Dec. 7, 1943. R. R. MACHLETT ET AL 2,336,271

ROTARY ANODE X-RAY TUBE

Filed Dec. 23, 1941 2 Sheets-Sheet 1

Fig. 1.

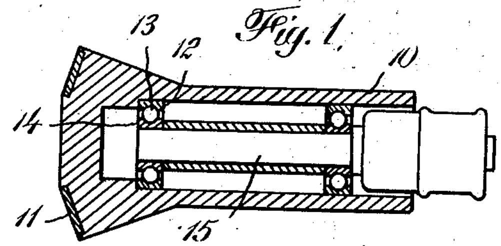


Fig. 2.

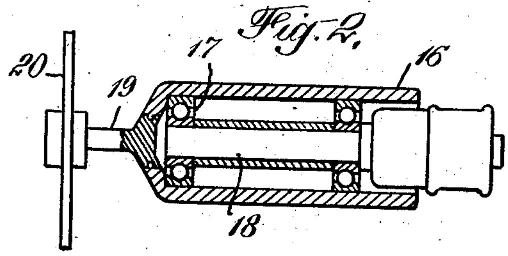
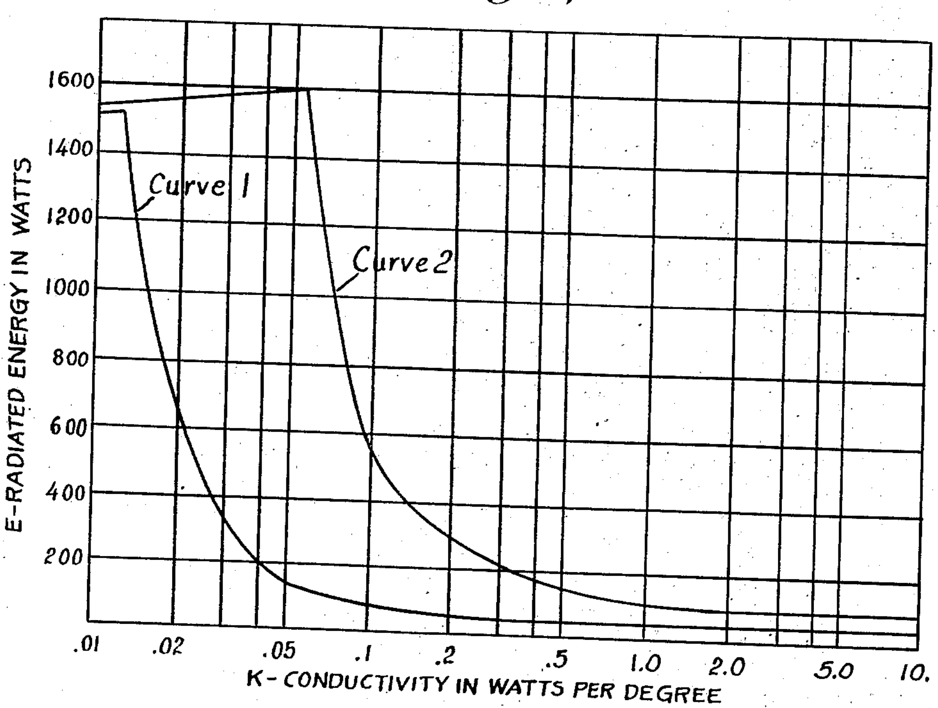


Fig. 5.



