CHAPTER 19

THE RESNATRON

By W. G. Dow and H. W. Welch

19-1. The Resnatron.—The *resnatron* is a high-power tetrode cavity resonator type of tube which, in terms of continuous power output at ultrahigh frequencies, has completely outdistanced any other development. In its present state, the resnatron is capable of delivering up to 60 kw of power at high efficiencies and at frequencies from 340 to 625 Mc. The theory of operation is similar to that of a Class C oscillator. Cavities comprising the oscillating circuits are within the vacuum envelope and are built integral with the electronic elements of the tube. For reasons both mechanical and electrical the tubes are continuously evacuated and demountable.

A schematic development of the resnatron is shown in Fig. 19-1. There are two resonant circuits consisting of coaxial cavities ¾ wavelength or ½ wavelength long. One cavity, called the *cathode cavity*, is formed between cathode and control grid. Another cavity, called the *anode cavity*, concentric with and surrounding the cathode cavity, is formed between screen and anode. The actual electrode structures form parts of the cylindrical walls of the cavities and are located approximately at positions of voltage maximums on standing waves set up in the cavities in oscillation. Transit time is such that electrons accelerated in the cathode cavity give up their energy to the r-f field in the anode cavity. The sharp bunching required by a Class C amplifier or oscillator is not derived from velocity modulation, as in other u-h-f oscillators, but from direct formation of dense bunches of electrons by means of varying potential between the control grid and the cathode. Use of the screen grid or tetrode structure in the resnatron speeds up electrons in transit from cathode to control grid, thus dispensing with some of the transit-time problems experienced with u-h-f triode oscillators. By means of a small capacitive probe between anode and cathode, energy is fed back into the cathode circuit to maintain oscillation. The frequency of oscillation is determined by the electrical length of the cavities which, for tuning purposes, is variable.

Power is coupled inductively from the anode cavity through a tunable coaxial transformer into a copper waveguide transmission system. Plate efficiencies of over 70 per cent may be obtained under the proper conditions. The high Q of the system makes wide-band modulation difficult, but with adjustment of feedback and loading, low-Q operation is possible with a very substantial reduction in efficiency.

A system built around the resnatron requires a 10- to 16-kv 100-kw power supply and a fast vacuum system capable of producing an ultimate vacuum of between 10^{-6} and 10^{-7} mm Hg pressure. Associated control circuits, modulating circuits, power-disposal systems, and maintenance equipment will depend on the use to which the resnatron is put.

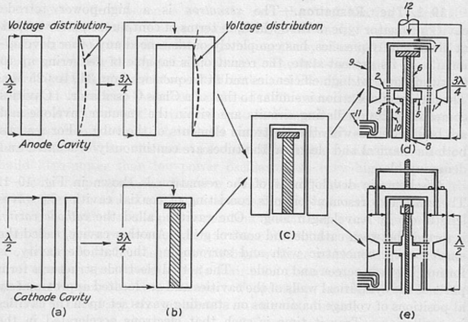


FIG. 19–1.—Schematic development of a resnatron from a pair of coaxial cavities. (1) Anode, (2) capacitive feedback probe, (3) screen grid, (4) control grid, (5) filament wire, (6) bellows for tuning, (7) tuning capacitance, (8) cathode-cavity tuning rod, (9) screen-anode by-pass condenser, (10) grid-cathode by-pass condenser, (11) coupling loop, (12) anode-cavity tuning rod.

Early work on tubes of the resnatron type was carried on in cyclotron laboratories, where the technique of producing large high-pumping-speed high-vacuum systems was developed. For mechanical and economical reasons, demountable tubes were necessary. The subsequent development of the resnatron, leading finally to truck-borne transmitter units, has indicated, under adverse conditions, the practicality of these techniques for producing high-frequency very high-power oscillations.

19–2. Structural Features of the Resnatron.—The schematic drawings in Fig. 19–1 show the essential components of a resnatron from an electrical point of view. Structurally these components are further complicated in form by cooling, mechanical, insulating, and vacuum requirements. A schematic cross section of a complete resnatron is shown in Fig. 19-2. Figure 19-3 is an exploded view of all the components ready for assembly, and Fig. 19-4 is a photograph of an assembled resnatron. This type of resnatron weighs about 250 lb. assembled.

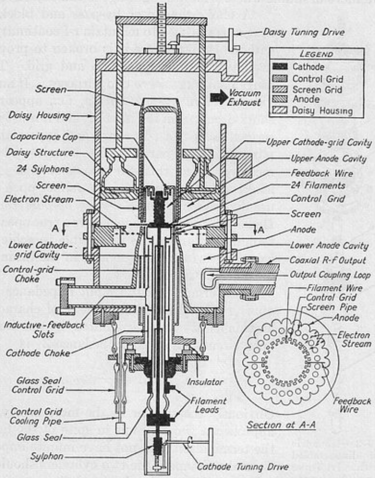


FIG. 19-2.—Vertical cross section of resnatron.

Figures 19-1 to 19-4 are self-explanatory and should be referred to frequently while reading the following sections, in which some of the structural features will be considered in more detail.

19-3. Cathode Cavity.—Cathode cavities of two types are shown in Fig. 19-5. Either type of cavity is electrically equivalent at the resonant frequency to a ¾-wavelength transmission line short-circuited at the lower end and open-circuited at the upper end. Tuning of the cathode cavity is accomplished by moving up and down an internal rod, carried by metal bellows. This mounts at its upper end the cap spaced close to the top of the cathode cavity to provide adjustment of the capacitive loading (see Fig. 19–5*a*).

The tuning capacitance, shown in Fig. 19–5*b*, is more sensitive to vertical motion of the tuning rod than the type shown in Fig. 19–5*a* and therefore more desirable where wide tuning range is the objective.

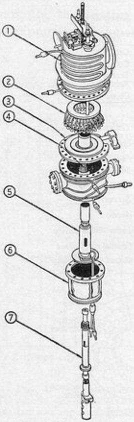


FIG. 19–3.—Isometric sketch of disassembled resnatron. (1) Tuner housing, (2) tuning plunger ("daisy"), (3) anode, (4) screen-grid assembly, (5) control-grid assembly, (6) cathode and grid insulator, (7) cathode assembly.

A choke-condenser by-pass and blocking arrangement is used to maintain r-f continuity of the cathode cavity where it is broken to provide d-c insulation between cathode and grid. This arrangement must serve two purposes. It must provide effective by-pass action, *i.e.*, appear like a short circuit from the interior, and it must prevent serious escape of r-f energy and appreciable coupling to other parts of the circuit. The ideal means of doing this is a coaxial section ¼ wavelength long terminated in a perfect open circuit, usually called a *quarter-wave by-pass condenser*. However, it is difficult to ensure a true open-circuit termination and quite impossible to achieve a ¼ wavelength for all frequencies in the tuning range of the resnatrons.

