Anode Materials for High Vacuum Tubes

Continued development of the high vacuum tube has played an extremely important part in the development of radio communication. Since the power output of a tube is proportional to the amount of heat that may be dissipated safely from its anode, the anode is one of the most vital parts of high vacuum tubes especially those used for transmitting purposes. Several materials have been found suitable for the anodes of transmitting tubes, depending upon the requirements of specific applications and the type of cooling adopted; these materials and their characteristics are discussed in this paper.

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DEVELOPMENT of radio communication has been marked by a series of periods, each of which has been the result of the application of some new device or devices. Without any question, the high vacuum tube is the device that has affected most profoundly every branch of the art. Development of the high vacuum tube has been continuous from the time the triode first was used. Today there are available in the United States tubes of all sizes ranging from the "acorn tube" to tubes capable of delivering 100 kw of radio frequency power. Tubes have been developed for many special applications to permit the desired results to be accomplished better, more easily, or more cheaply. To attempt even a hasty review of these developments would require far more space than is available here. For this reason the discussion will be limited to a more detailed consideration of one phase of the development of transmitting tubes, namely, the advances that have been made in the design and construction of anodes.

As is well known, in one of its simpler forms the vacuum tube consists of a filament or cathode which serves as a source of electrons, a plate or anode, and a grid consisting of a wire mesh or grating surrounding the cathode so that it may control the flow of electrons to the anode. The chief application of this device is to amplify a-c power to the levels desired. The action of the vacuum tube amplifier may be described as follows: The electrical impulse to be amplified is applied to the grid of the tube and thus controls electrostatically the flow of electrons from the cathode to the anode. The energy required to draw the electrons to the anode comes from a high voltage d-c supply in the anode circuit. The power required by the grid to vary this electron stream from the cathode to the anode ordinarily is only a fraction of the power flowing in the anode circuit; hence the tube is regarded as an amplifier. Strictly speaking, however, the action of the tube is that of a valve, the d-c power of the anode high voltage supply being converted into a-c power in the load. The efficiency of this energy conversion is never 100 per cent since there always must be some voltage drop between the anode and cathode of the tube, and hence some loss in the tube. Quantitatively, the energy loss is equal to the average energy with which the electrons bombard the anode. As a result of this bombardment the anode becomes heated and assumes some temperature at which the thermal loss by radiation, convection, and conduction equals the energy dissipated in the anode.

For any given tube there is a maximum amount of power that can be dissipated safely by the anode, if reasonable tube life is to be obtained. Then, as the conversion efficiency is determined fairly well by the mode of operation, it is seen that the a-c power output of the tube is proportional to the safe anode dissipation. Thus, in transmitting tubes, the anode dissipation rating is one of the most important factors in determining the amount of power the tube will deliver.

Anodes may be classified according to the principal method of cooling employed. In some types of tubes the anodes are cooled almost entirely by radiation, in others by convection, and in the third type by conduction.

RADIATION COOLED ANODES

Historically, radiation cooled anodes were the first developed. In this type of construction, the anode is operated at some fairly high temperature and heat is radiated directly by the anode to and through the glass walls of the bulb. It has been necessary to design such anodes to operate at fairly high temperatures in order to dissipate reasonable amounts of power in anodes of the size demanded by the electrical characteristics desired of a tube. With some types of anode materials it has been desirable to operate at temperatures as high as 1,000 degrees centigrade.

Operation of anodes at such high temperatures immediately brought up a host of problems. One of the most important was that presented by the liberation of gases from the anode. All materials suitable for anodes contain gases in the raw state. These gases are mainly hydrogen, nitrogen, carbon monoxide, and carbon dioxide. They are present throughout the body of the material. When the material is heated in a vacuum, these gases are liber-

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A paper presented at a meeting of the A.I.E.E. Washington, D. C., Section, Oct. 9, 1934; recommended for publication by the A.I.E.E. committee on communication; scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 28–31, 1936. Manuscript submitted May 8, 1935; released for publication Aug. 7, 1935.

ated at a varying rate, depending on the temperature and the time of heating. The major portion of these gases must be driven out of the anode during the manufacture of the tube so that in subsequent normal operation no appreciable amounts of gases are liberated. Residual gases in vacuum tubes become ionized under impact by electrons. If enough ions are generated in this way they partially neutralize the electron space charge that limits the flow of electron current between the cathode and anode. Increased current then flows through the tube, resulting in greater anode heating and more rapid gas liberation. This process quickly may become cumulative and lead to an arc discharge between the cathode and anode. If the tube be not protected by overload devices, such a discharge may result in an abrupt termination of the life of the tube by the melting of the cathode, grid, and anode.

