# Input Circuit Noise Calculations for

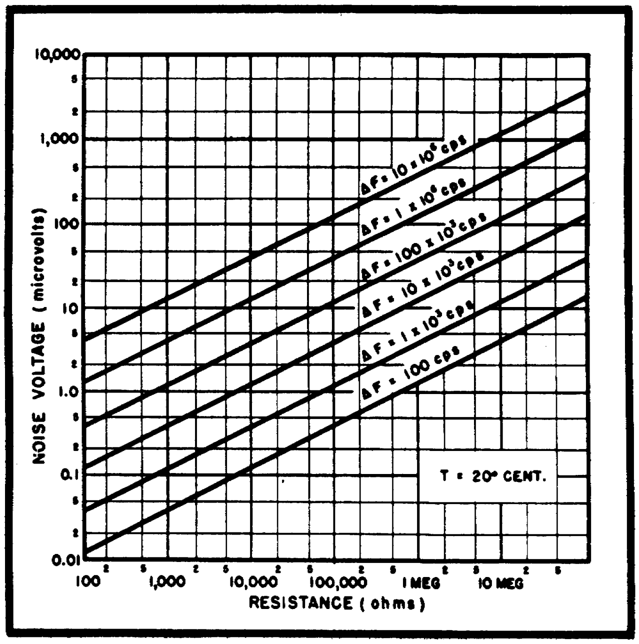


**Figure 1 (below)**
**Sample thermal noise circuits: Frequency, 1000 kc; Q, 100; L, 300 microhenries.**

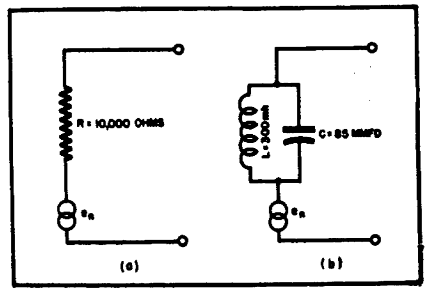


**Figure 2**
**Thermal agitation noise voltage versus resistance and bandwidth.**

Maximum receiver sensitivity is not, in most cases, determined by the gain of the particular receiver but by the magnitude of the input circuit noise, which is generated by the antenna, the tuned input circuit, and the first tube. This is true of a-m, f-m, and television, except that in f-m and television the random noise effect assumes a far greater degree of importance than in the standard broadcast band. The reason for this is twofold:

(*1*) At the frequencies where these two services operate, 50 to 250 mc, the relative value of the several different noise sources assume entirely new proportions and the heretofore unimportant and little known *induced grid noise* becomes one of the predominant components of the total.

(*2*) Most random input and tube noise is proportional to the square root of the bandwidth. Both television, with a 4-mc band, and f-m, with a 200-kc band, occupy much wider sections of the frequency spectrum than anything previously encountered by the commercial receiver engineer.

### *Thermal Agitation Noise*

When an alternating electric current flows through a conductor, electrons do not actually move along the conductor but they are displaced, an infinitesmal amount, first in one direction and then in the other. A voltage is built up across the conductor equal to the magnitude of the current times its resistance. Applying heat to the conducting material agitates the molecules of the conductor and, consequently, varies the instantaneous position in space of the electrons. This random electron motion is, in a sense, a minute noise current flowing through the material and is known as *thermal agitation noise.* That is, the application of heat agitates the electron distribution of the substance thereby creating the noise.

The magnitude of the short-circuit noise current is given by

$$i^2_n = \frac{4\,KT\,\Delta F}{R} \qquad (1)$$

where:

$\bar{i}^2_n$ = mean squared noise current (amperes$^2$)
$K$ = Boltzmann's Constant (joules per degree Kelvin), $1.37 \times 10^{-23}$
$T$ = temperature (degrees Kelvin)
$\Delta F$ = bandwidth (cps)
$R$ = resistance (ohms)

All noise currents and voltages are random fluctuations and occupy an infinite frequency band. Because of the random effect, the most convenient terminology to use in expressing their magnitude is average noise-power output. Mean-squared noise current or mean-squared noise voltage, either of which is proportional to average power, is generally used.

