SECTION 2

ADVANCED PRACTICAL RADIO ENGINEERING

TECHNICAL ASSIGNMENT

RECEIVER TUBES AT F.M. AND TELEVISION FREQUENCIES

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RECEIVER TUBES AT F.M. AND TELEVISION FREQUENCIES

SCOPE OF ASSIGNMENT

In this assignment will be discussed the ordinary types of vacuum tubes employing negatively biased control grids, with particular reference to their use in the ultra-high frequency range. Both receiving and transmitting type tubes will be covered.

It was evident early in the art that there is an upper limit to the frequency at which a particular tube will amplify and oscillate. One factor that produces such a limit is the capacitance between tube elements, another is that of lead inductance, and a third is transit-time effects. The effect of cathode lead inductance upon input loading has already been discussed in the previous assignment.

However, aside from the loading effect, lead inductance, as well as interelectrode capacitance, becomes part of the tuned circuit connected to the corresponding electrodes, and may so reduce the L and C of the connected external circuit as to make the latter impractical to build. It is therefore important that these circuit characteristics of the tube be minimized, and examples of how this is done will be given later, particularly when transmitting type tubes are discussed. Transit-time loading is an electronic effect that occurs within the interelectrode region, and will be discussed now.

TRANSIT-TIME EFFECTS

A vacuum tube circuit differs from an ordinary circuit in that in the case of the vacuum tube, electrons initially have to be physically transported from the cathode to the plate, and any change in current flow has to be similarly conveyed, whereas in an ordinary circuit there are free electrons *dispersed throughout the circuit*, and the production of current flow, or a change in this flow, takes place as quickly as the electromagnetic pulse from the source can travel to the outermost parts of the circuit. Such a pulse normally travels with the velocity of light.

In short, in an ordinary circuit the electrons are already there in every part of the circuit and ready to move as soon as the electromagnetic pulse reaches them, whereas in a vacuum tube circuit the electrons are everywhere except in the interelectrode space, and while the heated cathode is ready, the moment plate voltage is applied, to send them into this space en-route to the plate, it nevertheless will take an appreciable time, called transit time, for them to get to the plate, owing to their appreciable physical inertia. Because of this transit time, certain effects occur that are negligibly small in an ordinary circuit.

THE DIODE.—One of the effects

of this transit time is the flow of grid current even though the grid is negatively biased. This can be seen first from the analysis of current flow in a diode. In Fig. 1 is shown a thermionically emitting cathode A, and plate B, connected through a

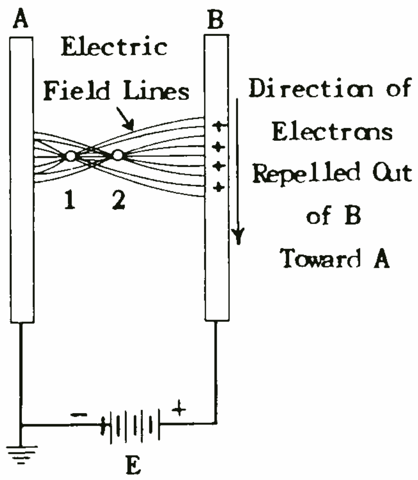


Fig. 1.—Action of electron flow in a diode tube.

source of voltage E. Normally there are as many positive charges (protons) as negative charges (electrons) in either A or B, and also in the connecting wires and battery E, so that there is no tendency for any charges to be induced on either electrode.

Now suppose that an electron is moved from the cathode to a position 1 in the interelectrode space. It is now closer to the plate than it was before, but the protons in A have not moved closer to the plate so they will not cancel its effect on the plate. Hence the electron at 1 will induce a net positive charge on the plate, or, to state it in another way, it will repel some free electrons on the inner surface of B partly out of it through the connecting wires and E around to A. This leaves a net positive charge on B.

As the electron moves closer to B (position 2), it induces a stronger positive charge on B—forces more electrons around from B to A. Thus, as the electron approaches B, stronger and stronger positive charges are induced on the latter until, when the electron reaches B, it suddenly and completely neutralizes the charge it has induced. What has happened is that an electron on A has moved over to B, and forced out an electron from B, and ultimately—at the other end of the connecting wires—caused an electron to enter A to replace the one that went to B.

The electron proceeding from the cathode to the plate also induces a positive charge on the cathode A. At first this induced charge on A is very strong, and that on B very weak, but as the electron moves away from A toward B, the induced positive charge on A grows progressively weaker, and that on B grows progressively stronger, in such manner that the sum of the two positive charges remains constant and equal and opposite to that on the electron.

It has been indicated that as the electron moves toward the plate, it repels electrons out of the latter around through the connecting wires and E toward A. The total amount of negative charge leaving B equals the amount of negative charge—that of the electron—approaching the plate. This *moving* charge represents a *current flow*, the faster the electron moves across from A to B, the greater is the current flow, since current flow is the rate at which charges pass a given point in the circuit.

One thing must be emphasized at this point in the discussion. The flow of current through the connecting wires and the battery E *began* the *moment* the electron under discussion left the cathode A and moved over to B, and not after the electron reaches the plate B. Indeed, after it reaches B, *current thereafter ceases*, unless another electron leaves the cathode at that precise moment.

The actual flow of current is due to a vast number of electrons, but the action of each is as described above: the electron in moving away from the cathode produces a *decreasing* positive charge there and an *increasing* positive charge at the plate. A positive charge decreasing with time at the cathode represents a current flow *into* the cathode; a positive charge increasing with time *at an equal rate* at the plate represents an equal current flow *out* of the plate. In the rest of the circuit there is a circulation of electrons that permits the positive charge to build up at the plate and to decrease at the cathode; this circulation represents the same current flow in the rest of the circuit.

THE TRIODE.—When the case of a triode or multi-grid tube is considered, the most pronounced effect of transit-time is that on the control grid. Consider the triode shown in Fig. 2, having a cathode K, grid G, and plate P. When the cathode is cold and not emitting electrons, the three electrodes act as a three-plate capacitor. Specifically, there is a certain amount of capacity between the cathode and grid—call this C_{gk} (cold).

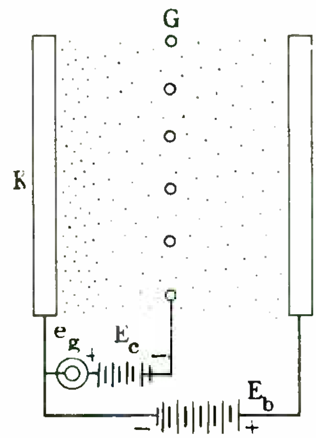


Fig. 2.—Capacity effect in a triode tube.

CAPACITY EFFECT.—Now suppose the cathode emits electrons, and that a positive potential is applied between the grid and cathode so as partially to balance the normal negative grid bias, E_c. The grid will charge up positive relative to the cathode (actually reduce some of the negative charge owing to E_c) because of the ordinary capacitor effect of C_{gk} (cold). But in addition electrons will be caused to flow from the cathode toward the grid and as these electrons approach the grid, they induce a stronger and stronger positive charge on it, *over and above that produced by C_{gk} (cold)*. The additional positive charge represents an *increase* in the capacity of G to K, and this increase, call it C_{gk} (hot), results in a somewhat higher capacity between G and K when the tube is operative than when it is cold.

The increase, or C_{gk} (hot) is around 1 to 3 μμf. It increases with increase in space current, i.e., with decreasing bias, and has important effects in determining the circuit constants for a video (television) amplifier, and also in the case of r-f and i-f amplifiers. Here the variable bias produced by the a.v.c. action will change the total capacity between the grid and cathode, and thus tend to detune the circuit. This is particularly marked in the case of high-gain amplifiers that have relatively small external tuning capacitors and thus rely to a large extent upon the tube capacity for tuning. A simple remedy that is quite effective is to place a resistor—about the normal bias value—in the cathode circuit. This introduces a small amount of degenerative feed-back and tends effectively to off-set the change in C_{gk} (hot). It may be noted that C_{gk} (hot) is equivalent to the cathode having moved closer to G, because the emitted electrons essentially produce a conductive surface closer to the grid.

TRANSIT-TIME LOADING.—Now suppose that an alternating voltage e_g, Fig. 2, is introduced. Consider a moment of time when this voltage is passing through zero in a positive direction. As it increases, the electrons emitted from the cathode increase in step with the grid voltage. If the change in e_g is relatively slow, (low frequency) then the increase in cathode current reaches the grid in a time relatively so short that e_g has not appreciably changed from its value when this increase started out from the cathode. In short, one can say that the increase in electron charge *in the vicinity of the grid* is also practically in phase with the alternating grid voltage.

It has been shown in the assignment on capacitors that when the charge is in phase with the voltage, the current—*which is the rate of change of charge with time*—leads the voltage by 90°. This means that the device upon which the charge accumulates is a capacitor. The relations are shown in Fig. 3. The

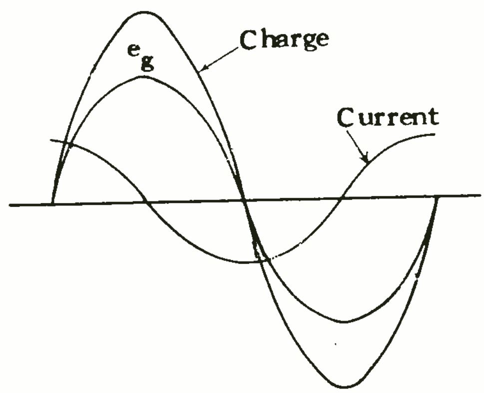


Fig. 3.—Relation between voltage and current as when charging a capacitor.

charge and resulting current referred to are those produced by the electrons in the interelectrode space, and produce the capacity C_{gk} (hot). In addition to these there are the charges that are produced on the cathode and grid surfaces owing to C_{gk} (cold).

As the frequency of e_g, the exciting voltage on the grid, is raised, the number of electrons leaving the cathode still varies in time or phase with e_g. But it takes a certain amount of time, called transit time, for these electrons to reach the grid plane, and it is only when they reach this plane that they induce their *maximum* positive charge on the grid. When they were just leaving the cathode they induced a positive charge on it, but this charge merely represented the protons in the cathode of an amount equal to the electrons. But the same electrons near the grid represent a new, induced charge effect—at the grid—and it is this additional effect that produces the capacity C_{gk} (hot).

The fact that the electrons take a certain amount of time to reach the grid means that the positive charge induced on it will *lag* e_g by a certain amount. Let T_g represent the transit time to the grid, and T, the time for one cycle of e_g, i.e., its period. Thus T corresponds to 360 electrical degrees and T_g represents a certain number of electrical degrees. For example, if T_g is one-half of T, then T_g corresponds to $360 \times 1/2 = 180°$. In general, the angle θ_g corresponding to T_g is

$$\theta_g \text{ (degrees)} = 360 (T_g/T) \qquad (1)$$

or in radians

$$\theta_g \text{ (radians)} = 2\pi (T_g/T) \qquad (1a)$$

The angle θ_g is called the "transit angle," or "grid transit angle."

From what has just been seen, it is clear that the induced charge on the grid will lag the grid voltage e_g by this angle θ_g, and that the charging current will also lead e_g by $(90° - \theta_g)$ instead of 90°. This is shown in Fig. 4. The fact that the current leads the voltage by less than 90° means that it has a component in phase with the voltage. This is shown in Fig. 5. It is to be remembered that all quantities

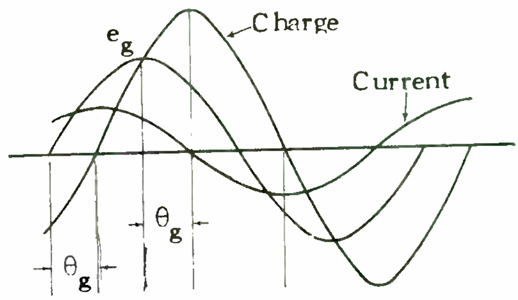


Fig. 4.—Relation of θ_g showing transit-time angle in a tube.

are a.c. in nature, and hence can be represented by vectors. The charge lags e_g by θ_g, and hence the total

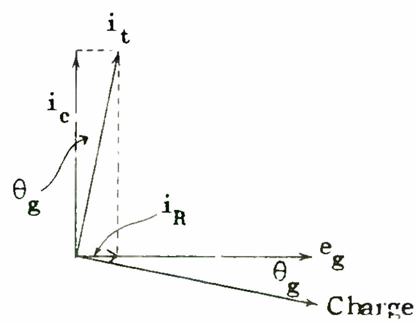


Fig. 5.—Vector relations for conditions of Fig. 4.

current i_t is θ_g degrees less than a full 90° ahead of e_g. As a result, i_t can be resolved into component i_c that is exactly 90° leading e_g, and i_R that is in phase with e_g.

This means that the impedance presented by the grid owing to transit time effect is that of a capacitor and resistance in parallel as shown in Fig. 6. The capacitor

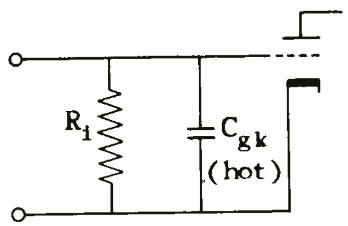


Fig. 6.—Showing input impedance of a tube R_i and C_{gk}.

is C_{gk}(hot) and is practically independent of frequency, although its reactance, of course, varies inversely with frequency. In addition to C_{gk}(hot) there is C_{gk}(cold) plus any capacity effects due to C_{gp} as derived in the previous assignment.

The resistive component is represented by R_i in Fig. 6. It is given by the formula*

$$R_i = \frac{1}{kG_m\omega^2 T_g{}^2} \qquad (2)$$

where k is a constant. This formula is practically correct if θ_g is not too great. For ordinary cases this holds over a range of frequencies for which the tube is useful. If θ_g is greater than about 90°, which means that T_g is about 1/4 T, or the period of the cycle of e_g is relatively short (high frequency), then the impedance may appear to be that of an inductance paralleled by a resistance, and the latter may become negative. However, ordinarily Eq. (2) and Fig. 6 apply.

PLATE TRANSIT TIME.—It was shown that an increase in grid-to-cathode capacity, C_{gk}(hot), is produced by the emitted electrons from the cathode being closer to the grid. This is true whether the electrons are in the space between the grid and the cathode, or between the grid and the plate. It has also just been shown that if the electrons take time to come from the cathode over to the grid, that the charge and the resultant current lag their positions for zero transit time by an angle θ_g, and thereby produce the effect of input resistance R_i, as well as C_{gk}(hot).

