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J. FORMAN

3,056,912

THERMOELECTRIC GENERATOR

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2 Sheets-Sheet 1

Fig. 1

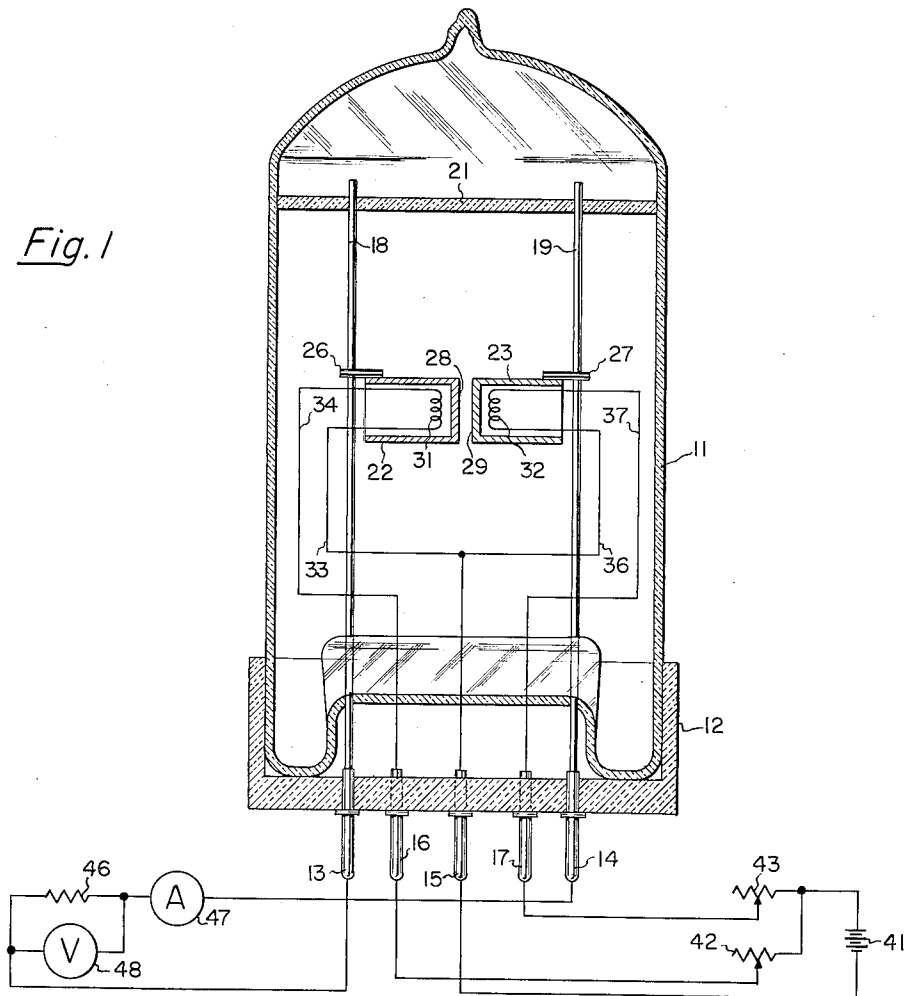
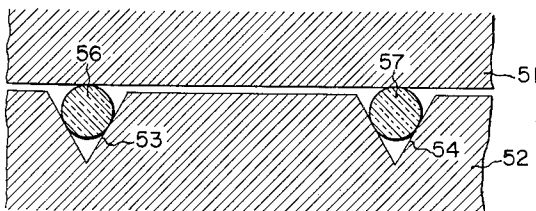


