NOISE IN VACUUM TUBES AND ASSOCIATED CIRCUITS
BULLETIN #51

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It is well known that there is a practical limit to the gain which may be utilized practically in amplifiers due to noise originating in the first part of the amplifier either in the circuits or in the tubes. Assuming that the noise caused by poor connections etc. has been eliminated, the remaining circuit noise is due to the thermal agitation of electric charges in the conductors of the amplifier circuit. The tube noise is caused by the plate current fluctuations etc. in the tubes.

The apparent mean square value of the thermal agitation voltage across a circuit connected to the input of an amplifier[1] over a sufficiently long time is:

(1) $$V^2 = 4KT\int_0^\infty R_{(f)} \left[G_{(f)}\right]^2 df$$

Where:

K is Boltzmann's constant, 1.372×10^{-23} joules per degree
T is the absolute temperature
f is the frequency
$R_{(f)}$ is the real component of the impedance
$G_{(f)}$ is the relative gain of the amplifier referred to its maximum gain.

Practically, this may be taken as:

(2) $$V = 7.4 \times 10^{-12} \cdot T^{1/2} df^{1/2} Z^{1/2}$$

The shot effect noise is given as:

(3) $$V_0^2 = A\int_0^\infty W_{(f)} \left[G_{(f)}\right]^2 df$$

Where:

A is a tube constant
$W_{(f)}$ is a function taking into account the frequency spectrum of the noise.
$G_{(f)}$ is the relative gain of the amplifier

Formulas (1) and (3) are very similar so that for any tube some value of resistance can be found which is equivalent to the tube as a noise generator. If this is done a practical formula to obtain the noise of the amplifier and tube is:

(4) $$V = 13 \times 10^{-11}\left[(R+R_0)(f_2-f_1)\right]^{1/2}$$

[1]The Measurement of Small Alternating Voltages at Audio Frequency, E.A. Johnson and C. Neitzert, the Review of Scientific Instruments-May, '35.

Where:

R is the resistance of the grid circuit at frequency of maximum gain
R_o is the apparent noise resistance of the first tube
f_1 and f_2 are frequencies above and below resonance at which the amplification is one-half of the resonant value
T is taken as 300°K

Equation (4) shows that the tube as a noise generator is equivalent to a resistance. The usual method is to express the tube noise as an equivalent input voltage for a given band width. If the tube noise is expressed as a resistor noise, it is independent of the band width so the equivalent resistor would be more satisfactory as an expression of the tube noise than the more usual equivalent microvolt input for a given band width.

Either formula (1) or (2) may be evaluated quite easily as soon as the temperature value and frequency range are settled. The usual band width is 10 KC., which will be chosen here and at a known temperature the equivalent noise voltage for any resistance can be found quite readily. For example, 25000 ohms has a noise voltage of 2 μv. The noise is proportional to the square root of the resistance so if the resistance is increased four times the noise will be doubled etc.

It is very difficult to evaluate formula (3) because the value of "A" cannot be found without measurements. The value of "A" is different for the same tube connected as a tetrode or pentode and as a triode and is different also for a tube acting as an amplifier than it is for the same tube acting as a frequency converter. The internal resistance of the tube also contributes some noise as this resistance can be considered to be at the cathode temperature. Computations show, however, that this noise is a minor part of the total noise contributed by the tube[2] Modern tubes are operated with sufficient emission so that the formula derived for plate current noise in the absence of much space charge does not hold for present day operating conditions. The value of gm effects the gain and the value of plate current affects the apparent mean square value of the noise voltage so for like simple structures it is to be expected that the value of gm divided by the square root of the plate current will be proportional to the noise and experimentally such is found to be the case.

It is not known exactly what causes the noise found in present day tubes. The principal reasons for noise in triodes probably are statistical neutralization of the space charge by positive ions, thermal agitation of electrons and a small residual shot effect, which is affected by the bias voltage, as shown for triodes. Multigrid tubes operated as screen or space charge grid tubes have considerably more noise than when they are connected as triodes. This will be discussed in more detail later.

As mentioned previously the best method of evaluating formula (3) is to measure the equivalent noise. The noise measurements described here were made with an intermediate frequency amplifier having a square law detector connected to its output. The measurements were made by reading the indication caused by the noise voltages, then adding a carrier voltage to the input to double the reading.

