The AEROVOX Research Worker

The Aerovox Research Worker is edited and published by the Aerovox Corporation to bring to the Radio Experimenter and Engineer, authoritative, first hand information on capacitors and resistors for electrical and electronic application.

VOL. 21, NO. 11 NOVEMBER, 1951 Subscription By Application Only

Introduction to Radar Techniques

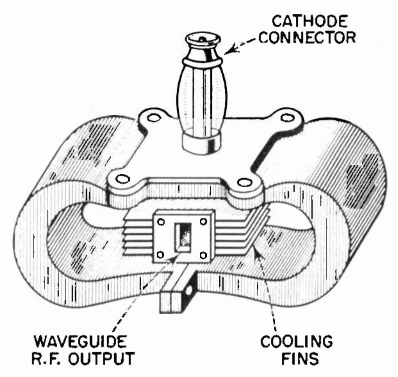
Part 2. The Magnetron Transmitting Tube

By the Engineering Department, Aerovox Corporation

THE previous issue discussed the functioning of the generalized radar set and enumerated the factors which determine its performance. Succeeding issues will deal with the special components of a typical microwave radar system. The present article describes the magnetron transmitting tube which is almost universally used as the high power r.f. generator in modern radar practice. A simplified theory of its operation will be developed and some practical aspects of magnetron design and operation will be discussed.

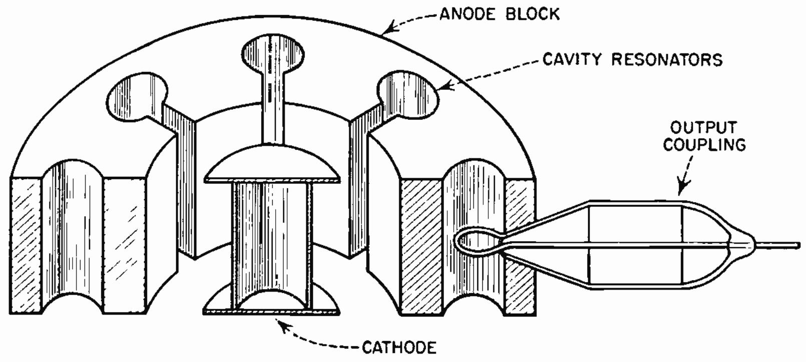
The magnetron tube is remarkably well suited to fulfilling the requirements of the pulsed radar system for short pulses of very intense r.f. energy at very high frequencies. It is probable that no other electronic development contributed as substantially to making microwave radar possible and practical. As a consequence, the magnetron has emerged since 1940 from the status of a laboratory curiosity to a highly developed vacuum tube category having dozens of standardized types. Pulsed power outputs range from a few watts to several million watts at frequencies extending from a few hundred megacycles to well over 30,000 megacycles. Operating efficiencies as high as 85% at 1200 megacycles have been reported by reliable observers. The physical appearance of a typical magnetron tube is illustrated in Fig. 1.

A magnetron is a diode electron tube in which a strong magnetic field is used perpendicular to the direction of electron flow. It is capable of generating extremely high frequencies at good efficiency because the frequency-limiting effects of electron transit time, which limit conventional negative-grid triodes to about 3000 megacycles, are reduced by the action of the magnetic field. A further advantage is gained from the fact that the resonant circuits are usually contained within the vacuum envelope of the tube, thus reducing lead inductance.