The gases contained in anodes commonly are driven off by heating during one of the last stages of manufacture. The assembled tube is sealed to a vacuum system where the glass bulb can be baked out to free it of adsorbed gases. The anodes are heated by 2 processes. One method is to apply a high positive voltage to the anode and bombard it with electrons from the cathode. Another method is to place a coil carrying high frequency currents around the glass bulb in such a way that the anode acts as the short-circuited secondary of a transformer. The induced currents then heat the anode.

Another factor that is important in the choice of anode materials for radiation cooled tubes is the total heat radiation emissivity. It is desirable to have this approach as nearly as possible the ideal of a black body, since for a given anode and anode operating temperature (determined by gas liberation) it permits the highest dissipation rating. At first thought it would appear that the size of the anode could be increased to get the desired dissipation rating in the event that a material of low emissivity were used. However, this would result in an increase in the electrostatic capacitances to the other electrodes of the tube. Because of the definite trend to higher frequencies in radio communication, it is absolutely necessary to keep interelectrode capacitances to a minimum so that capacitance charging currents, which of course entail losses, can be limited to reasonable values.

A third set of factors in the choice of anode material consists of the mechanical properties. The material must be capable of being worked into the desired shapes without undue difficulty or expense. It must maintain these shapes at the highest temperatures necessary during the manufacture of the tube. Only a very small amount of warping can be tolerated at the normal anode temperature as warping results in a change of electrical characteristics.

A fourth factor is the vapor pressure of the anode material. This must be low enough to avoid noticeable metallic deposits in the tube during manufacture. Deposits on insulators in a tube may result in excessive interelectrode leakage or excessive radio frequency losses in the insulators. Deposits on the glass bulb result in higher glass temperatures, because of increased radiation absorption and radio frequency losses, and may lead to gas evolution and strain cracks.

One of the first materials used for anodes in radiation cooled transmitting tubes was tungsten. A typical 250 watt tube made commercially about fifteen years ago had an anode in the form of 2 sheets of tungsten about $1^3/_4$ by $2^1/_2$ inches arranged about the grid. From the standpoint of gas content, ease of degassing, vapor pressure, and maintenance of mechanical shape at high temperatures, tungsten is a fairly desirable material for anodes. It has been found that the initial gas content of tungsten is of the order of 0.6 per cent by volume. The main constituent of the evolved gas is nitrogen, although there is considerable carbon monoxide and some carbon dioxide and hydrogen. The absence of oxygen undoubtedly is attributable to the ease with which this element combines with other elements, such as carbon. The major portion of the gas is liberated by heating to 2,200 degrees centigrade; no further gas is evolved by raising the temperature to 2,600 degrees. Such high anode temperatures, however, would be difficult to realize in actual manufacture of tubes.

Tungsten has 2 serious disadvantages: It is essentially a very hard metal and consequently difficult to machine and work into the desired shapes, and its cost is high. Because of these disadvantages it soon was displaced by molybdenum.

A study of the gases evolved when molybdenum is heated in vacuum has shown that to degas this material completely, it is necessary to heat it to a temperature of 1,760 degrees centigrade, as compared with 2,200 degrees for tungsten. In a typical experiment the total gas evolved was 5.6 per cent by volume, that is, approximately 10 times the volume gas content of tungsten. The various constituent gases are evolved at varying rates. Thus when degassing is carried at 800 degrees centigrade the major portion of the gas liberated is carbon monoxide, while at higher temperatures the gas evolved is

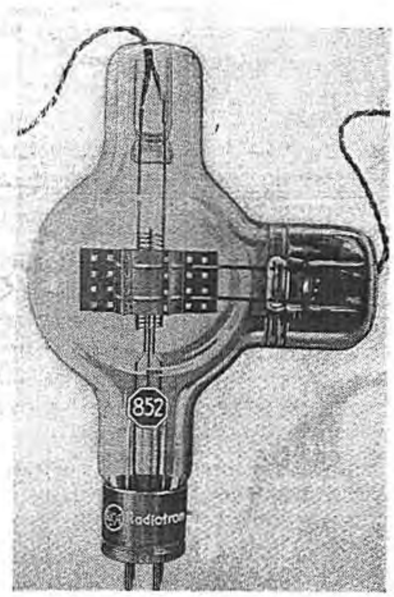

Fig. 1. A 75 watt tube with carborundum blasted molybdenum anode formed with integral cooling fins

mostly nitrogen. In heating at 800 degrees only about 15 per cent of the total gas in the sample is driven off. Further heating at 1,000 degrees contributes another 15 per cent. By raising the temperature to 1,200 degrees it is possible to drive off about 95 per cent of the gas in the sample.