Fig. 2



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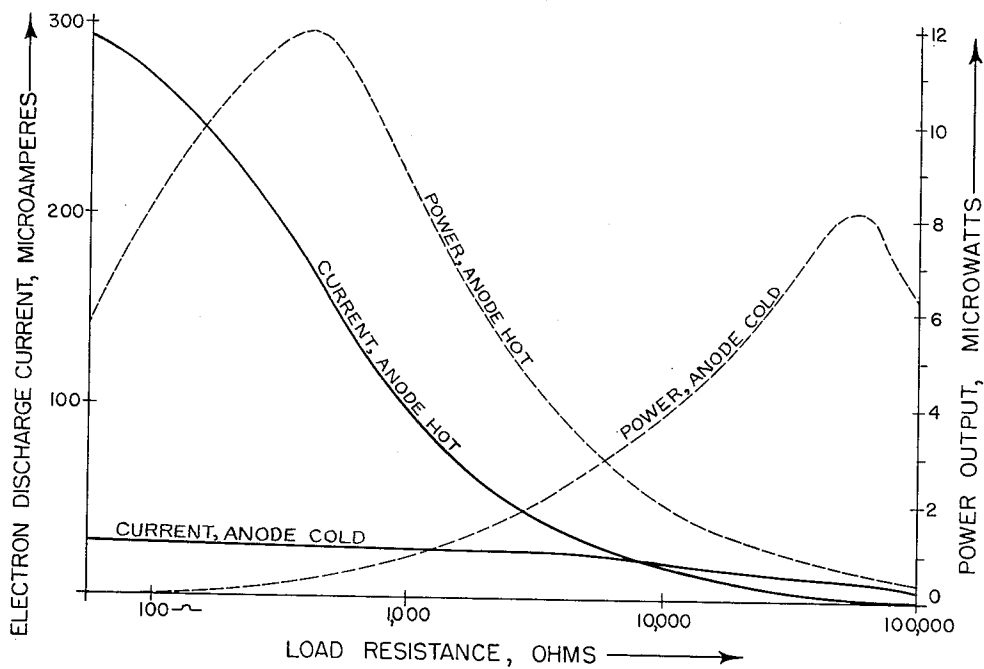
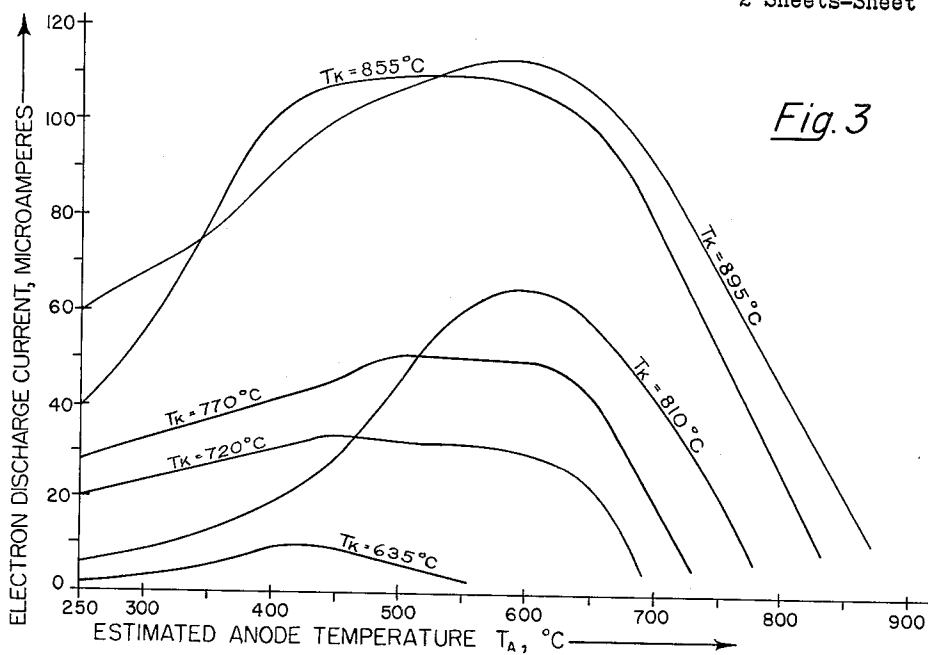
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This invention relates to electron discharge devices, and in particular to such devices having an emitter electrode heated to thermionic emission temperatures and a collector electrode.

In the design of a vacuum tube device there are several factors, the choice of which determines the perveance of the device. The perveance of a vacuum tube for a given tube structure is an essentially constant term in an expression giving the electron current due to the electron emission from the emitter electrode, commonly referred to as the cathode, which arrives at the collector electrode, commonly referred to as the anode. The perveance of a tube is known to depend on the tube geometry, notably the area and spacing of the emitter and collector electrodes, on the extent of evacuation of the tube envelope, and on the properties of the emitter surface as determined by the nature of its composition and by its temperature.

With respect to the collector electrode, however, much less attention has been paid to the condition of its surface, since it is not intended to function as an emitter, and since in fact the function of the tube would be defeated in many applications if the collector surface did serve as an electron emitter. For this reason the choice of anode material and its surface condition has been determined primarily by considerations of structural convenience and without regard to the possible influence of the condition of the anode surface, as distinguished from its shape, size, and placement, upon the perveance of the tube. These considerations apply to some degree to all electron discharge devices without limitation to diodes. Thus electron discharge devices may be relatively inefficient in operation due to failure to provide an anode surface condition conducive to maximum electron discharge current between cathode and anode.

It is an object of this invention, therefore, to provide a new and improved electron discharge device which avoids one or more of the disadvantages of the prior art devices.

It is another object of the invention to provide a new and improved method of effecting electron discharge currents between a thermionic emitter electrode and a collector electrode.

It is a further object of the invention to provide new and improved electron discharge devices of increased perveance resulting from the conditioning of both the emitter and collector surfaces.

It is yet another object of the invention to provide a new and improved electrical generator for transducing from thermal energy, applied to electrodes in an evacuated envelope, to electrical energy represented by an electromotive force developed between these electrodes and by the corresponding thermionic currents passing therebetween.