In the expression for various noise components the term $\Delta F$ refers to the effective bandwidth of the circuit. This is determined from a curve of power output versus frequency by dividing the area under the curve by the amplitude of the power at the noise frequency in question. For most calculations, however, where only approximate values are desired, the bandwidth between half power points, or .707 voltage points, will give sufficient accuracy.

The equation below expresses thermal agitation noise as a voltage in series with a given resistor:

$$\bar{e}^2_n = 4\,K\,T\,\Delta F\,R \qquad (2)$$

Both the above forms are true of all resistive circuit elements or combination of elements including parallel and series-tuned circuits.

Referring to Figure 1 (*a*), let us suppose a resistance of 10,000 ohms were connected to the input of an amplifier with a 5 kc bandwidth, i.e., 5 kc between half power points or an audio band of 2.5 kc. At room temperature, 20° C or 293° K, the terms $4KT$ in the expressions for noise simplifies to $1.6 \times 10^{-20}$, which may be used in most receiver calculations. The noise in Figure 1 (*a*) is therefore:

$$\bar{e}^2_n = 1.6 \times 10^{-20}\,\Delta F\,R$$

$$e_n = \sqrt{1.6 \times 10^{-20} \times 5000 \times 10{,}000}$$

$$e_n = 0.89 \text{ microvolt}$$

The noise bandwidth is generally determined by the narrowest element in the entire circuit under considera-

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| TRIODE AMPLIFIER | $R_{eq} = \frac{2.5}{g_m}$ |
|---|---|
| PENTODE AMPLIFIER | $R_{eq} = \frac{I_b}{I_b + I_{c2}}\left(\frac{2.5}{g_m} + \frac{20 I_{c2}}{g_m^2}\right)$ |
| TRIODE MIXER | $R_{eq} = \frac{4}{g_c} \quad g_c = \frac{g_m}{4}$ |
| PENTODE MIXER | $R_{eq} = \frac{I_b}{I_b + I_{c2}}\left(\frac{4}{g_c} + \frac{20 I_{c2}}{g_c^2}\right)$ |
| MULTIGRID CONVERTER or MIXER | $R_{eq} = 20 \frac{I_b(I_k - I_b)}{I_k g_c^2}$ |
| $R_{eq}$ = Equivalent Shot Noise Resistance; $g_m$ = Grid Plate Transconductance; $I_b$ = Average Plate Current | $I_{c2}$ = Average Screen Current; $g_c$ = Conversion Transconductance; $I_k$ = Average Cathode Current |

Figure 3
Equivalent shot-noise resistance formulas.[1]

**Efficient Design of Input Stages, a Critical Requisite in F-M and Television, Involves a Careful Consideration of Three Important Factors: Total Noise, Sensitivity and Signal-To-Noise Ratio. This Paper Discusses These Factors and Offers a Physical Concept of the Three Noise Components With Formulas and Data Necessary for Input-Circuit Calculations.**

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tion. In the example for Figure 1 ($b$) the bandwidth of the amplifier is narrower than the tuned circuit and therefore its $\triangle F$ is used in the calculations.

Figure 1 ($b$) is a simple parallel-tuned circuit where the noise generating resistance is equal to the tuned circuit impedance. Again let us assume the bandwidth to be five kc per second.

$$R = Q(\omega L) = 100 \times 1900 = 190{,}000 \text{ ohms}$$

$$\bar{e}^2_n = 1.6 \times 10^{-20} \Delta FR$$

$$e_n = \sqrt{1.6 \times 10^{-20} \times 5{,}000 \times 190{,}0000}$$

$$e_n = 3.9 \text{ microvolts}$$

Thermal agitation noise voltage may be calculated easily with equation (2) but by using the graph shown in Figure 2 the room temperature values may be found directly.