The formula for the input impedance Z_i to a quarter-wave by-pass condenser of characteristic impedance Z_0 and terminated by an imperfect open circuit having an impedance Z_L is

$$Z_i = \frac{Z_0^2}{Z_L} \tag{19–1}$$

Obviously the smaller Z_0 the more nearly Z_i will approach a short circuit in spite of the fact that the termination does not have infinite impedance. To make Z_0 small, the two cylinders should be as close together as the d-c insulation requirements will permit. This is in accordance with the common-sense judgment that a good by-pass or blocking condenser is one with its plates as close together as possible consistent with successful blocking of the d-c voltage. However, this expedient is inadequate if the by-pass comes to be substantially more or less than ¼ wavelength long. It was therefore found necessary for complete coverage of the tuning range to lengthen the by-pass condenser in the shift from high- to low-frequency operation. This at the same time has the possibly more important effect of making the interior of the cavity longer. The cavity

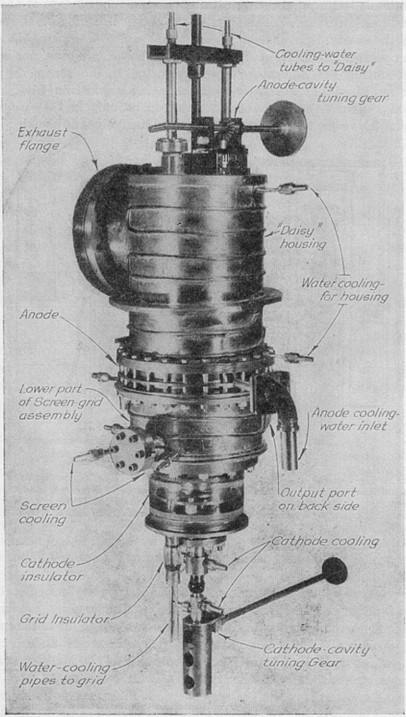
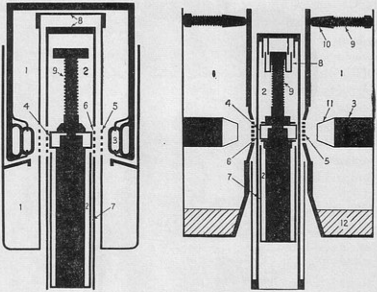


FIG. 19-4.—Assembled resnatron.

is also made longer at the upper end by raising the top caps of the grid and cathode structures which form the capacitive loading on the upper end of the cavity.

In operation, separate sets of grids and cathodes are used, one set for high frequency and one set for low frequency. In the case of the grids this is not absolutely necessary, since changing a grid from high to low frequency involves only a minor setscrew operation. In the case of the cathodes, however, the change is difficult, as it involves two solder joints one of which withholds cooling water at a pressure of 150 lb per sq in from the vacuum.



(a) (b)

FIG. 19-5.—Vertical cross sections showing essential features of two types of anode and cathode cavities. (1) Anode cavity, (2) cathode cavity, (3) anode, (4) filament wires, (5) screen grid, (6) control grid, (7) quarter-wave by-pass condenser, (8) tuning capacitance, (9) expanding bellows, (10) tuning plunger, (11) anode vane, (12) copper slug to shorten cavity.

19-4. Anode Cavity.—Anode cavities of the type shown in Fig. 19-5*a* are built on much the same principles as the cathode cavities. With this type of anode, tuning is accomplished by pressure on the top of the cavity, which distorts the metal plate enough to vary the capacitance between the top of the anode housing and the screen cap. At 500 Mc the variation in frequency possible with this tuning scheme is about 30 Mc. The inner wall and the lower half of the cavity are at the d-c potential of the screen. The upper half of the outer wall and the top of the cavity are at anode potential. A by-pass condenser for the r-f current between screen and anode structure is provided by extending the outer wall of the screen structure over the outer wall of the anode structure for ¼ wavelength. This presents a low impedance to the r-f current inside the cavity at the gap between screen and anode structures. This cavity, like the cathode cavities, may be thought of electrically as ¾ wavelength long with a short circuit at the lower end and capacitance loading at the upper end. The voltage distribution in this cavity is shown in Fig. 19–1*b*.

Figure 19–5*b* shows a form of the anode cavity that greatly extends the tuning range and, at the same time, reduces the Q of the cavity by eliminating energy storage in the tuning capacitance. The latter is desirable where wide modulation band width is the objective. The voltage distribution in this type of cavity is shown in Fig. 19–1*a*.

In this cavity the screen and anode are at the same d-c potential. The outer wall of the cavity is made continuous, and a sliding short-circuiting plunger having about 30-cm possible travel replaces the tuning condenser between screen wall and anode wall. The short circuit consists of a ring of sylphon bellows expanding radially between inner and outer walls of the anode cavity formed by screen structure and housing. This bellows ring is called the *daisy*, simply because it has the appearance of a daisy with the individual bellows as petals. The bellows carry considerable r-f current and are water-cooled. The water cooling (under 30 or 40 lb per sq in. pressure) also serves to expand the bellows, thus making good current contact with the walls. The daisy can be moved in the vacuum by means of rods passing through Wilson vacuum seals.

The daisy tuning plunger could easily accommodate the change in cavity length necessary to give the range of frequency desired (350 to 600 Mc). However, this change, about 2 to 1, would cause the electron stream to be badly displaced from the longitudinal center of the cavity in the low-frequency position. Such a design might introduce a tendency for higher harmonic moding (see Sec. 18–5). A better solution is to divide the range into two portions and, for the high-frequency portion, insert at the bottom end of the cavity a copper slug which effectively shortens the length of the lower half of the cavity. This slug is shown in place in Fig. 19–5*b*.

As indicated best in Fig. 19–2, the inner wall and lower portion of the anode cavity are formed by the screen structure, the upper part of the outer wall by the daisy housing, and the top by the daisy. The anode itself is mounted on the outer flange of the screen structure and supports the daisy housing. Both rubber and tin gaskets are provided at the joints at the top and bottom of the anode, for holding the vacuum and maintaining a current path. Extreme care must be taken in the approximately 100 soldered joints in the daisy assembly to avoid vacuum leaks. These leaks are especially troublesome because they are difficult to locate.

Vacuum leaks in other elements are not unusual but are in general easily located and repaired.

19-5. Electrode-structure Design. *General Considerations.*—The resnatron tubes are beam tetrodes employing fairly sharply focused electron beams, the beam section being a thin rectangle, as nearly as possible of the same size as the face of each filament, *i.e.*, 0.85 in. long by 0.050 in. wide. One primary reason for designing the electrodes to give sharp focusing is to minimize the screen current, because otherwise, at the high screen voltages used, screen dissipation would be excessive. At the high voltage levels used in the resnatron, secondary emission, usually a contributing factor to screen current in tetrodes, is not important. Another objective important in electrode design is to achieve the necessary focusing and plate-current values without drawing excessive grid current. Figure 19-6 is a sectional diagram of the electrode structure as used in the resnatron with the anode design that seemed to be the most satisfactory of those tried.

