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THERMO-ELECTRIC GENERATOR

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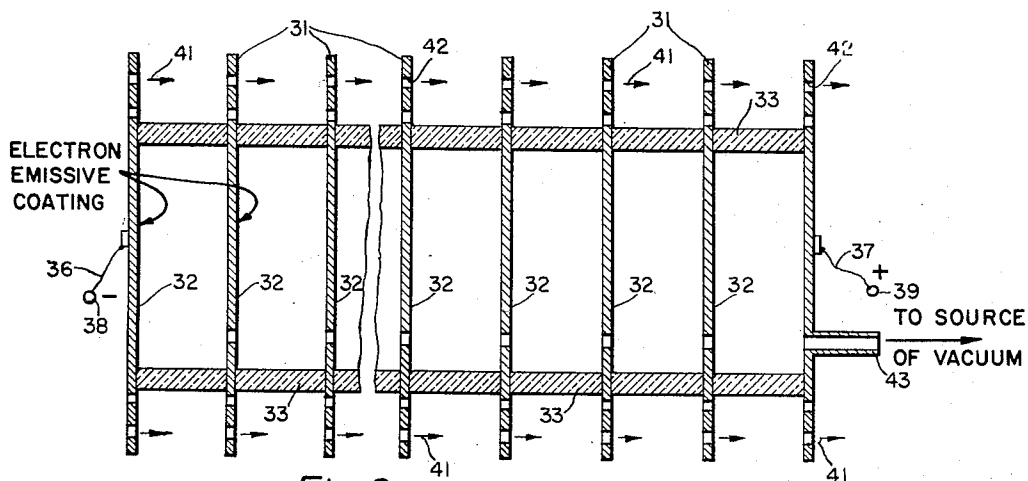