[2] A Study of Noise in Vacuum Tubes and Attached Circuits, F.B. Llewellyn, I.R.E. Proceedings, February 1930.

The RMS value of the noise voltage may be considered to be equal to:

(5) $$V_{RMS} = \left(E_1^2 + E_2^2 + E_n^2\right)^{1/2}$$

where E_1, E_2 etc. are voltages per frequency interval. If a carrier voltage is added to the input until the output of the square law detector is doubled, the RMS values of the two voltages are equal so the noise voltage is equal to the generator voltage. If we find the noise voltage to be 1.41 microvolts, an equivalent modulation can be found for any signal. The noise voltage of 1.41 is equivalent to two voltages, each 1.0 microvolt in value, which can be imagined acting on two frequencies each side of resonance. If we place a 10 microvolt signal in the grid, the effective modulation would thus be ten percent or it would be one percent for a 100 microvolt carrier. Thus, it can be readily seen that avc should not be allowed to increase the equivalent tube noise too much, otherwise, even a strong carrier will be modulated appreciably.

The noise levels of various triodes are given by Figure 1. The type 27 is given as an example of the first cathode type. The ratio of the gm to the square root of the plate current is poor in comparison with present day values, even though the cathode wattage is considerably greater than the present day values. The 6J5G has the highest value of gm of any of the present day receiving type triodes. The noise varies with the grid voltage, as shown by the two curves, although this seems to be only true when the grid is more than several volts negative so that the grid potential is appreciably below the normal potential minimum, which apparently increases the shot effect. The higher mμ tubes, such as the 6F5G etc. have a higher ratio of gm to the square root of the plate current than the 6J5G so, as would be expected, the noise voltage is lower than that of the 6J5G. If we place two tubes in parallel, the gain will be doubled and the plate current doubled so the noise will only be 70.7 percent of that for a single tube and this is shown by the curve for two 6F5G tubes in parallel.

Some values of noise voltages for pentodes are given in Figure 2. The noise for a 6D6 is considerably higher than for a 77 as would be expected because the 6D6 is a remote cutoff tube and has a lower ratio of gm to plate current than a sharp cutoff tube like the 77. The noise of two type 77 tubes in parallel is only 70.7 percent of that for one tube, as would be expected. A considerable reduction in noise occurs when the screen is connected to the plate as shown by the curves for the condition where the d-c potentials were left the same but the screen was tied to the plate for r-f potential, which caused the tube to act as a triode. Several reasons for this effect might be suggested. Mr. S. W. Seeley and Mr. W. S. Barden[3] suggested one reason at the Rochester I.R.E. Convention in 1935. The writer feels that the only reason there is more noise in the pentode than in the equivalent triode is that taking the screen current from the space charge region has the same effect as if the space charge were reduced so the shot effect causes an increase of noise.

The effect of varying heater voltage was next investigated experimentally for a triode and for a pentode. It is seen that the resultant curves

[3] Quantitative Influence of Tube and Circuit Properties on Random Electron Noise. Proceedings of the Institute of Radio Eng. Nov. 1935, 1270.

of Figure 3 have about the same shape. The noise is very high at low voltages where the shot effect is predominant but there is sufficient emission at five volts so any further increase in temperature causes practically no decrease in noise. It is believed that the slight rise at higher temperatures is caused by the plate resistance of the tube which is at cathode temperature, as mentioned before.

The effect of external plate impedance was investigated next, and the results are shown in Figure 4. It is seen that it has practically no effect as the noise is constant from 2000 ohms to 10000 ohms. The matching impedance for the two tubes in parallel would be about 35000 ohms. If the noise is equivalent to a signal on the grid, it would be expected that the noise and signal would always be amplified the same. The effect of plate voltage was next investigated. The tubes were operated at normal conditions except for plate voltage which could be varied. The noise is practically constant, as shown by Figure 5, until the plate voltage is reduced to the screen voltage below which point it rises fairly rapidly. The increase in noise here is probably caused by secondary emission and an increase of screen current.