In accordance with the invention, an electron discharge device, having in an evacuated envelope an emitter electrode arranged to be heated to a thermionic emission temperature and a collector electrode spaced therefrom, comprises in association with the collector electrode, means for increasing the magnitude of any electron discharge currents passing through the device by heating the collector electrode to an elevated temperature above 400° C. but at least about 100° C. less than the aforementioned emitter electrode temperature. More generally expressed, the collector electrode temperature should have a value above 400° C. but less than about 90 percent, on an

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absolute temperature scale, of the value of the emitter electrode temperature.

Also in accordance with the invention, the method of effecting electron discharge currents in an evacuated envelope between an emitter electrode heated to a thermionic emission temperature and a collector electrode comprises applying heat to the collector electrode to raise it to an elevated temperature above 400° C. but at least about 100° C. less than the emitter electrode temperature, whereby the magnitudes of the discharge currents obtainable are substantially greater than those obtainable when the collector electrode is subjected only to such heating as might be incidental to operation of the diode without the aforementioned application of heat to raise the collector electrode to such elevated temperature.

In accordance with a feature of the invention, an electrical generator comprises an evacuated envelope, emitter and collector electrodes therein having mutually confronting surfaces, means for heating the emitter electrode to a thermionic emission temperature and for heating the collector electrode to an elevated temperature above 400° C. but at least about 100° C. less than the aforementioned emitter surface temperature, and circuit connections through the envelope to the emitter and collector electrodes for utilizing the electrical energy, transduced from the thermal energy applied to the electrodes, which is represented by an electromotive force developed between the electrodes and by the corresponding thermionic currents passing therebetween.

In accordance with a further feature of the invention, an electron discharge device, having a vacuum tube envelope containing two heated electrodes with respective, mutually confronting, closely spaced surfaces of substantial area, comprises, on these electrodes, individual polished surface portions of closely matching shape forming the confronting surfaces, means for biasing these surfaces of the electrodes toward each other, and an arrangement for maintaining the relative spacing of these surface portions. This arrangement includes in one of the surface portions a plurality of notches, each having a predetermined depth and each having wall portions with a predetermined mutual angle of inclination opening outwardly toward the other of the surfaces, and also includes a plurality of insulating members having arcuate portions extending from the aforesaid other surface and seated in corresponding ones of the notches at points determined by the curvature of the arcuate portions.

For a better understanding of the present invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawings and its scope will be pointed out in the appended claims.

In the drawing,

FIG. 1 illustrates in sectional elevation a diode vacuum tube structure embodying the present invention and including in schematic representation certain circuit components associated therewith;

FIG. 2 is a lateral sectional elevation giving a detailed view of an alternative arrangement for maintaining electrode spacing in a tube structure generally similar to that of FIG. 1;

FIG. 3 is a graph, including a family of curves for various cathode temperatures, giving the relationship between the anode temperature and the electron discharge current in a diode structure; and

FIG. 4 is a graphical representation for cold and hot anode temperature conditions of the electron discharge current and of the corresponding power delivered to an external load as a function of the load resistance.

Referring now to FIG. 1 of the drawings, there may be seen in a sectional view taken vertically through its center

a vacuum tube structure comprising a vacuum tube envelope or evacuated shell including a cylindrical glass tube 11. The open end of the glass tube 11 is sealed at the bottom thereof within a shallow cup 12 of a reinforced plastic or resin material in conventional manner. Electrode lead pins 13, 14, 15, 16 and 17 protrude downward through the base 12 for effecting electrical connections to the interior of the envelope. The envelope has been sealed at its top in conventional manner after thorough evacuation using known techniques to obtain a high vacuum in spite of the tendency of certain gases to be adsorbed on the internal surfaces.

The structures within the tube are carried by a pair of posts 18 and 19, which are supported at their lower ends as they pass through the base 12 and at their upper ends by a mica disk 21, the periphery of which rests against the inside surface of the glass tube 11 near the top of the tube. The posts 18 and 19 are insulated from each other electrically and thermally by the material of the base 12 and the disk 21, and the lower ends of these posts form the above-mentioned lead pins 13 and 14 respectively.

An emitter electrode 22 and a collector electrode 23 are supported within the tube envelope by respective bracket members 26 and 27, the member 26 being spot-welded to the post 18 and to the left end of the electrode 22 and the member 27 being spot-welded to the post 19 and to the right end of the electrode 23. In this way conductive connections are obtained from the electrode 22 through the member 26 and post 18 to the pin 13 as well as from the electrode 23 through the member 27 and post 19 to the pin 14. The spaced electrodes 22 and 23 have the form of metallic cylinders, each closed at one end to provide mutually confronting spaced surfaces 28 and 29 respectively, while the cylinders are open at their other or outer ends. By appropriate design of the supporting structures, and if necessary with the inclusion of additional structural members such as 26 and 27 to hold the electrodes rigidly within the envelope, the confronting electrode surfaces 28 and 29 can be held in parallelism and closely spaced even though the confronting surfaces may be of substantial area. Alternative arrangements providing closely spaced electrode surfaces of large area are discussed hereinbelow in connection with FIG. 2 of the drawings.