TYPICAL RADAR MAGNETRON
FIG.1

Fig. 2 shows the internal structure of a microwave magnetron. A cylinderical cathode is mounted in the center of a solid copper anode bearing a number of resonant circuits machined in its inner surface. Each of these "cavities" is the equivalent of a parallel resonant circuit tuned to the desired magnetron operating frequency. The evolution of such microwave resonant circuits from the conventional parallel L-C circuit is demonstrated in Fig. 3. An external circuit may be coupled to these resonators by an inductance loop as in the low-frequency case. The entire assembly is inclosed in a vacuum-



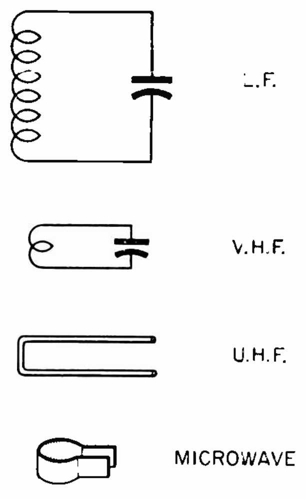
INTERNAL STRUCTURE OF MAGNETRON

FIG. 2

tight metal envelope and evacuated. A magnet, which may or may not be an integral part of the magnetron, is used to apply a magnetic field in a direction parallel to the cathode.

Theory of Operation

In any oscillator or amplifier tube the electrons possess energy of motion, or *kinetic energy*, which was gained from the applied d.c. voltage. This kinetic energy is converted to useful radio frequency energy when these electrons travel against a retarding r.f. field so that their velocity is reduced. In a triode, r.f. energy is added to the "tank" circuit by electrons which flow between the grid and the plate while the latter is at the negative part of the r.f. cycle. Electrons which are not decelerated by the retarding r.f. field dissipate their kinetic energy in the form of heat upon striking the anode. If all of the electrons could be slowed by



EVOLUTION OF CAVITY RESONATOR

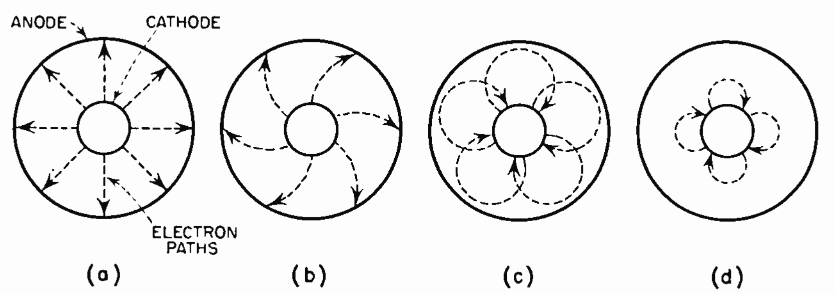
FIG. 3

the retarding r.f. field to zero velocity before reaching the anode, all of the energy gained from the d.c. field would be converted to r.f. energy, and the efficiency of the tube would be 100%. Such is far from the actual case, however. Triodes are severely limited at high frequencies because, for maximum energy conversion, the electrons must traverse the space between the grid and plate while the retarding field there is maximum. This dictates that the *transit time* should be less than about one-tenth of the period of one r.f. cycle for good efficiency. Electrons which are not so optimally phased do not interact with a strong retarding field and so are wasted. In going between the cathode and plate, the electrons in a triode have only one chance to interact with the r.f. field.

In the magnetron, the mechanism of energy conversion is much more perfect, however. Electrons may take the period of many r.f. cycles to reach the anode and may interact with a strong retarding field almost continuously during this time. How this can occur is illustrated in Figs. 4 and 5. In the absence of a magnetic field, the electrons in a magnetron would flow radially from cathode to anode as in any diode. See Fig. 4a. However, when a slight magnetic field is applied parallel to the axis of the cathode, the paths of these electrons are bent as in Fig. 4b. As the magnetic field strength is increased, a critical value is reached at which electrons no longer reach the anode, but describe a loop, or *orbit*, and return to the vicinity of the cathode. This is the condition called "cutoff", since no current reaches the anode. (Fig. 4a). If the magnetic field is increased further, the electrons orbits become very small as in Fig. 4d. Theoretically, the electrons return to the surface of the cathode with zero residual energy in a non-oscillating magnetron such as we have been discussing. This is because the electrons lose as much energy returning to the cathode against the d.c. field as was gained from it during the outward travel.