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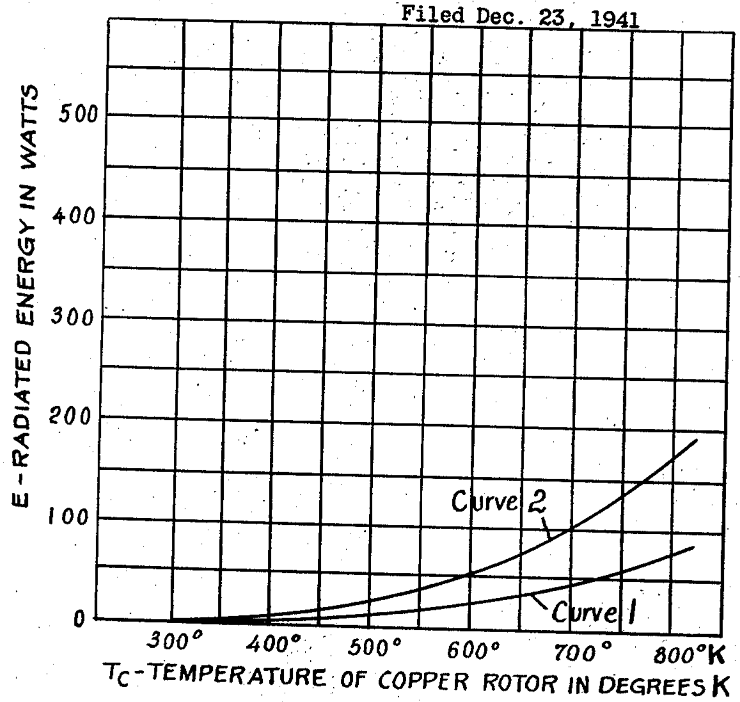

Fig. 3,

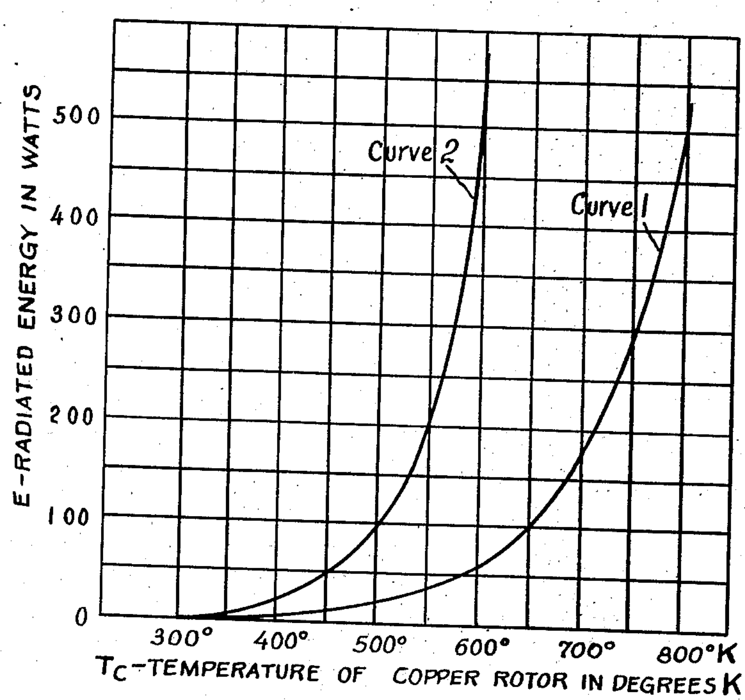

Fig. 4,

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ROTARY ANODE X-RAY TUBE

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6 Claims. (Cl. 250—143)

This invention relates to anode structures for use in X-ray tubes of the rotating anode type and is concerned more particularly with a novel anode structure, the use of which makes possible operation of such tubes for longer periods of time at higher energy inputs than is possible with tubes of present manufacture.

In rotating anode X-ray tubes as now commonly made, the anode structure rotates on ball bearings on a shank sealed through the wall of the envelope and the bearings almost entirely prevent transfer of heat to the exterior of the tube through the anode structure and shank, which is the conducting path used in conventional stationary anode tubes. The problem of dissipating the heat from a rotating anode tube is, therefore, of such major importance that it has received attention over a period of many years and various expedients for obtaining rapid dissipation of heat have been suggested and, in some cases, patented. Certain current trends in diagnostic practice, namely, so-called "spot film" or "Serialograph" work, and photoroentgenography for rapid chest survey work, both of which require the use of X-ray energy in greatly increased amounts, have recently laid still greater emphasis on this factor in tube design.