### Shot Noise

Another important component of the total receiver noise is known as *shot noise*. This noise is generated inside the vacuum tube and is due to the random fluctuations in the plate current of the tube, or, to state it in another manner, random variations in the rate of arrival of electrons at the plate. When amplified, this noise sounds as if the plate were being bombarded with pebbles or as if a shower of shot were falling upon a metal surface, hence the name *shot noise*.

Although generated essentially in the plate circuit of the tube, which is

| TUBE TYPE | APPLICATION | PLATE VOLTS* | SCREEN VOLTS | TRANSCONDUCTANCE MICROMHOS | EQUIVALENT NOISE RESISTANCE OHMS |
|---|---|---|---|---|---|
| 6AC7 | PENTODE AMPLIFIER | 300 | 150 | 9,000 | 720 |
| 6AC7 | PENTODE MIXER | 300 | 150 | 2,200 | 2,800 |
| 6AG5 | PENTODE AMPLIFIER | 250 | 150 | 5,000 | 1,650 |
| 6AG5 | PENTODE MIXER | 250 | 150 | 1,250 | 6,600 |
| 6AG7 | PENTODE AMPLIFIER | 300 | 150 | 11,000 | 1,540 |
| 6AK5 | PENTODE AMPLIFIER | 180 | 120 | 5,100 | 1,880 |
| 6AK5 | PENTODE MIXER | 180 | 120 | 1,280 | 7,520 |
| 6AK6 | PENTODE AMPLIFIER | 180 | 180 | 2,300 | 8,800 |
| 6AT6 | TRIODE AMPLIFIER | 250 | — | 1,200 | 2,100 |
| 6AU6 | PENTODE AMPLIFIER | 250 | 150 | 5,200 | 2,660 |
| 6BA6 | PENTODE AMPLIFIER | 250 | 100 | 4,400 | 3,520 |
| 6BA6 | PENTODE MIXER | 250 | 100 | 1,100 | 14,080 |
| 6BE6 | CONVERTER | 250 | 100 | 475= | 190,000 |
| 6C4 | TRIODE AMPLIFIER | 100 | — | 3,100 | 810 |
| 6C4 | TRIODE MIXER | 100 | — | 770 | 3,240 |
| 6C5 | TRIODE AMPLIFIER | 250 | — | 2,000 | 1,250 |
| 6C5 | TRIODE MIXER | 250 | — | 500 | 5,000 |
| 6J5 | TRIODE AMPLIFIER | 250 | — | 2,600 | 960 |
| 6J5 | TRIODE MIXER | 250 | — | 650 | 3,840 |
| ½6J6 | TRIODE AMPLIFIER | 100 | — | 5,300 | 470 |
| ½6J6 | TRIODE MIXER | 100 | — | 1,320 | 1,880 |
| 6K8 | CONVERTER | 250 | 100 | 350= | 290,000 |
| 6SA7 | CONVERTER | 250 | 100 | 450= | 240,000 |
| 6SB7-Y | CONVERTER | 250 | 100 | 950= | 62,000 |
| 6SC7 | TRIODE AMPLIFIER | 250 | — | 1,325 | 1,890 |
| 6SG7 | PENTODE AMPLIFIER | 250 | 125 | 4,700 | 3,100 |
| 6SG7 | PENTODE MIXER | 250 | 125 | 1,180 | 12,400 |
| 6SJ7 | PENTODE AMPLIFIER | 250 | 100 | 1,650 | 6,100 |
| 6SK7 | PENTODE AMPLIFIER | 250 | 100 | 2,000 | 11,000 |
| 6SL7 | TRIODE AMPLIFIER | 250 | — | 1,600 | 1,560 |
| 6SQ7 | TRIODE AMPLIFIER | 250 | — | 1,100 | 2,300 |

(*) VALUES OF PLATE VOLTAGE AND CURRENT AND SCREEN VOLTAGE AND CURRENT ARE FOR TYPICAL OPERATING CONDITIONS.
(=) CONVERSION TRANSCONDUCTANCE - MICROMHOS