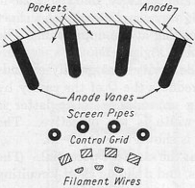


FIG. 19-6.—Horizontal quartered cross section of electrode structure.

Since the resnatron design is based on the use of continuous evacuation techniques it is not only inconvenient but quite impractical to use a type of cathode requiring processing in a vacuum; in accordance with cyclotron demountable-tube practice, tungsten filaments are used as cathode surfaces. The 24 tungsten strips of the cathode "cage" are each 0.050 by 0.015 in. in section, the 0.050 in. face being the useful emitting surface. The useful length is ¾ in. The normal filament excitation is 1800 amp at 2.5 volts for a cathode with all filament strips intact. If one or two or more are broken but not short-circuited, the tube will still function, but at a reduced power level. Figure 19-7 shows a half-section cathode assembly. The cages can be removed and replaced by a simple soldering operation.

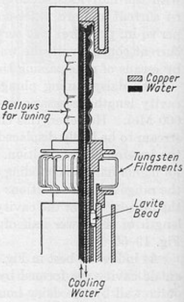


FIG. 19-7.—Section of cathode showing cooling-water channel.

Certain structural and cooling requirements affect electrode design.

The shape into which each of the 24 individual tungsten filament strips is bent provides an offset from the inner wall of the cathode cavity, so that this cavity can have appreciable radial depth, yet brings the emitting surfaces immediately out to a circle just inside the inner grid circle. It also permits the filament to expand lengthwise when heated, without serious sag or other displacement of its normal position relative to the grid.

The heating due to cathode-cavity circulating current on the interior surface of the grid cylinder, and that due to normal electron flow to the grid, is sufficient to make necessary special provisions for cooling the grid cylinder. The important path of heat flow away from the top half of the grid unit is via the grid cylinder to the built-in water channel shown in Fig. 19-8. In this figure the lower part of the grid is cut in section to show the water channel more clearly. It is desirable to keep the radius of the grid cylinder, especially where pierced by slits for electron transit, not too small to permit adequate heat transfer just below the slits.

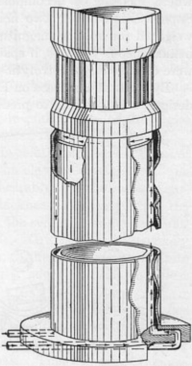


FIG. 19-8.—Section of control grid showing cooling-water channel.

The screen "wires" are hollow copper tubes, to permit the circulation of cooling water through them. These tubes extend inside the screen wall to the top of the structure, thus carrying away circulating-current losses as well as electron-current losses.

Attainment of Focusing Action.—Figure 19-9 gives the best pictured evidence of the actual sharpness of focusing of the beams. This is a photograph of a copper strip that was bent into the form of a circle, then inserted just inside the anode, forming in this way a temporary anode surface. A tube was operated for some time with this strip in position; the black markings are the results of electron-beam bombardment and indicate a very satisfactory sharpness of focus.

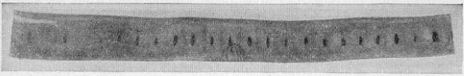


FIG. 19-9.—Photograph of copper anode strip showing effect of beam focusing.

Sharpness of focus is obtained by attention to the details of the shapes of grid and screen sections relative to the flat strips of cathode surface, in order to obtain the proper electric-field configuration. Figure 19–10 shows shapes taken by equipotential surfaces in the region of the field where focusing is accomplished for the electrode voltages specified. Superposition of the two field patterns, Figs. 19–10*a* and *b*, properly weighted for voltage magnitudes gives the field for a particular pair of instantaneous voltages, if space charge is ignored. These equipotentials were obtained by electrolytic-tank measurements on scaled sections.

By calculations based on Figs. 19–10*a* and *b* or similar figures for other designs, it is possible to predict the electrostatic grid-to-screen μ-factor

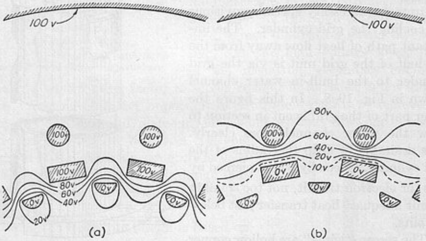


FIG. 19–10.—Equipotential maps around resnatron electrodes.

that gives the relative effectiveness of grid over screen in establishing an accelerating field at the cathode surface.

It is to be expected that focusing at ultrahigh frequencies will be somewhat different from that with d-c voltages because the fields will change during the flight of an electron. Probably the most important focusing action in resnatrons takes place while the electrons are still in the converging field in the grid-cathode pocket, because at that time electron velocities are low enough to give transverse fields time to act. In this region the r-f fields are strong, so that the focusing action during oscillation will almost certainly differ in detail from that with only d-c voltages applied. Focusing may be improved by the presence of the r-f field, or it may be made worse. The only significant experimental evidence is that the focusing into a thin flat beam is very satisfactory under conditions of normal use.

The details of the final electrode design are actually the result of a rather long trial-and-error process in which screen current and grid current were important criteria of success. In the resnatrons with anode and screen at separate potentials, operation was considered satisfactory and normal with a screen current of around 300 to 500 ma when the plate current was between 4 and 5 amp. In tubes with no separation of the d-c potentials, it was impractical to measure screen current separately, but it was possible to judge from the rise of water temperature in the screen-cooling circuit that screen dissipation was not excessive.

Grid-screen μ-factor.—Aside from focusing the electrons into a beam, it is necessary in determining the proper electrode design to ensure that the screen makes the proper contribution to the electron-accelerating field at the cathode surface. This contribution depends primarily on two factors: the size and aspect ratio of the cathode-grid pocket and the angles involved and the radial positioning of the screen tubes.

If the cathode surface is made too wide in relation to the thickness of the grid wires, the effectiveness of the grid on electron emergence at the center of the filament surface is reduced undesirably. If the cathode surface is made too narrow in relation to the thickness of the grid wires, the grid-screen μ-factor becomes too large, and the screen does not aid sufficiently in electron acceleration at the cathode. Grid current is then likely to become excessive. Chamfer of the corners of the grid wires is a definite aid in keeping grid current low. Square outer edges will tend to collect an undesirably large number of electrons.

For any given screen potential the radial placement of the screen tubes is of some importance. If they are too far out, the cathode-surface electron-accelerating field of screen origin and the converging focusing field in the grid-cathode pocket are too weak. This will tend to cause excessive grid current for a given cathode current. By moving the screen tubes closer to the grid, the grid-to-screen μ-factor is decreased. This should permit drawing any given cathode current with a less extreme upswing of the grid and, therefore, less grid current. Since a larger negative swing is required for cutoff, the total grid drive is not seriously affected. The grid bias must be correspondingly increased to retain cutoff where it belongs in the cycle in order to keep the angle of plate-current flow small.