All commercially successful forms of rotating anode tubes have relied on the principle that heat dissipation must take place by radiation from the surface of the anode structure. In practice, the anodes used include a cylinder mainly of copper, which is adapted to act as the rotor of an induction motor, and the cylinder is supported on the bearings and in turn supports at its extreme end the tungsten target. There are two principal variations in construction and, in the first, the target is in intimate contact with the copper rotor, while, in the second, the target is supported on a stem of refractory metal providing a path of low heat conductivity between the target and the copper rotor.

In the anode structures of the first type with the target in direct contact with the copper rotor, the high degree of heat conductivity between the two parts results in the entire structure assuming a practically uniform temperature during operation, so that the total surface is the medium of heat dissipation by radiation. The limit to the maximum amount of radiation obtainable is then determined by the maximum operating temperature of the copper that is permissible without detrimental effect on the bearings, the coefficient of thermal emissivity of the surface, and the dimensional limitations of the surface area imposed by practical considerations. Numerous expedients have been suggested to increase the radiation factor for the entire surface of the anode structure and the customary practice is to make the surface area as large as is consistent with convenient all-over dimensions of the entire tube and to blacken the copper surface artificially to increase the radiation factor.

With the second type of construction, much the greater part of the radiation is that from the target member of the anode assembly and there is very little radiation from the copper member, so that in considering heat dissipation from an anode of this type, it has generally been assumed that the conduction of heat from the target into the copper rotor is negligible. Various proposals for reducing the heat conductivity of the connecting member to its lowest possible limit have, accordingly, been made and the heat dissipation ratings of tubes constructed with those ideas in mind have been based on the radiation characteristics of the tungsten target alone. Thus, theoretically, since the all-tungsten target can be raised to a very high temperature without damage to itself, an extremely high rate of heat dissipation by radiation therefrom can be attained.

When conditions of practically continuous loading are encountered, however, as in fluoroscopy, it has been found that with prior tubes having the second form of rotating anode, the continuous heat dissipation rating is limited not by the radiating capacity of the tungsten member but by the maximum allowable temperature of the copper portion of the structure. This follows because unavoidable conduction of heat through the supporting member, when the target is at the high temperature for rapid radiation, eventually results in the copper rotor being raised to excessive temperatures. Thus, for this type of operation, the rating assignable to such tubes, while greater than that for tubes having rotating anodes of the first form, is still less than is desired for some applications.

The present invention is directed to the provision of a rotating anode structure of the second type, that is, one comprising a rotor mainly of copper, a tungsten target, and a connecting member between the two, which is of such construction that tubes in which it is employed may be operated at much higher ratings than prior tubes. The invention is based on a departure from the former practice of attempting to keep the copper rotor from exceeding permissible operating temperatures by reducing the conductivity of the connection between the rotor and the tungsten target as much as possible and, instead, involves increasing the radiation factor of the copper rotor and, at the same time, restricting the conductivity of the connection within limits. When the proper conditions, which will presently be explained, are fulfilled, it is found that increasing the radiation factor of the rotor does not result merely in the increase in total radiation from the structure represented by the increased radiation from the rotor itself, but, instead, produces a much greater and wholly unexpected increase in total radiation.

For a better understanding of the invention, reference may be had to the accompanying drawings in which

Figs. 1 and 2 are longitudinal cross-sectional views, respectively, of the two forms of rotating anode structure above mentioned;

Fig. 3 is a graph illustrating the results obtained by increasing the radiation factor of the copper rotor of a rotating anode structure of the type shown in Fig. 1;

Fig. 4 is a graph similar to Fig. 3 illustrating the results obtained by increasing the radiation factor of the copper rotor of a rotating anode structure of the type shown in Fig. 2; and

Fig. 5 is a graph representing the relations between total energy radiated from an anode structure of the type shown in Fig. 2 and the conductivity of the connecting member between the copper rotor and tungsten target of such an anode structure.

The rotating anode structure shown in Fig. 1 is of a well-known type which includes a copper cylinder **10** in the end of which is embedded the tungsten target **11**. The copper cylinder is adapted to serve as the rotor of an induction motor and within the cylinder and in contact with it near either end are outer races **12** in which run balls **13**. The balls also run in inner races **14** mounted on a shank **15**, which is sealed through the wall of the envelope.