Figure 4
Approximate calculated equivalent noise resistance of various receiving-type tubes.

not a convenient reference point for sensitivity or signal-to-noise ratio calculations, the shot noise is nearly always referred to as a noise voltage in series with the grid. Since the following equation is true,

$$e_g = \frac{i_p}{g_m} \qquad (3)$$

where

$e_g$ = a-c grid voltage,
$i_p$ = a-c plate current, and
$g_m$ = transconductance,

by simply dividing the noise current in the plate circuit by the transconductance of the tube the shot noise may be referred to the grid and expressed in terms of grid voltage.

Another step is taken, however, to simplify the noise nomenclature. Suppose a given tube has a shot noise equal to $e_n$ microvolts in series with its grid. It is perfectly valid to imagine that this voltage could be replaced by a resistance whose thermal agitation noise is equal to $e_n$ (the shot noise) and consider the tube to be free of noise. This imaginary resistance, which when placed in the grid of the

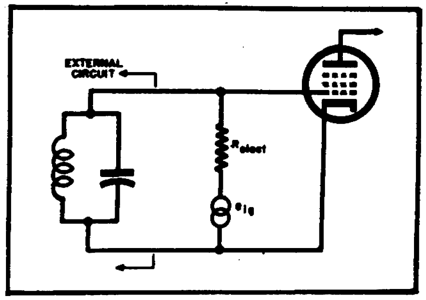


**Figure 5**
**Position of induced grid noise in vacuum-tube circuit.**

tube generates a voltage equal to the shot noise of the tube, is known as the shot noise equivalent resistance or just as the equivalent noise resistance of the tube. The advantage of this terminology is that when the equivalent noise resistance of the particular tube is known, the noise volts may be calculated directly for any given bandwidth by substituting values in the following formula:

$$e_n^2 = 4 K T \Delta F R_{eq} \qquad (4)$$

[1]W. A. Harris, *Fluctuations in Vacuum Tube Amplifiers and Input Systems*, RCA Review; April 1941.

where $R_{eq}$ = equivalent noise resistance or at room temperature

$$e_n^2 = 1.6 \times 10^{-20} \Delta F R_{eq} \qquad (5)$$

If the noise were expressed as a voltage or current its value would be correct only for one particular bandwidth.

By knowing the $R_{eq}$ of any two given tubes their relative shot noise merit is also known regardless of what bandwdith they are to operate at, while if the noise voltages were given alone the operating bandwidth at which the calculation was made would also have to be noted if the relative merits of the two tubes were to be defined.

Noise-equivalent resistance values for a number of different tube types (triodes, pentodes, and converters) and for various circuit applications (amplifiers and mixers) can be calculated by applying the expressions presented in the chart, Figure 3.[1]

When the term converter is used it refers to a tube that is used for frequency conversion where the single

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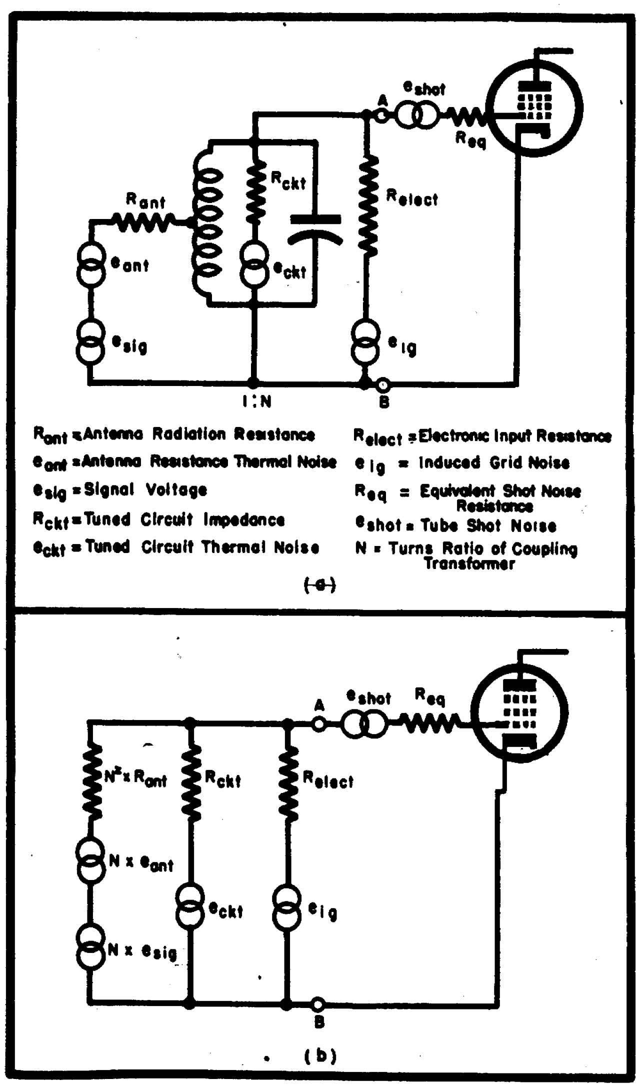