As far as the capacity effect is concerned, it is immaterial where the electrons come from, so long as they are in the neighborhood of the grid in phase with the grid voltage e_g. This implies an infinite velocity from their origin to the grid. They could come from the plate, or from some external electrode and still produce C_{gk}(hot). Actually they come from the cathode.

However, if the electron charge takes time to come to the grid from the cathode, the phase shift θ_g occurs, and input loading R_i develops. It would therefore appear that the time it takes for the electrons to proceed from the *grid to the plate*, or T_p, would also affect R_i. If T_p is appreciable compared to the time of one cycle, this might affect the value of R_i.

This is true, but only to a

*See W. R. Ferris, "Input Resistance of Vacuum Tubes as Ultra-High Frequency Amplifiers," *Proc. I.R.E.*, January, 1936.

minor degree. Actually, the electrons approaching the grid from the cathode induce an *increasing* positive charge, with time, on the grid, and cause a current flow i_1, Fig. 7.

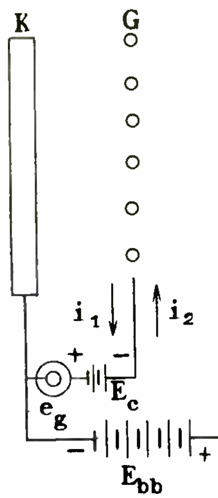


Fig. 7.—Current flow in the grid of a vacuum tube owing to induced charges.

On the other hand, electrons receding from the grid toward the plate induce a *decreasing* positive charge, with time, on the grid, and cause an opposite flow i_2. The product of the number of electrons by their velocity in the grid-cathode space represents current flow in that region, and also determines i_1 in the grid as well. A similar product for the electrons in the plate-grid region determines the current flow in that region as well as i_2. Under d-c voltage conditions, as well as low-frequency a.c., these two space currents, and hence i_1 and i_2 are equal, so that the net grid current $(i_1 - i_2)$ is zero.

Note, however, that these opposite grid currents are due to the finite velocity of the electrons in the interelectrode regions. In addition to them there is a current owing to the electron charge varying in the vicinity of the grid; this is the charging current that gives rise to C_{gk} (hot).

If there is a lag between this charge and the grid voltage e_g, Figs. 4 and 5 have shown that an in-phase component is obtained, which means that $(i_1 - i_2)$ is not zero. This can come about from a low velocity of the electrons either in the grid-cathode or grid-plate region. A more exact analysis made by Dr. D. O. North* leads to a rather involved formula that is more accurate than Eq. (2), and indicates that R_1, or rather its reciprocal, the input *conductance* g_1, is proportional mainly to the square of the sum of the two transit times.

Ordinarily, however, the plate transit time T_p is much smaller than the grid transit time T_g, and hence has but a minor effect upon R_1. This is because in the grid-cathode space the negative grid counteracts to a great extent the pull on the electrons of the positive plate, so that the accelerating force on the electrons is low, as is therefore their velocity. The transit time T_g is correspondingly large.

In the grid-plate region, the negative grid helps repel electrons over to the plate, so that the accelerating force is high and the transit time T_p is consequently small. Hence R_1 is due mainly to T_g. However, it is important to understand the effects of electrons approaching and those receding from an

*"Analysis of the Effects of Space Charge on Grid Impedance," *I.R.E. Proc.*, Jan. 1936.

electrode in order to appreciate the action of such tubes as the Klystron and the Magnetron, and that is why it was discussed in some detail here.

OTHER EFFECTS OF TRANSIT TIME.—The principal effect of transit time is that of input loading in the grid circuit. At sufficiently high frequencies, it will reduce the voltage gain to unity and thus render the tube useless as an amplifier. However, there are other effects of transit time that are of importance in determining the behavior of the vacuum tube at u.h.f.

TUBE CHARACTERISTICS.—At low frequencies, a grid voltage e_g acts as if μe_g volts were directly inserted in the plate circuit. The amplification factor μ is a real number, such as 15, so that μe_g is in phase with e_g and merely μ times as large as it in magnitude.

At high frequencies, the equivalent plate voltage μe_g begins to lag e_g owing to transit-time effects. This can only be because μ has become a complex number instead of a real number. This is illustrated in Fig. 8. Here e_g is taken as the reference vector. At high frequencies, μ lags e_g by an angle θ, so that it can be written as

$$\mu = \mu_r - j\mu_i$$

where μ_r is its real component, and μ_i is its imaginary component. As a result of this, the plate current flow is not in phase with e_g even if the plate load is a resistance.

Similar effects are noted with regard to the internal plate resistance r_p, and the quantity $G_m = \mu/r_p$. At low frequencies, this is an inphase quantity and is known as transconductance, but at high frequencies its lagging phase characteristic makes it take on reactance components, so that it is called by the more general name of "*transadmittance.*"

The *magnitudes* of μ, r_p, and G_m do not vary very much in the normal high-frequency range of operation, but their phase does. This merely introduces a phase shift in the output voltage of the tube when employed as an amplifier, and is generally of no consequence. But when the tube is to be used as an oscillator, such phase shift is of great importance, and requires that the feed-back from plate-to-grid be modified accordingly. This may impose some difficult requirements for the feed-back circuit in order to obtain the proper phase shift in this circuit for oscillation at the frequency desired.

FACTORS AFFECTING TRANSIT-TIME LOADING.—The input loading was given by Eq. (2), namely

$$R_1 = \frac{1}{kG_m\omega^2T_g^{\,2}} \qquad (2)$$

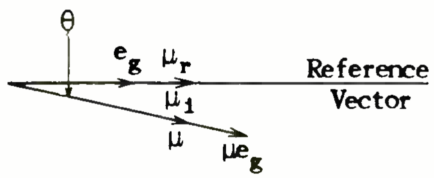


Fig. 8.—μ shown as a complex value.

from which it is clear that R_i varies inversely as G_m, and as the square of the frequency $(\omega/2\pi)$ and the transit time. The transit time varies inversely as the *square root* of the net d-c voltage, which is $E_b + \mu E_c$, where E_b is the plate voltage, and E_c the bias voltage. This is because the grid transit time depends upon the *net* voltage acting in the grid-cathode space, and this is the *algebraic* sum of the plate voltage E_b and μ times the grid bias voltage, or μE_c.

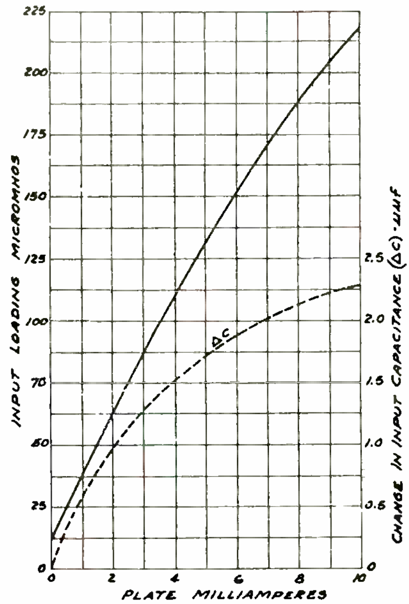
In Fig. 9 is shown the variation in input loading (measured as a conductance $g_i = 1/R_i$) and also that of C_{gk} (hot), with plate current, for a 6AC7 tube at 40 mc. As one varies the grid bias, for example, the G_m will vary, as will also the plate current. The higher the latter is, the greater is G_m and the lower is R_i, or g_i is higher. At the same time the hot capacity increases because the G_m has increased, and rendered the effect of grid signal voltage e_g more pronounced. Suppose it is desired to know the input loading for a plate current of 6 ma at 90 mc. The value of g_i for 6 ma at 40 mc is given in Fig. 9 as 150 µmhos. Therefore, at 90 mc the value will be

$$g_i = \left(\frac{90}{40}\right)^2 150 = 759 \text{ µmhos}$$

or

$$R_i = 1/g_i = \frac{1}{759 \times 10^{-6}} = 1{,}319 \text{ ohms}$$

The effect of an increase in the electrode voltages is to speed up the electrons and therefore decrease their transit time. This, in turn, reduces the input loading because it reduces the lagging phase angle θ_g. The latter, as well as the corresponding transit time T_g, vary inversely as the velocity, and the velocity varies as the square root of the net voltage so that T_g^2 varies inversely with the FIRST POWER of the voltage. But the G_m varies as the *square root* of the net



E_f = 6.3 volts   Screen volts = 150
Plate volts = 250   Grid volts = varied
Suppressor volts = 0   Frequency = 40 megacycles

Courtesy of I.R.E. Proc., Sept. 1943.

Fig. 9.—Variation of input loading with plate current.

voltage, so that it comes about that the input conductance varies directly with $G_m T_g^2$ and hence finally inversely as the square root of the net voltage.

The significance of this statement is that if all electrode voltages (except the heater) are increased by the same ratio, the input loading will decrease as the square root of this ratio. For example, if all voltages for the 6AC7 tube are doubled, then the input conductance for an *original value* of plate current of 6 ma will be decreased approximately to

$$150 \times 10^{-6} \div \sqrt{2} = 106.1 \times 10^{-6}$$

or

$$106.1 \ \mu\text{mhos}$$

Note that if all voltages (including the bias) are doubled, the plate current will increase from the initial value of 6 ma. Thus Eq. (2) serves as a basis for calculating the input loading for a tube for voltages or frequencies other than those for which data is furnished.

It would therefore appear of value to operate the tube at high electrode potentials. Such operation, however, is limited by the amount of plate dissipation the tube can handle, and generally only a very moderate increase is possible. Nevertheless, it will be noted that tubes especially built for u.h.f. work are generally designed to operate at rather high plate potentials, and special means must be employed to dissipate the excess heat.

In the case of transmitting tubes, the electrode spacings are generally greater than those in the smaller receiving tubes, but the plate voltage is generally higher, and counteracts the tendency of the increased spacing to increase the transit time. Nevertheless, such tubes are generally built with as small a spacing and as small electrodes as possible, and thus the problem of heat dissipation from a small volume tends to limit very markedly the power output of such a tube.

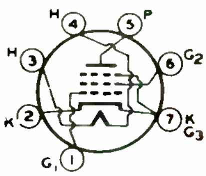
RECEIVING TUBES

Considerations of transit time have had a marked effect upon the design of tubes for u.h.f. work. One of the earliest, and still very successful modifications of ordinary tubes, was that made by Thompson and Rose. Reference is made to the "acorn" tube.

THE ACORN AND U.H.F. MIDGET TUBES.—If the linear dimensions of a tube are increased by a factor M, then the input conductance is increased by the factor M^2. This is because if each dimension of the electrodes is increased M times, the area is increased M^2 times, and this in turn would make the G_m be M^2 times as great. For example, if each dimension is doubled, the area is four times as great, and the effect is as if there were four of the smaller tubes in parallel, so that the change in plate current for a given change in grid voltage, i.e., the G_m, will be four times as great. On the other hand, the G_m varies approximately inversely as the square of the electrode spacing, so that if the latter is doubled, the G_m is one-quarter as great. Hence if all dimensions are increased (or decreased) by a factor M, the G_m of the tube (which normally indicates its merit), is unchanged. This indicated that small tubes could be made to have much the same amplifying properties as the normal size receiving tubes.

The transit time may be assumed to vary directly with the interelectrode spacing, at least for ordinary plane electrodes. Hence, if the interelectrode spacing is doubled, the transit time is doubled, and since g_1 varies as $G_m T^2$, g_1 will be quadrupled, for G_m has not changed but T has doubled. This verifies the statement made at the beginning of this section.

It therefore occurred to B. J. Thompson* to design a tube of greatly reduced dimensions known as an "acorn" tube. This was a specially built miniature tube in which the interelectrode capacitances and lead inductances, as well as the transit time effects, were reduced to a minimum, and at the same time the G_m and other tube characteristics were maintained at about the same value as those for the normal size receiving tubes. The leads were short and thick (which cut down the inductance effects) but necessitated that the tube be connected into the tuning circuits by means of a special socket.



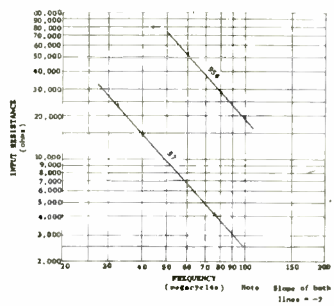
Bottom View of 9001 and 9003 Socket Connections

(*Courtesy of RCA Guide for Transmitting Tubes*)

Fig. 10.—U.H.F. midget tube and socket arrangement.

A later improved version is shown in Fig. 10, and is known as the "U.H.F. Midget." This is made to fit in a more conventional type midget socket, but has characteristics practically the same as the original "acorn" type tube. One important improvement is that two cathode leads are brought out of the tube, thus minimizing the cathode lead inductance, as explained previously. Owing to the small size, the input and output capacitances in the case of the pentode type are only about 3 μμf, which is possibly half that of the larger tubes in spite of the closer spacing. At the same time, the closer spacing reduces the input loading to a small value.

Some idea of this can be had from measurements made by W. R. Ferris* and reproduced in the form of a curve in Fig. 11. This is for the 954 "acorn" pentode tube, which corresponds to the 9001 type. For comparison, a large type 57 type pentode is also illustrated.



(*Courtesy of I.R.E. Proc., Jan. 1936.*)

Fig. 11.—Comparison of input resistance of acorn tube and a larger tube.

As an example, note that the 57 tube at 90 mc has an input resistance of only 3,000 ohms, whereas the 954 has an input resistance of 24,000 ohms, or 1/24,000 = 41.7 μmhos = g_1.

*See B.J. Thompson and G.M. Rose, Jr., "Vacuum Tubes of Small Dimensions for Use at Extremely High Frequencies," *Proc. I.R.E.* Dec. 1933.

*Loc. Cit. (which means reference previously cited in this assignment.)

The G_m of the 954 tube is 1,400 µmhos with 250 volts on the plate, 100 volts on the screen, and -3 volts on the control grid.

At a sufficiently high frequency, its input conductance g_1 will rise from 41.7 µmhos (at 90 mc) to a value equal to its G_m, or 1,400 µmhos. This frequency, call it f_o, can be found by proportion, if it be remembered that g_1 varies as the square of the frequency. Thus

$$\left(\frac{f_o}{90}\right)^2 = \frac{1{,}400}{41.7}$$

or

$$f_o = 90\sqrt{\frac{1{,}400}{41.7}} = (90)(5.8) = 522 \text{ mc}$$

At this frequency the gain should be reduced to unity, and therefore this frequency indicates an upper limit to this tube's operation. Actual measurements by Ferris* have indicated a gain of unity or better at about 430 mc, which is in reasonable agreement with the above calculation.