In actual manufacture it is usually not desirable to use such high temperatures as the foregoing indicates are necessary for complete degassing of the anode, as the rate of evaporation of the molybdenum becomes high enough to cause deposits on the glass bulb and on insulators. Fortunately, complete degassing is not necessary because, regardless of the temperature at which degassing is carried on, the rate of gas evolution can be reduced to a negligible value by operating the anode at a sufficiently lower temperature. Long manufacturing experience has shown that molybdenum anodes that have been degassed at a brightness temperature of 1,300 to 1,400 degrees centigrade subsequently can be operated safely at temperatures as high as 1,000 degrees. Furthermore, a small amount of gas evolution can be tolerated if the tube contains active "getter" which will combine with or absorb the gases as fast as they are generated.

With molybdenum anodes ways and means soon were sought to decrease the temperature for the desired power dissipation. One way adopted was by the addition of fins which would increase the radiating area of the anode. It was found desirable to make the fins out of the same piece of metal as the anode because of the poor heat conductance between 2 pieces of metal brought together by some process such as riveting. Later it was found that the radiation emissivity of the anode could be increased by roughening the surface by carborundum blasting. Figure 1 shows a 75 watt tube in which both these methods to decrease anode temperature are employed. The anode is made of 2 strips of molybdenum folded to form radiating wings integral with the anode. The whole anode assembly then is carborundum blasted. This anode is shown at the left in figure 2.

By these means, the safe dissipation of molybdenum anodes was increased, thereby partly overcoming the low radiation emissivity characteristic of the metal. However, it is still desirable to operate the anodes at fairly high temperatures, sometimes as high as 1,000 degrees centigrade, in order to keep the anode dimensions small. These higher temperatures result in another and undesirable effect, largely in tubes employing a flat type of construction. The appearance of hot spots on the anode is common in such tubes, even when the construction is perfectly symmetrical, and is attributable to the fact that electrons attempt to travel from the cathode to the anode in lines normal to the anode surface. With anode thicknesses commonly used when the material is molybdenum, the center of the anode usually operates at a visibly higher temperature than the edges. This temperature difference produces warping or buckling, and consequently the electrical characteristics of the tube are subject to change. To overcome this in anodes of flat construction, it sometimes has been necessary to resort to elaborate constructions using channel pieces to give additional strength to those sections of the anode operating at higher temperatures. In anodes of circular construction, the heating produced is much more uniform, as the electrons flow from the central cathode in radial lines. In such anodes, the problem of warping generally is solved adequately by ridges pressed into the metal when the sections of the anodes are formed.

From a mechanical standpoint, molybdenum is a fairly satisfactory material. It does not soften or anneal even at much higher temperatures than are used during degassing.

Another material that has wide application to radiation cooled transmitting tubes is graphite. In comparison with molybdenum and tungsten, typical graphite samples suitable for use as anodes contain comparatively large amounts of adsorbed gases. The volume content of gases may be of the order of 10 times that of molybdenum; this is exclusive of the gas trapped in the cavities of the graphite. In addition, the volume of a graphite anode may be of the order of 10 times that of an equivalent metal anode, resulting in a 100-fold increase in gas that must be removed from the anode in the exhaust of the tube. By suitable pretreatment, the gas content of the anode can be reduced very greatly. One method consists among other processes of heating the anode to a high temperature in a vacuum furnace. It has been found that at 2,100 degrees centigrade it is possible to degas graphite so that subsequent heating at a higher temperature gives no further gas. As with molybdenum, the gas evolved, especially at the higher temperatures, is mainly nitrogen. An anode that has been degassed completely, reabsorbs only a fraction of the gas it originally contained if stored under proper conditions. In actual exhaust of a tube containing such a pretreated anode, the time required for completion of the degassing is not much different from that required by a molybdenum anode. Again it is found that if the anode is degassed at some given temperature, the rate of gas evolution can be reduced to a negligible value by dropping the temperature to some lower value. In a typical test the degassing was carried on at 1,300 degrees centigrade; on dropping the temperature to 1,000 de-