**Figure 6 (below)**
**Approximate electronic input resistance versus frequency.**

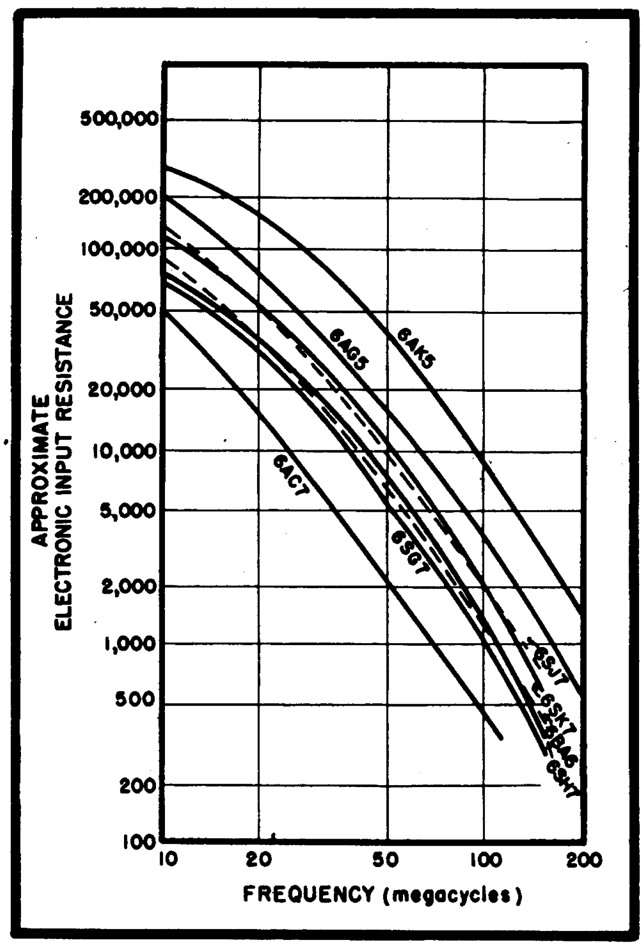


**Figure 7**
**Position of various noise sources in input circuit.**

(*Continued from page* 15)

tube acts as the local oscillator and the mixer (6SA7); the term mixer where two tubes are used, one as the mixer (6SG7), and one as the local oscillator (6C4).

After the equivalent noise resistance is known the value of rms noise voltage at the grid of this tube can be calculated by applying the same expression that is used for thermal agitation noise,

$$\bar{e}^2_n = 1.6 \times 10^{-20} \Delta F R \qquad (2)$$

or by using the graph of Figure 2.

Figure 4 presents calculated equivalent noise resistance values for a number of commonly used tubes acting as various types of circuit elements. These are, of course, approximate figures.

It can be seen from Figures 3 and 4 that the noise resistance or voltage is at a minimum for a triode, increasing for the pentode and the multigrid tube, following in that order.