Fig. 2

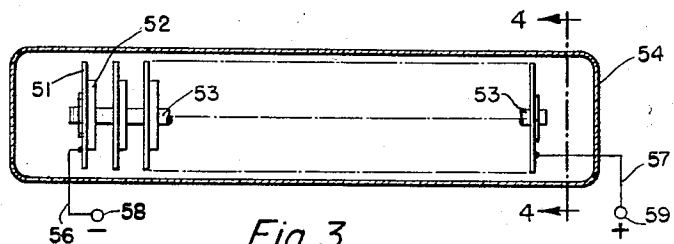


Fig. 3

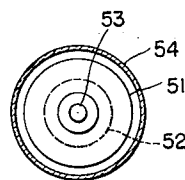


Fig. 4

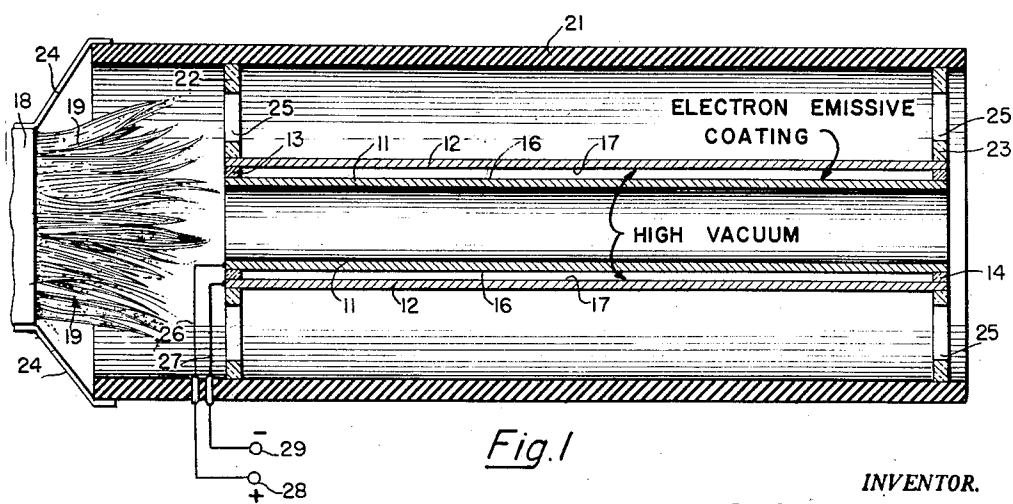


Fig. 1

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1

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THERMO-ELECTRIC GENERATOR

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This invention relates to direct current electric generating apparatus and has for its object to provide improved apparatus, not involving the use of mechanically moving parts, which will convert input energy in the form of heat into output energy in the form of direct current (D. C.). Although the apparatus provided by this invention is essentially a heat-D. C. converter, the invention is, as will be seen later, such that it may be used to produce output D. C. from other forms of energy input, the production of heat being an intermediate stage in the conversion chain. Thus the invention may be used to convert A. C. to D. C. by producing heat from the A. C. and translating the heat into D. C.

In accordance with the invention, an electric generator comprises mutually confronting anode and cathode structures, the surface of the anode structure being of a conductive metal and the surface of the cathode structure being of another material having a relatively very high thermionic emission property at elevated temperatures. The generator further comprises means for sealing the space between the anode and cathode structures and for maintaining this space substantially free from substances retarding electron propagation, means for continuously heating both of the anode and cathode structures to elevated temperatures while maintaining the anode surface at a temperature at least approaching that of the cathode surface, and circuit connections to the anode and cathode structures for utilizing the electromotive force developed therebetween at the elevated temperatures as a result of the net electron flow from the highly emissive surface of the cathode structure to the anode structure.

In accordance with a feature of the invention, a direct current electric generating apparatus comprises a plurality of diodes in cascade, each individual diode consisting of an electron emissive layer such as a layer of low work function upon a metallic base, the other face of this metallic base constituting the anode of a preceding diode, and consisting of an anode for the aforementioned individual diode which, except in the case of the last diode, constitutes the metallic base of a succeeding diode, the metallic base being such that there is developed at the junction with the emissive layer an internal "contact" potential (Peltier E. M. F.) making the anode positive relatively to the cathode, means being provided for heating all the diodes so that in each one thereof the anode and its cathode are maintained at substantially the same temperature, the arrangement being such that output current can be taken by means of a load circuit connected between the anode of the last diode and the cathode of the first.

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

In the drawing,

2

Fig. 1 is a central cross-sectional view along the length of a generally cylindrical apparatus constituting an electric generator in accordance with the invention;

Fig. 2 is a central cross-sectional view of an alternative form of apparatus constituting a direct current electric generator comprising a plurality of diodes or cells in cascade; and

Figs. 3 and 4 are side and end elevations respectively of still another form of the electric generator of the invention with the generator housing cut away in Fig. 3 and shown in section in Fig. 4.

Referring now to Fig. 1 of the drawing, there is shown in cross-sectional view an electric generator comprising mutually confronting cylindrical cathode and anode structures 11 and 12 respectively. The structures 11 and 12 are metal tubes arranged concentrically with the smaller tube 11 inside of the larger tube 12. The tubes are maintained in concentric relationship by ring-shaped insulating members 13 and 14 near the ends of the tubes and sealed to the tubes, as by cement or by glass-to-metal bonding techniques, to provide air tight closures for the annular space between the tubes. Thus the rings 13 and 14 constitute means for sealing the space between the cathode and anode structures and for maintaining this space substantially free from substances retarding electron propagation across this space. The sealing preferably is accomplished while the tubular assembly is evacuated, leaving the interior space a high vacuum to permit generally radial electron flow between the outer surface 16 of tube 11 and the inner surface 17 of tube 12. It is noted that the sealed electrode structure must be capable of withstanding the operating temperatures required to obtain suitable electron emissive properties at the cathode surface.

One, and only one, of these mutually confronting structures has its surface treated to provide a high thermionic emission property. Thus, the surface so treated may be the inner or outer surface, and it may be the surface which, during operation, has a somewhat higher temperature or a somewhat lower temperature, or, in many cases the surfaces may have the same temperature during operation, depending upon the particular arrangement used for supplying heat and the heat transfer properties of the system. As an example, in Fig. 1 the inner surface 17 of the anode structure 12 is of a conductive metal and the outer surface 16 of the cathode structure 11 is of another material, of a type discussed hereinbelow, which has a relatively very high thermionic emission property at the elevated operating temperatures.