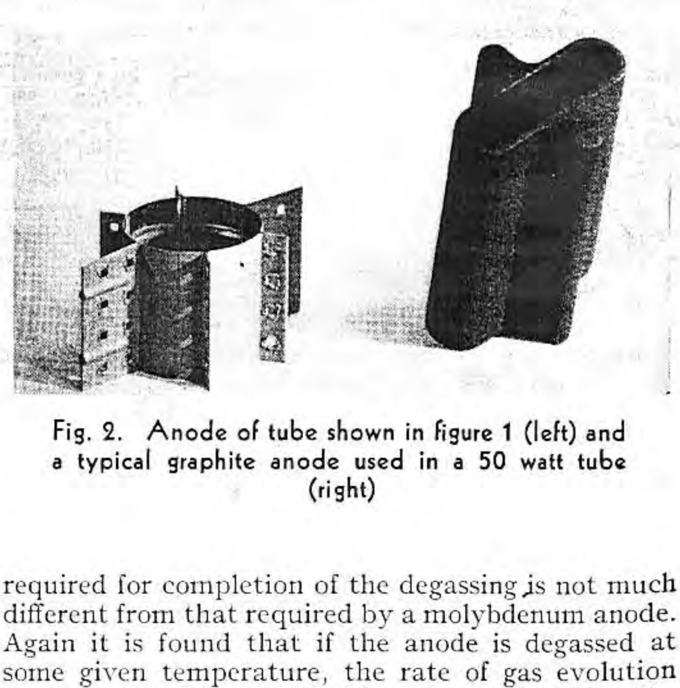

Fig. 2. Anode of tube shown in figure 1 (left) and a typical graphite anode used in a 50 watt tube (right)

grees no further gas was evolved, although on increasing the temperature to 1,600 degrees considerably more gas was liberated. The total radiation emissivity of graphite depends on the treatment the surface has received. In comparison with molybdenum, graphite anodes operate at a visibly lower temperature for the same power radiation. At first thought this would seem to make graphite a much better anode material, because the energy radiated varies as the fourth power of temperature, and by operating at the same temperature as permissible with molybdenum much greater anode dissipation could be obtained. One factor militates against this, however. Glass is nearly opaque for the major portion of the radiations from anodes at the usual operating temperatures. Thus, regardless of whether the anode be metal or graphite, most of the radiated energy is absorbed by the glass and then is removed from the bulb mainly by convection air currents and reradiation. Any increase in the dissipation rating of a tube with a given bulb size must result in an increase in bulb temperature and consequent decrease in safety factors.

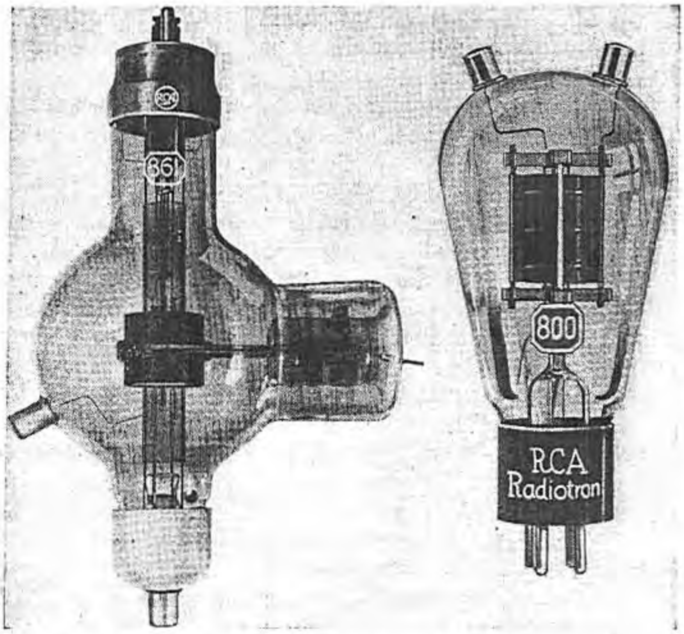

Fig. 3 (left). A typical tube with graphite anode

Fig. 4 (right). A typical tube with carbonized nickel anode

The fact that graphite anodes operate at a lower temperature than tungsten or molybdenum has been criticized. It seems that some users of transmitting tubes judge the operating efficiency of tubes by observing the color temperature of the anode. With tungsten or molybdenum anodes this is easily possible because at the normal operating temperature the anodes are distinctly orange-red in color. With graphite, however, practically no color can be seen in normal operation so that it is very difficult to judge how much energy is being lost in the anode.