There are at least two limits to any desirable effects that may be achieved by moving the screen in. One is the ultimate requirement, in the face of a falling grid current, of an excessively large grid bias in relation to the size of the self-bias resistor. Another is that as screen tubes are moved in they begin to be electrostatically hidden behind the control-grid sections, and the effect of the screen on the cathode gradient therefore ceases to increase with reduction of screen radius.

19-6. Anodes.—Anode structures are illustrated in Fig. 19-11. In the anodes shown in Figs. 19-11*a* and *b*, the actual anode surface is formed by pipes carrying the cooling water. In models shown in Figs. 19–11*c* and *d*, a single water channel behind the anode surfaces serves to carry away losses. The final design as shown in Fig. 19–11*d* was a compromise of several objectives. This anode is very simple to construct, being cast and machined.

The flow of water and the thickness of the copper wall between the electron beam and the water is such as to permit sufficiently rapid removal of heat. The final design, with 20 gal per min of cooling water at 180 lb pressure, has dissipated as much as 100 kw in static tests. The type shown in Fig. 19–11*b* proved incapable of handling large amounts of power.

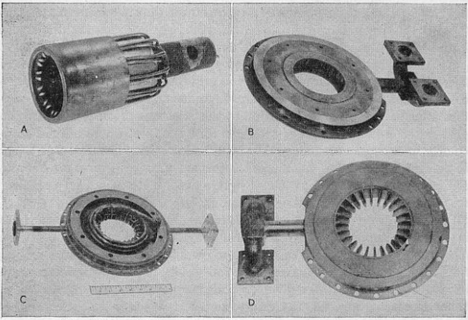


FIG. 19–11.—Photographs of different types of anode structures.

The "pockets" in Fig. 19–11*d* have two side walls and a back wall but no top or bottom walls. These pockets were to act as a trap for secondary electrons by making most of the secondaries strike walls of the pockets rather than reach the screen. This feature became less important at the high voltages used, as shown by comparison of the tetrode characteristics for low screen voltages, 100 to 500 volts in Figs. 19–13*b*. The sharp rise in plate current that occurs just as the plate voltage passes from below screen potential to above screen potential is a good approximate measure of the number of secondaries emitted by the anode when it is at screen potential, due to primaries whose energies correspond to screen potential. The ratio of secondaries to primaries in the tetrode characteristics in Fig.

19-13 is a maximum when the primary electron energy is near 400 ev and falls off to a barely discernible effect at 10,000 ev.

A study of the equipotentials for this electrode configuration indicates that along the path of the beam nearly all the potential difference between screen and anode is traversed by an electron between its crossing of the screen circle and its crossing of a circle just inside the ends of the anode fins. This is the circle *AA* in Fig. 19-12. It is only while the electron is in a strong gradient that interaction takes place, therefore the interaction distance is approximately that between the screen circle and some circle *AA*, rather than between the screen circle and the face of the anode that stops the electrons. This space should be as short as possible to shorten transit time.

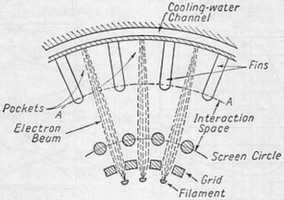


FIG. 19-12.—Cross section of electrode structure showing beam of electrons and interaction space.

The capacitance between screen and anode, which is one of the important factors in determining Q, depends upon the nearness of the ends of the fins to the screen wires; also, it is affected by the electrostatic field configuration near the ends of the fins in much the same way that the interaction distance is affected. Where low Q is desired, the objective of design should be to make this capacitance as small as possible, which suggests shortening the fins, and to make the interaction distance as short as possible, which suggests lengthening the fins. Obviously a compromise has to be made.

19-7. Static Characteristics.—Some of the static characteristics of the resnatron are shown in Fig. 19-13. It is difficult to take complete plate characteristics except at very moderate grid voltages, because of the danger of excessive screen dissipation at very low plate voltages. Also special provision is necessary to insulate the screen from the anode in obtaining tetrode characteristics for the resnatron with the half-wave cavity.

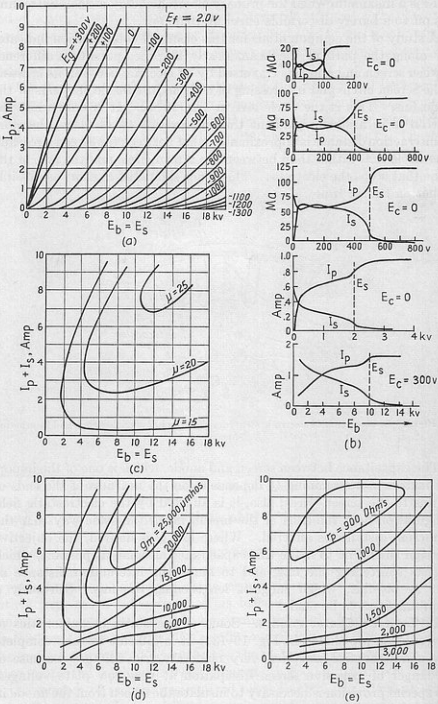


FIG. 19–13.—Some static characteristics of the resnatron.

One of the significant figures obtained from these static curves is the grid-to-screen μ-factor. This lies between 15 and 25, depending on the details of screen placement and grid design mentioned. Also of interest are the values of transconductance. These lie between 6000 and 25,000 μmhos, depending on the values of screen and grid voltages used, as well as on the details of screen placement and grid design.

19-8. Equivalent Circuit.—The structural features of resnatron construction have been described in the preceding sections. Two resonant coaxial cavities, one within the other, are built integral with the electrode structure of a beam tetrode. These have been described as equivalent to ½- and ¾-wavelength cavities at the resonant frequency of operation.

The analysis of resnatron behavior can be simplified to lumped-constant circuit analysis by use of the equivalent circuit shown in Fig. 19-14. A more exact equivalent can be given by showing the various by-pass capacitors and the tuning capacitors. For simplicity, however, we shall assume that by-pass action is effective and that tuning can be accomplished in both resonant circuits by one means or another. Thus we may represent these capacitive elements as short circuits or as lumped with the existing capacitance. The circuit shown is usually known as the *grid-separation* or *grounded-grid circuit.* If the feedback capacitance is omitted, use as a tuned u-h-f amplifier is possible.

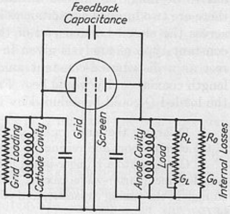


FIG. 19-14.—Equivalent circuit of resnatron for ultrahigh frequency.

