated class C amplifier as they occur in the various cases of our calculation. The ratio of the maximum instantaneous to the average plate current at carrier conditions is from 6 to 7; it drops to 5 if a relatively lower bias is used. The ratio between the average plate current at the peak of modulation and that at carrier conditions is less than 2 with a constant bias and greater than 2 in a self-biasing scheme. The departure from the theoretical factor may be as large as ± 25 per cent. The maximum instantaneous plate current reached at the crest of a 100 per cent modulation audio cycle is from 9 to 9.5 times the average plate-current value at carrier conditions.

Compensated Class C Operation

From our entire discussion it is evident that the shortcomings inherent in conventional class C operation with high modulation have their primary cause in the fact that the radio-frequency grid excitation voltage is of constant amplitude. This is almost rigidly fixed in magnitude as soon as the carrier output, operating plate voltage, and grid bias are specified. However, the constant excitation voltage compatible with the carrier condition proves to be inadequate for other plate voltages during modulation as the positive and negative crests are approached.

Generally speaking, the excitation voltage is too high on the negative and too low on the positive swing of the audio plate voltage. Therefore, logically, any means that is capable of properly changing or "compensating" the grid-excitation voltage during each audio cycle will bring about a decided improvement in class C operation. One can imagine a variety of schemes which will effect the desired compensation. But essentially all of them can be described as *auxiliary modulation of the excitation stage*. For example, one can apply modulation directly to the plates of the exciter tubes by means of a special choke and audio transformer of small size, the primary of which is energized by the main modulators, or a suitable tap can be provided on the main modulating transformer for the same purpose. Another possibility in "compensation" is in the varying of the bias of the excitation stage or of earlier stages of the power amplifier, thus influencing the radio-frequency amplitude of the exciter voltage.

The effect of the compensation at the positive crest of modulation is this: In the case of a constant bias, due to the increased grid voltage amplitude the tube is able to produce greater outputs and hence the point of "power equilibrium" in Fig. 3 shifts in the direction of lower values of E_{min}, corresponding to higher outputs and higher efficiency. One can always adjust compensation so as to make the power output at the crest of modulation equal to exactly four times the carrier output. In operation with self-bias the immediate influence of compensation is an increase in the bias at higher plate voltages because of the grid swinging into the region of heavier grid currents. This, therefore, counteracts the natural loss-of-bias tendency in noncompensated modulation. In addition, the shift of the power equilibrium point also takes place. An important result common to both modes of operation is an increase in the efficiency and a reduction in the "effective" plate loss. Thus, in one instance, a UV-848 tube boiled vigorously when 100 per cent modulation was applied. One could clearly distinguish in the boiling the sixty-cycle pitch of the modulating frequency indicating that boiling occurred just at the apex of the audio cycle. However, boiling disappeared as soon as compensation of the grid excitation was applied, and would reappear as soon as the compensation was taken off.

In self-biased operation it is possible to carry compensation so far that the bias will actually increase on the upswing of the modulation voltage and decrease on the negative half cycle of modulation. Such action reminds one of the classical self-oscillator. The main difference is that in a 100 per cent modulated self-oscillator the grid bias and grid excitation vary rigidly from zero to approximately twice carrier value at the modulating frequency, while in a compensated class C amplifier the magnitude of the audio bias variation can be adjusted at will. In other words in a self-oscillator the excitation is strictly proportional to the audio plate voltage and is therefore modulated to the same degree as is the plate, while in a compensated amplifier the percentage of auxiliary modulation of the excitation can be varied from zero to any desired level and will generally be much less than 100 per cent.

In Fig. 1 the paths of the biases are plotted both for compensated class C operation and for a self-oscillator. One may note that graphically the dynamic characteristics of a self-oscillator at any point of modulation may be represented by strictly parallel lines with slope equal to the ratio of grid and plate coupling turns, while in a class C amplifier, compensated or noncompensated, the slope of the instantaneous dynamic lines changes during the entire audio cycle.

At the negative crest of modulation, when the modulated plate voltage sweeps through zero, the grid compensation reduces the excitation voltage and thus tends to relieve the grid from excessive heat dissipation. In this respect the compensation scheme is superior to the grid-leak bias arrangement as it simultaneously decreases the bias, and with it, the unnecessary power loss in this region of operation. Generally, by the application of compensating methods, lower and more economical biases can be used, without impairing operation at high modulation voltages.

In Figs. 5 and 6 the extreme right panels demonstrate oscillographically the effect of compensation. In both cases the average audio variation in grid current is reversed 180 degrees in phase to that in the absence of compensation. Therefore, in self-biased operation the audio variation of bias during an audio cycle becomes more consistent with class C operation at any instant. At the same time in both cases the output wave, shown as the lowest record, *does not reveal any appreciable distortion.* In addition calculation indicates better efficiency as compared to noncompensated operation.

A simple though partial solution to the problem of compensating the grid may be achieved by purposely making the exciter stage regulation high. From calculation as well as from the oscillographic records of Figs. 5 and 6 it is quite clear that with any noncompensated scheme the average grid current decreases with increasing plate voltage and vice versa. This means that the load on the exciter stage varies in the same manner. Hence if the regulation of the exciter stage is high the oscillation amplitude in the exciter tank circuit, which determines the excitation voltage, will increase and decrease elastically in the manner which is required for compensation. Such regulation can be preadjusted, for example, by inserting a resistor in the plate-voltage supply line to the exciter, or by other simple external means. The limitation of this method lies in the fact that on the positive half cycle of modulation the average grid current and bias may soon acquire a constant value, preventing a further unloading of the excitation stage.

Conclusions

The graphical method which has been described enables one to carry out a point-by-point analysis of the class C performance of a tube throughout an entire audio modulation cycle with accuracy and ease. It brings out the fact that operation with generator bias differs markedly from operation with self-bias when the process of modulation is considered. Detailed investigation shows that audio distortion is introduced into the output wave by the amplifier itself. In the case of generator bias this distortion is due to the shortage in output at modulation peaks while with self-bias it is due to an excess of power output on peaks. A study of the tube charts shows that in general the least distortion can be obtained by the use of a proper combination of the two bias methods. During modulation one must consider "effective" rather than actual plate dissipation; this becomes a distinct limitation on operation when the amplification factor of the tube is low. The audio distortion due to the class C amplifier itself can be eliminated by the use of grid "compensation" or auxiliary audio modulation of the excitation stage. This auxiliary modulation enables one to imitate the attractive features which exist in a self-oscillator so as to obtain an increase of bias and excitation at the crest of audio modulation and a corresponding decrease at its ebb. Operation under compensated conditions proves to be highly desirable in reducing the effective plate dissipation and in considerably increasing the over-all efficiency of the tube.

Compensation can also be instrumental in the improvement of modulated operation if "cathode" bias obtained from a series plate current resistor is used with class C amplifiers in accordance with recent tendencies in transmitter engineering practice.