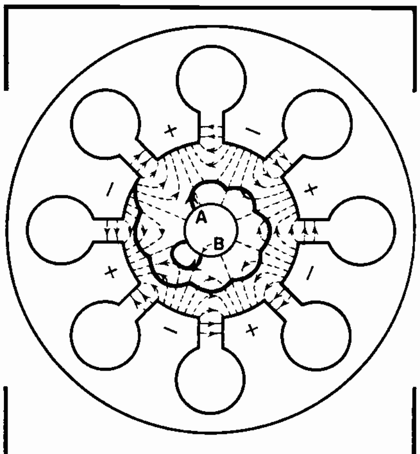
The above considerations are true of a *static*, non-oscillating, magnetron. When r.f. oscillations, such as might be started by noise voltages or other transients, are present in the cavity resonators, these conditions are greatly modified. The r.f. voltages associated with these oscillations produce fringing electric fields in the *interaction space* between the cathode and anode which extract energy from the whirling electrons in a truly remarkable manner.

Fig. 5 shows the instantaneous distribution of these fields within the magnetron interaction space. The arrows indicate the direction of the force which the fields exert on an electron. The electric fields vary sinusoidally with time, so that one-half cycle later the arrows are reversed. It will be noticed that retarding fields exist across each alternate gap. An electron starting from point "A" travels against the r.f. field during its first orbit, and so delivers energy to the resonant circuit. Having delivered part of its kinetic energy, it no longer can return to the cathode surface but comes to rest some distance from it. It is then re-accelerated by the d.c.



ACTION OF MAGNETIC FIELD IN DIODE
(Field Perpendicular to Paper)

FIG. 4



PATHS OF ELECTRONS
IN MAGNETRON
FIG. 5

field and, since the fringing r.f. field has reversed in the meantime, passes the next resonator gap against the r.f. field. This process continues with the electron progressing closer to the anode with each orbit and converting part of its kinetic energy to r.f. energy each time it passes a gap. Thus, an in-phase electron has many chances to deliver energy to the oscillating circuit and reaches the anode surface with little residual energy to be converted into heat.

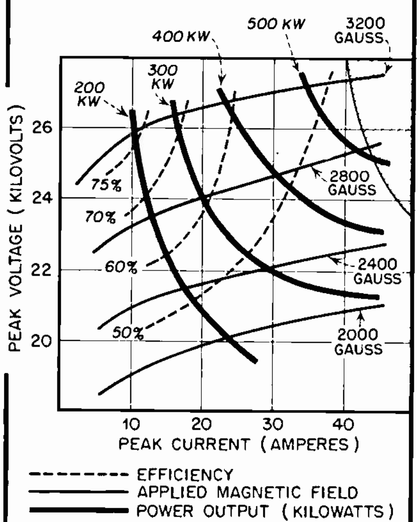
Conversely, consider an electron emitted at point "B" in Fig. 5. Here the fringing field is such as to accelerate the electron. Since the r.f. field does work on the electron, energy is subtracted from the useful output of the tube and its efficiency is reduced. However, such out-of-phase electrons are eliminated from the interaction space after only one orbit since, in gaining energy from the oscillating circuit, they have more than enough energy to reach the cathode on the return trip. The result is that these electrons bombard the cathode and dissipate their residual energy as heat. This gives rise to two effects which are unique characteristics of magnetrons. One effect is that the returning, or *back-bombarding*, electrons dislodge other electrons from the surface of the cathode. This *secondary emission* greatly enhances the current normally available from the cathode, making higher power possible. The other effect is that the bombarding electrons sometimes dissipate enough heat at the surface of the cathode to permit the normal cathode heating power to be disconnected without interrupting operation. Thus, in the magnetron, even the otherwise wasted electrons are utilized to improve the overall efficiency of the tube.