The output loading is indicated in Fig. 19-14 as being adjustable. The mechanism of adjustment is contained in the output coaxial line-to-waveguide transformer. Internal copper-loss-loading conductance is indicated separately in the diagram, but may be thought of as lumped in with the output-loading conductance. The grid loading actually includes power losses of the following four distinct kinds:

1. Circuit losses in the cathode cavity
2. Power dissipated in the grid self-bias resistor
3. Grid dissipation due to electrons striking the grid
4. Cathode dissipation due to cathode back-heating, *i.e.*, electrons returning to the cathode after receiving energy from the r-f field during their time of flight

The feedback capacitance consists of a probe extending from the cathode through the grids into the anode cavity. For the present it will be assumed that feedback is in the proper phase and magnitude to maintain oscillations. A more detailed analysis of the feedback requirements will be given in Sec. 19-13.

19-9. Q of the Anode Cavity.—A simple analysis was given in Chap. 18 to show the nature of the relation among circuit constants, shunt impedance, and Q of the anode tank circuit for normal operation of a circuit of the type shown in Fig. 19-14.

Although the anode cavity shown in Fig. 19-5*a* is in a sense a distributed-constant circuit, a study of the figure suggests that in fact it is more nearly a lumped-constant circuit. The anode and the r-f shielding ring just below it intrude into the cavity sufficiently far to be the controlling factors in the cavity capacitance; the tuning capacitance at the top has to be fairly prominent in order to provide adequate tuning; thus, there are two lumped capacitances in series, while the circuit is completed across the closed bottom end of the anode cavity. Thus, the lumped-constant type of analysis given in Chap. 18 is probably as nearly correct as a distributed-constant analysis based upon a uniform ¾-wavelength coaxial cavity would be. From either analysis, it is apparent that the loaded Q could be reduced by taking the following steps:

1. Enlarging the outer radius of the anode cavity, thus increasing the size of the current loop, and raising the value of L.
2. Changing to a plunger-tuned half-wave cavity instead of the capacitance-tuned three-quarter-wave cavity, thereby eliminating the capacitive energy storage in the tuning capacitor, and correspondingly lowering the effective value of C.
3. Reducing to an absolute minimum the capacitance from anode to screen in the neighborhood of the anode. This would be aided by eliminating the shield ring beneath the anode and by refinements in anode-design details.

All these changes are incorporated in the cavities shown in Fig. 19-5*b*. The enlargement of the outer radius is carried as far as is practical without giving the tube excessive weight and bulk. The daisy, as described in Sec. 19-4, is used to furnish plunger-type tuning. The anodes are designed with screen-anode capacitance in mind as well as other considerations.

19-10. Shunt-impedance Requirements.—In the discussion of shunt impedance in Chap. 18 the first three of the following considerations were mentioned:

1. From the standpoint of efficient operation the shunt impedance should not be below the optimum value, but can be moderately above it without marked ill effects.
2. The optimum shunt impedance is roughly proportional to the d-c plate supply voltage.

3. For a given angle of operation, the optimum shunt impedance is roughly inversely proportional to the d-c plate current.

4. In wide-band operation, the loaded Q, and therefore the shunt impedance, should not exceed a given value.

Thus 1 and 4 in combination indicate that the proper shunt impedance to use, where low-Q wide-band operation is wanted, is just the optimum value, no more, no less, while 2 and 3 in combination indicate that, in order to obtain the low shunt impedance needed for low-Q operation, tubes should be used that operate satisfactorily at as low d-c plate voltage and as high d-c plate current as possible. These considerations dictated the changes from the type of anode cavity shown in Fig. 19–5*a* to the type shown in Fig. 19–5*b*. The Q is lowered by decreasing C and increasing L. It is also possible by modifications in output coupling to reduce markedly the tank-circuit shunt impedance which in turn allows operation at lower plate voltages and higher plate currents. For high shunt impedance (high Q), operation with 16,000 volts on the plate at 2.5 to 3 amp is typical. By reducing load impedance (low-Q operation) these values are changed to 10,000 volts at 4 or 5 amp.

It is possible to provide feedback coupling adequate to ensure even with moderate r-f plate voltages the large grid drive necessary to draw the large currents required for low-Q operation.

19–11. Parasitic Oscillations.—Almost any oscillator while under development will have unwanted modes of oscillation, and the resnatron is no exception. Several types of parasitic resonances have been observed. One was an accidental 1000-Mc resonance in the cavity between control grid and screen grid. This was eliminated by adding capacitance between the top of the control grid and the top of the screen grid. Another resonance at almost the same frequency was attributed to a circumferential mode excited by asymmetrical placing of the feedback wires. A third resonance, obtained only in the type of cavity shown in Fig. 19–5*a*, is attributable to the $\lambda/4$ mode, possible because of the open circuit at the top of the cavity. This mode is especially likely to occur when the desired $3\lambda/4$ mode is being heavily loaded for low-Q operation. In this case the $\lambda/4$ mode, which is normally not heavily loaded, probably has a higher Q than the desired mode. The tendency of the oscillating system would be of course to oscillate in the high-Q rather than the low-Q mode. This parasite may be eliminated by a small series-resonant circuit coupled into the cavity, which detunes the undesired mode until feedback conditions necessary to excite the mode are no longer satisfied.

19–12. Transit-time Effects.—The effect of transit time on the operation of triodes and tetrodes at ultrahigh frequencies has been discussed in Chap. 18. The transit angle for the time of flight of electrons from the cathode to the grid is a large fraction of the total transit angle in the resnatron, because when the electrons first leave the cathode they are moving very slowly. The electron stream does not constitute plate current until it passes the screen, so the grid-to-screen transit angle adds to this effect. Also, plate current exists as long as any electron remains in transit to the anode, so that perhaps half of the screen-to-anode transit angle also contributes to the total transit-angle delay between grid voltage and fundamental frequency component of plate current. This angle must be added to the 180-deg phase difference between grid voltage and plate voltage necessary for optimum performance in ordinary low-frequency oscillators of this type. The effect of transit angle on feedback is discussed in Sec. 18–4.

No accurate measurements of transit-time phase delay were made in the resnatron, but rough calculations indicate that phase delays between 30 and 120 deg should be expected, depending on details of handling, voltages, spacings, etc.

In triodes a considerable difference in velocities of the individual electrons entering the grid-anode space results from the fact that all electrons do not leave the cathode at the same time during a cycle of oscillation. The introduction of a screen between the grid and the anode in the resnatron causes *all* the electrons that traverse the grid to be rapidly accelerated to such an extent that the differences between the grid-traverse velocities become quite unimportant as far as any effect on the time it takes the electrons to reach the plate is concerned. Thus the introduction of the screen suppresses the debunching action incidental to cathode-to-grid transit, and so tends to permit maintaining a good operating angle, if other conditions are right.