Means are provided in the FIG. 1 arrangement for heating the emitter electrode, for example the electrode 22 or at least its electrode surface 28, to a thermionic emission temperature and for heating the collector electrode, for example the electrode 23 or at least its electrode surface 29, to an elevated temperature above 400° C. but less than a temperature of efficient thermionic emission for the collector surface 29 and between about 100° C. and 400° C. less than the emitter surface temperature. In the illustrated embodiment this means comprises two heater elements 31 and 32 disposed individually adjacent to and within the cylindrical emitter and collector electrodes 22 and 23 respectively and near the ends thereof whose external surfaces form the respective electrode surfaces 28 and 29. These heater elements are supported within the electrode structures by respective pairs of insulated lead conductors 33, 34 and 36, 37 so that the heater circuits are insulated electrically from the electrode structures. Thus the heating of the inner ends of the electrodes 22 and 23, and specifically of the electrode surfaces 28 and 29, is accomplished by radiation from the heater elements 31 and 32, which are surrounded by and supported in closely spaced relationship to the portions of the electrode structures which are desired to be heated. The lead conductor 33 from the element 31 and the conductor 36 from the element 32 are connected to a common lead pin 15, while the conductors 34 and 37 from the respective heater elements pass to pins 16 and 17 respectively.

The aforementioned means for heating the electrodes also includes means for energizing the heater elements 31 and 32 to maintain the surfaces 28 and 29 at the specified temperatures. The last-mentioned means in-

cludes a source of heater energy, illustrated in the form of a battery 41 one terminal of which is connected, when the device is in use, to the lead pin 15 and thence to one side of each of the heater elements 31 and 32. In circuit with the battery 41 is a variable resistor 42, the tap of which is shown connected to the lead pin 16 and thence through the conductor 34, the heater element 31 itself, and the conductor 33 back to the battery 41. By virtue of these connections the emitter electrode 22 is arranged to be heated to a thermionic emission temperature. The energizing means for the heater elements further includes another variable resistor 43 in circuit with the battery 41. The adjustable tap of the resistor 43 is connected to the lead pin 17 and thence through the conductor 37, the heater element 32 itself, the conductor 36, and the lead pin 15 back to the battery 41. Thus the resistor 43 is a part of a means for heating the collector electrode to the desired temperature mentioned hereinabove.

The circuits shown connected to the tube structure in the illustrated embodiment further include a load impedance 46 connected across the lead pins 13 and 14 so as to be in circuit with the emitter and collector surfaces 28 and 29. An ammeter 47, preferably of low impedance, is connected in series in this circuit, while a voltmeter 48, preferably of high impedance, is connected in shunt across the load impedance 46.

In the operation of the electron discharge device represented in the drawing the resistor 42 is adjusted in a manner well known in the art to obtain the desired thermionic emission temperature in the surface 28 of the emitter electrode 22. This temperature varies considerably in accordance with the material constituting the surface 28, and the material of this surface may be prepared in accordance with any of the techniques known to the art of thermionic devices. For example, the surface 28 may be an oxide-coated cathode, in which case the electrode structure 22 may be of any suitable alloy such as platinum-iridium or nickel-platinum. Konel metal is well known for this purpose, and metallic nickel itself has been used successfully in the structure shown in the drawing. The surface 28 may be prepared by applying a coating of an alkaline earth carbonate such as barium carbonate and activating by heating, this forming process producing a barium oxide emitting surface. In such a case the resistor 42 preferably is adjusted to obtain a thermionic emission temperature at the surface 28 of approximately 700-900° C. The higher temperature involved in the activation and forming procedure for the emissive surface may be obtained by a temporary application of higher voltages between the lead pins 15 and 16.

It will be appreciated that the arrangement and operation thereof thus far described, with the exception of the inclusion of the heater element 32 within the collector or anode electrode 23 and the connections to the resistor 43, are rather similar to the conventional diode arrangement of the type used, for example, in circuit with a signal source, not shown, connected in series with the load impedance 46 and the ammeter 47 in the external circuit. With such arrangements signal currents pass through the ammeter 47 and the impedance 46 to develop corresponding signal potentials across the impedance 46, as may be indicated by the voltmeter 48.

Also in accordance with a recognized phenomenon, sometimes referred to as the Edison effect, the external circuit arrangement illustrated in the drawing may be used to record the passage of small currents through the ammeter and the load impedance in the absence of an applied electrical signal. The very small energy represented by these currents and by the corresponding voltages developed across the impedance 46 is transduced from the thermal energy introduced into the device from the source 41 of heater energy. Thus in a specific structure involving electrode surfaces 28 and 29, each of approximately 0.01 square inch area and spaced about 0.01 inch from each other, the resistor 42 was adjusted

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to obtain a dissipation of 4.95 watts in the heater 31, whereupon the ammeter 47 recorded a current of 60 microamperes through the load resistance 46 and a corresponding potential drop thereacross without the application of an external electromotive force to the diode and load circuit.