Of course, the above discussion assumes that the electrons which are delivering energy rotate around the cathode at a velocity which will keep them in step with the alternating r.f. field. This *synchronous* velocity is achieved by adjusting the operating voltage E for a given magnetic field B, since the rotational velocity of the electrons is equal to E/B. Thus, the electrons in a magnetron which are phased so as to deliver energy to the resonators remain in the interaction space during many r.f. cycles while the out-of-phase ones are eliminated after one orbit. The net effect of this *electron sorting* is to build up a whirling space charge pattern having the general shape shown in Fig. 6. Since most of the electrons are in the regions of retarding r.f. fields at any instant this pattern has half as many "spokes" as there are resonators in the anode.

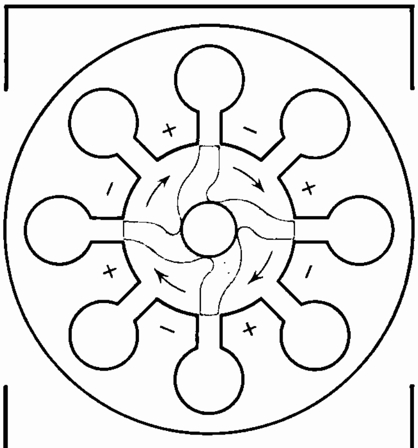
Practical Considerations

Although the above discussion applies to both pulsed and continuous-wave magnetrons, the former type is used exclusively in radar applications. In such usage, a rectangular voltage pulse is applied between the cathode and anode of the magnetron. This voltage has a peak amplitude ranging from about 3 kilovolts to over 60 kilovolts for different magnetrons. For convenience, since it is difficult to isolate the anode from the output transmission line and antenna parts, the anode is usually grounded and the cathode is pulsed *negatively*.

The duration of the voltage pulses is usually very short, ranging in dif-



TYPICAL MAGNETRON
PERFORMANCE PLOT
FIG. 7



ROTATING SPACE CHARGE
IN MAGNETRON
FIG. 6

ferent applications from about one-quarter to ten *microseconds*. These pulses are applied at regular intervals called the *pulse repetition rate*. Pulse rates ranging from 200 to 5000 p.p.s. are commonly used. The product of the pulse duration in microseconds and the pulse rate in p.p.s. is called the "duty cycle." This factor defines the ratio of time the magnetron is oscillating to the time it is off. Many radar magnetrons operate at 1000 p.p.s. and a pulse duration of 1 microsecond, or a duty cycle of .001. This means that the magnetron is "on" only 1/1000th of the time. The *peak* current drawn during the pulse may be of the order of tens or even hundreds of amperes, although the *average* current as indicated by a d.c. meter in series with the magnetron would be much lower, being the peak current times the duty cycle for essentially rectangular pulses.

A *performance plot* of a typical pulsed magnetron is shown in Fig. 7. It shows the power output and efficiency of the magnetron as a function of applied peak current and voltage for various fixed values of magnetic field. From such data, the radar designer can select an appropriate operating point to meet given requirements. Notice that power output and efficiency increase with increasing magnetic field. The shaded area indicates regions of instability due to internal arcing.

Although the modern magnetron has been instrumental in extending the limit of efficient radio frequency generation at least one-hundred times, it is encountering the same kind of limitations above 30,000 megacycles which confine conventional triodes to the frequencies below 300 megacycles.

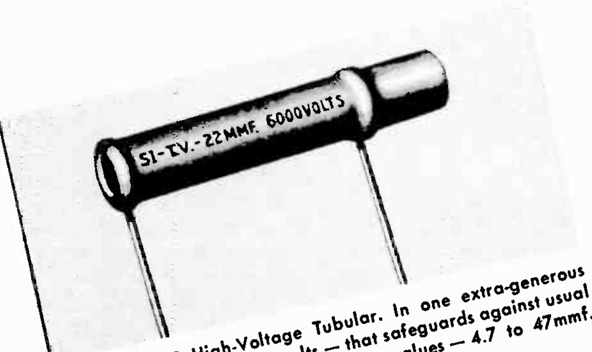
the COMPLETE Hi-Q* CERAMIC CAPACITOR LINE

HANDY! That's the big idea behind Hi-Q* Ceramic Capacitors (products of Electrical Reactance Corporation, a subsidiary of Aerovox Corporation).