The introduction of the screen grid also reduces the time of flight of the electron through the interaction region between grid and anode in which the electron by its movement converts d-c power into a-c power. By reducing this *interaction time* a large operating angle, which results in poor efficiencies, is avoided. (Plate current associated with any electrons starts flowing when the electron passes the screen and continues to flow until the electron reaches the anode.)

Cathode back-heating caused by the return to the cathode of electrons which left late in the cycle is fairly marked in the resnatron. It shows up as an increase in filament resistance so that as power output is raised filament current falls off. It is necessary to reduce the filament heating power by between 15 and 40 per cent during operation, if it is desired to keep the filaments at their normal rated temperature and therefore resistance. Cathode life is shortened if this is not done. The resnatron cathode is tungsten and is designed for large heating power. In thoriated or oxide-coated filaments requiring small heating power, back-heating can cause immediate destruction of the filament.

19-13. Feedback Circuit.—A qualitative analysis of feedback conditions in the resnatron is all that can be given because of the many unknown factors in resnatron operation.

Two feedback schemes were used with the resnatron. These are shown in the equivalent circuit in Fig. 19-15. Points *P*, *G*, and *C* refer, respectively, to the plate, grid, and cathode. It will be noted that the heavy line portion of this circuit is essentially the same as Fig. 19-14 except for the substitution of the equivalent current generator y_mE_g and the plate admittance of the tube y_p for the electrode structure shown in Fig. 19-14.

The dotted lines indicate the first type of feedback used on the resnatron, known as *external feedback* because the feedback power is actually coupled out of the anode circuit, carried through a coaxial line containing tuning stubs and back into the cathode cavity. This method is theoretically desirable because the section of transmission line makes possible variation of phase of feedback as well as magnitude. However, the additional vacuum joints, glass output seals, tuning plungers, etc., are the source of serious practical difficulties, which led to the use of an *internal feedback* system consisting of molybdenum wires fastened to the cathode and extending through the grids to the anode. These wires form a capacitance between the anode cavity and the cathode cavity. This capacitance is shown as C_f on the diagram. This type of feedback has the disadvantage of being adjustable neither in magnitude nor in phase. It does have the advantage of simplicity in construction and can be made to work by proper tuning of the anode and cathode cavities.

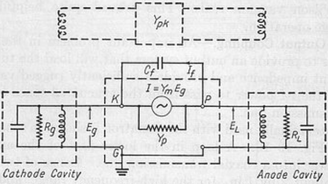


Fig. 19-15.—Equivalent circuit of resnatron for analysis of feedback conditions.

The circuits shown in Fig. 19-15 are variants of the general equivalent network of a grounded-grid oscillator discussed in Secs. 18-8 to 18-10 and shown in Fig. 18–4. It is unnecessary to repeat the discussion of the conditions for oscillation and the phase relations obtained during steady-state oscillation since presentation in Chap. 18 and the vector diagram of Fig. 18–9*b* apply directly to the resnatron oscillator.

It should be pointed out that the Q's of the cavities are important since in a resonant circuit the rate of change of reactance with frequency at resonance is proportional to the Q of the circuit. This indicates that if the cathode cavity is a lower Q circuit than the anode cavity it will have less effect on the resonant frequency. The smaller effect, which would be the normal expectation, is actually observed in operation.

On the other hand, as has been shown above, the tuning of the cathode cavity will determine the phase of the feedback voltage and thus the efficiency. This also was observed in operation.

Some recent tests have been made with an adjustable feedback capacitance mounted on the anode instead of the cathode and controlled through Wilson vacuum seals. This proved quite helpful for wide-tuning-range operation.

19–14. Output Coupling.—An important problem in the use of the resnatron is to provide an output system that will load the tube with the proper shunt impedance and provide a sufficiently rugged vacuum-tight avenue for the r-f power to pass from the evacuated space to an atmospheric transmission line.

The system finally used with the resnatron is shown in schematic cross section in Fig. 19–16. A loop in the lower part of the anode cavity couples power into a coaxial transmission line. Loops of two sizes were used, one about 2 by 1 in., for the high-frequency range, and one about 2 in. square for the low-frequency range.

The coaxial line-to-guide transformation is accomplished by passing the coaxial line completely through the short (6-in.) dimension of the guide. Inside the guide the outer conductor is replaced by a glass cylinder that forms the vacuum seal through which power is radiated by the inner conductor. The inner conductor thus acts as an antenna across the narrow dimension of the guide. The entire interior of the line is evacuated through the opening into the anode cavity.

The reactance of the loop is compensated for, and optimum phasing of currents in the inner conductor serving as an antenna is obtained, by means of a tuning plunger in the section of the coaxial line extending through the guide. The length L is made more than ½ wavelength for any frequency of operation so that any phasing desired can be obtained. This plunger is operated through Wilson vacuum seals.

The coaxial output line is passed through holes in the guide that are near one side of the guide, as shown in Fig. 19–16*b*. Because the impedance of the guide increases from the edge to the center, by choice of a correct position for these holes a fairly satisfactory broad-band match can be obtained.

In early work with the resnatron this general type of transformation was used but with a movable plunger in the stub end of the waveguide below the passage of the coaxial line. It was found, however, that this tuner and the coaxial-line tuner were so close together that their actions were not independent, and the two adjustments gave little greater flexibility than the coaxial-line tuner alone. The waveguide stub was therefore closed off with a copper plate about ¼ guide wavelength from the coaxial-line passage.

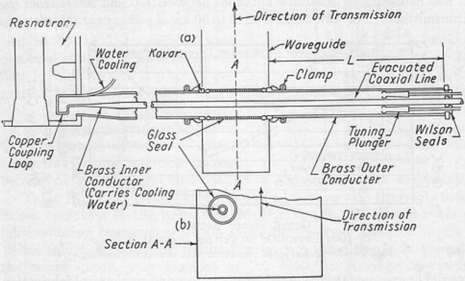


FIG. 19-16.—Schematic drawing of output coupling system.

The loops and the inner conductor are made of tubing to permit passage of cooling water. The loops are of copper, but the coaxial line is of brass to improve the functioning of the sliding contacts of the tuning plunger. A Kovar-to-glass seal is used in the glass cylinder. The section containing the glass is soft soldered in place and can easily be replaced in case of breakage.

In Fig. 19-15 the load impedance R_L is shown as a pure resistance. Actually, of course, it will have a reactive component and will therefore affect the frequency of oscillation. At every operating frequency there is some position of the output tuner that makes the output circuit resonant. At this position the shunt impedance is low and, depending on the mutual inductance of the coupling loop, may be lower than optimum for the given operating conditions. If this is the case, optimum loading occurs when the tuner is slightly detuned from this resonant position. Since it can be detuned in two directions, there are two settings for optimum load impedance, but they differ in that the reactances coupled into the load are of opposite signs and therefore result in operating frequencies that may differ as much as 10 Mc. This means that, when the tube is oscillating with feedback prongs providing grid excitation adequate to maintain oscillation over the entire range of output tuner adjustment, the grid excitation for maximum drive, the plate-circuit efficiency, and the frequency will vary through a characteristic cycle as the tuner is adjusted. This effect is shown in the data presented in Fig. 19–17.