In the structure illustrated in Fig. 1, the tungsten target embedded in the end of the copper cylinder is in such intimate contact therewith that the entire structure reaches a practically uniform temperature during operation and the total surface of the structure is the medium of heat dissipation by radiation. In order to increase the radiation factor for the rotor, the practice has been to design the structure so as to provide as large a radiating surface as is permissible, having in mind the over-all dimensions of the tube, and also to blacken the surface of the copper. When the surface of the copper is thus blackened, its radiating capacity is increased and the total energy dissipated is then the sum of that radiated from the tungsten and that from the surface of the copper. With such a construction, the temperature to which the structure can be raised is limited to that beyond which the bearings are detrimentally affected.

The anode structure illustrated in Fig. 2 is of the second type and it includes a copper rotor cylinder **16** running on bearings **17** on a shank **18** sealed through the wall of the envelope. At the inner end of the cylinder is mounted a connecting member **19** of a refractory metal, such as molybdenum, and at the free end of the connecting member is a tungsten disc **20** held in place on the connecting member in any suitable manner.

Both of the structures shown in Figs. 1 and 2 may be considered as consisting of a tungsten member T and a copper member C joined together by a path K having thermal conductivity. The mathematical expression for the total heat energy radiated from such a structure is then as follows:

$$E=R_t(T_t^4-T_o^4)+R_c(T_c^4-T_o^4)$$

In the above equation, the factors are:

E = energy radiated
R_t = radiation factor for tungsten member (dependent on area and coefficient of emissivity)
R_c = radiation factor for copper member
T_t = absolute temperature of tungsten member
T_c = absolute temperature of copper member
T_o = absolute temperature of surroundings

If, as in the practical structures under consideration, T_o is less than one-half the values of T_t and T_c respectively, the error involved in ignoring T_o is less than 6%, so that it is permissible to eliminate T_o and thus simplify the equation, so that it is as follows:

$$E=R_tT_t^4+R_cT_c^4$$

The input energy is all applied to the tungsten member of the structure and, hence, when the system is in equilibrium, the energy radiated from the copper is equal to that conducted into it from the tungsten through the thermal path connecting them. Therefore, $R_cT_c^4=K(T_t-T_c)$, K being the conductivity of the connecting path. From this expression,

$$T_t=\frac{R^c}{K}T^{c4}+T^c$$

which makes it possible to express E as a function of T_c, as follows:

$$E=R_t\left(\frac{R^c}{K}T_c^4+T_c\right)^4+R_cT_c^4$$

To illustrate graphically how E varies with T_c under different conditions, the graphs of Figs. 3 and 4 have been prepared and the curves there shown all relate to an anode structure having a tungsten member with a surface area of 80 sq. cm. and a copper member with a surface of 100 sq. cm., since those are the dimensions of a practical structure. The radiation factor for a smooth tungsten surface of 80 sq. cm. has been determined from published data, according to which $R_t=1.17\times10^{-10}$. The radiation factor for copper depends on the condition of the surface and this factor has been determined experimentally for a surface of 100 sq. cm., both in a polished condition and also blackened for maximum radiation. The values thus ascertained are

$R_c=6.85\times10^{-11}$, polished
$R_c=2.95\times10^{-10}$, blackened

The factor K is also subject to variation, depending on the manner in which the two members are joined together. If the tungsten makes the best possible thermal contact with the copper, the two members are at practically the same temperature, in which case K can be considered equal to infinity. If the members are joined through a third member, the conductivity of that member will depend on the material of which it is made and other considerations. Thus, the member is to serve the practical purpose of supporting the tungsten as a distance from the end of the copper cylinder in a structure which is to rotate at a high speed, such as 3600 R. P. M., and it is important that the target disc rotate without any whipping action.

Therefore, the connecting member must have the necessary strength and rigidity for the purpose and such practical considerations are factors in determining the conductivity of the member actually used. A value of K that can be readily obtained in a practical structure is .044 watt of energy per degree absolute of temperature difference between the tungsten and copper members, but less conductivity may be obtained at some sacrifice of other characteristics of the member.

