Amplifier Load Impedance Reduction

GENERAL design equations are derived for output watts, efficiency, and load impedance, and it is shown that a range of at least 10:1 in load resistance can be made available with a change of output watts of only 1.3:1.

The discussion is put in terms of a specific tube and the essential design of an amplifier of 34 db gain, with voltage and current feedback, and an internal impedance equal to the directly-fed 50-ohm load, having an output of 10 watts, is given. An output stage design (600 ohms) with no restriction on supply voltages, demonstrates the use of a low anode voltage (compared to the screen voltage) without a special output tube.

The procedure described provides an alternate solution to the more general graphical methods using tube characteristic curve plots, giving all practical information, supply voltages, currents and some insight into the operation of tubes with low impedance loads. (British Patent No. 2515/44)

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THE DESIGN of amplifiers to deliver power into low-value load impedances over a wide range of frequencies, without the use of large ratio output transformers, or special tubes, is possible by departing radically from the usual ratio of screen and anode voltages for pentode and tetrode tubes. High-ratio output transformers have bulk and limited frequency response range, even when great care is used in design and construction. Few tubes, used in a conventional manner, can be properly loaded directly with impedances of the order of 600 ohms and less, so specially designed tubes are frequently necessary.

When voltage and current feedback is applied in such amplifiers to stabilize the gain and internal impedance the design of these networks becomes more difficult when the output load impedance is high. The plate-to-ground capacitance of the output stage, which is far larger than that of previous stages, will be of greater influence on the high frequency response if the load impedance is high, while the unwanted feedback from anode-to-grid is larger with larger load impedances since the gain of this stage is higher.

There are many reasons, therefore, why it would be advantageous to feed the low-load impedance directly, provided this does not involve use of a special tube. This can be done with the normal tubes by using an anode voltage substantially smaller than the screen voltage.

The author has shown[1] the general design of circuits operating under incipient waveform distortion conditions. The method used differed from conventional practice in that a symbol (p) was introduced to represent the ratio of the negative anode voltage variation to the steady voltage sustained by the tube. To make the treatment general, the positive output voltage change is defined as 1/Nth of the negative, and the corresponding current variations are given the ratio M:1; the values of M and N being defined in a specific case by the proposed use of the tube circuit.

The steady anode voltage is defined as (E_b) the maximum and minimum voltages as E_b' and E_b'' and the corresponding maximum and minimum currents as (I_a') and (I_a''). The output volt-amperes, efficiency and load are then derived, and are as follows (for the case where I_a' is negligible compared to I_a and under maximum output conditions just prior to overloading by waveform distortion: (k) is a numerical constant of value depending on the waveform, being 0.125 for a sine wave).

$$\text{Volt amperes} = I_a pkE_b(N+1)/N \qquad (1)$$

$$\text{Efficiency} = pk(M+1)(N+1)/N \qquad 2)$$

$$\text{Load Res.} = pE_b(N+1)/NI_a \qquad (3)$$

$$I_a = (K_a/\mu^m)(E_s+\mu E_g)^m \qquad (4)$$

Equation 4 shows for the range of currents normally used, the power law relationship that exists for the tube current in terms of the electrode voltages. Here (E_s) is the screen-to-cathode voltage for a pentode or tetrode (or the anode to cathode voltage for a triode), (E_g) is the grid-to-cathode voltage, (μ) is the grid to screen (or grid-to-plate, for a triode) amplification factor, (K_a) is a constant having a value depending on the design of the tube,[2] and (m) is the index of the assumed power law relationship.

E_g 5 results when (E_g) is defined as sE_s/μ where (s) is a number of positive sign if the maximum grid-to-cathode voltage is positive, and vice-versa. For instance, in the case of operation with "zero" grid current, s is 0; in the case of operation with zero grid bias to an input having equal positive and negative values, s is +1. In this way, the designer will know the value of s

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[1] Wireless Engineer, Vol. 21, August 1944, pps. 368 to 376.

[2] K_a can be determined from published tube data by taking the quotient of the zero-grid-voltage plate current and 3/2 power of the screen voltage. Having found this value, the simplest way to find K_a is to use the given value for μ. This will be quoted for triodes, but not for pentodes and tetrodes in terms of its value considering the tube as a triode (i.e. the μ we want is the grid-cathode, screen-cathode control voltage). One quick way of finding this μ for pentodes and tetrodes, is to find the grid bias which will substantially cut off the cathode current and divide it into the screen voltage. Another way, not involving a knowledge of μ, is to find the transconductance G at a given current I, assumming the exponent is 1.5.

by consideration of the desired function of the tube circuit.