19–15. Transmission Line.—In the use of the resnatron transmitters it was necessary to locate the antennas between 100 and 200 ft from the transmitters. For transmission of 15 to 30 kw of power over this distance coaxial line seemed impractical because of loss and mechanical fabrication difficulties. This led to the choice of waveguide.

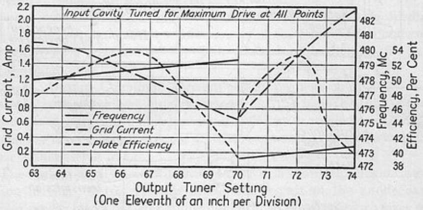


FIG. 19–17.—Behavior of resnatron with changes in loading.

In order to handle the power adequately at both extremes of the tuning range two sizes of guide were used, one for high-frequency tubes and one for low-frequency tubes. For high-frequency operation the guide used was 6 by 15 in.; for low frequency the guide was 6 by 22 in.

It was found by experiment that simple bolted flange connections with copper facings bent back from the main length served as entirely satisfactory joints between sections of guide. These were used throughout and ensured greater freedom from frequency sensitivity than could have been obtained with other radically different types of joints.

19–16. Power Disposal.—Two distinct types of load-disposal devices were needed in experimental work with the resnatron: one to serve either as a wattmeter or as a calorimeter to calibrate various types of wattmeter; the other to serve as a simple means of power disposal without much reference to power measurement. It was necessary for the first type to have quick response and get into thermal equilibrium in a minute or two for any given condition, which required using a small amount of water and passing it through very rapidly. However, it was permissible for this device to be frequency sensitive, as tuning devices were available for matching it to the line at various frequencies. The second type of device needed to offer a flat termination for all frequencies, but quickness of response or measuring provisions were unimportant. Both types have been devised and are described in Chap. 24.

19-17. Operating Data.—With c-w operation, operating plate-circuit efficiencies from 40 to 60 per cent at 50- to 75-kw output were observed with the tubes that had the best type of anode. Up to 70 per cent at 30-kw output was obtained with tubes of an earlier design having narrower tuning range and higher Q. The actual efficiency of interaction was greater than these figures, because cathode and grid losses had to be supplied from the tank circuit.

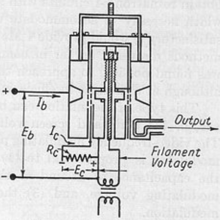


FIG. 19-18.—Direct voltages and currents in resnatron circuit.

Table 19-1 gives typical values of electode voltages and currents used in c-w operation of the resnatrons (see Fig. 19-18). The data are for a low-frequency resnatron with an anode of the type pictured in Fig. 19-5*b*, equipped with three feedback wires each extending ½ in. beyond the screen pipes, with filament at 2.0 volts, an average operating vacuum of less than 10^{-6} mm Hg, and a 2- by 2-in. output loop. Grid excitation was tuned for maximum plate efficiency, and in a direction to make the input cavity look capacitive to the feedback voltage.

TABLE 19-1

λ, cm	E_b, kw	I_b, amp	kw_{in}	kw_{out}	Plate efficiency, %	E_c, volts	I_c, amp	R_c, ohms
75.0	13.0	6.2	80.6	50	62.0	1300	1.20	1084
75.0	15.5	7.2	111.0	70	63.1	1900	1.15	1650
75.0	16.7	7.2	120.0	75	62.5	2000	1.00	2000
75.0	16.4	7.9	129.4	80	61.8	1600	1.40	1140
75.0	17.0	8.1	137.5	85	61.8	1500	1.40	1070

19-18. Modulation.—In order to meet the requirements for use it was desirable to be able to modulate the resnatrons with modulating frequencies from about 50 kc to about 2.5 Mc. Because of this broad frequency range, video amplifiers were necessary in the modulation circuits, and for that reason the modulation frequencies, power levels, etc., will be spoken of here as the video frequencies, video power levels, etc.

At the 2.5-Mc end of the video-frequency range, the chief problem is to obtain resnatron r-f circuits with a Q low enough to give the 5-Mc band width necessay to accommodate the 2.5-Mc side bands. A reasonably satisfactory Q would provide 4 Mc between half-power points. By using methods discussed earlier in connection with loading and feedback, it was found possible to approach this band width under some conditions, although at a sacrifice in efficiency.

This type of modulation can be produced by swinging the grid voltage, or the plate and screen voltages simultaneously, at a video rate. The video-frequency modulating power required of the output stage of the modulator is proportional to (1) the upper video-frequency limit, (2) the capacitance to ground of the resnatron electrode driven by the modulating voltage, and (3) the square of the voltage required for modulation.

The reason for this is of course that the effective video-frequency conductance to ground of the driven electrode must be made high enough to give, in connection with the capacitance burden, a video-output-stage time constant (RC) small in inverse proportion to the upper video-frequency limit. A noninductive shunting resistor must be added externally to get this conductance, if the internal video-frequency conductance to the driven electrode is not sufficiently high. Such a shunting resistor was used in the resnatron transmitter circuit. The video power required in the output stage for any given total value of output-stage conductance is of course proportional to that conductance and to the square of the video voltage that is required to accomplish modulation.

The capacitance from the grid or from the plate and screen to the cathode amounts to a few hundred micromicrofarads. The modulation voltage necessary to drive the anode-screen combination must have a peak value approaching the anode d-c voltage, *i.e.*, between 8000 and 10,000 volts. It is possible, however, to get reasonably effective grid modulation with a video voltage having a peak value amounting to between 2000 and 3000 volts.

Calculations indicated that it would require about 5 kw of video-frequency power to provide grid modulation and at least 15 kw to provide plate-and-screen modulation. Grid modulation was therefore employed as requiring less equipment and less power. Even to get 5 kw of video power required putting about 15 kw of d-c power into the plate circuit of the modulator tubes.

The last stages of the modulating circuit used in the completed transmitters employed the circuits shown in Fig. 19-19. The final stage used Federal Telephone and Radio type-125A water-cooled tubes, operating not quite Class A. Since the grids of the 125A tubes offer purely capacitive loads to the driver stages, it is possible, with the circuit shown, to drive either one or two 125A tubes from the same driver stage. Thus one 125A tube was provided to modulate each resnatron, but one modulator driver stage could drive two 125A's.