Present day converter tubes were next investigated with results, as shown in Figure 6. The Hivac A15 is a "universal" tube. The noise level, as a converter tube, is fairly high. There is practically no difference between the 6L7G and 6A8G in the normal operating region. The 6J8G should have a fairly low noise level when compared to the 6A8G because its ratio of gc to the square root of the plate current is better. It is believed that the noise values of both the 6L7G and 6J8G are high because of a higher ratio of screen current to plate current as compared to the heptode tubes, such as the 6A8G. The Phillips EK-2 tube has a sharp cutoff characteristic with a resultant high gc to plate current ratio and, as would be expected, is better for noise than the 6A8G tube. In all cases the converter tubes have necessarily higher equivalent noise voltages than the amplifier tubes because the value of gc is only about one-third the value of gm for the same plate current. It is also seen that the noise changes very little as the injection voltage is made greater than 12 volts. If the injection voltage is much less than 12 volts, under rated conditions, the noise increases rapidly.

The possibility of lowering the noise by changing operating voltages was next investigated in the case of the 6A8G, as shown by Figure 7. Three values of injection voltage were used, one for 100 volts on the screen and one for 50 volts on the screen, and the other for 30 volts on the screen. The noise with 50 volts was less than with 100 volts. The screen voltage was reduced until the noise was a minimum which occurred at 30 volts. This voltage was too low to be useable however. The rapid rise of noise with g_4 bias shows why care should be taken in applying avc voltage to a converter tube in the first stage as the equivalent modulation will remain high so the noise may actually increase as the signal is increased, rather than decrease, as it should, because the amplifier sensitivity decreases with avc voltage. A similar study of the type 77 shows that the minimum noise is obtained near the rated operating conditions. Figure 8 shows the results of plotting μv of noise versus screen voltage using two plate voltages and two bias voltages. The minimum noise occurs with 3 volts bias and 85 volts screen with very little increase at 100 volts, the rated operating point.

The effect of the detector on the signal to noise ratio is of some interest. A square law detector and a linear detector were used with the same amplifier. The audio frequency and high frequency gains were changed so that the same modulated input gave the same audio output which was 52 volts in the plate of a 6V6G tube. The noise was the same for the same output voltage. The noise for a linear detector increases then stays about constant when the carrier becomes large compared to the noise voltage. The noise for a square law detector should increase linearly with the carrier. The slight flattening off of the noise curve is due to the detector being only an approximate square law detector.

It is interesting to check theoretically the signal to noise ratios of the two detectors. The signal outputs of the linear and square law detectors are:

Linear Detector Output = KE_1MA_1
Square Law Detector Output= $CE_2^2MA_2$
Where A_1 and A_2 are the audio gains after the detector.
M is modulation percentage.

In general, three cases arise as the audio output for the linear detector is either greater than, less than, or equal to the output of the square law detector. Assume that the two signal outputs are equal.

$$KE_1A_1 = CE_2^2A_2$$ as "M" is the same in each case

Let: $E_2 = XE_1$

Then: $$A_1 = A_2\frac{C}{K}X^2\frac{E_1^2}{E_1} = A_2\frac{C}{K}X^2E_1$$

For constant carriers E_1 and E_2, the noise for a linear detector is:

$$KNE_1A_1$$

The noise for a square law detector is:

$$CE_2^2NA_2$$ where N is the noise modulation

Now $$KNE_1A_1 = KNE_1A_2\frac{C}{K}X^2E_1 = CNE_1^2X^2A_2 = CNE_2^2A_2$$

Thus the two noise outputs are equal.

Similarly a general analysis will show that the noise is the same at all levels except in the case of very weak signals where the carrier voltage is less than several times the noise voltage.

Values of noise voltages have been given for resistances and measured for various tubes. It is quite interesting to compare the two methods of coupling a voltage from the antenna to the receiver, that is by using a tuned circuit connected to the grid of a tube or by connecting the antenna directly to the grid of a tube and stepping up the voltage to the next grid the same amount as the antenna coil steps up the voltage. Before attempting this comparison, however, it is necessary to study the antenna and coil.

Figure 10 shows the equivalent circuit of the antenna and transformer. The average antenna for the broadcast reception has a resistance of about 20 ohms, an inductance of 20 microhenries and an equivalent capacity of 100 to 200 μμf. The noise voltage of the antenna may be considered as a generator in series with the antenna and signal voltage. An analysis of Figure 10 shows that X_2 or $(\omega L_2 - 1/\omega C_2)$ when tuned to make I_2 maximum will be equal to:

$$\frac{X_1 \omega^2 M^2}{X_1^2 + R_1^2} \qquad \text{where } X_1 = \omega L_1 - \frac{1}{\omega C_1}$$

When this is done

$$I_2 = \frac{j\omega ME}{R_1 R_2 + \omega^2 M^2\left(1 - \frac{X_1^2}{X_1^2 + R_1^2}\right) + jX_1\left(R_2 + \frac{R_1 \omega^2 M^2}{X_1^2 + R_1^2}\right)}$$

Two practical cases arise.