One of the disadvantages of graphite as an anode material is its low tensile strength. In order to compensate for this weakness, the minimum wall thickness has been made at least $^1/_{16}$ inch. Consequently, graphite anodes are heavier than equivalent metal anodes. A typical graphite anode as used in the so-called "50 watt tube" is shown at the right in figure 2. Usually, more rigid supporting means are required, which may have to be rather elaborate for some kinds of service where there is a great deal of vibration such as in aircraft communication. There is also an advantage in the heavier wall thickness needed with graphite anodes. The heat conductance in the plane of the anode surface is so good that the entire anode operates at practically uniform temperature. The warping that occurs with metal anodes thus is avoided, and consequently the electrical characteristics of a graphite anode tube are more nearly constant. The absence of hot spots when graphite anodes are used means that the anode loss is radiated more uniformly over the anode surface. The glass bulb also operates at a more uniform temperature.

Mechanically, graphite does not present any serious problems. It is a soft material and therefore readily permits machining operations such as milling, grinding, and drilling.

The vapor pressure of graphite is low enough so that bulb blackening can be avoided during the exhausting of the tube. Careful selection of grades of graphite appears necessary here, because what ordinarily is termed graphite is in reality a complex mixture of a wide variety of forms of carbon, ranging from amorphous carbon to true graphite. Some of these forms produce undesirable effects, which can be eliminated partly by suitable treatment of the anodes. A typical tube with graphite anode is shown in figure 3.

Another metal that has found considerable application as an anode material, particularly in transmitting tubes of smaller sizes, is nickel. Nickel lends itself readily to a process called carbonizing. The nickel anodes are heated to a medium temperature in a hydrocarbon vapor such as natural gas. This treatment deposits a well-adhering layer of amorphous carbon or soot on the nickel. The radiating property of this layer approaches that of a black body—hence the desirability of this material.

The gas content of nickel is of the same order of magnitude as that of molybdenum. However, since it has a melting point of 1,450 degrees centigrade compared with 2,600 degrees for molybdenum, nickel anodes must be degassed at a lower temperature. The vapor pressure limits the degassing temperature to about 1,000 degrees centigrade, as this is the highest temperature at which nickel can be maintained without noticeable evaporation.

Nickel is formed very readily into the shapes desired for anodes. Care must be given to strengthening the anodes with ridges and the like in order to avoid warping during exhaust. Like other metals, nickel anodes have the advantage over graphite that they can be made very light in weight, so that elaborate supporting structures are not needed. Figure 4 shows a typical tube in which a carbonized nickel anode is used.

Other materials have found some application in transmitting tubes, resulting in some special characteristics; but the materials already mentioned have been used most widely.

CONVECTION COOLED ANODES

So far attention has been given only to radiation cooled tubes. Anodes can be cooled also by convection air currents. In order to accomplish this, the anode is made part of the vacuum envelope. This imposes further requirements on the anode material. Obviously it must be impervious to gases, that is, vacuum tight. Since the anode can form only part of the vacuum enclosure because leads to the various electrodes must be brought through insulating seals, it must be possible to make a vacuum tight seal between the insulating material and the anode material. Copper has been found to be a very convenient anode material because it readily can be sealed to glass. In designing such a seal, the characteristics of glass and copper are taken into consideration. Two important factors are the higher coefficient of thermal expansion of copper compared with that of glass, and the fact that a copper to glass seal has a greater strength in compression than in tension. If the seal be so designed that the copper is on the outside and the glass inside, then as the seal cools from the temperature at which it is made the boundary between copper and glass is subjected to compression. In order to reduce this compressional stress, the copper is thinned out so that its thickness in the region where the copper and glass join is only a few thousandths of an inch. If the copper is thinned in this way it can stretch and thus relieve some of the stress on the seal. In making such a seal the thinned edge of the anode is heated in flames to oxidize it. At the same time the glass is heated until it is soft. The glass and copper then are brought into intimate contact and more heat is applied until the glass has dissolved the copper oxide. This solution has the characteristic orange color associated with copper to glass seals. The glass now is left in intimate contact with the copper. Such seals, when properly made, are perfectly vacuum tight.