Turning now to operation of the electron discharge device in accordance with the present invention, the resistor 43 is adjusted to permit the flow of heater current through the heater winding 32 such that the aforementioned elevated temperature is obtained at the collector or anode surface 29. This surface, along with the entire electrode structure 23, conveniently may be of metallic nickel.

While the present invention is not dependent in any way upon the validity of any theoretical considerations which may be developed herein, it is possible that the improvement in operation of the electron discharge device obtainable by the heating of the collector surface 29 is due to a lowering in the work function of that surface. It will be understood that the temperature of the surface 29 should not reach the temperatures of substantial high thermionic emission for that surface, since it is desirable to achieve as high a net electron current flow as possible from the emitter surface 28 to the collector surface 29. Surprisingly enough, however, the maintenance at the collector surface of the elevated temperatures specified herein has been found to cause the diode structure and the load impedance to carry electrical signals having substantially increased magnitudes under otherwise similar circumstances. With nickel electrode structures and a barium oxide coating on the emitter, temperatures of the collector surface within an approximate range of 400-750° C., depending on cathode temperature, have been found to cause very substantial increases in the perveance and in the discharge currents delivered by the diode.

Thus with 4.95 watts dissipated in the emitter heater 31, as described hereinabove, and an adjustment of the resistor 43 to cause the dissipation of 2.6 watts in the collector heater 32, the current through the ammeter 47 and the load impedance 46 increased from 60 to 505 microamperes. To ascertain that a similar improvement would not have been obtained by dissipating the same total heating power in the emitter heater 31 alone, the resistor 43 was adjusted for zero volts across the heater 32 while the adjustment of the resistor 42 was changed to increase the power dissipated in the heater 31 to 7.55 watts. This causes the current to decrease to 40 microamperes. The fact that the last reading was lower than the 60 microampere reading obtained with only 4.95 watts dissipated in the emitter heater may be explained by the sensitivity of the structure to minor changes when the current and power levels are so low or possibly may be due to exceeding the optimum cathode emission temperature or to migration of barium from the surface 28 to the surface 29 at high temperatures.

It will be appreciated that, assuming the applicability of the theoretical discussion hereinabove, it would be possible to obtain a surface composition or structure on the collector electrode such that its work function actually would not be decreased substantially when it is heated to the elevated temperatures specified herein, and that this possibly might defeat the improvement expected as a result of the heating of the collector surface. Nevertheless a 5-fold to 10-fold improvement in the perveance of the tube at low load impedances, and a substantial improvement in the power output of the tube used as a generator when the external resistive load matches the internal impedance of the generator, easily are obtained with the nickel electrode 23, whether or not contaminated by some barium transported from the surface 28; the ordinary skill of the tube designer and manufacturer will permit the avoidance of ineffectual collector surfaces which are not substantially improved by the heating of

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the collector surface in accordance with the present invention.

While the FIG. 1 arrangement has been found convenient for experimental purposes, a great variety of diode structures and methods of heating the electrodes obviously may be utilized in carrying out the present invention. For example, many arrangements of electrode heaters are possible. The two heaters 31 and 32 even might be formed as a unitary structure with a larger part of the heater structure adjacent to the emitter electrode and the smaller part adjacent to the collector electrode, so that upon application of a specified potential across the entire heater a predetermined amount of heat will be radiated to each of the electrode structures to obtain the temperatures, within the ranges discussed hereinabove, desired at the two electrode surfaces. An alternating current electrical source may be substituted, of course, for the direct current source 41. Numerous other arrangements for heating the electrodes, and particularly the collector electrode, by radiation or conduction may be resorted to, and one or both electrodes even might be heated by radiation from a surface outside of the envelope 11. Alternatively the collector electrode, or both electrodes, might be heated by the waste heat in hot gases such as the combustion products of a fuel-burning apparatus with suitable thermostatic control of the entrance gases to maintain the desired temperature at each electrode. In any event, the method of effecting electron discharge currents in the evacuated envelope 11 between the emitter electrode 22 heated to a thermionic emission temperature and the collector electrode 23 comprises applying heat to the collector electrode to raise it to the aforementioned elevated temperature, whereby the magnitudes of the discharge currents are substantially greater than those obtainable when the collector electrode is not subjected to heating, except such as might be incidental to operation of the diode without the application of heat to raise the electrode 23 to the specified elevated temperature. It will be understood that the thermionic emission temperature specified herein and in the appended claims for the emitter surface ordinarily is not the lowest temperature at which some emission may occur, but rather is a temperature, within the range of substantial emission for the emitter surface involved, which would be chosen in accordance with conventional design practice for such a surface; in other words, a temperature high enough to afford efficient cathode emission but not so high as to prejudice unduly the life of the heater and emitter structures.