Shot noise is unique among the noise sources in the sense that the shot-noise voltage should be considered to exist in series with the grid inside the tube. The reason for this is that nothing can be done to the external grid circuit that will alter the magnitude of this component. Even though the shot noise must be tolerated, its effect can be minimized by designing the input circuit for maximum signal at the grid. This does not reduce the magnitude of the noise but does improve the signal-to-noise ratio of the receiver.

***Induced Grid Noise***

Also present in the receiving tube is a third source of noise which is generated internally in the tube but whose magnitude and effect are determined partially by the external input circuit. Known as *induced grid noise,* this minute current is induced in the grid wires of the tube by random fluctuations in the plate current. It is known that a varying electron beam will induce a current in any nearby conductor. Therefore, the fluctuating plate current which is in a sense a varying electron beam, will induce a noise current in the nearby grid conductors.

The input impedance of a vacuum tube has a reactive and a resistive component. At relatively low frequencies the resistive component is very high (below about 30 mc); as the frequency is increased the resistive component decreases and its magnitude eventually becomes comparable to or even lower than the external grid circuit impedance. The resistive component is composed of two parts, the portion due to transit time effect, and the portion due to the inductance of the cathode lead.

An expression for induced-grid noise[2] for tubes with control grid adjacent to the cathode follows:

$$\overline{i^2}_{i.g.} = 1.4 \times 4 K T_K \ \Delta F \, g_{elect}$$

or when expressed in the form of a voltage generator,

$$\overline{e^2}_{i.g.} = 1.4 \times 4 K T_K \Delta F R_{elect} \qquad (6)$$

where: $T_k$ = cathode temperature (degrees Kelvin)

$G_{elect}$ = electronic (transit time) component of input conductance

$R_{elect}$ = electronic component of input resistance

From equation (6) it can be seen that the induced grid noise is proportional to the electronic or transit time component of the input resistance. Measurement of the total input resistance is a comparatively simple matter with the use of a high frequency $Q$ meter, but the separation of the electronic and the cathode inductance components, which are essentially two resistances in parallel between the grid and ground, is a very difficult matter. Since most high-frequency tubes are constructed with either two cathode leads or one very short lead, assuming the total measured input resistance to be electronic would not introduce too great an error. Another factor in favor of this approximation is that it would be the case for maximum induced grid noise and any error introduced would more than likely be on the safe side.

Cathode temperature in most receiving tubes, which almost exclusively use oxide-coated cathodes, is approximately five times the normal room temperature in degrees K. Equation (6) can be rewritten therefore as

$$\overline{e^2}_{i.g.} = 5 \times 4K T \Delta F R_{elect} \qquad (7)$$

where: $T$ = room temperature (degrees Kelvin), or when $T$ = 300 degrees Kelvin

$$\overline{e^2}_{i.g.} = 8 \times 10^{-20} \ \Delta F R_{elect} \qquad (8)$$

In circuit calculations this noise is essentially in series with a resistance

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[2]D. O. North, *Fluctuations Induced in Vacuum-Tube Grids at High Frequencies*, Proc. IRE; Feb. 1941.

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equal to $R_{elect}$ located between the grid and ground; Figure 5.

The approximate input resistance for a number of common receiving tubes in the frequency range of f-m and television is given in Figure 6. This chart can be used to find approximate input resistance values for induced grid-noise calculations.

### *Total Noise Calculations*

Calculations of total input noise are made by using the grid of the input tube as a reference point. There are many sources of noise and each must be calculated and referred to the grid reference point before a summation is made. Since noise is a random effect and calculated on a power basis, the separate components cannot be added directly but as the square root of the sum of the squares.

$$\text{Total Noise} = \sqrt{\bar{e}^2_1 + \bar{e}^2_2 + \bar{e}^2_3 + \text{etc.}} \quad (9)$$

The various noise voltages that must be referred to the first grid are:

(1) Thermal agitation noise of the antenna radiation resistance.