(a) if X_1 is very small

$$I_2 = \frac{j\omega ME}{R_1 R_2 + \omega^2 M^2}$$

I_2 will be a maximum when $\omega^2 M^2 = R_1 R_2$

$$I_2 \text{ max.} = \frac{jE}{2\sqrt{R_1 R_2}}$$

(b) If R_1 is small compared to X_1, I_2 (approx.) $= \dfrac{\omega ME}{X_1 (R_2 + R_1)}$

I_2 will be a maximum when $\omega^2 M^2 = X_1^2 \dfrac{R_2}{R_1}$

$$I_2 \text{ max.} = \frac{E}{2\sqrt{R_1 R_2}}$$

In either case the effective resistance of the secondary coil is increased twice at optimum coupling. It is interesting to assume Q= 200 and L = 250 microhenries. R then is $\omega L/Q$ or 7.2 ohms. The impedance of the coil will be $\omega L X Q$ or 314,000 ohms. When coupled into the antenna the impedance will be only one-half of that or 157,000 ohms which gives an equivalent input noise of 5.05 microvolts for a 10 KC band width. The maximum gain will be $\omega L/2\sqrt{R_1 R_2}$ or 64.5 times. The equivalent noise of the 6K7G tube is 1.25 microvolts so the 6K7G tube operating at a gain of 64.5 would give 80.6 microvolts or 15.9 times that of the coil. The antenna gain assumed here is better than would be realized in practice because of tracking difficulties etc. If the coupling is reduced the impedance of the coil will increase, thus increasing the noise and at the same time the gain will go down thus making the difference between coil and tube less than that shown above.

It is interesting to note the conditions for optimum coupling as regards the signal to noise ratio.

Let $\omega^2 M^2 = Y^2 X_1^2 \frac{R_2}{R_1}$

The gain is $\frac{Y\omega L}{\sqrt{R_1 R_2}\,(1+Y^2)}$

The impedance is $\frac{\omega^2 L^2}{R_2(1+Y^2)}$

The noise is $\frac{K\omega L}{\sqrt{R_2(1+Y^2)}}$

Where $K = 13 \times 10^{-9}\sqrt{df}$

If $df = 10000$

$K = 1.3 \times 10^{-8}$

The signal to noise ratio per unit input voltage is:

$$\frac{Y\omega L}{\sqrt{R_1 R_2}\,(1+Y^2)} \times \frac{\sqrt{R_2(1+Y^2)}}{K\omega L} = \frac{Y}{K\sqrt{R_1}\,\sqrt{1+Y^2}}$$

If Y is unity, the value is $\frac{1}{K\sqrt{2R_1}}$

If Y is large, the ratio is $\frac{1}{K\sqrt{R_1}}$

or an improvement of only 1.41 times.

The signal to noise ratio per microvolt input for a 20 ohm antenna is

$$10^6 \times \frac{Y}{1.3\times10^{-8}\sqrt{R_1}\,\sqrt{1+Y^2}} = \frac{100\,Y}{1.3\sqrt{20}\,\sqrt{1+Y^2}} \text{ or } \frac{17.2\,Y}{\sqrt{1+Y^2}}$$

The maximum gain for a 20 ohm antenna is $\frac{\omega L_2}{\sqrt{R_2}} = \frac{Y}{4.46(1+Y^2)}$