When the method is carried out, as indicated in the drawing, for transducing from thermal to electrical energy, the procedure comprises heating both electrodes of an evacuated diode structure having respective, mutually opposed, closely spaced emitter and collector surfaces to maintain the emitter electrode surface at a thermionic emission temperature while maintaining the collector electrode surface within the aforementioned elevated temperature range. In such a case the electrical load 46, in circuit with the electrodes 22 and 23, is energized with the electrical energy which is transduced from the thermal energy applied to the electrodes and which is represented by an electromotive force developed between the electrodes and by the corresponding thermionic currents passing therebetween. It is noteworthy that these thermionic currents are increased substantially by the maintenance of the collector electrode at such elevated temperature, in spite of the fact that the temperature difference between the electrodes has been decreased thereby.

Although the power obtainable from the diode structure described hereinabove without the application of an external potential source is not large, it nevertheless is substantial, and the thermal generator of this feature of the invention may be made to produce very sizable and obviously useful amounts of energy by decreasing the spacing of the electrodes and increasing their area.

When waste heat, for example from rocket or jet exhausts, is used for heating both electrodes, as proposed hereinabove, a generator device without moving parts, of indefinitely long life, and free of maintenance difficulties is achieved. Numerous structural arrangements for realizing the suggested electrode configuration at relatively small cost and in a relatively small volume will present themselves. For example, electrode surfaces in the form of relatively large discs or rectangular plates may be maintained with the desired small spacing, preferably less than 0.001 inch and in the neighborhood of 0.0005 inch, by the use between the electrode surfaces of spherical or cylindrical insulating spacers having an accurately predetermined radius and which are seated in V-shaped grooves machined to a predetermined V-angle in the opposed surfaces.

Referring now to FIG. 2, which illustrates a form of electrode arrangement similar to that just mentioned, there is shown in sectional elevation the surface portions of the opposing emitter and collector surfaces 51 and 52, it being understood that either of these may be the emitter structure and the other the collector. One of these surface portions, for example 52, is provided with a plurality of V-shaped grooves or notches 53 and 54. The depth and angular inclination of the walls of these grooves may be determined very accurately using known techniques for machining such grooves. Seated in these grooves are respective insulating members 56 and 57, which may be rods, having circular cross sections of closely predetermined diameter, so that the radii of curvature of the portions of the members 56 and 57 which contact the sides of the grooves 53 and 54 are closely controlled. The portions of the members 56 and 57 protruding from the grooves serve to maintain the surface 51 at the predetermined close spacing from the surface 52. A spring arrangement, not shown, may be provided to exert a mechanical bias force urging the electrodes having the surface portions 51 and 52 toward each other to maintain the members 56 and 57 in place with approximately equal pressure on the several members. The natural elasticity of supporting members, such as the posts 18 and 19 in the FIG. 1 arrangement, may serve to provide the necessary mechanical bias.

With respect to the tube illustrated in FIG. 1 and described hereinabove, measurements have been made to determine the electron discharge currents generated in this tube and passed through a suitable external load resistor under various conditions of cathode and anode temperatures. Such data are recorded in the graph of FIG. 3, in which estimated anode centigrade temperatures, T_a , are represented along the abscissa and corresponding electron discharge currents in microamperes are represented along the ordinate. A family of six curves is shown for various conditions of cathode temperature, T_k , as indicated above each curve in the drawing. It will be seen that high emission currents can be expected with the oxide emitter at the usual cathode temperatures within the approximate range of 750 to 850° C.

In any case it will be seen from FIG. 3 that an anode temperature of at least 400° C. is advisable for high discharge currents, and that the highest currents are obtained when the anode temperature is about 100° C. to 400° C. less than the cathode temperature. It may be noted also that a representative anode surface temperature of about 825° C., corresponding to an absolute temperature of about 1100° K., would require anode temperatures within the range of roughly 400° C. to 725° C. for maximum currents, corresponding to absolute temperatures of the anode surface of between about 675° K. and 1000° K. Accordingly, in general, anode temperatures for maximum current should be less than about 90% of the cathode temperature and preferably more than about 60% of the cathode temperature, with temperatures expressed on an absolute scale. Similar temperature relationships, either expressed in the usual temperature terms, such as

anode temperatures having values in centigrade degrees equal to the specified number of degrees less than the cathode temperature, or expressed in terms of relative temperature on an absolute scale, may be adopted with corresponding beneficial results for other types of emitter and collector surfaces.

To obtain the greatest improvement in electron discharge levels in carrying out the present invention, attention should be given to the choice of the impedance of the external load. The curves in the graph of FIG. 4 illustrate the effect of load impedance variations when the tube arrangement described hereinabove is used as a generator with the anode cold, or unheated, and with the anode hot, or heated to the temperatures giving relatively high outputs.