It is not usually possible to obtain satisfactory grid modulation of an oscillator, for reasons having to do with the biasing circuit. In order to be self-starting, an oscillator must employ self-bias rather than fixed bias, and any simple self-biasing circuit tends to suppress changes in grid-bias

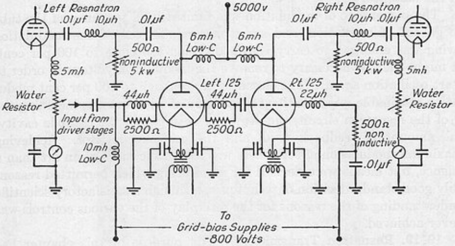


FIG. 19-19.—Resnatron modulator, last stage.

voltage from such causes as change in biasing resistor or introduction of a d-c voltage in addition to the bias. Thus to permit grid modulation at all, the biasing circuit must be given a time constant long compared with modulation-frequency periods. On the other hand, satisfactory oscillator stability, as, for example, when plate modulation is used, is best if the grid-bias-circuit time constant is short compared with modulation periods. Also, it is difficult to approach 100 per cent grid modulation closely except by using relatively little or even no grid bias. These problems are familiar in the radio art and involve no new principles. It was, however, found possible to achieve a combination of circuit constants that gave about 80-per cent grid modulation with satisfactory stability for the video band width used. Linearity was not good, but that was not important.

Under certain conditions of operation the resnatrons exhibited an inverted type of grid modulation, in which oscillation died out at the maximum *positive* swing of the grid modulation voltage and was a maximum at the *negative* swing. This was observed at various high and low modulation frequencies, and was studied briefly but with some care at a 400-cycle modulation frequency, using oscilloscopes to verify polarities, rise and decline of oscillation, etc. At times both normal and inverted modulation response were observed simultaneously, showing fading out of oscillation at both peaks and valleys of the modulation-voltage cycle. The study of the modulation of the final transmitter was not carried out in sufficient detail to enable any assured determination as to which of the two types of modulation predominated. Usable modulation was obtained, which was, for wartime purposes, the important consideration. Reasonably stable behavior of either type of modulation was obtainable in the laboratory.

The percentage of modulation was limited by a tendency of the tube to go out of oscillation, and sometimes remain out, if the modulation swing was enlarged to carry the modulation too close to 100 per cent. It might then be necessary to remove the modulation voltage in order to start oscillation again. The closeness of approach to 100 per cent modulation attainable was sensitive to a variety of adjustments, including the Q of the resnatron circuit, the degree of detuning of the cathode cavity, the amount of feedback used, and the grid-bias resistor. Achieving maximum modulation effectiveness was for a time more of an art than a science, but means were devised for monitoring which permitted reasonably good standardization of techniques, although a satisfactory scientific understanding of the reasons for the interplay of the various controls was never achieved.

19–19. Resnatron Transmitters.—The purpose of this chapter has been to outline the features of the resnatron oscillator and to mention methods of analysis, techniques, and concepts that are useful in working with the resnatron. Very little has been said about associated equipment required for a complete transmitter.

The resnatron tubes formed the basis for truck-mounted transmitter units to be used in the field and therefore to be self-contained. To carry the components for each transmitter unit the following 10 trucks (eight 10-ton) and a trailer were used:

Three primary power-generation trucks, each carrying a 75-kw diesel engine-generator unit with generator switching and synchronizing equipment

Two rectifier trucks, containing transformers and tube racks for the main power rectifier, which supplied 100 kw of d-c power, and for the modulator rectifier, which supplied 35 kw of d-c power; also remote-control switching, protective, and relaying apparatus

Two transmitter trucks, each mounting two resnatrons with associated output systems, vacuum pumps, water-circulating system, heat exchanger and blower, modulator, panels for determination and control of vacuum, and panels for control of resnatrons and modulator

Two antenna trucks
One workshop truck
One water trailer

The various components were selected to permit simultaneous operation of any two of the four resnatron oscillators mounted in the transmitter trucks, the other two tubes normally being kept under vacuum in stand-by position ready for immediate use. One Federal Telephone and Radio type 125A modulating tube was mounted with each of the four resnatrons, because of the electrical necessity for close positioning of the modulator-output stages to the resnatrons. Each transmitter truck carried low-level and driver modulator stages capable of driving any two of the four 125A tubes.

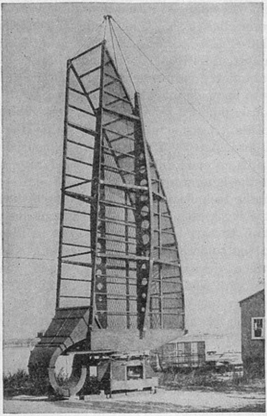


FIG. 19-20.—A swivel-mounted horn-fed antenna of the parabolic half-cheese type.

The resnatrons delivered power through a short tunable coaxial-type transformer into a copper waveguide transmission system. Enough waveguide, with necessary special measuring and switching components, was provided to serve two antennas each located some 200 ft from the transmitter trucks.

One tube in each truck was normally assembled for use in the low-frequency band and connected to a 22-in. guide system, the other tube being assembled for high-frequency operation and connected to a 15-in. guide system. Each antenna truck carried a swivel-mounted horn-fed antenna of the parabolic half-cheese type (see Fig. 19–20).

Although the two antennas were alike as to reflector size and dimensions, one of them was equipped with a horn designed for 460- to 625-Mc operation and connected to the 15-in. guide transmission system, while the other had a 340- to 520-Mc horn served from the 22-in. guide system.

The vacuum system for resnatron use must be a high-speed system in order to pump out quickly gas formed from arcs in the tubes and to enable internal changes to be made quickly in emergencies.

The continuously pumped-tube operation worked out more smoothly in field service of the truck-mounted assembly than the most optimistic predictions had anticipated. The use of the continuous evacuation system proved to be no more difficult in the field, after establishment of routine, than in the laboratory. It was found entirely practicable to train a crew of radio technicians, having no formal education above the elementary school level, to maintain the vacuum system in excellent operating condition, to learn how to locate and correct leaks, make minor tube repairs, do the soldering involved at certain points in assembly, etc. Furthermore in field use the vacuum-system conditions became increasingly better with passage of time because of the improved cleanliness of the vacuum system resulting from hours of continuous operation. It was possible for the crew to replace used cathodes and change feed-back prongs, a change that involved breaking and reestablishing the vacuum, without impairing the general high-quality level of vacuum conditions obtained as a result of continuous use.

An indication of the practicability for field use of this type of apparatus can be obtained from the time required for an experienced crew to get the outfit into operation in a new location. This involves unpacking or uncrating the tube parts, assembling the tubes, mounting the 125A tubes in their water jackets, checking the operation of all the control, relaying, and water-circulating systems, assembling the waveguide and r-f transmission system, establishing the vacuum, outgassing the tubes, and getting full power adjustments made. On one occasion, when an accurate check was made, this was accomplished by an experienced crew of eight men in 45 working hours.