So far, the conditions of maximum output have been defined as: (a) a minimum current of negligible value compared to the maximum; (b) a maximum current defined by equation (5) in terms of the tube parameters, the screen voltage, a power law and the ratio (s) of the maximum grid voltage to the grid "cut-off" voltage (E_s/μ).

With pentodes and tetrodes a further condition has to be specified, since the anode (and screen) current-voltage characteristics show a marked change at low anode voltages at the "knee" of the characteristic, and, since the characteristic exhibits substantially constant current for voltages down to this "knee," clearly the greatest output will result when the anode voltage attains the "knee" value simultaneously with the attainment of maximum current on the maximum positive grid voltage. From elementary theory, and as a matter of experience, the "knee" voltage is a fraction of the screen voltage. Letting this fraction be (q) a relation between E_b and E_s is possible in terms of (p) $(1 - p)E_b = qE_s$. Hence equation (5) becomes:

$$I_a = (K_a/\mu^m)E_s^m(1+s)^m \qquad (5)$$

$$I_a = (K_a/\mu^m)[(1-p)E_b/q]^m(1+s)^m \qquad (6)$$

Output va · =

$$(K_a/\mu^m)pk[(1-p)/q]^m\left(\frac{N+1}{N}\right)(1+s)^m E_b^{m+1} \qquad (7)$$

Load Res. =

$$\frac{p}{(1-p)^m}\,\frac{N+1}{N}\,\frac{q^m\mu^m}{E_b^{m-1}(1+s)^m K_a} \qquad (8)$$

Equations (7) and (8) are obtained by substituting (6) in (1) and (3) and (2), including all factors which are known, or may be postulated. A variety of optimum conditions for design may be deduced from them by considering each quantity in turn as a variable. In the present case, the ratio (p) is chosen for consideration.

Condition for Optimum Output

For a given tube, μ^m/K_a with given values of V, s, N, k and q, the optimum output is obtained when $p(1 - p)^m$ is a maximum. By differentiation, this $p = 1/(1+m)$. Over a normal range of plate current variation (say 10:1), the value of m may be taken as 1.5, so that the optimum value of p, for the above conditions of operation, is 0.4.

By inspection of the plate characteristics of normal pentode and tetrode tubes, a value for q of 0.2 has been found to satisfy nearly all types; some may have a lower "knee" voltage than 0.2 of the screen voltage, but very few have a higher value. From (5) the normal condition of operation in which $E_s = E_b$ corresponds to a p value of 0.8. However, using the optimum value of $p = 0.4$, derived for the above conditions, together with $q = 0.2$, in equations (5), (7), and (8), gives the following results: (a) the output is 2.63 times as great for $p = 0.4$ as when $p = 0.8$; (b) the load resistance is 0.096 of the normal value; (c) E_s is raised to three times E_b.

The above results of taking this condition (where E_b is considered constant but the ratio E_s/E_b is a variable), are very striking and useful in the present case where direct loading of the output stage is required. For it will be shown that there is a wide range of p values on either side of the optimum value of 0.4, over which the load resistance can have a range of at least 10:1, without greatly affecting the output power.

Output Characteristics

To determine the output characteristics of a specific Class A tube operated with a given steady plate voltage, the output waveform will be assumed sinusoidal by having the grid driven by a waveform which causes this to be so, generally by the aid of overall feedback on the previous stages, if the input is sinusoidal. This assumption is not imperative, since the waveform of