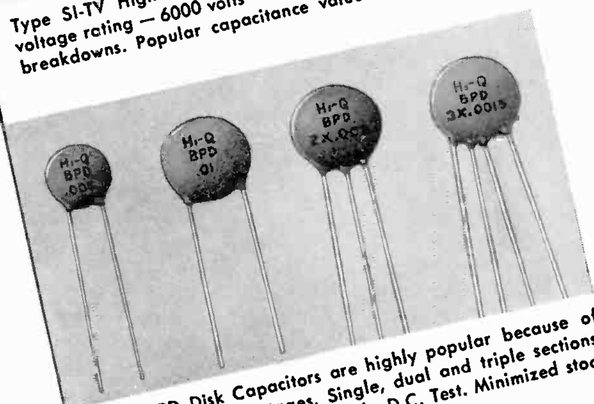
Handy because Aerovox has selected only those types and values in greatest demand. You can get the right type for your particular need, yet you don't have to wade through a lot of types and values you'll never use.

Handy because, to an already live selection, there's now added Type SI-TV High-Voltage Tubular Ceramics. This popular item comes in just **one voltage rating** — 6000 volts — taking care of ALL voltage needs. The extra-generous voltage rating safeguards against usual breakdowns. And you, as serviceman, experimenter, custom-set builder, research worker or other user, can now afford to stock an assortment of popular capacitance values, all of the **one safe voltage rating.**

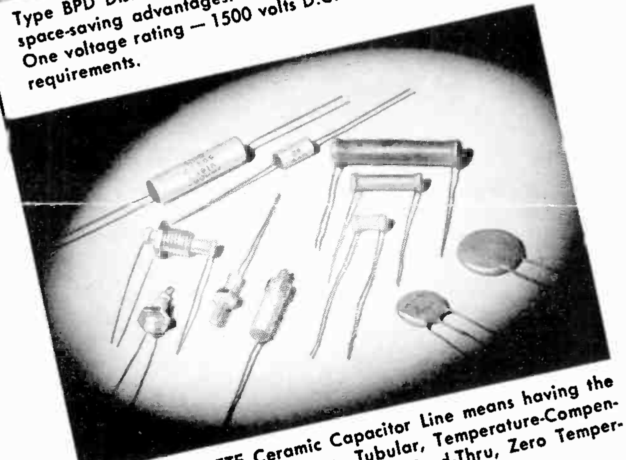
Ask your Aerovox jobber for these Hi-Q* Ceramic Capacitors. Ask to see the up-to-date listings. **Order your needs** from that jobber!



Type SI-TV High-Voltage Tubular. In one extra-generous voltage rating — 6000 volts — that safeguards against usual breakdowns. Popular capacitance values — 4.7 to 47mmf.



Type BPD Disk Capacitors are highly popular because of space-saving advantages. Single, dual and triple sections. One voltage rating — 1500 volts D.C. Test. Minimized stock requirements.



The COMPLETE Ceramic Capacitor Line means having the required type every time. Tubular, Temperature-Compensating, Stand-Off, High-Voltage, Feed-Thru, Zero Temperature Coefficient types.

LOOK FOR THE YELLOW-AND-BLACK WINDOW CARTON!

Aerovox Hi-Q* Ceramic Capacitors come packed that way. Five pieces to carton. Contents always in sight. Buy them by the carton or by the piece. Hi-Q* Ceramics are always clean, fresh. **OK in every way.**

*Trade Mark registered U. S. Pat. Off. by Electrical Reactance Corp.