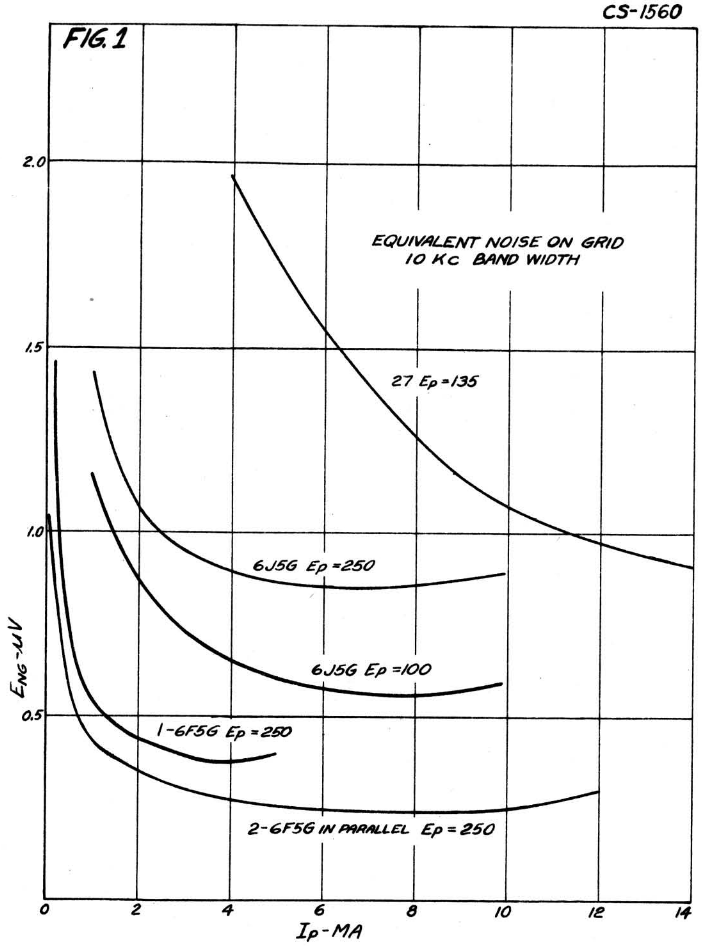
If y = .65, the gain for the coil discussed previously will be

$$\frac{129 \times 0.65}{1+0.65^2} = 59$$

The noise will be $\frac{1.3\times10^{-8}\times 1570}{\sqrt{7.2\times1.425}} = 1.3\times10^{-8}\times490 =$ 6.35 microvolts.

The tube noise will be 59 x 1.25 or 72 microvolts. The ratio will be 72/6.35 or 11.45 which compares with 15.9 for the ideal case. In practice the coupling will be even weaker so practically we can say that a good tuned circuit will have about one-tenth of the noise of a coupling tube of the remote cutoff type.

CS-1560



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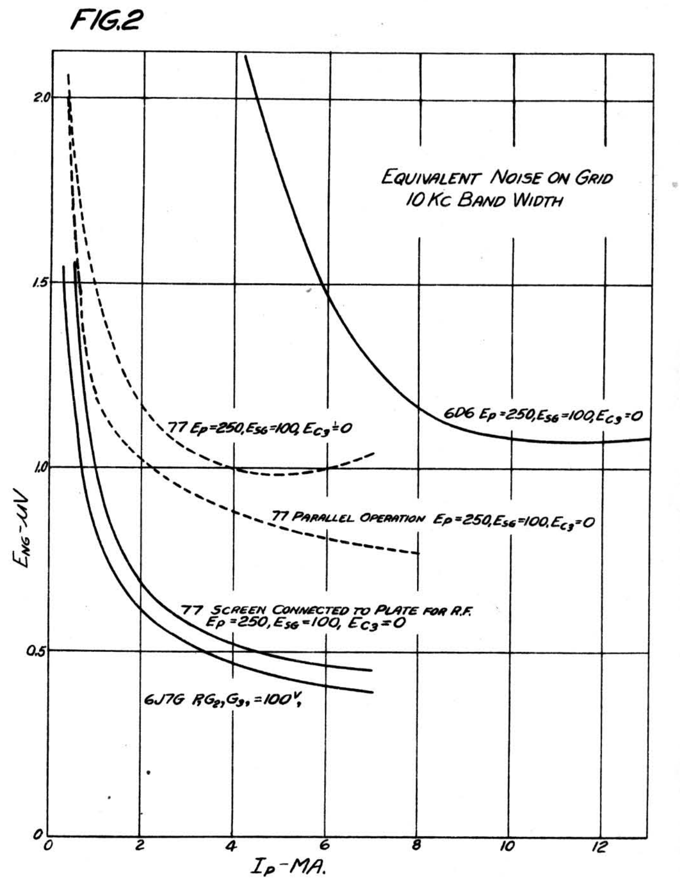
CS-1561