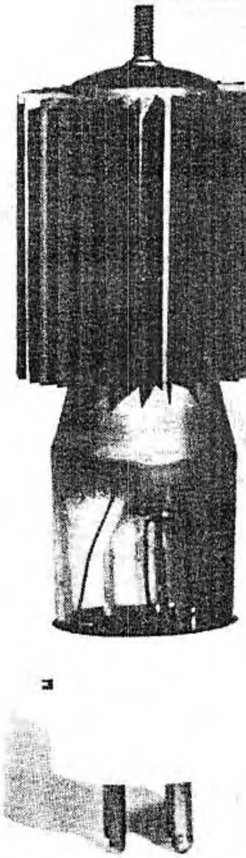

Fig. 5 (left). A typical tube with convection cooled anode

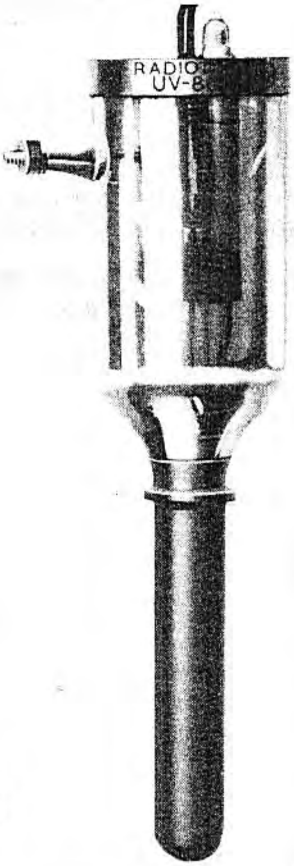

Fig. 6 (right). A typical tube with conduction cooled anode

In degassing the anodes of tubes made in this way, considerably lower temperatures are permissible than can be used in degassing the radiation cooled anodes previously described. In the first place, copper has a melting point of only 1,083 degrees centigrade. Secondly, since the anode is now part of the vacuum enclosure, it cannot be heated to temperatures too near the softening point or there will be danger that the pressure of the atmosphere might collapse it. Keeping the temperature of the anode below this point, the degassing of a tube readily is accomplished, so that subsequent operation at temperatures as high as 300 degrees centigrade is possible.

The dissipation of heat from such an external anode tube is largely by convection currents. In order to increase the safe allowable dissipation, more area can be added to the anode by attaching fins. In order to be effective, these fins should have adequate heat conductivity and be in intimate contact with the anode. Further increase in dissipation can be secured by the use of forced cooling. It really is surprising to find how much heat can be removed from such a fin structure by means of an air stream supplied by an ordinary fan. A typical tube with a convection cooled anode is shown in figure 5.

CONDUCTION COOLED ANODES

A third method of cooling anodes is by conduction. In order to accomplish this, the anode again is made part of the vacuum enclosure. The portion of the anode that becomes heated during operation of the tube is inserted in a water jacket, which is so constructed that a high velocity water stream can play over the anode. Heat then is conducted by the anode directly to this water stream and is carried off. It is important to have a high water velocity because otherwise steam pockets may form and result in dangerous overheating of the anode at those points. By proper design of water jacket and adequate flow of water, it is possible to carry off as much as 250 watts per square inch of anode surface.

Because of the large amounts of heat that can be carried off by conduction cooling, this method is used exclusively in high power tubes, those with ratings of a few kilowatts or more. The construction of conduction cooled anodes is the same as that described for a convection cooled anode. The anode usually is made of drawn copper, and the open end is turned to a thin edge and sealed directly to the glass portion of the tube. A typical conduction cooled tube is shown in figure 6.

CHOICE OF MATERIAL DEPENDS ON REQUIREMENTS

In concluding this discussion, it can be seen that several materials are suitable for use in constructing transmitting tube anodes. The final choice of material must depend on all the limitations involved. For example, if the physical dimensions of the anode must be very small for operation at very high frequencies, it is helpful to construct the anodes of tungsten, as they then may be operated at high temperatures where they can radiate fairly high amounts of power. Again, if an inexpensive construction is required, carbonized nickel is a satisfactory material. Where weight must be kept at a minimum, with a high degree of strength, molybdenum is very useful. Where uniformity of characteristics is desired, graphite is a very suitable material. If high heat dissipation is required, forced convection or conduction cooled copper anodes are most satisfactory. With such a variety of materials and designs available, the engineer is enabled to make a choice that best fits the purpose at hand.