Load resistance in ohms is represented in FIG. 4 along the abscissa on a logarithmic scale. The two solid line curves give the electron discharge currents in microamperes, using the ordinate scale at the left of the graph, for the two cases of cold anode and hot anode, as indicated adjacent to the curves. It is noted that decreasing the load resistance causes the current to increase when the anode is heated, and that load resistances less than about 6,000 ohms must be used to obtain relatively high currents greater than those obtainable without heating the anode.

The two dashed line power curves in FIG. 4 indicate that the tube arrangement or generator of the invention tends to have a low effective internal impedance. The power output curves are identified on the graph for the hot and cold anode cases and relate to the ordinate scale in microwatts at the right of the graph. These curves again show a cross-over at about 6,000 ohms for the two anode conditions. Power output with the anode hot exceeds the highest obtainable without heating the anode when the load resistance has any value within the range between about 100 and 1,000 ohms, and the maximum power was recorded with a load of about 400 ohms. It appears from the curves of FIG. 4 that a few trials will show the best load impedance for a given tube structure and anode temperature.

While there have been described what at present are considered to be preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention. It is aimed, therefore, in the appended claims to cover all such changes and modifications which fall within the true spirit and scope of the invention.

What is claimed is:

1. An electrical generator, comprising: a vacuum tube envelope; emitter and collector electrodes therein having mutually confronting spaced surfaces; two heater elements individually adjacent to said emitter and collector electrodes; and means for energizing said heater elements to maintain said surface of said emitter electrode at a thermionic emission temperature and to maintain said surface of said collector electrode at an elevated temperature above 400° C. but at least about 100° C. less than said emitter surface temperature.

2. An electron discharge device comprising, in combination, a vacuum tube envelope, an emitter electrode and a collector electrode in the envelope having closely spaced apart mutually confronting emitting and collecting surfaces, means for heating said emitter electrode to a thermionic emission temperature, separate means for heating said collector electrode to an elevated temperature above 400° C. but at least approximately 100° C. less than said emitting surface temperature of the emitter electrode, and circuit connections through said envelope to said emitter and collector electrodes.

3. An electron discharge device comprising, in combination, an evacuated envelope, an emitter electrode in the envelope having a relatively flat emitter surface, a collector electrode in the envelope having a relatively flat

collector surface, means mounting the electrodes in the envelope with the respective flat surfaces thereof in parallel mutually confronting relationship and spaced apart not more than approximately .01 inch, means for heating the emitter electrode to a thermionic emission temperature, and means for heating the collector electrode to an elevated temperature above 400° C. but between about 100° C. and 400° C. less than the emitter surface of the emitter electrode.

4. An electron discharge device comprising, in combination, an evacuated envelope, an emitter electrode in the envelope having a relatively flat emitter surface, a collector electrode in the envelope having a relatively flat collector surface, means mounting the electrodes in the envelope with the respective flat surfaces thereof in parallel mutually confronting relationship and spaced apart not more than approximately .01 inch, means for heating the emitter electrode to a thermionic emission temperature, and means for heating the collector electrode to a temperature below that of the emitter electrode.

5. An electron discharge device for directly transducing thermal to electrical energy comprising, in combination, a substantially evacuated chamber, an emitter electrode in the chamber having a relatively flat emitter surface, a collector electrode in the chamber having a relatively flat collector surface, means mounting the electrodes in the chamber with the respective flat surfaces thereof in parallel mutually confronting relationship and spaced apart less than approximately .01 inch, means for heating the emitter electrode to a thermionic emission temperature, and means for heating the collector electrode to a temperature cooler than that of the emitter electrode, and a circuit connection for each electrode leading out of the chamber.

6. In an electron discharge device for directly transducing thermal to electrical energy, an emitter electrode having a smooth electron emitting surface, a collector electrode having a smooth electron collecting surface in close confronting relation to the emitting surface of the emitter electrode and spaced therefrom a distance no greater than approximately .001 inch, circuit leads connected to the emitter and collector electrodes, and means for heating said emitter electrode to a thermionic emission temperature and for heating said collector electrode to a temperature cooler than that of the emitter electrode.

7. A device for converting heat directly into electricity, including, in combination, a cathode electrode having an electron emitter surface, an anode electrode having an electron collecting surface, means mounting the cathode and anode electrodes with their respective emitting and collecting surfaces in close mutually confronting relation and spaced apart from one another a distance no greater than approximately .0005 inch, means maintaining the space between said confronting surfaces of the electrodes in a substantially evacuated condition, and means for maintaining the temperature of the cathode electrode at an elevated temperature level to cause the propagation of electrons from the emitter surface of the cathode electrode to the collector surface of the anode electrode and for simultaneously maintaining the temperature of the anode electrode at an elevated temperature level cooler by at least 10 percent, on an absolute temperature scale, than the temperature of the cathode electrode.