A gain of at least unity, actually appreciably better, is required for a tube to oscillate. The 9002 midget *triode* can actually oscillate at 600 mc. The circuit is shown in Fig. 12 (courtesy RCA). Tuned quarter-wave lines are used for the plate and grid. For a plate input of 1.6 watts, the oscillator will perform smoothly up to the above frequency.

DISC-SEAL.—A tube introduced by G.E. and partially removed from the secret list (Fall, 1944) is their type GL-464-A, and known as the "light-house" tube, from its appearance, or more generally as the disc-seal tube. The basic structure of the disc-seal tube in shown in Fig. 13. It is a triode, and differs

*Loc. Cit.

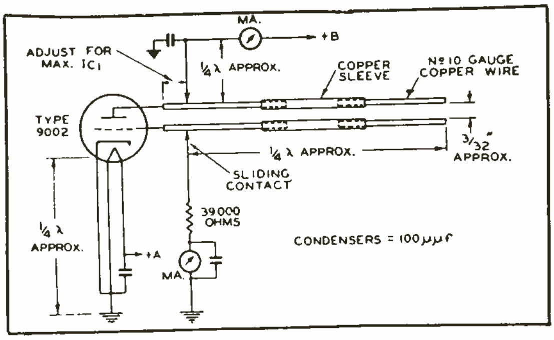
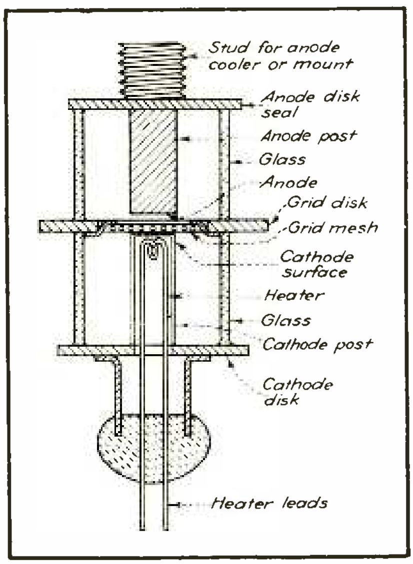


Fig. 12.—Oscillator circuit using a 9002 tube which will operate at 600 mc.



(Courtesy of Electronics, Feb. 1945.)

Fig. 13.—Light-house tube construction.

from the conventional type tube in that the elements are in simple, parallel planes or layers, instead of being fitted around one another in concentric shells. (Pentode tubes in this form can also be built.)

This construction is not only very rigid mechanically, but results in some very worthwhile advantages for u.h.f. applications. The grid is essentially a disc that makes contact to an external ring. The latter is its lead, and the inductance and r-f resistance of such a connection is very low, and can be incorporated into a cavity resonaator, as will be explained below.

The interelectrode capacitances are very low: C_{gp} = 2.0 μμf, C_{gk} = 2.7 μμf, and C_{pk} = 0.1 μμf. The latter value is of particular interest: owing to its low value, the tube is very well suited for operation as a grounded-grid amplifier.

The construction of the tube is based on a recognition of the fact that the tube and external circuit should form one integrated unit for operation at u.h.f. This fact has been recognized by others; Southworth, for example, has several patents on cavity resonators combined with tube elements into an integrated whole.

The manner in which McArthur*, of the General Electric Company, has utilized this idea has resulted in a very practical structure that can then be combined with any desired cavity resonator to furnish, for example, an oscillating circuit. The basic idea is to employ the principle of two reentrant cavity resonators: one comprising the plate and grid, and the other the grid and cathode. This is illustrated in Fig. 14.

The top cavity is loaded by the plate-to-grid capacity at the reentrant portion, and by the output load coupled to it by the loop; while the lower cavity is loaded by the grid-to-cathode capacity. The grid-to-cathode capacity acts as a mutual coupling, *and the only coupling* between the two cavities, so that the device is essentially a tuned-plate tuned-grid or tuned-plate tuned-cathode oscillator. The latter is the preferred type as it is simpler to ground the central web

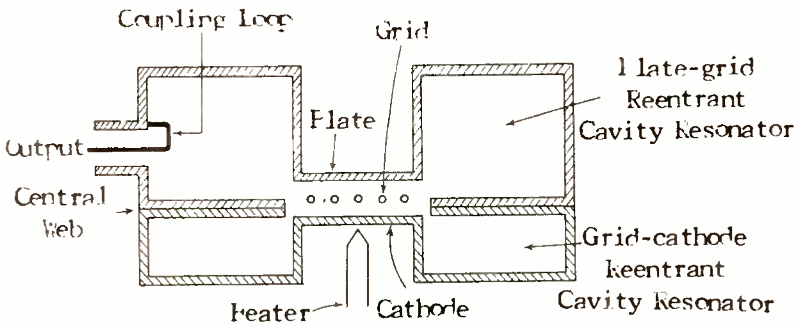
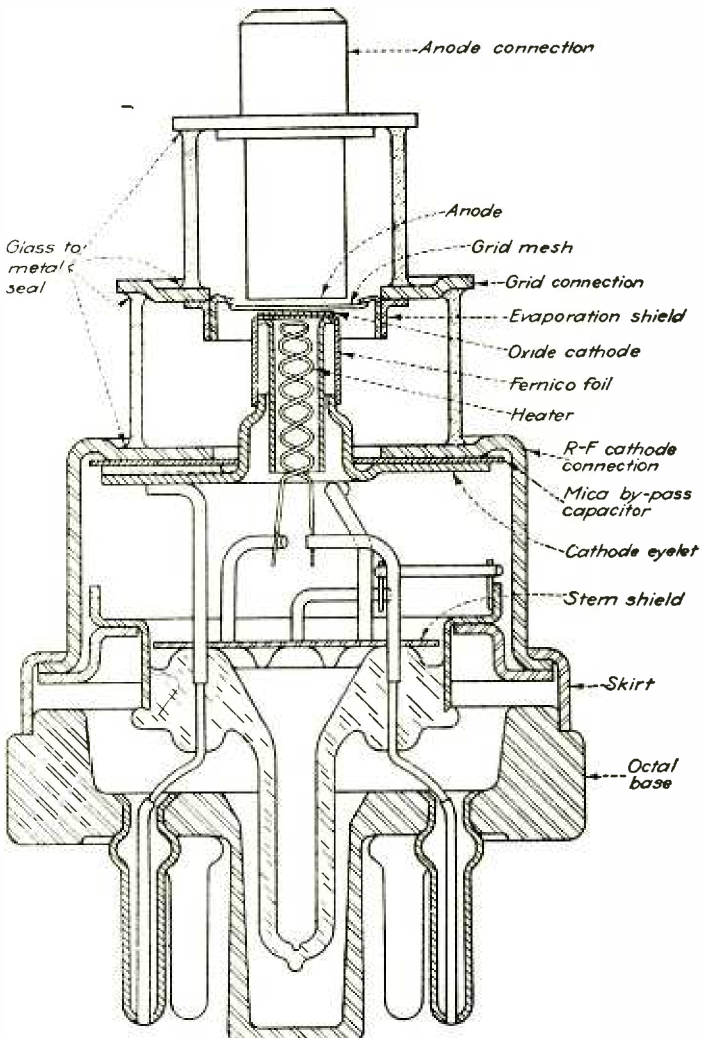


Fig. 14.—Basic idea of the use of cavity resonators with a tube as a part of the assembly.

*E. D. McArthur, "Disk-seal Tubes," *Electronics*, Feb. 1945.

to which the grid is connected. It is further to be noted that the tube elements are located, in fact, constitute the reentrant portion of the cavities, where the impedance is highest. This is the most desirable location, in general, for a tube in a tuned circuit. Note that lead inductance loses its significance, the leads are essentially the walls of the cavity resonator.

The actual construction of one form of these tubes is shown in Fig. 15. Note the glass-to-metal seals at various points. Further note that the cathode, for example, is by-passed to a concentric metal portion designated as "R-F cathode connection" in the figure by means of the mica by-pass capacitor. The value of this capacitance is 50 μμf, for the GL-464-A tube. This enables the cathode to be a continuation of the lower reentrant cavity and yet

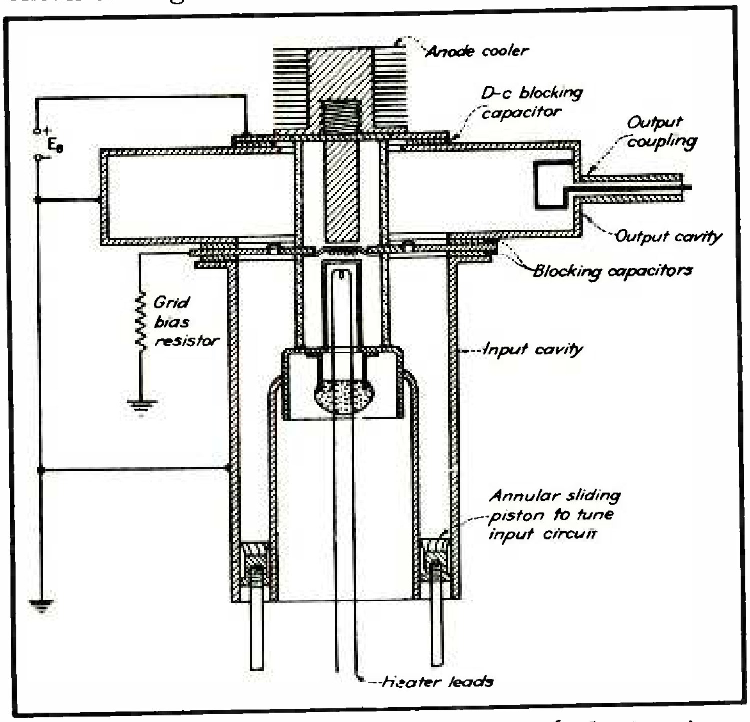


(Courtesy of Electronics, Feb. 1945.)

Fig. 15.—Showing the construction of a tube for use in an integrated assembly.

be biased at a different d-c potential from that of the cavity, which is normally grounded.

Another example of a disc-seal tube combined with two cavity resonators is shown in Fig. 16. In this illustration can be seen not only the u.h.f. features of the circuit, but also the method of introduction of d-c plate and grid-bias voltages, as well as a-c or d-c heater voltage. Note in particular that no elaborate filtering is required for the heater leads since the cavity resonator and the cathode construction serves effectively to shield the heater leads from the u.h.f. fields.



Courtesy of Electronics, Feb. 1945.

Fig. 16.—Disc-seal tube showing cooling fins and the connections for operating potentials.

Another important practical point is that while the u.h.f. fields are confined to the interior of the cavity resonators, the heat generated is not so confined and is free to flow to the outer walls and be absorbed by an external cooling medium, such as air. Note in connection with this the radiating fins on the top of the plate in Fig. 16.

Another important feature of the layer construction is that the transit time is very low, and thus the tube can operate at very high frequencies. The exact value is not given, but is certainly considerably above 100 mc. A further feature of the tube is that its G_m is very high, namely 7,000 μmhos. This is accomplished by close grid-cathode spacing: a value of 4.0 mils in some of the commercial tubes, and a value as low as one mil in some developmental tubes.

While the design center maximum voltage is given as 300 volts for the GL-464-A tube, meaning that this is the maximum central plate voltage about which normal variations can be permitted to occur, nevertheless an absolute maximum voltage of 500 volts is permitted. It can also be operated as a power oscillator. One use is in generating pulses, i.e., oscillations that occur in groups whose envelope is a rectangular wave, as shown in Fig. 17.

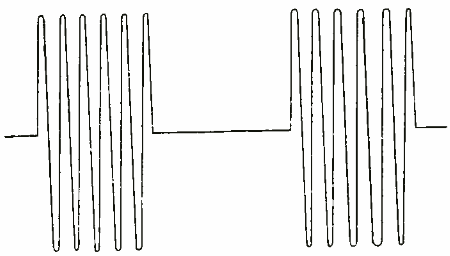


Fig. 17.—Type of pulses which can be produced by GL-464-A tube.

*PULSE OPERATION**.—This can be accomplished, for example, by having the tube normally biased beyond cut-off, but arranging a modulator tube, by means of a step-up transformer or similar means, to raise its voltage periodically to a very high value. During this time, the bias is insufficient to cut off the plate current, i.e., the tube is operative. The action is therefore as if the plate supply voltage were periodically switched on for a short interval, during which the tube can oscillate.

Since the "on" period is relatively short compared to the "off" period, the tube has plenty of time to cool off between times, and can therefore be operated at a very high voltage during the "on" period. As an example of this, the heater of the GL-464-A tube may be operated at 7 volts instead of 6.3 volts in order to increase the emission and hence the peak current during oscillations. The plate voltage can be increased to 3,000 volts maximum, whereupon the peak cathode current will be as high as one ampere, which is a truly high current for such small tube.

The operation at such a high voltage must be limited to 5 µsec maximum, as the tube elements do not have high heat storage capability, and will rise to a dangerously high temperature during the "on" period, even though they may cool down to a fairly low temperature during the "off" period. The maximum average plate dissipation is 10 watts. From this, the minimum time "off" period can be calculated for a maximum "on" period of 5 µsec.

Let T_o be the "off" period. Then $T_o + 5$ equals the total time in µseconds for an "on" plus an "off" cycle. The maximum input is 3,000 v. × 1 amp. equals 3,000 watts. This lasts for 5 µsec and represents an amount of energy input equal to 5 × 3,000 = 15,000 watt-µsec. Assume that the plate efficiency is 40%. Then 15,000 × .6 = 9,000 watt-µsec. is the energy dissipated at the plate. The average plate dissipation over the entire "on-off"

*An interesting example of pulse transmission for communication purposes is given by E. M. Deloraine and E. Labin: "Pulse Time Modulation," *Electrical Communication*, Vol. 22, No. 2, 1944.

cycle must not exceed 10 watts,* and is given by

$$\frac{9000}{T_o + 5} = 10$$

or

$$9{,}000 = 10T_o + 50$$

from which

$$T_o = \frac{9000 - 50}{10} = 895\ \mu\text{sec}$$

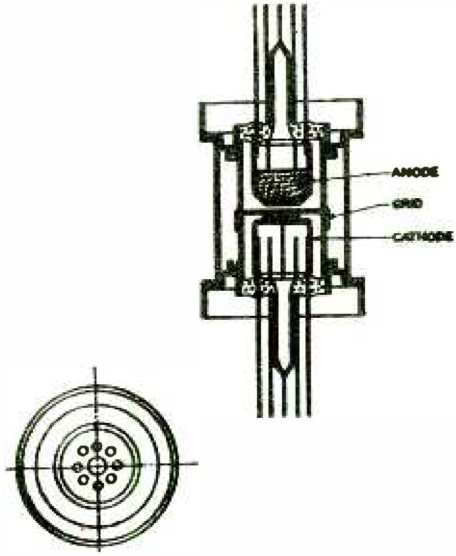
The total time is $T_o + 5 = 900\ \mu$sec. The repetition rate or frequency for the pulses will therefore be

$$f = \frac{1}{900 \times 10^{-6}} = 1{,}111\ \text{cycles/sec}$$

Note that where pulse transmission is desired, a relatively small tube can be employed and operated safely at very high voltages to give large instantaneous power output.