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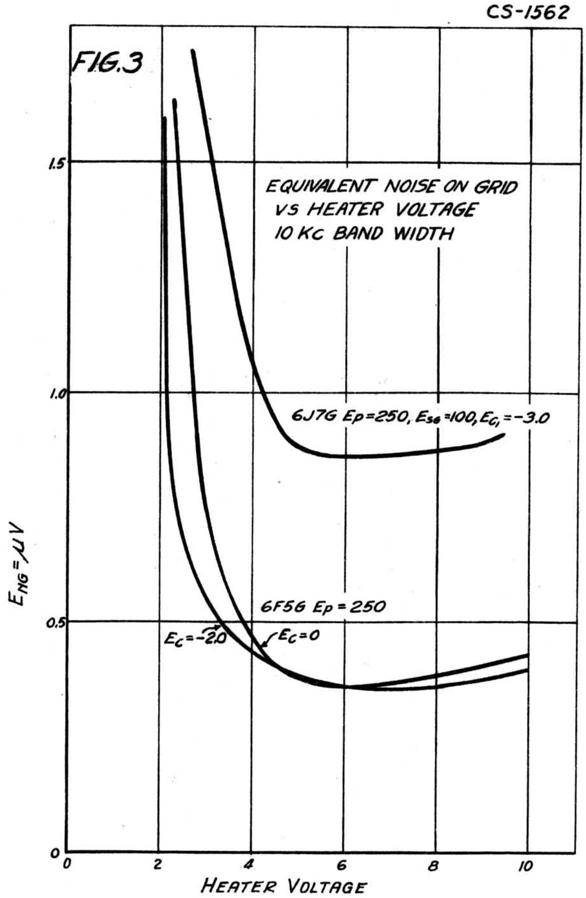
CS-1562



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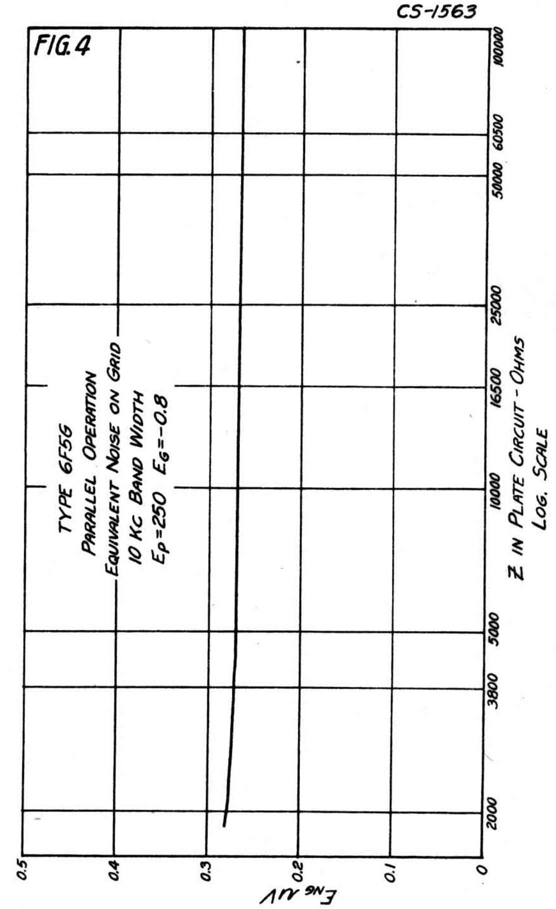