The curves in Fig. 3 illustrate the relationship between total energy radiated and the temperature of the copper rotor. For those curves, the factor K is taken as infinity, as is appropriate in consideration of a rotating anode structure of the first type. In the graph, E (total radiated energy) is plotted as a function of T_c (absolute temperature of the copper member), for the two conditions in which the copper is polished, so that $R_c=6.85\times10^{-11}$ (curve 1), and is blackened, so that $R_c=2.95\times10^{-10}$ (curve 2), respectively.

In Fig. 4, similar curves have been plotted for an anode structure of the second type, with K as .044. Curve 1 in Fig. 4 shows the relationship between E and T_c, with the copper polished, and curve 2 shows the same relationship with the copper blackened.

In considering the curves of both graphs, it must be borne in mind that a value of about 700° abs. (427° C.) is about the upper limit of a safe value of T_c. A comparison of Figs. 3 and 4 will then show that the result of blackening the copper rotor of a structure of the second type produces a much greater gain in total radiation than similar blackening of the rotor of a structure of the first type. Thus, Fig. 3 shows that, in the range of operating temperatures from about 400° to 700° abs., blackening the rotor of a structure of the first type approximately doubles the total energy radiated, whereas blackening a similar rotor of a structure of the second type produces much greater increases in the total energy radiated. At 600° abs., for example, blackening the rotor of a structure of the second type increases the total energy radiated about nine times.

In comparing the curves of the two graphs, it should be recalled that, in actual practice, the area of the blackened copper surface in an anode structure of the first type is usually somewhat greater than that assumed in plotting the curves and hence, the total dissipation obtainable from such a structure will be somewhat greater than the value of 95 watts indicated at $T_c=700°$ abs. However, it has been found, although it is not indicated on the charts, that in order to obtain radiation of the same total amount of energy as is radiated at $T_c=700°$ abs. from an anode of the second type having a blackened copper cylinder, an anode of the first type with a blackened rotor would have to have a radiating area of approximately 2200 sq. cm. This area is to be compared with the total area of 180 sq. cm. assumed in the example and the use of an anode having a total radiating area of 2200 sq. cm. would necessitate the use of an envelope of much greater over-all dimensions than would be desirable for most purposes.

In order to determine the range in which the effect of augmenting the heat dissipation from the rotor, as by blackening it, produces a disproportionate and unexpected increase in heat dissipating capacity of an anode structure of the second type, curves have been plotted to show the values of E as a function of K. For this purpose, the equation

$$E=R_t\left(\frac{R_c}{K}T_c^4+T_c\right)^4+R_cT_c^4$$

was employed with T_c taken as 700° abs. and R_t and R_c as the values previously assumed. E was then computed for various values of K through the range from .01 to 10 watts per degree of absolute temperature difference between the tungsten and copper members. For those values of K which would result in T_t (which equals

$$\frac{R_c}{K}T_c^4+T_c)$$

exceeding 1900° abs. which is a practical maximum working value, it was assumed that T_t, must not exceed that temperature and the value of E was then computed on that basis rather than on the basis of $T_c=700°$ abs. Thus, the two curves of Fig. 5 represent the relationship between E and K when maximum limits of 1900° abs. are placed on T_t and of 700° abs. on T_c, respectively. Curve 1, in Fig. 5 shows the relationship with respect to a polished copper rotor and curve 2 for a blackened copper rotor.

A comparison of the curves of Fig. 5 shows that, for a structure of the particular dimensions referred to, limitation of the value of K between the limits of approximately .012 and .5 results in an increase in total radiation produced by blackening the rotor which is entirely disproportionate to the added radiation from the rotor and is wholly unexpected. The curves indicate that the most advantageous condition is that with K between .04 and .06 and equal to approximately .05, which is a value that can be readily secured in practice. Values lower than .04 would be somewhat difficult to obtain in practice without going beyond desired dimensional limitations or sacrificing desirable characteristics for the conducting member.