Means are provided for continuously heating both of the cathode and anode structures 11 and 12 to elevated temperatures while maintaining the anode surface 17 at a temperature at least approaching that of the cathode surface 16. Any of numerous types of heat sources can serve this purpose. It is recommended that the heating arrangement be such that the entire generator, or at least the parts thereof in the vicinity of the anode and cathode structures, be maintained under approximately isothermal conditions. The generator of the present invention is particularly useful when waste heat is available for this purpose. In Fig. 1, a combustion chamber 18 is shown from which issues a frame 19 so that the exhaust gases tend to pass through the space within the tubular anode structure 11. The burner 18, for example, may be part of a jet engine, so that its exhaust gases are utilized to actuate the generator.

A cylindrical outer casing 21 is provided, within which the sealed anode-cathode structure is supported by end members 22 and 23 having numerous holes 25, permitting the heating gases to pass along the outer surface of the anode structure 12 as well as along the inner sur-

face of the cathode structure 11, so that both structures 11 and 12 and their interior surfaces 16 and 17 are maintained at about the same temperature. The burner 18 is shown supporting the casing 21 through brackets 24.

Circuit connections in the form of wires 26, 27 pass through the casing 21 from the cathode and anode structures 11 and 12 respectively, and the outer ends of these wires are connected to terminals 28 and 29 respectively. Thus, the circuit connections are arranged for utilizing the electromotive force developed between the anode and cathode structures at the elevated temperatures of operation as a result of the net electron flow from the highly emissive surface 16 of the cathode structure 11 to the surface of the anode structure 12. The operation of the diode or cell generator of Fig. 1 will be more readily understood in connection with the discussion hereinbelow of the arrangements of Figs. 2-4.

A wide choice of dimensions is available for the diode cells of the generators of the invention. In an arrangement of the type shown in Fig. 1, the anode and cathode structures may be made as elongated as is needed to supply the current required by the load circuit. The radial dimensions also may be varied widely, although space charge and efficiency considerations make it advisable to maintain a rather small spacing between cathode and anode surfaces, say less than, roughly, a quarter of an inch and ordinarily less than 0.020 inch, preferably of the order of 0.005 inch.

In a preferred construction for converting heat directly to D. C. a generator comprises, within an enclosing envelope, a stack of similar, parallel co-axial nickel discs each coated on one side only with an oxide electron emissive layer, insulating rings being provided to space the discs closely from one another, the discs all facing the same way so that each oxide surface is faced by a nickel surface, said discs extending through the wall of the envelope to provide external fins for the application of heat. With this arrangement a load circuit is connected between the two end discs and, on application of heat to the external fins, a current will flow in this circuit. The total E. M. F. available is the summation-resultant of the individual E. M. F.'s of each diode section provided by the discs, while the current is a function of the emissive surface area and interelectrode spacing of any individual diode, the oxide surface of each disc with the opposed nickel surface of its neighbour constituting the cathode and anode respectively of a diode. No anode battery is required, the power in the load being provided solely from the heating of the cathodes.

Preferably the spacing rings, which may be of vacuum tight ceramic form, in conjunction with the annular portions of the discs which are sandwiched between them, the circular wall of a cylindrical envelope whose end walls are constituted by the two end discs (the last disc, which is an anode only, requires no oxide coating), the discs and rings being suitably machined and otherwise prepared in known manner to provide vacuum tight joints. The envelope may be sealed, in which case it may be either evacuated or provided with a suitable inert gas filling, or it may be of the continuously exhausted type, having an exhausting tube through which it is put in communication with a continuously running exhausting pump.