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FIG.5

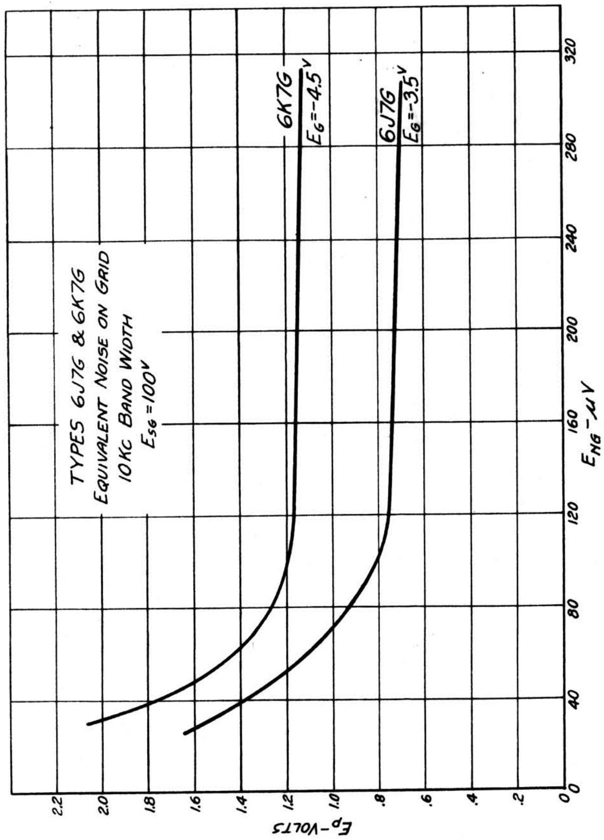

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FIG.6

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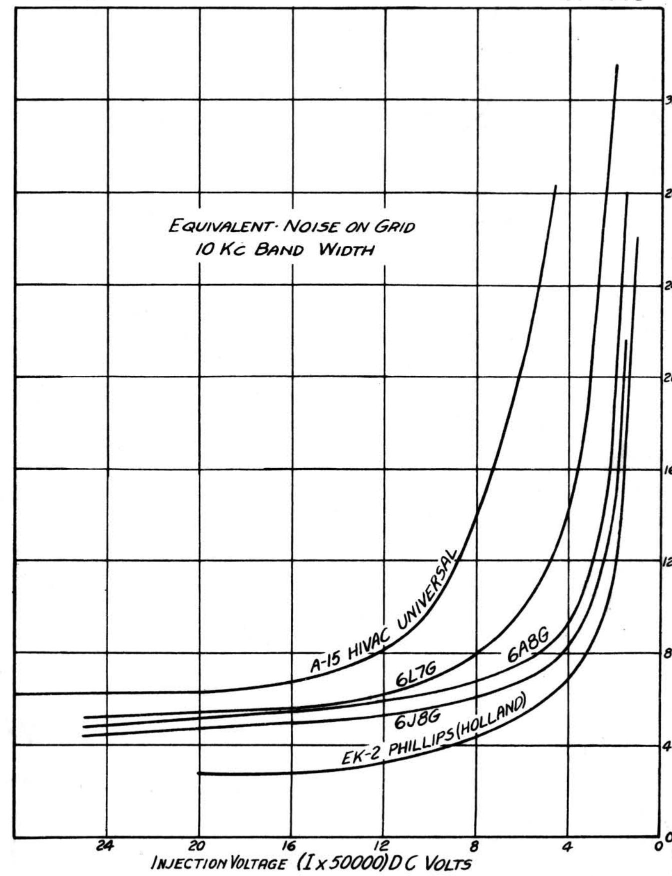