U.H.F. METAL TRIODE.—Now there will be given a description of a tube built by two Russian engineers that has interesting possibilities.** A picture of the tube in cross-section appears in Fig. 18. It will be apparent that this tube is also built in the form of parallel planes for the cathode, grid, and plate.

The cathode and grid are mounted as a single unit, and then the plate is sealed in. The glass seals



(Courtesy of I.R.E. Proc., May 1944.)

Fig. 18.—Metal triode tube of special construction using coaxial connections.

on the two ends of the metal cylinder permit coaxial lines to be connected to the cathode and plate, whose connections come out at opposite ends. At the time the tubes were developed the interest was apparently at frequencies where resonant lines instead of cavity resonators were considered desirable to use in conjunction with the tubes.

The cathode is an oxide-coated disc heated by a heater in the form of a flat spiral. The grid is made in the form of a mesh of tungsten wire about 2 mils (thousandths of an inch) in diameter, with a distance of 7.8 mils from wire to wire. This mesh is welded between two nickel disks, each of which has a central

*This assumes the energy all to be dissipated at the plate. Actually, an appreciable portion of the energy is dissipated at the grid, which is generally driven positive during individual r-f cycles.

**A Metal Triode for Ultra-High-Frequency Operation," N.D. Deviatkov and M. D. Gurevich, translation by A. M. Gurewitsch, *I.R.E. Proc.*, May 1944.

hole through which the mesh is exposed and through which the electrons pass en route to the plate. The grid assembly is then welded to a supporting cylinder to which a glass seal is attached.

The cathode is attached to a cylinder concentric and within the grid cylinder. The cathode cylinder is welded to connectors passing through the glass seal, thus making it and the grid into a unit structure.

The plate, as shown, is a flat-ended cone at the bottom end of a cylindrical portion, and is solidly filled with copper to improve the heat conduction. It is interesting to note that the plate is spaced only 7.8 mils from the grid, and the latter has even closer spacing to the cathode (dimension not given). This provides a very small transit time.

The electrode capacitances are as follows: C_{gp} = 2 μμf, C_{gk} = 1.8 μμf, and C_{pk} = 0.2 μμf. It is interesting to compare these values with those given for the G.E. Disc-seal tube: they are quite comparable. Low interelectrode capacitances are important, as it permits the associated resonant lines to be more nearly λ/4 in length and thus permits higher impedances to be offered by these lines to the tube if the lines are not loaded down.

In Fig. 19 is shown the arrangement of the tube in conjunction with two resonant coaxial lines to function as an oscillator. The interesting point here is that the tube functions as a grounded-grid oscillator. Thus the grid, as well as the outer conductor of each coaxial cable, is at ground potential for r.f. The cathode connects to the inner conductor of the left-hand

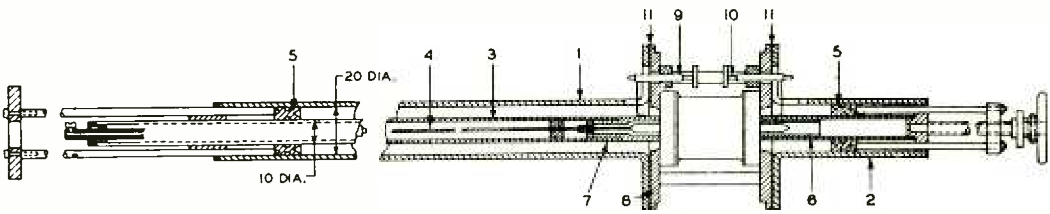


Fig. 5—Cross section of the circuit used in conjunction with DCM-1.
1—Outside tubing of the grid-cathode resonator.
2—Outside tubing of the plate-grid resonator.
3—Inside tubing of the grid-cathode resonator.
4—Heater connection of the cathode.
5—Tuning pistons for the plate-grid and the grid-cathode resonator.
6—Plate connection.
7—Cathode connection.
8—Grid connection.
9—The movable plate of the feedback condenser.
10—The fixed plate of the feedback condenser.
11—By-pass condenser.

(Courtesy of I.R.E. Proc., May 1944.)

Fig. 19.—Metal triode useful as a grounded grid oscillator showing the construction details.

coaxial line, and the plate to the inner conductor of the right-hand line. One side of the heater connects to the inner conductor; the other side runs as a wire within the tubular inner conductor.

The lines tune by means of plungers. The plate line has an opening through which power can be withdrawn by means of a line connection. A point of interest is the method of obtaining feedback. This must be between the cathode (input) and the plate (output). Since C_{pk} is only 0.2 μμf, additional adjustable capacity, represented by elements 9 and 10 of Fig. 19, is provided to furnish the requisite amount of feedback.

The performance of this tube (designated as DCM-1) is rather interesting. It will oscillate up to 1,500 mc, although more satisfactory operation is obtained at frequencies of 1,200 mc and below. At 30 cm (1,000 mc) the output is 1 watt for a d-c input power of 10 watts. This corresponds to an efficiency of 10%. At 50 cm (600 mc) the output was 3.5 watts for an input of 10 watts, corresponding to an efficiency of 35%.

A point worthy of note is that if the transmission lines are increased in length from $\lambda/4$ to $3\lambda/4$, the losses are increased so that more d-c input power is required. As a result, the operation of the tube is impaired. This is particularly the case if the plate line is increased in length.

The tube can also be used as a converter for wavelengths of 25 cm or more, and as a grounded-grid amplifier. In the latter case, Fig. 19 applies, provided that feedback capacitor having plates 9 and 10 is removed. As an amplifier, the tube is stable up to 1,200 mc (λ = 24 cm) and affords a stage gain of between 3 and 4 at this frequency. Operation was with zero grid bias, and a plate voltage of 200 to 220 volts. The plate current was rather high: 30 to 40 ma.

This tube is an indication of what can be done with negative-grid receiving tubes. The maximum frequency of operation appears to be about 1,200 mc, although this limit has probably been extended. There thus appears to be a gap before one reaches 3,000 mc, at which the Klystron tube (to be described) takes over. The gap is even more pronounced when one comes to transmitter tubes of appreciable power output as will be seen in the next section.

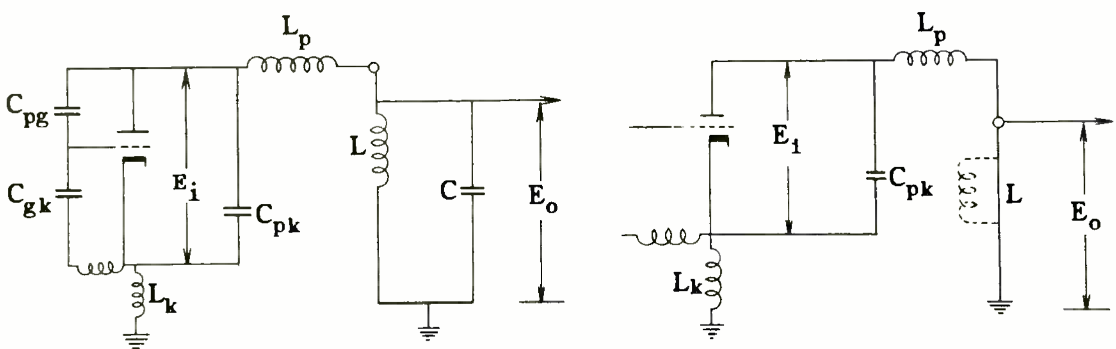
TRANSMITTER TUBES

It has been seen that owing to lead inductance, interelectrode capacity, and transit-time effects, the use of negative-grid tubes of the receiving type at the higher frequencies is severely limited. When larger power tubes used in transmitters are considered, it is found that the limitations are even more severe. This is evident when it is considered that the tubes must be larger to handle the larger powers involved, and hence inherently have greater lead inductances, interelectrode capacitances, and possibly greater transit-time effects.

In the case of transit time, the greater interelectrode spacing necessary tends to increase this factor, but the higher voltages required tend to decrease the transit time and thus offset the effects of increased spacing. As a result, while transit-time effects are appreciable, they are often not the limiting factor in a transmitter tube; rather the lead inductance and interelectrode capacitance set an upper frequency limit. This limit—at least for the larger negative-grid tubes commercially available—appears to be about 300 mc.

CIRCUIT LIMITATIONS.—It will be instructive to examine in somewhat more detail the limitations imposed by lead inductance and interelectrode capacitances. In Fig. 20(A) is shown the plate circuit of and C the capacitance of the tank circuit.

An inspection of Fig. 20(A) indicates that the external tank circuit is only part of the resonant circuit, of which the other part is C_{pk} and $L_p + L_k$, and is within the tube. Hence, if a voltage E_1 is developed within the tube, only a fraction of it, E_o, appears externally. Since only E_o can be impressed upon the grid of a following tube in amplifier action, or upon the grid of the same tube in os-



(A) (B)

Fig. 20.—Circuit showing tube inductance and capacitance effects in a circuit.

a tube. The inductance of the plate lead is L_p; that of the cathode, L_k. It will be assumed that the latter is really composed of two leads to eliminate feedback, as has been described in the previous assignment. Nevertheless, the inductance L_k does appear in the plate circuit, as shown. The total interelectrode capacity C_t is that between the plate and cathode, C_{pk}, paralleled by C_{pg} and C_{gk} in series; L is the inductance of the external tank circuit, cillator action, it is clear that if L_p and C_{pk} are appreciable compared to L and C, then E_o will be a small fraction of E_1.

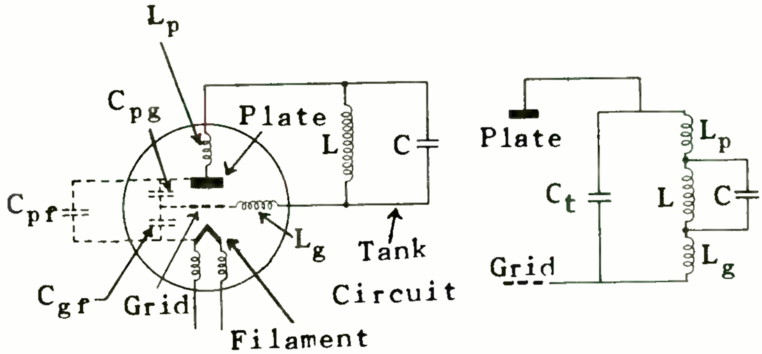
As the frequency of operation is increased, L and C must be decreased until C is zero and only the interelectrode capacity C_{pk} is employed, and L becomes a straight connection or wire of inductance comparable to L_p and L_k. This is illustrated in Fig. 20(B). In this case E_o will be very small and the tube will fail to function as an amplifier, or as an oscillator.

In the case of many oscillator circuits, the arrangement is as shown in Fig. 21(A). In this case, the plate and grid inductances are involved, and the total interelectrode capacitance is C_{pg} paralleled by C_{pf} and C_{gf} in series, i.e.,

$$C_t = C_{pg} + \frac{C_{gf}C_{pf}}{C_{gf} + C_{pf}}$$

The equivalent plate circuit is shown in Fig. 21(B), and again the output voltage across L and C is but a fraction of that developed between the plate and grid.

RESONANT LINES.—If a transmission line is employed instead of lumped circuit elements, then practically the same considerations hold. Thus, the larger C_t is, the shorter the line must be (compared to a quarter wavelength). It will be recalled that a line less than λ/4 and shorted at its far end has an inductive input reactance. Such a line can tune with C_{pk}; this has been discussed in the assignment on transmission lines. However, if L_p and L_k or L_g are present, they will further reduce the length of transmission line required since they furnish some of the requisite inductive reactance.



(A) (Courtesy of U.H.F. Technique Electronics, 1942.) (B)

Fig. 21.—Tube capacitance and inductance in an oscillator circuit and the equivalent circuit.

Ultimately, a frequency will be reached at which the transmission line must be of zero length. One can regard the λ/4 line as being completely within the tube. In such a case, operation is still possible if externally there is added a λ/2 line. The total electrical length is now 3λ/4, and while the losses of such a line are greater than a λ/4 line, operation in many cases is still feasible.

If the lead inductances are relatively small, but the interelectrode capacitances are comparatively large, then a circuit as shown in Fig. 22 will afford somewhat higher frequency of operation. In this circuit, two tubes are employed in conjunction with a half-wave line shorted at each end for the plate circuits. The tube capacities are essentially cut in half, in that half is associated with one-half of the $\lambda/2$ line, and the other half is associated with the other half of the $\lambda/2$ line, so that the latter is shortened by a smaller amount.

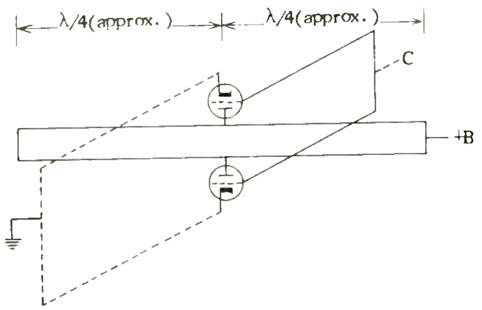


Fig. 22.—Circuit with large tube C used to obtain higher frequency operation.

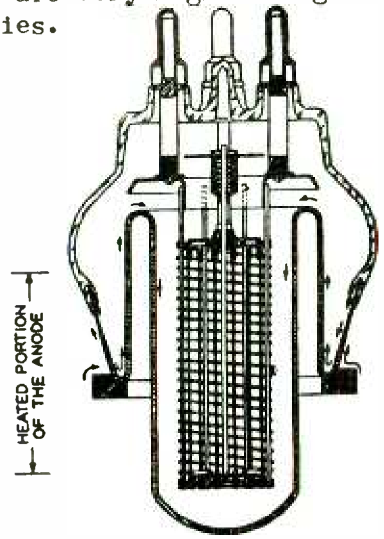
REDUCTION OF LEAD INDUCTANCE.—Lead inductance can be reduced by keeping the lead length as short as possible, and by using as large a cross-section of conductor as possible. This also minimizes the resistance of the lead by reducing skin effect. Short heavy leads have another advantage in that the tube elements can be rigidly supported by the leads in a glass dish or seal. In this way, insulation is not necessary as spacers between, and also as supports of the tube elements, where they would be subjected to the high temperatures of the elements. (The r-f losses of an insulator increase markedly with temperature.)