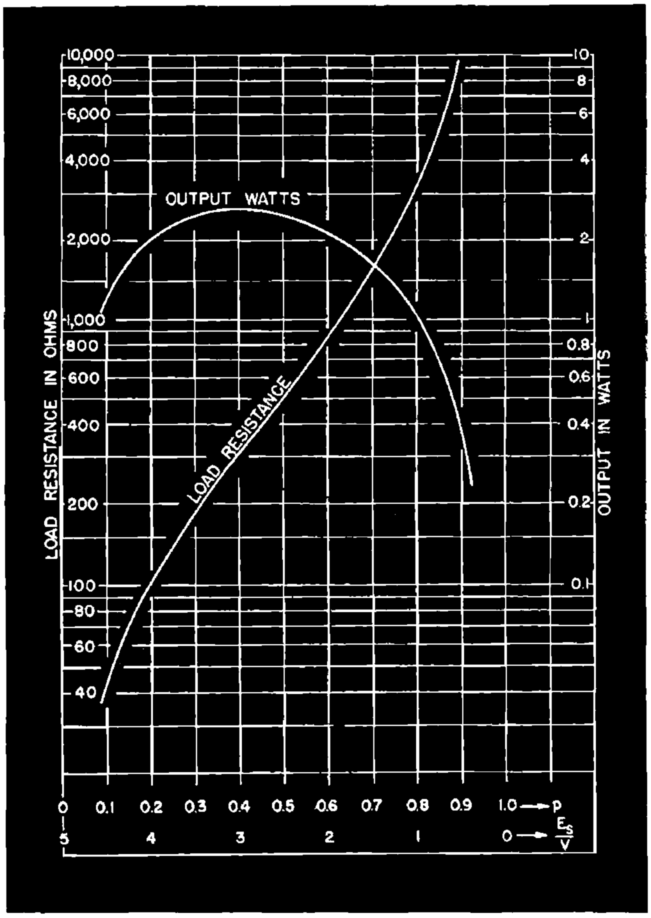


Fig. 1: Showing curves for output watts and load resistance plotted on a logarithmic scale, against values of (p) and O to 1 on a linear scale. Effects of alternate values may be seen by shifting curves bodily up or down by an amount corresponding to the ratio of the alternation

the output is immaterial to the discussion; it merely enables (M) and (N) to be assigned the value unity, and defines (k) as 0.125.

Grid current operation will not be assumed, so that (s) can be given the value zero. Although, again, this assumption does not affect the type of output characteristics. Assume (q) = 0.2, the exponent m = 1.5, and E_b = 100 volts. In the specific case of telephone repeater stations, the latter permits the use of the normal 130-volt supply, with an allowance for the steady voltage drop on the plate choke or transformer, and for automatic grid bias if required.

The tube factor μ^m/K_a will be taken as 20,000, since a wide variety of output pentodes and tetrodes have this value; e.g., British EL 50, 6L6G, 807. With these values, equations (7), (8), and (2) become,

$$\text{watts} = 14p(1-p)^{1.5} \qquad (7a)$$

$$\text{resistance} = 358p/(1-p)^{1.5} \qquad (8a)$$

$$\text{efficiency} = p/2 \qquad (2a)$$

Fig. 1 shows curves for the output watts and load resistance plotted on a logarithmic scale, against values of (p) from 0 to 1 on a linear scale. In this way, the effects of alternate values may be seen by shifting the curves bodily up or down by an amount corresponding to the ratio of the alteration. The ratio E_s/E_b corresponding to the (p) values has also been shown.

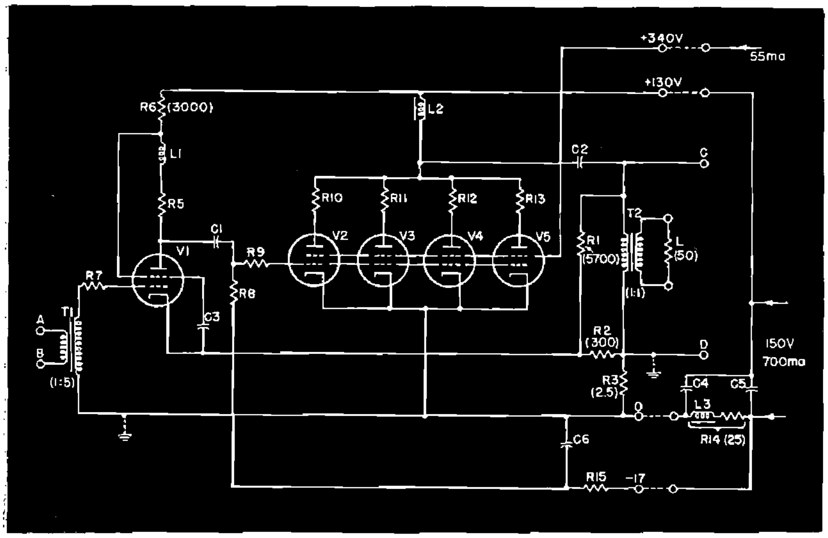
Over a range of from 2 to 4 for E_s/E_b about twice the output watts are obtainable compared with normal operation and over a range of 10:1 in load resistance, while the geometric mean of this resistance range is about one-tenth the normal value.