In plotting the curves of Fig. 5, the principal elements of the cathode structure, namely, the copper member and the tungsten target were assumed to have radiating surfaces of 100 sq. cm. and 80 sq. cm. respectively. If other values for those areas were chosen, curves relating to such a structure and plotted in the manner of Fig. 5 would be generally similar in form and shape to those of Fig. 5. But the critical values of K would be different from those of .012 and .5 ascertained from Fig. 5. Analysis shows that the factor

$$\frac{R_c}{K}$$

in the equation for E is the factor whose values will determine the significant points on the curves. R_c is directly proportional to the area of the surface of the copper rotor, and hence the limits for the values of K resulting in disproportionate increases in total radiation produced by augmenting the radiating capacity of the rotor, as by blackening its surface, are directly proportional to the area of the rotor. Therefore, instead of the limiting values of K being .012 and .5, which are those for a rotor having a surface of 100 sq. cm., the values of K are .00012A and .005A, A being the area of the rotor in square centimeters. The most advantageous value of K is then approximately .0005A.

From the foregoing, it will be apparent that by the application of the principle of the invention, namely, augmenting the radiation factor of the copper rotor and, at the same time, restricting the conductivity of the connection between the copper and the tungsten within the limits of approximately .00012A and .005A, it is possible to construct a rotating anode X-ray tube having a maximum rating much higher than that of a similar prior tube containing an anode structure of the same type and dimensions. In the case of tubes mounted in rayproof or shockproof enclosures, further limitations may be imposed by the necessity of cooling the tube within the enclosure. Also, limitations may be imposed because of the oil and other insulating materials used and of the parts employed for the enclosure. However, shockproof X-ray units containing oil immersed tubes embodying the invention have been constructed which have a rating of 5 MA. at 85 PKV for thirty minutes continuously, or indefinitely for intermittent operation in which the rest periods are equal to the operating periods, the latter not exceeding ten minutes maximum. Such a rating is a practical working rating for fluoroscopy and is obtained without artificial cooling means. That rating is equal to the ratings of the best shockproof tubes of the stationary anode type in which a substantial proportion of the heat generated in operation is carried to the exterior of the tube through the anode shank and dissipated from the exposed portion of the shank.

We claim:

1. A rotary anode for use in an X-ray tube which comprises a cylindrical member made mainly of a metal of good electrical and heat conductivity and having a blackened surface, a target of a refractory metal, and a connection between the member and the target having a heat conductivity ranging from about .00012A to about .005A watts per degree abs. of temperature difference between the target and the member, A being the area in square centimeters of said surface of the member.

2. A rotary anode for use in an X-ray tube which comprises a cylindrical member made mainly of a metal of good electrical and heat conductivity and having a blackened surface, a target of a refractory metal, and a connection between the member and the target having a heat conductivity ranging from about .0004A to about .005A watts per degree abs. of temperature difference between the target and the member, A being the area in square centimeters of said surface of the member.

3. A rotary anode for use in an X-ray tube which comprises a cylindrical member made mainly of a metal of good electrical and heat conductivity and having a blackened surface, a target of a refractory metal, and a connection between the member and the target having a heat conductivity ranging from about .0004A to about .0006A watts per degree abs. of temperature difference between the target and the member, A being the area in square centimeters of said surface of the member.

4. A rotary anode for use in an X-ray tube which comprises a cylindrical member mainly of copper and having a blackened radiating surface, a target of tungsten, and an element connected to the member and supporting the target, the element serving as a heat conducting path between the target and member and having a heat conductivity ranging from about .00012A to about .005A watts per degree abs. of temperature difference between the target and member, A being the area in square centimeters of said surface of the member.

5. A rotary anode for use in an X-ray tube which comprises a cylindrical member mainly of copper and having a blackened radiating surface, a target of tungsten, and an element connected to the member and supporting the target, the element serving as a heat conducting path between the target and member and having a heat conductivity ranging from about .0004A to about .005A watts per degree abs. of temperature difference between the target and member, A being the area in square centimeters of said surface of the member.

6. A rotary anode for use in an X-ray tube which comprises a cylindrical member mainly of copper and having a blackened radiating surface, a target of tungsten, and an element connected to the member and supporting the target, the element serving as a heat conducting path between the target and member and having a heat conductivity ranging from about .0004A to about .0006A watts per degree abs. of temperature difference between the target and member, A being the area in square centimeters of said surface of the member.

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