Another method of decreasing lead inductance is to employ several leads from the electrode. The leads must be spaced from one another by a sufficient distance to render mutual inductance effects between them negligible. The inductance of two leads in parallel is less than that of one lead of equal volume. Thus, it will be found that in some u.h.f. tubes, multiple connections are brought out from various electrodes. This is not to be confused with the use of two cathode leads to minimize cathode lead inductance loading effect, described in the previous assignment. A method of reducing lead inductance by modifying the tube shape is also possible. This is discussed in the next article.

GLASS SEALS.—One of the most important limitations to the operation of a power tube at ultra-high frequencies, particularly when it is pulsed, is that of maintaining a safe temperature of the glass seals through which the connecting wires pass. In the case of the "lighthouse" tube the safe temperature is given as 150°C. (design center)and 175°C. maximum. The use of a connector that is a good heat conductor and has sufficient bulk is helpful in keeping the temperature within the rating.

One reason for the glass seals overheating is that of skin effect. In Fig. 23 is shown a large high-frequency water-cooled triode. In order to reduce the inductance of the internal connections by making them short and of large diameter, it is necessary to make the anode or plate in a folded form as shown. It nas a feather edge which is sealed in the top glass dome containing the other electrodes.

The current does not flow from the inside surface of the anode to the outside surface by passing through the metal, but instead, owing to skin effect, flows all along the feather edge, as shown by the small arrows in the figure. This causes heating of the glass seal, and may be great enough to cause it to soften and implode. Other causes for heating may be dielectric losses in the glass, as these are very high at high frequencies.



(Courtesy of Ultrashort Electromagnetic Waves.)

Fig. 23.—Showing current flow owing to skin effect and how it heats the glass seals.

TRANSIT-TIME, TRANSMITTING TUBES.—The formulas and analysis given previously for transit-time effects are based on the assumptions that the grid swing was small, and that the plate voltage was constant and had no a-c component. Even with these restrictions, the theory and formulas apply with good accuracy to small receiving type tubes.

AMPLIFIER STAGE.—When the Class C amplifier is considered, however, it is found that the theory of transit-time effects is far from complete, and, in general, information only of a qualitative (inexact, nonmathematical) nature is available. Nevertheless, such information affords an insight into the effects of transit time upon the larger transmitter tubes that are usually operated as Class B and Class C amplifiers.

Consider a Class C amplifier, for example. The relation between the plate and grid voltages and the plate current is shown in Fig. 24.

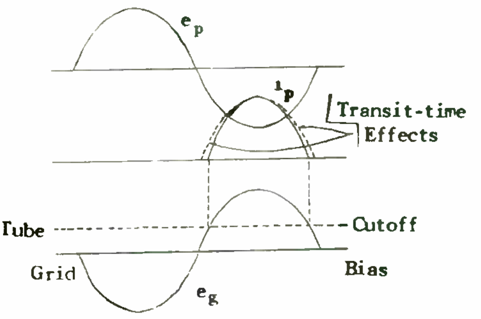


Fig. 24.—Transit-time effects in a class C amplifier.

A common value of grid bias is approximately twice the cutoff value for the tube. The plate current flows in pulses as illustrated by i_p in the figure. Note that for more than over 180° of the cycle, the grid is driven beyond the cutoff point of the tube. During that time, the plate voltage rises to its peak-positive value while the grid is driven to its peak-negative value.

At low frequencies, the plate current is practically in phase with the grid voltage and ceases during the time that the grid is at cutoff or beyond, as is indicated in Fig. 24. But at high frequencies, it has been shown that the electron density does not keep in phase with the grid voltage except at the cathode, and this is probably true only for small signal swings.

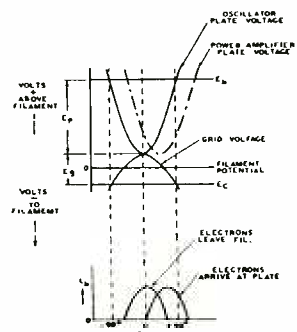
As a result, at the time when the grid reaches cutoff, there are still electrons in the space between the grid and the cathode. Those in the grid-cathode space are repelled by the negative grid toward the cathode and strike it at high velocity, thereby raising its temperature and producing losses at that electrode.

Electrons in the grid-plate space are repelled by the grid and attracted by the plate and so continue their journey to the plate. For large grid and plate voltages, the transit time for the electrons is increased, as will be explained below. Hence, the time of current flow to the plate exceeds that for which the grid would permit current flow at low frequencies; i.e., at u.h.f. the angle of plate current flow is greater than at low frequencies. As a result, not only does peak-plate current flow when the plate voltage e_p is at a minimum, see Fig. 24, but it also flows at times when the plate voltage is appreciably greater than its minimum value.

This is illustrated by the dotted line extensions of i_p in Fig. 24 that are labelled "transit-time effects." Clearly, plate current flow, at such times, means increased plate losses, just as is the case at low frequencies if the bias is adjusted arbitrarily to increase the angle of flow.

A factor that was considered negligible in the case of receiving tubes becomes important here, namely, grid-plate transit time. Dr. North's analysis assumed that the plate voltage remained constant during the a-c cycle and equal to the "B" supply voltage. This is clearly not the case if there is a load impedance in the plate circuit (which is true for any practical circuit) as the voltage drop in the load impedance must be subtracted from the constant d-c supply voltage in order to give the plate voltage, and since there is an r-f voltage across the load, this must give an r-f voltage of opposite phase between the plate and ground.

However, in a receiving tube this r-f plate voltage will not be very great compared to the "B" supply voltage because the tube is operated as a Class A amplifier of limited grid swing and with the grid negative at all times. Hence the results obtained by Dr. North under the above simplifying assumption of constant plate voltage are in good agreement with experiment. In a Class C amplifier, however, the grid swing is very great, and the corresponding plate voltage variations are very large, too, as shown in Fig. 25.



(Courtesy of I.R.E. Proc., April 1938)

Fig. 25.—Showing large plate voltage variations in a class C amplifier as a result of transit time.

For example, at the positive peak of the grid swing, the plate is not very much more positive than the grid. This means that the grid-plate transit time is large because the accelerating force between the grid and plate is small. On the other hand, at that moment the grid is positive with respect to the cathode, so that the accelerating force on the electrons in the grid-cathode region is large and the grid-cathode transit time is correspondingly small.

At some other moment of the cycle within the angle of current flow, the grid is negative with respect to the cathode and the plate is considerably more positive with respect to the cathode. As a result, the grid-cathode transit time is increased but the grid-plate transit time is decreased. This tends to equalize the transit time during various parts of the a-c cycle, but at a value greater than is the case for a Class A amplifier, where only the grid-cathode transit time is of importance. The result is increased input loading and phase shift of the current within the tube, i.e., μ becomes a complex rather than a real number.

The increased losses not only limit the output of the tube in order that the safe plate dissipation not be exceeded, but they also reduce the power amplification of the tube at the higher frequencies and ultimately render the stage useless as a power amplifier.

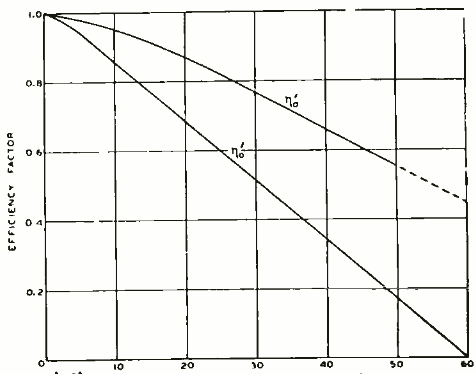
OSCILLATOR.—When the tube is operated as an oscillator, it is found that the output drops even more rapidly with frequency than it does as a power amplifier. While this can be ascribed, in part, to the fact that part of the output is returned by means of the feedback path to the input, in order to self-energize the stage, nevertheless this accounts for only a small part of the reduction in output.

A more important reason appears to be the shift in phase of the output voltage with frequency owing to transit time. This will be rendered clearer by the aid of Fig. 25. In practically all u.h.f. oscillators, feedback is via the appropriate interelectrode capacity, augmented, if necessary, by an externally connected capacitor. (Refer, for example, to Fig. 19.) At u.h.f., such a capacitive coupling path has a very low reactance, so that the feedback voltage is practically in phase-opposition to the plate voltage, since they are both derived from the plate tank circuit.

Hence the phase between the plate and grid voltage is 180°, as indicated in Fig. 25. However, owing to transit-time effects, the time that the electrons arrive at the plate is later than when they began to move from the cathode. Just upon arrival at the plate, they have maximum velocity, hence the plate current is at a maximum then. Therefore, the plate current pulse has its peak later than the minimum in the plate voltage and maximum in the grid voltage. The *fundamental component* of the plate current pulse is therefore also delayed and no longer is in time phase with the plate voltage, but lags it by a corresponding angle, or the *power factor* of the output circuit is reduced from unity, and hence for the same peak plate voltage and current magnitudes, the power output is reduced.

The fact that the peak of the plate current pulse is delayed means that it occurs at a time when the plate voltage has risen from its minimum value. Hence the plate power (dissipation) is increased—at the expense of the output power. In Fig. 25 is shown in dotted lines the plate voltage when the tube is operated as a power amplifier instead of as an oscillator. In this case, the plate voltage does not have to be 180° out of phase with the grid voltage since the grid is driven from a separate source. Accordingly, the phase of the plate voltage can shift so as to be in phase with the fundamental component of the plate current pulse, and thus unity power factor obtained with resulting higher output.

As an example of the superiority of a tube operating as a power amplifier over the same tube operating as an oscillator, Fig. 26, has



(Courtesy of RCA Review, July 1939)

Fig. 26.—Illustrating that the efficiency is greater for a tube acting as an amplifier than as an oscillator.

been prepared by Haeff.* Here η'_a represents the efficiency factor of the power amplifier, and η'_o that of the oscillator. Each is the ratio of the efficiency at the high frequency of operation as compared to the higher value of efficiency obtained at low frequencies. These are plotted against the index transit angle, corresponding to the peak grid and minimum plate voltages. The transit angle, it will be recalled, is the ratio of the transit time to the time (period) of one electrical cycle multiplied by 2π or 360°, depending upon whether the transit angle is to be expressed in radians or degrees.

It will be observed that at any transit angle, corresponding to some high frequency, the amplifier efficiency factor is greater than the oscillator efficiency factor, i.e., the amplifier efficiency does not drop as rapidly with frequency from its maximum low-frequency value as does that of the oscillator. The curves indicate that when the transit angle reaches 60 degrees, the efficiency and hence output of the oscillator should drop to zero. However, as stated previously, the theory has not been rigorously developed as yet, and a value of 180° for the limiting transit angle has been given by another man.* In any event, the tube can function at a higher frequency as an amplifier, and in some cases the circuit considerations may act as a limiting factor rather than transit time.

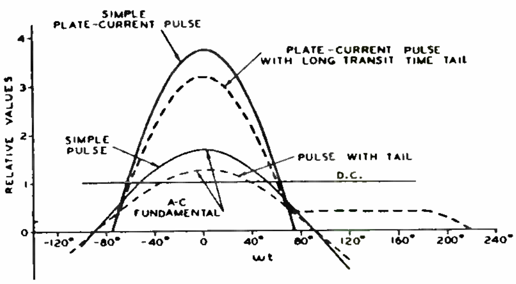
BOMBARDMENT OF GLASS WALLS.—It has been found that in tubes of ordinary design, some electrons manage to stray out of the plate-cathode region and make a very circuitous path before they arrive at the plate. In many cases, they bombard the glass walls of the tube and release secondary electrons from the glass, which leisurely travel to the plate. If such bombardment oc-

*"Effect of Electron Transit Time on Efficiency of a Power Amplifier," A. V. Haeff, *R.C.A. Review*, July, 1939.

*"Triode Oscillators for Ultra-Short Wavelengths," M. R. Gavin, *The Wireless Engineer*, June, 1939.

curs, the spot under bombardment becomes positive because the rest of the glass, being an insulator, cannot furnish electrons to the spot to replace those it has lost by secondary emission. Thus the spot, becoming positive, attracts more electrons; the bombardment increases, and ultimately the glass envelope may puncture at this point.

Whether or not the glass envelope punctures, the presence of electrons of long transit time causes the plate current to tail off slowly instead of dropping to zero when the grid voltage reaches the cutoff point. This is illustrated in Fig. 27. The presence of current



(Courtesy of I.R.E. Proc., April 1938.)

Fig. 27.—Owing to long transit time, plate current "tails" off slowly, instead of dropping to zero.

when the plate voltage is rising produces additional losses, and the output for the same input is reduced to about 75 per cent. Clearly, this effect should be minimized.

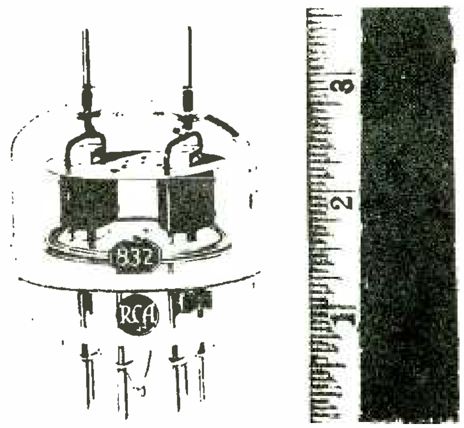
A method that has been successfully employed is to have the plate structure extend beyond the cathode and grid elements at each end. The plate thus forms a shield and prevents the escape of electrons. This will be further discussed when representative tubes are treated in detail.

GENERAL POWER TUBE CONSIDERATIONS.—The preceding discussion can now be summarized to afford a general view of power tube considerations. Many of the factors involved oppose one another, so that compromises must be made. For example, in order to develop a large amount of power, a tube must also be able to dissipate the corresponding large amount of power in the form of heat energy. This indicates that the tube elements must be of sufficient size to conduct and radiate away this heat energy. Also large clearances are required to avoid voltage breakdown, and large conductors are required to carry the currents involved.