Also, the order of this range approaches more nearly that required for modern transmission methods. For example, an output of 10 watts may be required for carrier telephone operation of a cable of impedance 50 ohms. This could be met with 4 tubes of this type in parallel, by operating them at a (p) value of 0.32 or (E_s/E_b = 3.4), without the use of a step-down output transformer, since the single tube output and load resistance are 2.5 watts and 200 ohms respectively.

It is possible to raise the output by increasing E_b above the assumed value of 100 volts, but it is not possible to produce a large reduction in the load resistance value, since the output is proportional to the 2.5th power of E_b, but the resistance is inversely proportional to its 0.5th power. Moreover, there is a wide choice of tubes whose maximum permissible screen voltage lies between 300 and 400 volts, all of which can be used if anode voltages around 100 are used.

The provision of the feedback patch impedance is also facilitated by this method of operation. In the case of voltage feedback, the same value of potentiometer across the load resistance will dissipate one-tenth the total output of the tube, by comparison with normal operation, since the load resistance is around one-tenth the normal value. Alternatively, if the normal potentiometer gives difficulty owing to its high impedance and the associated circuit residuals, then the impedance can be reduced appreciably without incurring too great a power loss.

Fig. 2: Typical circuit for amplifier. Detailed explanation appears in text of this article



As regards the current feedback resistance, difficulty is often experienced when this resistance must be placed in series with the load, since it may give a marked loss in E_b. The value of this resistance is proportional to the load resistance (for a given voltage feedback ratio) and a given ratio of load-to-internal impedance. From equation (6), the steady plate current will be proportional to $(1 - p)^m$, (since the steady current is proportional to the maximum), while from equation (8) the load resistance (and hence the current feedback resistance) is proportional to $p/(1 - p)^m$. The product of these is proportional to p, so that reduction of p value will reduce the steady voltage drop on the current feedback resistance.

Class A Amplifier Design

An example of basic design of a class A amplifier taking its main plate supply from a given voltage will be considered. The case cited above where an output of 10 watts into 50 ohms is desired, will not be completed as regards the output stage and its associated components.

Assuming that a stabilized gain of 34 db is required, and that the output transformer (if any) will be of 1:1 ratio, then this gain may be split into 14 db on the input transformer of 1:5 ratio, plus 20 db from the amplifier proper. One stage of amplification prior to the output stage will enable sufficient open circuit gain to be obtained to insure high gain stability, and permits the use of simplified formulae for the feedback network calculations.

On this basis, the voltage feedback ratio required will be ½ x 10 or 0.05 (the 2 in this case provides an internal impedance equal to the load), while the current feedback resistance will be 0.05 times the anode load, i.e., 2.5 ohms. The steady plate current of the 4 tubes in parallel will be one-half I_a (since the output is assumed to be sinus-

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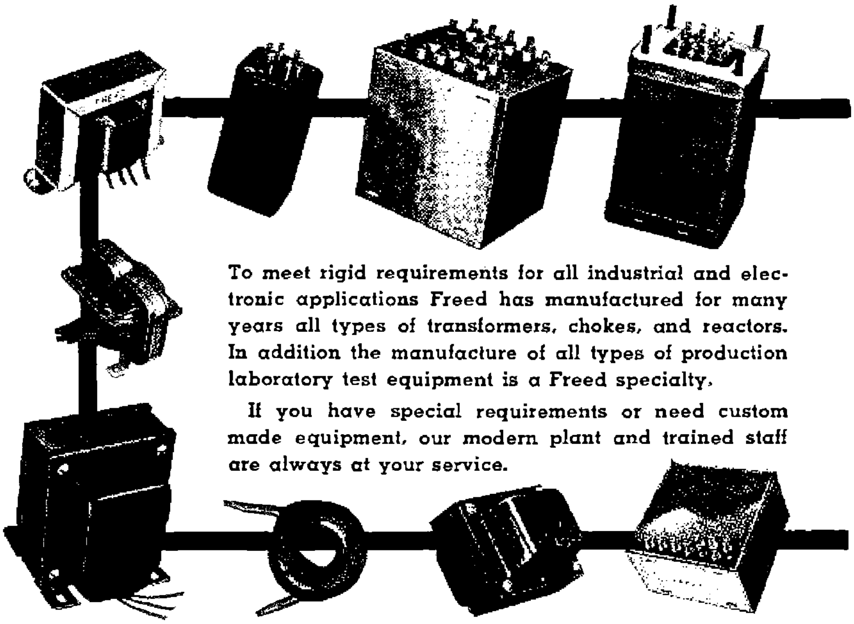