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FIG.7

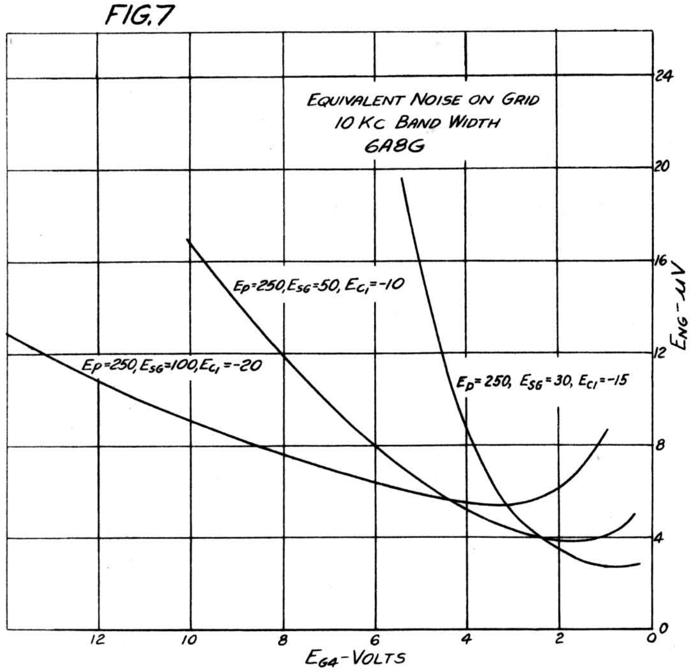

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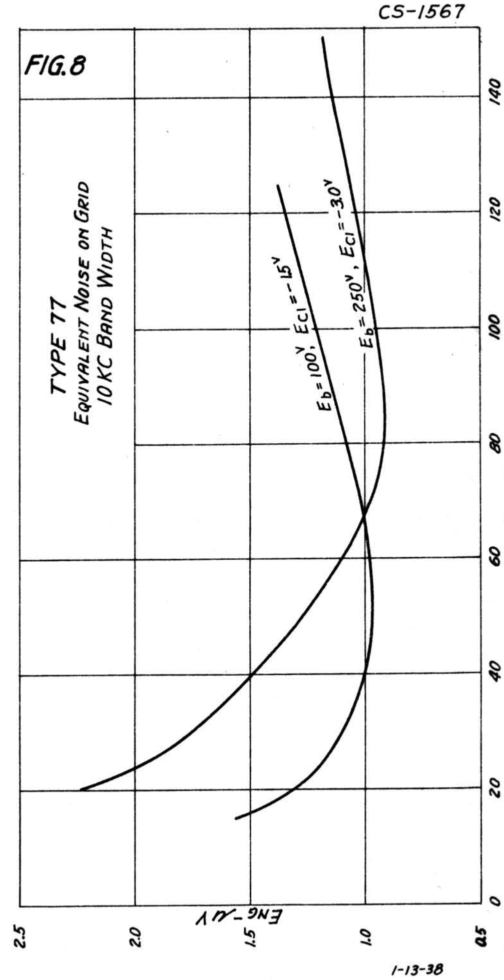
FIG.8



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CS-1568

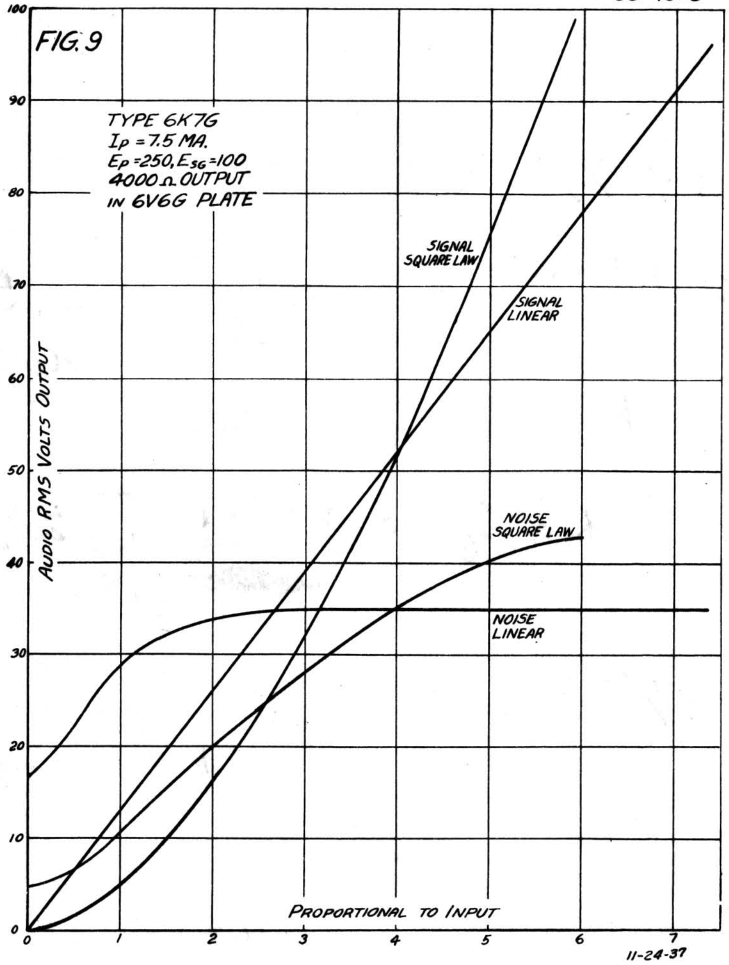
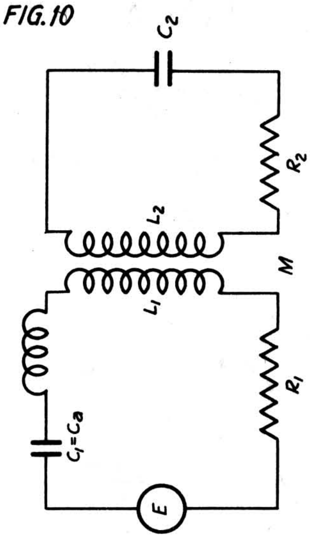


FIG. 10



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