On the other hand, in order to operate at very high frequencies, the tube elements must be small, in order that interelectrode capacitances and lead inductances be kept at a minimum. The result is that a compromise must be effected between power output and frequency of operation. By redesign of the tube elements and envelope, as well as by the use of water or air cooling, fairly large amounts of power output can be had at fairly high frequencies.

Transit-time effects demand small electrode spacings, whereas low interelectrode capacitances would indicate larger separation between the electrodes. Once again, a compromise must be effected such that—as far as possible—the two contradictory requirements produce about the same upper limit to the frequency. As stated previously, a factor that aids in the reduction of transit time is the high voltages normally employed. Because of this electrode spacings in a power tube can be appreciably greater than those in a receiving tube, although even then the spacings in many u.h.f. tubes are rather small.

RCA 832 BEAM TETRODE.—As an example of a low-power u.h.f. tube, consider the RCA 832 beam tetrode. A tube very similar to this has been described by Samuel and Sowers* of the Bell Telephone Laboratories. The 832 tube is shown in Fig. 28.

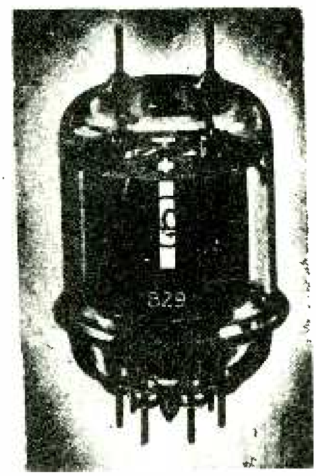


(Courtesy of RCA Review, July 1939.)

Fig. 28.—View of an RCA 832 beam tetrode (a low-power u.h.f. tube).

The output is 22 watts at 150 mc, and it may be operated at frequencies as high as 250 mc at reduced input.

A companion tube, the 829, is capable of even higher output. At 200 mc, the 829 is capable of 83 watts output with less than one watt r-f grid drive. At 250 mc, its input must be reduced to 89 per cent of that at 200 mc owing to the increased losses in the tube. A picture of the type 829 is shown in Fig. 29. It will be noted that the construction is very similar to that



(Courtesy of RCA Guide for Transmitting Tubes.)

Fig. 29.—Picture of an RCA 829 tube.

of the 832 tube, which will be described here in some detail.

ADVANTAGES OF PUSH-PULL CIRCUIT.—The push-pull circuit is particularly well adapted to u.h.f. operation. In order to appreciate this, a discussion of the push-pull circuit is necessary. This is shown in Fig. 30. Although lumped input

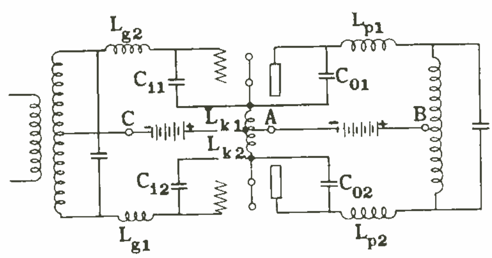


Fig. 30.—Showing a push-pull circuit adapted to u.h.f. work.

*"A Power Amplifier for Ultra-High Frequencies," A. L. Samuel and N. E. Sowers, *Bell System Technical Journal*, January, 1937.

and output circuits are shown for convenience, the same arguments apply to tuned transmission lines.

The push-pull circuit is inherently symmetrical to ground, and the cathodes are therefore essentially at ground potential, since they are at the center of symmetry of the circuit. Thus, the by-passing of screen grids, for example, to the cathodes is essentially by-passing them to ground. In passing, it may be noted that two-wire lines are inherently balanced to ground and therefore well suited to this type of circuit.

Note portions of the circuit labelled CA and AB in Fig. 30. These are called mid-branch portions of the circuit, and their impedances are known as mid-branch impedances. In these portions, only the *even* harmonic currents flow if the tubes are well balanced; no fundamental nor other odd harmonic currents flow here. If the mid-branch impedances are high, the even harmonic currents will be reduced, but the operation will not be materially impaired, whereas, if the impedance to the odd harmonic currents—specifically the fundamental—were high, considerable reduction in power output and marked instability would result.

From a practical viewpoint, the push-pull circuit is easier to by-pass for the fundamental current because theoretically none flows in the mid-branch portions of the circuit where high impedances may be encountered. Thus, referring to Fig. 30, fundamental current does not flow in mid-branch paths CA and AB, but it does flow through L_{p1}, L_{p2}, L_{k2} and L_{k1}. If these inductances can be kept low, little feedback effects, such as from L_{k1} and L_{k2}, need be experienced, and therefore little loading, owing to cathode lead inductance, need be encountered.

It is with respect to this that the placing of both tubes in the same glass envelope shows up to advantage. The close proximity of the tubes means that interconnections can be made very short, thus minimizing inductance effects. Then, from this cross-connection, a relatively longer lead of higher inductance can be brought out to the socket.

This is illustrated in Fig. 31.

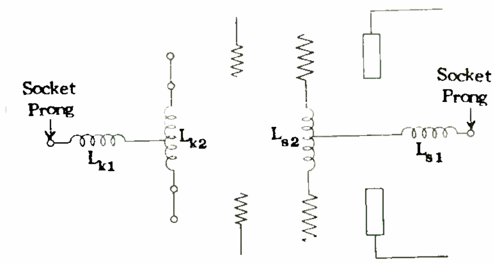


Fig. 31.—Means of reducing loading owing to cathode lead inductance.

Here cross-connections, L_{k2} and L_{s2}, are for the cathodes and for the screens, respectively, and being within the tube, can be kept very short and low in inductance. In these leads, fundamental and higher odd harmonic currents flow.

Leads L_{k1} and L_{s1} are longer connections, of higher inductance, to the socket prongs. In these leads, even harmonic currents flow, and if the inductance of L_{k1} or L_{s1} tends to suppress such currents, no serious effects upon the tube operation will occur. This is particularly important as regards the screen grids. A low-impedance connection between these, directly by-passed to the cathodes by a capacitance within the tube—as is the case here—results in the screen grid being substantially at r-f ground potential. This, in turn, assures stable operation even at high frequencies. The screen grid cross-connector forms one plate of the by-pass capacitor in close proximity to the other plate which is connected to the cathode cross-connector.

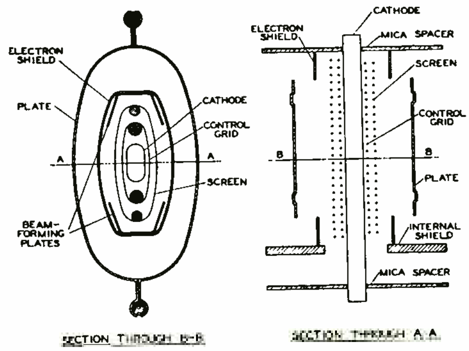
On the other hand, if the tubes were connected together externally, as is normally the case for two separate tubes operating in push-pull, then it is clear that the cross-connections would involve the higher impedance paths of twice L_{s1} or twice L_{k1}. Reduction of the impedance of the cross-connection of the cathodes reduces the degenerative feedback effects in the tube, since fundamental current flows only in each half of L_{k2} instead of in two socket-prong connections of the nature of L_{k1}. Thus, input loading, owing to cathode lead inductance, is minimized.

The use of a screen grid tube at u.h.f. requires a word of explanation. Ordinarily, triodes would be preferred. However, low power tubes such as the 832 are often operated in tunable circuits, and are required to operate over a range of frequencies. A triode would require neutralization, and this would not be effective over a range of frequencies, whereas a pentode is self-shielding, particularly if the screens are maintained at r-f ground potential as described above.

A beam tetrode has the additional advantage that the electrons are formed into beams between the control grid wires. The screen grid wires are aligned with the control grid wires so that the beams pass between them too. As a result, the screen current is small, and this not only results in a higher efficiency of operation, but also in reduced heating of the screen grid.

Another item that reduces interaction between the input and output circuits is a flat disc shield extending horizontally across the tubes below the plates; see Fig. 28. The plate leads are brought out at the top, and the control grid leads at the bottom. Note that each plate lead begins as a double lead of U-shape, in order to reduce the inductance. Further, the ends of each unit are shielded to decrease the number of stray electrons that would reach the glass walls, or insulators, and bombard them.

Fig. 32 gives a line drawing of



(Courtesy of RCA Review, July 1939.)

Fig. 32.—One method of reducing interaction between input and output circuits.

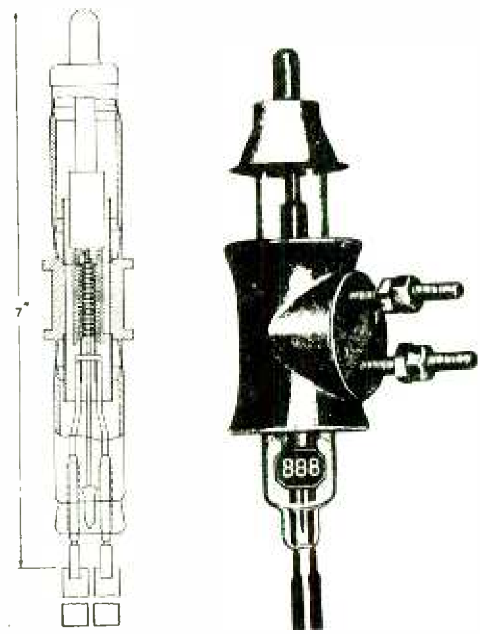
the tube structure. The control grids are cooled by the large-diameter side rods that support them. The side rods are each connected to a short wide strap having a blackened surface to increase its radiating ability. The strap is connected to the external grid terminal.

It is important that the control grids (and the screen grids, as well) be cooled adequately. In order to reduce the transit time, the control grid should be fairly close to the cathode. In the 832, the spacing is about 10 mils (.010"). This causes the grid to be heated appreciably by the cathode, and, in addition, an appreciable amount of cathode material may be distilled over on the grid, whereupon, it becomes thermionically emissive. To prevent such grid emission, the grid must be cooled to a point where such emission is negligibly small.

As a concluding observation, it may be noted that the tube is capable of an output of 10 watts at 250 mc, and because of the relatively low plate and screen voltages required (425 and 250 volts respectively), it is particularly well suited for mobile installations.

RCA 888 TRIODE.—The type 888 triode is a larger water-cooled tube that operates with full input up to 225 mc and has an output of approximately 800 watts operating Class C, c.w. It is shown in cross-section and in complete form in Fig. 33. The water jacket is an integral part of the tube.

Such cooling is particularly necessary at the higher frequencies, because of the increased losses owing to increased dielectric losses in the insulation, transit-time loading, and particularly because of the reduced size of the tube necessitated by its operation at ultra-high frequencies. Thus, the total length of the grid structure to a point of external contact, and the



(Courtesy of I.R.E., Proc., April 1938.)

Fig. 33.—RCA 888-water cooled triode.

full length from the top of the filament to the outside lead, is about 1/10 meter. The leads are essentially a continuation of the electrode itself, thus making it essentially a section of a transmission line circuit which can then be continued externally.

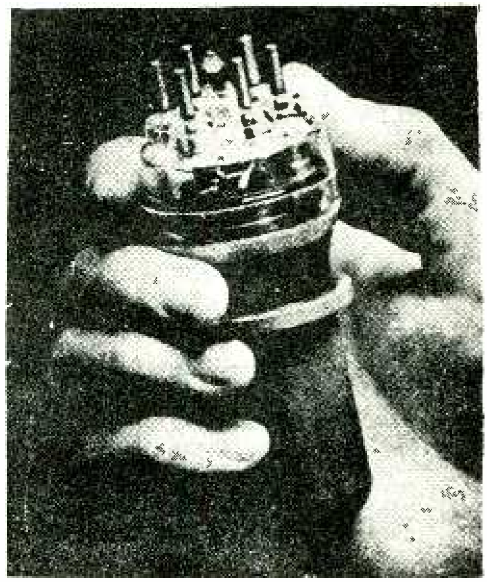
CONSTRUCTION FEATURES.—The plate is a copper cylinder one inch long and less than one inch in diameter, and yet the water surrounding it will easily absorb one kilowatt plate dissipation.

Several things may be noted from the cross-sectional view. (1). There is no internal insulation; the leads are large and can directly support the electrodes. (2). Note the two cylinders extending from the water jacket: one above and one below the jacket, and the solid ends of the grid and filament. These act as shields and prevent electrons from escaping from the interelectrode space and bombarding the glass walls of the tube as well as finding a path of long transit time. (3). The interelectrode spacings are very small, although this fact is merely suggested by the cross-sectional view. Thus, the clearance between grid and filament is only 0.060 inch and that between the grid and plate is 0.090 inch. (4). The diameter of the enclosing glass cylinders has been made very small so that the inductance of the leads will be at a minimum, since they are close to the external circuit. The glass forms the only insulation. Further, contact to the plate is made directly, and no consideration need be made as to lead length since this is part of the outside envelope of the tube.

The filament is of tungsten, as this is a very rugged emitter and can withstand the effects of the high plate voltage (3,000 volts, maximum). The grid is made of tantalum, a metal that not only can withstand high temperatures, but tends to absorb gases and thus to improve the vacuum.

GENERAL ELECTRIC TUBES.—Besides the Lighthouse tube described previously, which is made in some of the larger sizes as well as that described, General Electric makes several other power tubes designed for u.h.f. operation.

GL-8002 AND GL-8002-R.—This is the smallest of a line of tubes adapted for u.h.f. work and particularly for wide-band operation such as television. The GL-8002 is illustrated in Fig. 34; it requires



(Courtesy of I.R.E. Proc., Sept. 1941.)

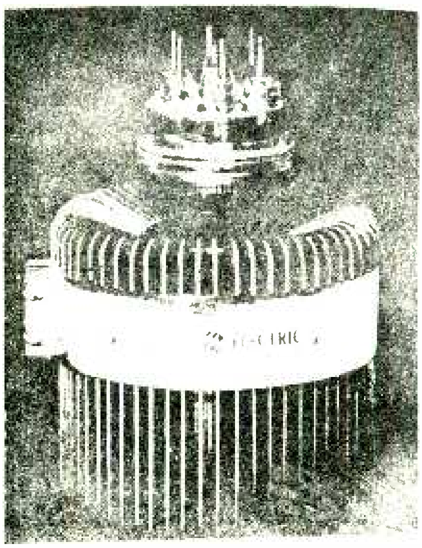
Fig. 34.—Photograph of a GL-8002 water cooled tube.

water-cooling. In Fig. 35 is shown the same tube adapted for air-cooling (GL-8002-R); in this case cooling fins are employed instead of a water jacket. A discussion as to the relative merits of the two types of cooling will be given further on.