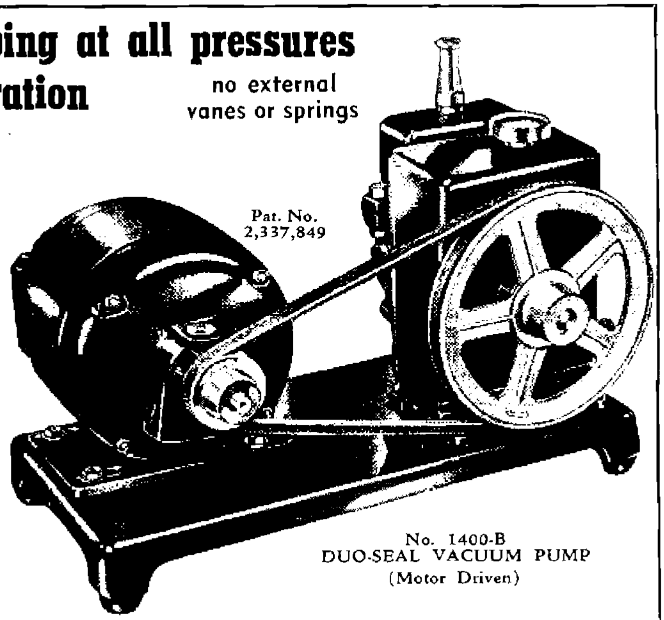

Load Impedance Reduction

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oidal), and can be calculated from equation (6), using $p = 0.32$, $E_b = 100$ volts, $q = 0.2$, $s — 0$, μ'''/K_a — 20,000 (for one tube), and $m = 1.5$. A value of 625 ma is obtained.

The steady screen voltage will be 340, from the relation for q whilst the grid bias will be approximately one-half the negative grid base of the tubes, i. e., $E_s/2\,\mu$ and, if μ be assumed 10 for these tubes, the grid bias will be 17 volts. In practice this value should be experimentally adjusted until incipient overloading on both positive and negative peaks of the output waveform is produced at maximum excitation, because the bias should be such as to produce a steady current equal to one half the maximum; otherwise the postulated output of 10 watts will not be obtained.

Fig. 2 shows a typical circuit for this amplifier, with the above specific values in parenthesis. The tube V1 is a pentode or tetrode having the usual inductive plate impedance L1, R5 to give maximum high frequency response in conjunction with the plate-to-ground capacitance. R10 to R13 are 10-ohm oscillation-stopper resistances and the plate choke L2 is designed to carry 625 ma dc and the small ac component due to its inductance. The load of 50 ohms has been shown coupled to the plate via a 1:1 transformer T2, since it is probable that a balanced output will be needed if the load is comprised by a symmetrical transmission line. Alternatively, if the load is asymmetric, T2 may be deleted and the load connected between C and D; in this case the ground may be transferred from the zero potential lead to D.

The voltage feedback is given by R1 and R2, while R3 provides the current feedback. As the sum of the voltages on R2 and R3 must be fed into the cathode circuit of V1 for negative feedback, R2 is made of convenient value to provide the necessary steady grid bias for V1, say 300 ohms, when R1 becomes 5,700 ohms to give the 0.05 ratio. The loss on the shunt feedback path is therefore less than one-hundredth of the wanted output, say 0.1 watt, and is negligible, despite the low and convenient order of resistance used. In order to prevent local feedback on V1, the screen is decoupled to the cathode by condenser C3 and a series plate resistance R6, which must be some 3,000 ohms in order not to reduce unduly the value of R2 and R3. The usual repeater station plate supply voltage of 130 volts has been shown, and this allows 30 volts steady drop on L2, i.e., a dc resistance of 48 ohms.

The grid bias of −17 volts can normally be taken from the usual −21 volt supply via decoupling circuit R15 and C6, but an alternative has also been shown where 60 cycle rectifying units provide the power supplies. The smoothing choke for the 130 volt plate supply, plus additional resistance if necessary to make up R14, is placed in the negative lead and provides the grid bias for the output stage. In this case the rectifying unit will have to deliver some 150 volts at around 700 ma.