The invention is based upon consideration of a phenomenon which is known but of which no use seems to have been made hitherto. In a thermionic diode the current flow from cathode to anode does not cease when the anode voltage is reduced to zero but continues at a definite value which investigation shows to depend principally not only upon cathode temperature but also upon the area of the cathode, the materials of which the cathode and anode are made and the anode-cathode spacing. Although, with a known diode, this current is so small as to be practically useless—this is probably why the phenomenon has been so largely ignored in the past—it is the result of conversion of heat in the cathode to D. C.

in the load circuit. With a known diode this current amounts to about one hundredth of the saturation current and disappears when the anode is made about 1 volt negative to the cathode.

Although the invention is not dependent for its usefulness upon the correctness and sufficiency or otherwise of the theory now to be advanced, it is believed that the current in question is to be explained in terms of the emission velocities of electrons from the cathode. Consider the case of a diode with anode and cathode (including connection leads thereto) all of the same metal, the cathode only being heated. There is no contact potential difference between anode and cathode and all emitted electrons, having passed the potential barrier due to the image force, will travel to the anode.

The diode then functions as a direct-current electric generator whose internal or thermionic E. M. F. (E_T) is given by the expression

$$E_T = \phi \left(\frac{T_c}{T_a} - 1 \right) + \frac{2kT_c}{e} \log \frac{T_c}{T_a}$$

E_T vanishing when $T_a = T_c$ where T_a and T_c are respectively the temperatures of the anode and cathode, ϕ is the work function of the metal, and k and e are constants.

Such a diode will in fact convert heat at the cathode into D. C. in an external load circuit between anode and cathode but, however, the conversion will be of very low efficiency, and the power available in the external circuit will be a very small fraction of the total power supplied. This is, of course, because in a known diode such as that described the conversion is purely incidental, no attempt being made to construct the diode for the purpose of such conversion. The present invention takes such conversion as its object and produces a discharge device in which such conversion is rendered much more efficient and which will give useful D. C. power outputs.

Consider now the case of a diode in which both the cathode and anode are of the same base metal and maintained at substantially the same temperature—an essential requirement for any major increase of efficiency—the cathode however being rendered emissive by being provided with either (a) a layer of metal of low work function, such as thoriated tungsten or tantalum-coated tungsten; or (b) a monatomic layer of an emissive metal of low work function e. g. caesium; or (c) an oxide or other semiconducting layer; or (d) with a cathode as in case (c), the anode, however, being provided with a monatomic layer of low work function.

In this case (d), it can be shown that the thermionic E. M. F. does not necessarily vanish when $T_a = T_c$, but that there is a residual E. M. F.

$$E'_T = E_p + \frac{kT_c}{e} \log \frac{A_c}{A_a}$$

where E_p is the Peltier E. M. F. and A_a and A_c are respectively the emissive constants of the anode and cathode surfaces.

In case (a), with pure metals, $A_a \approx A_c$ and the net E. M. F. is Peltier E. M. F., so that the internal E. M. F. is but a few millivolts. In this case (a) therefore, the net current in the external circuit will be very small, due to the height of the potential barrier (high work function) at the anode. In case (b) however, in which there is a monatomic layer of caesium or other metal of much lower work function than that of the anode and which will emit electrons strongly on heating, the Peltier E. M. F. is zero and the net E. M. F. will depend upon whether A_c is greater or less than A_a . If the work function of the anode is high, the output current will obviously be small. In case (c) in which a highly emissive oxide layer is applied to the cathode, the Peltier E. M. F. is high, of the order of 1 to 2 volts at 1000° K., and predominates. This arrangement gives maximum internal E. M. F. but the current is limited by the work function of the anode. In case (d) the internal E. M. F. is as in case (c) but the current is increased because the anode

work function is reduced by the monatomic layer applied thereto. The first two factors which make up the present invention and which together transform an electron discharge device in which the conversion of heat into direct current is a negligible incidental, to one in which there is substantial and useful conversion, are the selection of materials such that either case (c) or (d) applies and the adoption of a structure such that the anode and cathode are maintained at substantially the same temperature.