(2) Thermal agitation noise of the tuned grid circuit.

(3) Shot noise of the input tube.

(4) Induced grid noise of the input tube.

(5) Grid circuit noise of the following stages referred *back* to the first grid.

In Figure 7 (*a*) appears a diagram of a practical input circuit and the location of all the circuit parameters and noise voltages. Figure 7 (*b*) is essentially the same except that the antenna circuit is reflected through the transformer and considered to exist at the grid. This is the diagram that is most useful in calculating the total input circuit noise.

The steps necessary to find specific values for each of these factors are shown in Figure 8. Antenna radia-

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**Figure 8**
**Procedure for calculating various noise voltages.**

*(1)* $R_{ant}$ – Depends upon specific antenna

*(2)* $e_{ant} = \sqrt{1.6 \times 10^{-20} R_{ant} \Delta f}$ – or directly from *Fig. 2*

*(3)* $R_{ckt} = Q\omega L = \frac{Q}{\omega C}$

*(4)* $e_{ckt} = \sqrt{1.6 \times 10^{-20} R_{ckt} \Delta f}$ – or directly from *Fig. 2*

*(5)* $R_{elect}$ – From accompanying chart, *Fig. 6*

*(6)* $e_{ig} = \sqrt{8 \times 10^{-20} R_{elect} \Delta f}$

*(7)* $R_{eq}$ – From accompanying chart, *Fig. 4*

*(8)* $e_{shot} = \sqrt{1.6 \times 10^{-20} \Delta f R_{eq}}$ – or directly from *Fig. 2*

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tion resistance varies widely with the type of antenna chosen, but for f-m and television work it is generally in the order of 75 to 300 ohms. When the noise is known in terms of an equivalent resistance, as is the case here for the antenna, tuned circuit, and shot noise, the equivalent voltage can be either calculated or obtained directly from Figure 2.

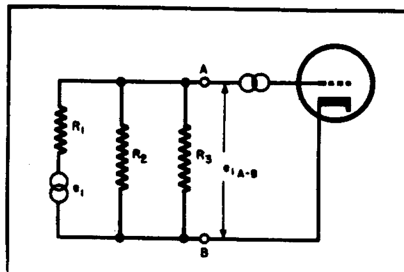
In order to add the antenna, tuned circuit, and induced grid noise to the shot noise the effective voltage of these three components at the grid, or between the points $A$ and $B$, must be known. Each must go through what is essentially a resistive divider and may be calculated as shown in Figure 9.

After knowing the magnitude of the separate sources that exist between $A-B$, the total noise voltage is

$$e_{total} = \sqrt{e^2_{shot} + (e_{ant.} \text{ at } A-B)^2 + (e_{i\text{-}g.} \text{ at } A-B)^2 + (e_{ckt} \text{ at } A-B)^2} \qquad (10)$$

One other factor may effect this total, however. If the total noise of the following stages, which is calculated similarly, ignoring the antenna of course, is appreciable it must be added to the constants of Figure 9. In

Figure 9
Circuit for reflecting various voltages to the grid.




To find the effective voltage of the antenna, the tuned circuit, and the induced grid noise at the grid of the tube let $R_1$ equal one of the above noise resistances and $e_1$ its generated voltage. If $R_2$ and $R_3$ equal the other two noise resistances the effective voltage at the grid is

$$e_{1\,A-B} = \frac{e_1}{R_1 + \dfrac{R_2 R_3}{R_2 + R_3}} \times \frac{R_2 R_3}{R_2 + R_3}$$

This calculation must be performed for the three components in turn.