The above reference to the use of 60 cycle rectifier units to supply this amplifier may appear somewhat contradictory, in view of the assumption that only a given 100-volt supply was available, but nevertheless a low plate voltage with respect to the screen voltage is essential to the design for directly feeding a low impedance. To demonstrate this point, a case where E_b is not fixed, but direct feed is still required, will now be described.

In wideband oscillators, it is almost impossible to design an output transformer which will not degrade the frequency characteristics of the output. A typical case occurred in the design of an oscillator covering a frequency range of 60 cycles to 1.4 megacycles, with an output of 6 watts into 600 ohms over the whole frequency range. This was desired from a single tube and, in particular, the same tube as was used in the previous example. In this case, since a rectified ac power supply could be used, there was no restriction on the values of the plate and screen voltages in the initial stages of the design.

From the efficiency equation (2a), for M and N equal to 1, and k = 0.125, i.e., sinusoidal operation, and since efficiency=Output Watts 1 Dissipation, it will be be seen that the dissipation is 2W/p, where W denotes the output watts. Inspection

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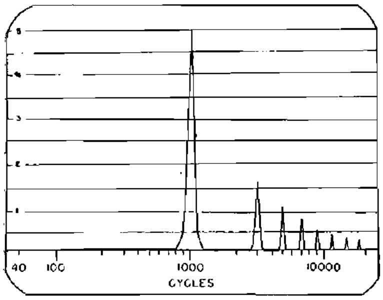

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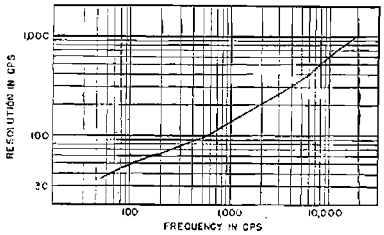

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of Fig. 1 shows that the dissipation will decrease with increase of p, i.e., with increase of load resistance. Hence it becomes possible to get more than the previous output from the tube, by raising E_b, particularly since the load resistance is much higher (per tube) than the previous example.

Since the output is proportional to the 2.5th power of E_b, whereas the load resistance is proportional to the 0.5th power, a relatively small increase will give the desired output, provided the maximum dissipation is not exceeded. To save space, the curves of Fig. 1 can be used to give a close estimate of the required operating conditions, since the increase of E_b will be small, without re-casting the equations to a form not dependent on this voltage.

For a load resistance of 600 ohms. (p) would be 0.54 and the dissipation 8.9 watts, if E_b were 100 volts. Thus raising the dissipation three times, by increasing E_b to 100 x $(3)^{0.4}$, or 150 volts, should meet the maximum dissipation requirement and provide the additional output desired. Checking back, gives a (p) value of 0.58, for $E = 154$, and output of 6.6 watts, a dissipation of 23 watts, and a screen voltage of 325 volts, all of which are just about right for the given job.

Within the limits of electrode voltage and dissipation, some combination of conventional tubes and applied voltages can always be found to feed a given power into a given load resistance. Other than these limits, the only remaining tube factor is μ'''/K_a and this is easily derived for any tube by taking the zero-grid-volts plate current and dividing it into the 1.5th power of the screen voltage.

While Class A operation has been assumed in the examples, the method is independent of waveform, and Class B or C can be handled merely by giving M, N, and k the appropriate values. For instance, with Class B operation (half wave with zero steady current, per tube), (M) and (N) will be infinity, and (k) will be 0.25. Inspection of (7) and (8) will show that such a change in operating method does not alter the general conclusions drawn previously as regards the ratio of plate and screen voltages for feeding power directly into low-load resistances.

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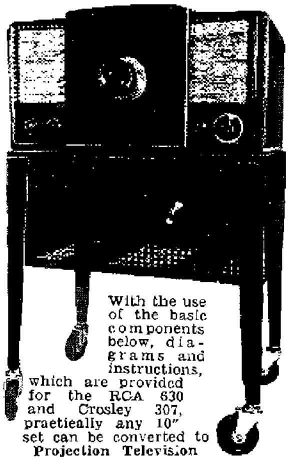

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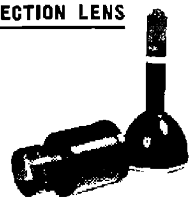

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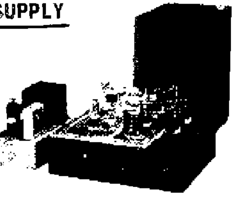

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