CONSTRUCTION DETAILS.—The construction of the tube can be understood from the following description in conjunction with Fig. 36. While this is for the air-cooled GL-8002-R, the internal construction is the same for both.

The filament is of pure tungsten, in the form of a double helix..

Three leads are brought out from it (one from the center) so that it can be operated with the two filament sections in parallel, thus reducing

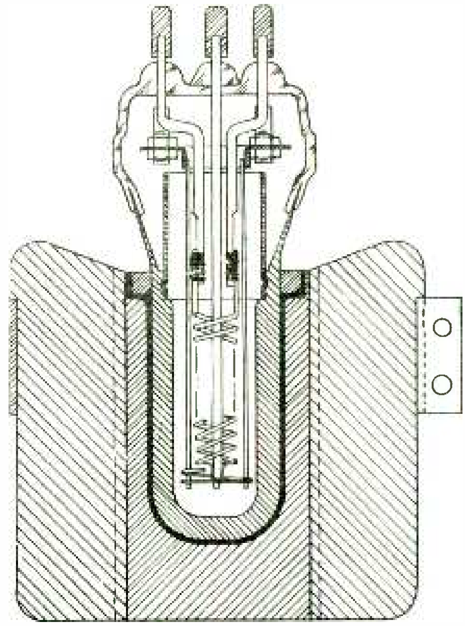


(Courtesy of I.R.E. Proc., Sept. 1941.)

Fig. 35.—Photograph of a GL-8002-R, air-cooled version of the GL-8002.

its inductance. The grid consists of a helix of wire wound on six stay rods mounted from a supporting collar. The latter is held rigidly in position from the three grid leads which in turn are sealed in a molded terminal flare together with the cathode leads. In this way the grid-cathode structure can be assembled accurately and then sealed into the anode cavity.

The grid-filament spacing is 0.060 inch, and the grid-plate spacing is 0.084 inch. Compare these with the RCA 888; the dimensions are almost identical. Such small clearances call for very careful assembly in manufacture, as a few mils variation would adversely change the tube characteristics, if not actually cause a short circuit. Also the assembly must be very rigid to prevent changes in spacing owing to mechanical shock, etc.



(Courtesy of I.R.E. Proc. Sept. 1941.)

Fig. 36.—Showing construction details of the GL-8002-R tube.

The plate is 1-1/4 inches long and 1-1/8 inches in diameter, and can dissipate 1,200 watts. Since the d-c input is given as 3,000 watts, an output power of 3,000 - 1,200 = 1,800 watts is indicated. The plate voltage is 3,500 volts; the plate current, 1 ampere*. A pair of these tubes can be operated stably up to 250 mc, although the

*These are maximum values, and are not employed simultaneously, i.e., either a maximum value of 3,500 volts may be used, or a maximum value of 1 ampere, or any combination such that the product (d-c input) is 3,000 watts.

above ratings apply only up to 150 mc.

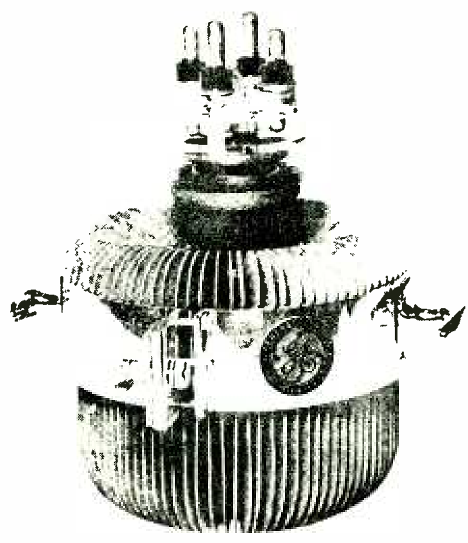
COMPARISON OF WATER-COOLED AND AIR-COOLED TUBES.—It will be of some interest to compare the water-cooled and air-cooled tubes. The various interelectrode capacitances are the same: C_{gp} = 9 μμf, C_{gk} = 9 μμf, and C_{pk} = 0.5 μμf. This is because the GL-8002-R air-cooled tube is exactly the same as the water-cooled tube, with the exception that the cooling fins take the place of the water jacket. The diameter of the tube is thereby increased, and this additional bulk cuts down the maximum frequency limit of the air-cooled tube to 120 mc as compared to 150 mc for the water-cooled tube. Nevertheless, two air-cooled tubes can be used to develop 3 kilowatts in a frequency-modulation transmitter.

GL-889.—The type GL-889 is a larger water-cooled tube having a maximum output of 10 kilowatts at a plate potential of 7,500 volts, operating Class C (key-down condition). It is particularly suited for the output stage of a medium-powered television transmitter. It has a plate dissipation rating of 5 kw and a power-input rating of 16 kw for Class C telegraph service up to 50 mc, but can be operated under reduced ratings up to 150 mc.

This tube is illustrated in Fig. 37, and the corresponding air-cooled type in Fig. 38. The latter has the same plate dissipation

(Courtesy of I.R.E. Proc., Sept. 1941.)

Fig. 37.—Photograph of a GL-889, a medium power, water-cooled tube.



(Courtesy of I.R.E. Proc., Sept. 1941.)

Fig. 38.—Photograph of the air-cooled version of the GL-889.

rating of 5 kw, but owing to its larger anode size, its maximum frequency rating is only 25 mc, and it can be operated under reduced input only up to 100 mc. Two tubes in an f-m transmitter, however, can furnish 10 kw up to 50 mc.

CONSTRUCTIONAL DETAILS.—The filament is a cylindrical cage-like structure consisting of 6 strands of pure tungsten wire, and is equipped with a spring between two cup containers in a region remote from the heat zone in order to put a certain amount of tension on the filament strands. This takes care of their expansion as they heat up and insures their remaining straight. The strands are connected to molybdenum leads which connect to plates in such fashion that alternate strands are in parallel.

The grid and filament terminals are copper thimbles sealed to a four-post molded pyrex dish, as may be seen at the top of Figs. 37 and 38. These thimbles connect to the filament and grid by means of copper rods 3/8 inch in diameter. The inductance of the lead-ins is thus kept at a low value. The grid has two leads to eliminate coupling between excitation and neutralizing circuits, as will be explained later.

It is of interest to note that the water-cooled Type 889 has an output of 1 kw up to 108 mc for television purposes, and 10 kw for f-m purposes. The reason for the smaller output as a television transmitter is due to the wide-band operation required in such service. Owing to the wide frequency band, the plate load resistance must be made rather low, so that the tube does not operate into optimum load impedance and hence furnishes less output.

NEUTRALIZATION.—These larger tubes are generally operated at one frequency—that assigned by the Federal Communications Commission. Hence they need be neutralized for only one frequency, which simplifies matters considerably. Nevertheless, owing to lead inductance, some problems in neutralization arise. In Fig. 39 is shown a push-

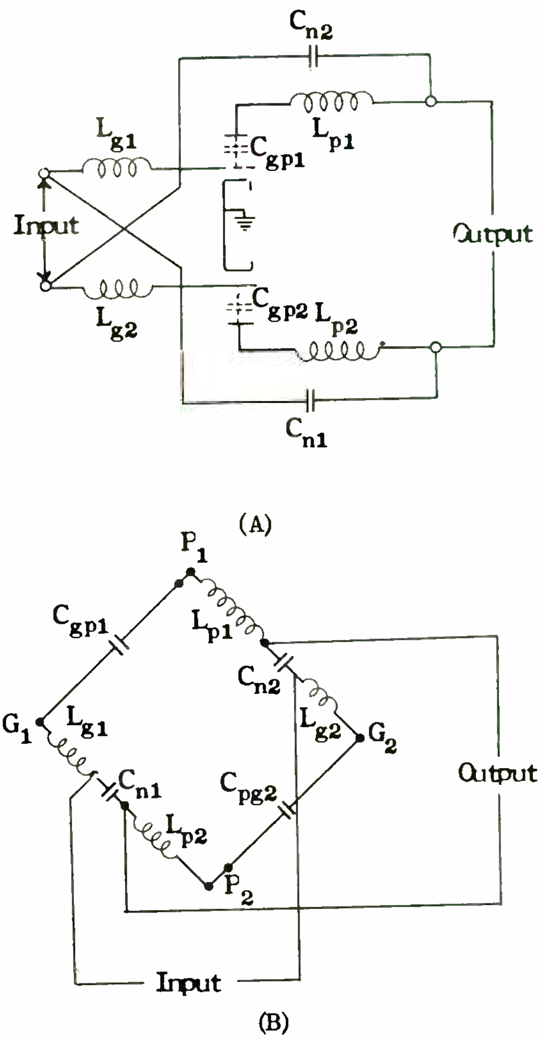


Fig. 39.—Actual and simplified versions of a push-pull neutralized power amplifier.

pull neutralized power amplifier circuit. Grid lead inductances are represented by L_g (such as L_{g1} and L_{g2}); plate lead inductances by L_p; plate-to-grid capacitances by C_{gp}, and neutralizing capacitors by C_n. Cathode lead inductances have been omitted since they do not affect the neutralization of the effects of C_{gp}, although they produce loading of their own, as has been described previously.

In Fig. 39(A) is shown the actual circuit (with the tuned input and output elements omitted), whereas in (B) a simplified circuit is drawn showing only those portions of the actual circuit that are relevant to the neutralizing process. It will be observed, particularly from (B), that the input circuit feeds the two grids through their lead inductances L_{g1} and L_{g2}. The currents drawn by the grids are those owing to their being driven positive during the peak portion of the cycle, to input loading effects, and to such capacity currents as may be drawn by grid-to-cathode capacity, etc. These currents produce voltage drops in L_{g1} and L_{g2} of appreciable magnitudes because the currents themselves are of appreciable magnitudes.

This can be objectionable for several reasons:

1. The grid current drawn at peak cycles varies with the degree of excitation in a nonlinear (nonproportional) manner. This would tend to upset the neutralization made at one level of excitation when the latter is changed.

2. Where wide-band operation is desired, as in television, it may be that the phase shift of the sidebands, which are farthest from the carrier in frequency, will be such as to produce voltage drops in L_{g1} and L_{g2} which change the neutralization made at carrier frequency, i.e., neutralization over a band of frequencies will be rendered more difficult.

3. Since input loading varies inversely as the square of the frequency, it is evident that the effect of such currents in the form of voltage drops across L_{g1} and L_{g2} will be different at different frequencies.

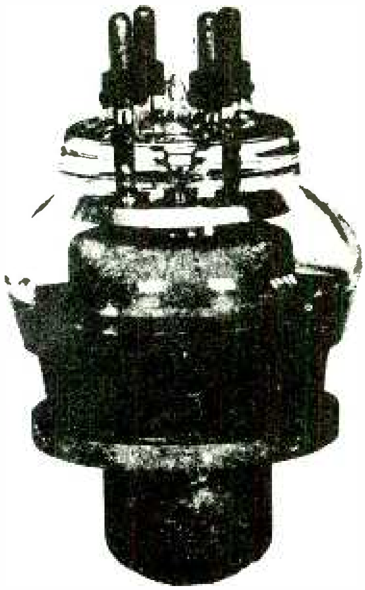
It is therefore advisable to avoid having the signal currents flow through circuit elements that are also common to the neutralizing circuit. The same reasoning holds for the plate circuit, i.e., L_{p1} and L_{p2} are common to the output circuit and to the neutralizing circuit, and the output currents will produce undesirable voltage drops and reactions in the neutralizing circuit.

The solution is much the same as that employed to decouple the grid circuit from the plate circuit by the use of two cathode leads. This was discussed in the previous lesson: input loading due to cathode lead inductance. If two grid leads are provided, then only the grid itself is an inductance common to the input and neutralizing circuits, and the two lead-ins and socket connections to the input and neutralizing circuits are separate. Thus the common coupling inductance is greatly reduced.

In a similar manner two plate leads can be brought out to reduce the coupling between the output and neutralizing circuit. In the case of the larger tubes, where connections are made directly to the copper anode, such division of leads is not feasible, but in the smaller tubes that are self-cooling, two plate leads are often brought out. They may be used to separate the output from the neutralizing circuit, or connected in parallel to reduce the lead inductance and skin resistance, as explained previously. Furthermore, in tubes where the leads come out of opposite ends of the tube, half-wave transmission lines with the tube located at the center of the line are also possible, with the attendant reduction in the effects of the tube capacitances and lead inductances in shortening the external lines.

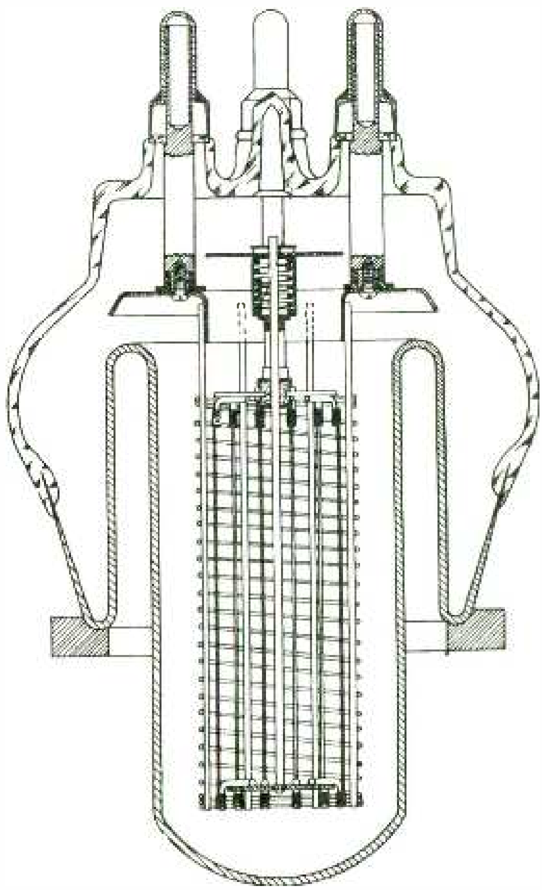
GL-880.—This tube is the largest one of this line, and is designed for a plate dissipation of 20 kw. It is adapted to operate at full rating up to 25 mc, but can be operated at reduced input up to 50 mc. It is of interest to note how the maximum frequency rating goes down as the tube size goes up. This is apparent from what has been stated previously: the greater the output desired, the larger must the tube be and hence the lower the maximum frequency.