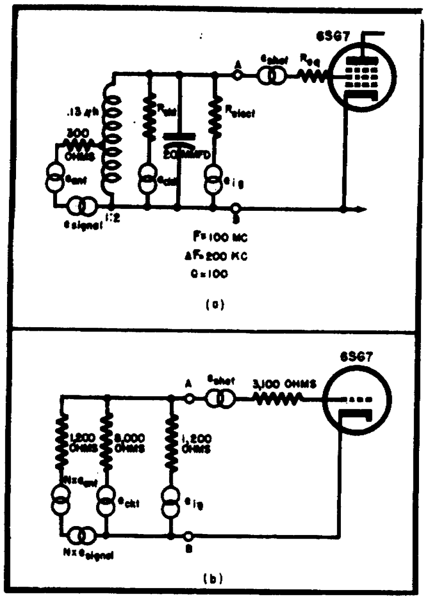



**Figure 10**
Typical f-m receiver input circuit.

reflecting it to the first grid the second stage noise should be divided by the gain of the first tube. When the gain is about ten or more this factor may usually be neglected.

Effective signal voltage across $A-B$ is calculated in the same way as the antenna noise in Figure 9. The signal-to-noise ratio is now also known.

Since the signal-to-noise ratio is determined by the signal strength and the total noise at the grid of the input tube, for a receiver that has a mixer, such as 6SK7, for the input tube, the signal-to-noise ratio may be considerably improved by the addition of an r-f tube, such as a 6SG7, which has considerably less total noise. By adding additional r-f tubes (6SG7s), however, since the total noise and signal at the grid will be the same, the signal-to-noise ratio will not be improved.

**Sample Circuit Calculations**

For a sample problem let us calculate the total noise at the grid of an f-m receiver r-f amplifier stage, assuming the circuit in Figure 10(*a*) to be under consideration.

As a simplification of procedure the steps in the calculation will be numbered.

(*1*) $N^2 R_{ant} = 1200$ ohms (calculated)
(*2*) $R_{elect} = 1200$ ohms (Figure 6)
(*3*) $R_{ckt} = Q\,\omega\,L = 8000$ ohms (calculated)
(*4*) $R_{eq} = 3100$ ohms (Figure 4)

At this point it will be convenient to redraw the circuit as shown in Figure 10(*b*).

(*5*) $N\ e_{ant} = 2$ microvolts (Figure 2)

(*6*) $e_{i.g.} = \sqrt{8 \times 10^{-20} \times 200 \times 10^3 \times 1200} = 5$ microvolts (equation (*8*))

(*7*) $e_{ckt} = 6$ microvolts (Figure 2)
(*8*) $e_{shot} = 3.5$ microvolts (Figure 2)

The next step is to find the effective voltage of each source between the grid and ground (or $A-B$) as shown in Figure 9.

$$(9)\quad e_{ant}\,A-B = \frac{2}{1200+1040} \times 1040 = 0.93 \text{ microvolt}$$

$$(10)\quad e_{i.g.}\,A-B = \frac{5}{1200+1040} \times 1040 = 2.3 \text{ microvolts}$$

$$(11)\quad e_{ckt}\,A-B = \frac{6}{8000+600} \times 600 = 2.5 \text{ microvolts}$$

And the total noise is therefore

$$(12)\quad e_{total} = \sqrt{3.5^2 + 0.93^2 + 2.3^2 + 2.52^2} = 4.9 \text{ microvolts}$$
(equation (*10*))

**Conclusions**

Selection of an input tube for a television or f-m receiver is dependent:

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upon many varying circuit conditions and individual requirements. The choice of using balanced or unbalanced input, permeability or capacitor tuning, noisy pentodes or quiet triodes that possibly require neutralization, among others, lies entirely with the design engineer. Considering these reasons and various engineering and economic compromises, no particular tube can be chosen and defined as *the input tube.* Complete noise information about the circuits involved is, necessary, however, as this is one of the determining factors for good sensitivity and signal-to-noise ratio.

## TRANSMITTER BUILDING

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though it does leave some blind spots. In practice this has not been found to be objectionable.

In the rear workroom a soundproof booth was constructed to house a United Press teletype. This has also been quite adequate, but is frequently a problem in small buildings where it is necessary to place teletype equipment close to studios. This booth is constructed of celotex walls with a dead-air space and a rock wool packing. It provides about a 40-db sound transmission loss.