8. A device for converting heat directly into electricity, comprising, in combination, a cathode electrode having an electron emitter surface, an anode electrode having an electron collecting surface, means mounting the cathode and anode electrodes with their respective emitting and collecting surfaces in close mutually confronting relation and spaced apart from one another a distance no greater than approximately .0005 inch, means maintaining the space between said confronting surfaces of the electrodes substantially free from substances retarding electron propagation thereacross, and means for maintaining the temperature of the cathode electrode at an elevated tempera-

ture to cause the propagation of electrons from the emitter surface of the cathode electrode to the collector surface of the anode electrode and for simultaneously maintaining the temperature of the anode electrode at an elevated temperature cooler than the temperature of the cathode electrode.

9. A device for converting heat directly into electricity, comprising, in combination, a cathode electrode having an electron emitter surface, an anode electrode having an electron collecting surface, means mounting the cathode and anode electrodes with their respective emitting and collecting surfaces in close mutually confronting relation and spaced apart from one another a distance no greater than approximately .0005 inch, means maintaining the space between said confronting surfaces of the electrodes substantially free from substances retarding electron propagation thereacross, means for raising the temperature of the cathode electrode to an elevated temperature to cause the propagation of electrons from the emitter surface of the cathode electrode to the collector surface of the anode electrode and for simultaneously maintaining the temperature of the anode electrode at an elevated temperature cooler than the elevated electron propagating temperature of the cathode electrode, and a circuit connected across said cathode and anode electrodes for utilizing the electrical energy transduced from the thermal energy applied to said electrodes and having an impedance approximately matching the effective impedance across the electrodes.

10. In a device for directly transducing thermal energy to electrical energy, an emitter electrode having a smooth electron emitting surface, a collector electrode having a smooth electron collecting surface in close confronting relation to the emitting surface of the emitter electrode and spaced therefrom a distance no greater than approximately .0005 inch, circuit leads connected to the emitter and collector electrodes, and means for heating said emitter electrode to a thermionic emission temperature and for heating said collector electrode to an elevated temperature above 400° C. but between approximately 60 and 90 percent, on an absolute temperature scale, of said emitter electrode temperature.

11. A device for directly transducing thermal energy to electrical energy comprising, in combination, an emitter electrode having a relatively flat electron emitter surface, a collector electrode having a relatively flat electron collector surface, means mounting the electrodes with their respective emitter and collector surfaces in parallel mutually confronting relationship and spaced apart less than approximately .001 inch, means maintaining the space between said confronting surfaces substantially free of substances retarding electron propagation thereacross, means for heating the emitter electrode to a temperature providing effective thermionic emission, means for heating the collector electrode to a temperature cooler than that of the emitter electrode, and a circuit connected across said electrodes for utilizing the electrical energy transduced from the thermal energy applied to the electrodes.

12. A device for directly transducing thermal energy to electrical energy comprising, in combination, an emitter electrode having a relatively flat emitter surface, a collector electrode having a relatively flat electron collector surface and disposed with its collector surface in mutual confronting relation to the emitter surface of the emitter electrode, means interposed between the confronting surfaces of the electrodes and spacing the surfaces from one another not more than .001 inch, means for heating the emitter electrode to a thermionic emission temperature, and means for heating the collector electrode to a temperature below that of the emitter electrode.

13. In a device for directly converting thermal energy to electrical energy, a cathode electrode and an anode electrode, a surface portion of the cathode electrode being of a material having a relatively high thermionic emission property at highly elevated temperatures, a surface por-

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tion of the anode electrode being of another material and electrically conductive, means mounting the electrodes in confronting relation to one another with the said surface portion of the cathode electrode directly opposed to said surface portion of the anode electrode and such that the distance separating said surface portions is no greater than approximately .001 inch, and means maintaining the space between said confronting surface portions substantially free from substances retarding electron propagation thereacross.

14. In a device for directly converting thermal energy to electrical energy, a cathode electrode and an anode electrode, a surface portion of the cathode electrode being of a material having a relatively high thermionic emission property at highly elevated temperatures, a surface portion of the anode electrode being of another material and electrically conductive, means mounting the electrodes in confronting relation to one another with the said surface portion of the cathode electrode directly opposed to said surface portion of the anode electrode and such that the

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distance separating said surface portions is no greater than approximately .0005 inch, and means maintaining the space between said confronting surface portions substantially free from substances retarding electron propagation thereacross.

References Cited in the file of this patent

UNITED STATES PATENTS

2,034,571	Found	Mar. 17, 1936
2,034,572	Found	Mar. 17, 1936
2,126,787	Le Bel	Aug. 16, 1938
2,191,594	Spencer	Feb. 27, 1940
2,414,137	Branson	Jan. 14, 1947
2,510,397	Hansell	June 6, 1950
2,688,648	McIlwaine	Sept. 7, 1954
2,759,112	Caldwell	Aug. 14, 1956
2,782,337	Robinson	Feb. 19, 1957
2,847,643	De Boisblanc	Aug. 12, 1958
2,863,074	Johnstone	Dec. 2, 1958