Fig. 40 shows a picture of this tube, and Fig. 41 gives a cross-sectional view. It is to be noted that it is intended for water-cooled operation only. The most important feature of this tube is the folded or reentrant anode structure. Plate voltages as high as 10,000 volts can be employed. For such high voltages, sufficient length of glass insula-



(Courtesy of I.R.E. Proc., Sept. 1941.)

Fig. 40.—Photograph of a GL-880, high power, water-cooled tube.



(Courtesy of I.R.E. Proc., Sept. 1941.)

Fig. 41.—Cross-sectional view of the GL-880.

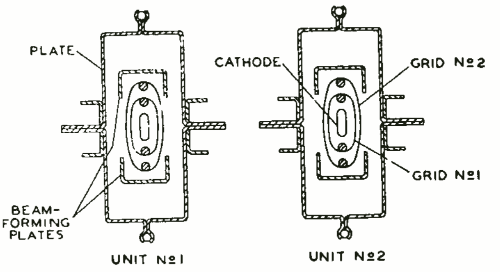
tion path must be provided. If the glass were run from the top of the anode upward, the lead lengths and hence inductances would be excessive. By folding the anode over, as shown, adequate glass length is obtained, and yet the lead lengths are relatively short.

The output of the Type GL-880 is 45 kw for Class C telegraphy up to 25 mc. As a plate-modulated broadcast transmitter, two tubes will deliver 50 kw. For frequency-modulation two tubes can deliver 50 kw up to 50 mc. A further point is that the tube is very well suited to television work because the required plate load impedance is less than that necessitated by bandwidth considerations.

ADDITIONAL CONSIDERATIONS.— Some additional considerations pertaining to power tubes will be given here:

1. When oxide-coated cathodes are employed, some of the active material tends to distil over to the grid, particularly if the spacing is small, and make it an emitter too. Close spacing also enables the cathode to raise the grid to a fairly high temperature unless adequate heat conduction to the outside is provided. By making the grid of certain nickel-base alloys, its emission can be reduced considerably. Further, the use of silver-copper alloy for the side rods instead of nickel, for instance, provides a better heat-conducting path to the outside. The silver-copper alloy has about the same high heat conductivity as that of copper, but is appreciably harder and stiffer.

2. By adding fins to the anode (in the ordinary small tube where the elements are enclosed by the glass envelope), greater heat radiation from the plate can be obtained. An example is the RCA-829 illustrated in Fig. 42. While carbon is



(Courtesy of I.R.E. Proc., Jan. 1942.)

Fig. 42.—Partial view of the internal structure of an RCA-829.

a very good radiator of heat, its use in u.h.f. tubes is inadvisable because the resistance of the contact of the lead-in to the carbon plate is usually too high, and a low-resistance contact is important at ultra-high frequencies. Another disadvantage is that in the case of an oxide-coated cathode, the carbon plate cannot be heated to a high enough temperature to degas it sufficiently during manufacture. A carbonized nickel anode is found to be very satisfactory, particularly when radiating fins are provided.

3. Another anode material that is coming to the fore is zirconium, in the form of a plating on another metal, such as molybdenum. Zirconium has two important advantages:

a). It forms a very efficient heat radiating surface; and b). It acts as a getter in cleaning up residual gases in the tube. One peculiarity of its action is that at 1,400° C it absorbs such gases as carbon monoxide, carbon dioxide, and oxygen very readily, but gives off hydrogen, whereas at 350° C it absorbs hydrogen very readily. To take advantage of this, the piece of zirconium is located in the tube where the temperature varies from 1,400 to 350° C. The use of zirconium as a plating has permitted the rating of several tubes to be revised sharply upward.

4. One difficulty encountered in the double or push-pull beam tetrode tubes is that of maintaining the screen grids, beam-plates, and cathodes at uniform potentials. For example, if the screen grid has appreciable length, the inductance of this length of electrode will cause an r-f potential to exist between the top and bottom of the electrode. Similarly, an r-f potential will exist across the ends of the other screen grid, but in phase opposition to that in the first screen grid.

Such potentials prevent the screens from being effectively at r-f ground potential and thus shielding the input from the output circuits, so that considerable energy may flow from the grid input circuit to the plate output circuit. To eliminate this effect, cross-connections are made between the two screens at the top and at the bottom. Since the screens have voltages 180° out of phase, such cross-connections act as very effective short circuits to the voltages and eliminate almost entirely the r-f potential difference between the top and bottom ends of either screen grid. Similar cross-connections for the beam-plates and cathodes result in a tube which even at 200 mc is relatively stable, and only a fraction of a watt is fed through the tube.

AIR-AND WATER-COOLING.—Some further remarks will be of value in the understanding of the features and relative merits of air- and water-cooling of the tubes. Generally speaking, an air-cooled tube requires less auxiliary equipment, and that of a simpler nature, than is required by a water-cooled tube. In addition, the maintenance of water-cooled equipment is a greater item of expense than that of air-cooled equipment.

The water must be pure so as not to form scale on the outside surface of the anode. This generally requires a closed system for the pure water, with a heat exchanger that permits this water to be cooled by ordinary water, or by fans in a kind of radiator system. Such a system is clearly complicated.

Another factor is that solid metallic piping from the anode, which is positive to ground, to the circulating pump which is at ground potential, would constitute a direct short circuit across the high-voltage plate power supply. It is therefore necessary to break this metallic pipe line and insert a sufficiently long section of rubber hose or ceramic tubing. The only electrical connection between the metallic pipe terminating in the anode and the other section of metallic pipe terminating in the grounded circulating pump is the column of water in the insulated section of the line. If the water is sufficiently pure, and the length of this column sufficiently great, then the leakage current through the column of water can be kept within satisfactorily small limits. Note that two insulated sections are required: one in the intake line and one in the exhaust or outgo line of the water system, and these insulating sections are expensive items.

A third factor is that the water cools the anode, but not necessarily, or least directly, the other components of the tube. In particular, the glass and glass seals run hotter than the anode, and hence absorbed gas (gas initially dissolved in the material) will be collected by the coolest element—the anode. During operation these gases may be released and produce a "flashback," a sudden arc that occurs in the tube and which will wreck the tube unless the plate circuit breakers open momentarily and extinguish the arc. Air-cooled tubes seem to be more free from this trouble, presumably because the anode runs hotter than the other parts of the tube, particularly the glass walls, which are directly and intensely cooled by the air blast. As a consequence the absorbed gas is probably collected by the cooler glass walls rather than by the anode, and hence is less apt to be released during operation.

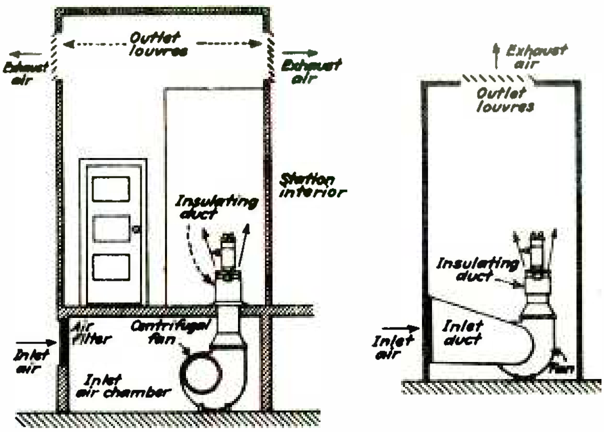
Finally, care must be exercised in the design of a water-cooling system to see that the water does not boil within the jacket. Normally the water is forced through the system under high pressure and at a high velocity. The motion of the water in the jacket is of a turbulent rather than lamellar (streamline) nature. Such turbulent motion exerts a kind of scouring action on the thin film of steam that may form on the anode walls, and thereby reduces its thickness. Since this film has high heat-insulating properties, any reduction in its thickness permits greater heat transfer.

If the anode gets hot enough to form bubbles of steam at any point, the heat transfer will be reduced at that point and the anode will overheat locally and puncture. Such formation of steam bubbles at localized regions of the anode can be caused by excess heating at these regions by the grid-focusing action of the tube. Owing to the beam-forming properties of the grid, the plate current, even in an ordinary triode, tends to be in the form of beams or sheets of electrons, which strike the plate at points opposite the openings in the grid structure.

Thus the plate is heated directly by the beams of electrons at these regions, and then the other regions of the plate—those in the shadow of the grid structure—are heated by conduction from the first-mentioned regions. If the anode has fairly heavy wall thicknesses, then on its outer surface the heat will be spread more uniformly. But in a water-cooled tube, thin anode walls are desirable, in order to increase the heat transfer to the water; therefore the danger of local heating and formation of steam bubbles requires that the dissipation limit of the anode be reduced from a value of 500 to 750 watts per square inch of the heated anode portion, down to one-half of this value or even less.

Air-cooled tubes depend upon the large cooling area of the fins, and a thick anode wall is permissible, and even desirable for fastening the fins to it. Hence for air-cooled tubes the above value of 500 to 750 watts per square inch need be reduced by only about 20 per cent to take into account grid-focusing action.

In view of the above, it might appear that air-cooling is far superior to water-cooling in all respects. The installation, for example, is relatively simple and inexpensive. In Fig. 43 are shown typical mechanical layouts for a high power transmitter (left), and for a low power transmitter (right).



(Courtesy of Electronics, June 1940)

Fig. 43.—Typical mechanical layouts for high- and low-powered transmitters utilizing air-cooled tubes.

Usually individual blowers and compartments are employed for each stage, although one blower can be employed for several stages.

However, air-cooling has several disadvantages, too. One has already been noted: the increased bulk of the anode when equipped with cooling fins increases its capacitance to ground. This serves as a severe limitation on its upper frequency in u.h.f. operation, as has already been noted. Indeed, the subject of cooling methods is of particular importance in the case of u.h.f. tubes, as these are particularly compact and require the most effective removal of heat.

Another disadvantage of air-cooled tubes is that the tube proper is soldered into the fin structure, rather than merely slipped into it. The reason is that the solder forms a heat-conducting bridge of low thermal resistance between the anode proper and the cooling fin structure. If such a tube fails, it is not feasible to have the station personnel unsolder the tube and solder a new tube into the cooling fin structure; instead, the whole device as a unit must be replaced and shipped back to the manufacturer. As such it is a much more bulky item than a water-cooled tube with the water jacket removed.

As the tube power rating is increased, the tube size of necessity increases. From a fundamental rule of geometry, a two-fold increase in the linear dimensions of the tube (length, width, etc.) causes an eight-fold increase in the volume and only a four-fold increase in the surface. In other words, the volume grows at a faster rate than the surface as the tube size is increased. This means that a much greater amount of heat must be passed through a relatively smaller surface.

Ultimately a size of tube is reached such that the fin surface required for air-cooling is excessive, whereas the water jacket size for water-cooling is still reasonable. Hence the largest tubes are in general water-cooled. Water-cooling is also generally employed where a great deal of heat must be extracted from a compact structure, such as a magnetron tube. An illustration of this will be given in the next assignment.

RESUME'

This concludes the assignment on u.h.f. negative-grid tubes. First the question of transit time was taken up, and it was shown that owing to this factor, even a negatively biased grid would absorb considerable power from the signal source.

Next it was shown how this loading of the input circuit could be reduced by reducing the tube dimensions. As two examples, the acorn and midget tubes were discussed. Other tubes, such as the G. E. Lighthouse and a Russian development tube were then treated.

The final portion of the assignment concerned itself with transmitting type power tubes, and the various problems of small size, high dissipation, and small clearances were then taken up. Many different types of transmitter tubes were studied, and the assignment finally concluded with a discussion of the problems associated with water- and air-cooling, and their relative merits.

RECEIVER TUBES AT F.M. AND TELEVISION FREQUENCIES

EXAMINATION

1. (A) What two effects upon the impedance of the grid input circuit does transit-time loading have?

(B) What effects does transit-time loading have upon the plate output circuit?

2. (A) Compare the manner in which loading due to cathode lead inductance and loading due to transit time vary with frequency.

(B) What is the apparent *resistance* connected between the grid and cathode of a tube operating at 200 mc, if the input *conductance* at 70 mc is 320 μmhos.

2. (C) Suppose all the voltages were doubled at 70 mc. What would the input conductance be?

3. (A) Why is the transit-time loading less in an acorn tube?

(B) Explain why the acorn tube has practically the same transconductance as the larger type tubes.

4. (A) How does the input capacity of the acorn tube compare with the larger size tubes?

4. (B) A tube has a G_m = 10,000 µmhos, and an input conductance of 50 µmhos at 100 mc. At what frequency will the gain of this tube be reduced to unity when operating into another similar tube?

5. (A) What is the advantage of pulse transmission with respect to the transmitter tube, and what operating features and design must the tube have?

(B) Suppose the repetition time of the pulses is 1,000 per second, and the duration of each pulse is 4 µseconds. Suppose the peak input to the tube is 2,000 watts (80 % efficiency) during the pulse time. What is the average rate of energy output over an entire "on-off" cycle?

6. (A) What compensating factor in a transmitter tube prevents the relatively large interelectrode spacings from producing an excessive value of transit time?

(B) What other factors set an upper frequency limit to the operation of the tube?

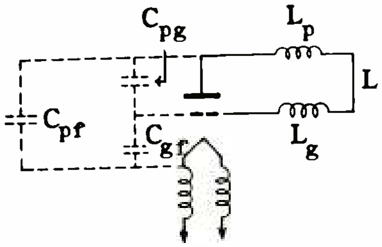
(C) Why is it important to have as much as possible of the tube tuned circuit external to the tube?

7. (A) Refer to the figure. The values of the various circuit elements are

L_p = .08 μhenry

L_g = .07 μhenry

L = .03 μhenry (straight wire connection acting as external tank inductance)



C_{pg} = 2.3 μμf

C_{gf} = 2.0 μμf

C_{pf} = .15 μμf

Calculate the highest frequency at which this tube can possibly oscillate in this circuit.

7. (A) (Cont'd.)

(B) What advantage is obtained by using a half-wave instead of a quarter-wave line in conjunction with two tubes?

8. (A) What effect has transit time upon the losses occurring at the cathode, as for example, in the case of a Class C amplifier?

(B) What effect has transit time upon the plate dissipation?

(C) How does transit time affect the angle of plate current flow?

9. (A) Why can a tube function as a power amplifier at a higher frequency than it can as an oscillator?

(B) Would you consider this a disadvantage for normal purposes? Why?

10. (A) Give three advantages of constructing a tube in the form of two tetrodes for push-pull operation in the same glass envelope.

(B) What type of tube construction with regard to element connections minimizes the reaction of the input and output circuits upon the neutralizing circuit? Can this construction be used for any other purpose instead?