The third factor is the adoption of a structure such that the ratio of useful power to that lost by radiation and conduction is greatly increased and such that the voltage behind the external flow of current is enough to provide useful output power. As already stated the voltage for this current is only about half a volt per diode. In accordance with this invention, therefore, the discharge device is provided with a plurality of diodes structurally and electrically in series in the same envelope. In this way a considerably higher voltage than half a volt is attainable and by the use of stacked discs as already described with a single disc forming the anode of one diode and the cathode of the next, this higher voltage is obtained without making the device of prohibited or inconvenient overall dimensions.

The fourth factor is the adoption of very small cathode-anode spacing, in practice, a spacing of the order of 0.1 mm. This needs little explanation for obviously, other things being equal, an increase in the spacing will decrease the current.

The fifth factor is the use of cathodes of large emissive area for bulk and over-all size. This is why the disc type of structure is preferred though concentric stacked cylinders could be used in place of discs, each successive pair of cylinders resembling those illustrated in the Fig. 1 arrangement. Numerous possible alternative series, parallel, and series-parallel combinations of physical relationships and electrical connections among the discs or tubes constituting the diodes will be apparent.

A sixth factor which is preferably adopted, is the coating of the anodes with a monatomic layer of metal, such as tantalum, of lower work function than the base metal of the cathode. The advantage of this is that it reduces the contact potential (across the cathode-anode space) which opposes space charge effects restricting cathode current flow.

Finally, in carrying out the invention, the design is made such that heat is transmitted efficiently from a hot gas or other external heating source to the internal cathodes.

In a preferred embodiment of the invention illustrated in cross section in Fig. 2 of the accompanying drawing, nickel discs 31, each coated on one side with an oxide emitting layer 32, are stacked into a cylinder with individual discs separated by small insulating spacer rings 33, all the oxide-coated surfaces facing the same way. Each one of the oxide-coated cathodic surfaces 32, and the confronting anodic surface of the next adjacent disc-shaped metallic base 31 to the right thereof, together form an individual diode, so that the entire cylindrical structure of Fig. 2 constitutes a plurality of these diodes arranged in cascade. External connections 36 and 37 are provided to the end discs only, and are connected to terminals 38 and 39 respectively. In use the device thus constructed is placed in a suitably shaped container through which heater gases (indicated by the arrows 41) are passed through suitable holes 42 in the discs 31 at a temperature such as to raise the cathodes to about 850° C. or higher.

It will be understood that the peripheral portions of the discs 31 serve as heating fins for their central portions, and that other directions of flow of the gases past the device also may be utilized. In any case it will be seen that this arrangement of the outer portions of each disc serves to transfer heat substantially equally to both left-hand and right-hand surfaces of the central portions

of the disc. Accordingly, the peripheral portions of the discs and the arrangement for directing the hot gases past them provide means for heating all of the plurality of cascaded diodes so that in each one thereof its anode and cathode surfaces are maintained at substantially the same elevated temperature. The spacer rings 33 and the portions of the discs therebetween form the circular wall of a cylindrical enclosing envelope through which the discs extend to provide the external fin portions for the application of heat to the internal diode structure. The two end discs form end walls so that, when properly machined and treated, the envelope may be made vacuum-tight.

In use heat from the gases causes emission from the cathodes and is thus transformed into current in the external circuit. Theoretical considerations indicate that power outputs in the neighborhood of seven or eight horse-power per cubic foot and thermal efficiencies of the order of 35% or 40% or higher are obtainable from such a device with correct design, lagging against heat losses, and so on. In the arrangement of Fig. 2, the evacuation may be accomplished by continuous exhaustion of the central spaces by connecting a conduit 43 through the end discs to a vacuum pump, not shown.

An alternative structure is illustrated in Figs. 3 and 4 of the accompanying drawing. In this structure, the discs 51 having emissive coatings 52 on their right-hand surfaces are mounted on a central stem 53. The battery or pile of diodes thus formed is mounted in an evacuated tube 54 of refractory material such as borosilicate glass, or a vacuum tight ceramic or porcelain, capable of withstanding operating temperatures of about 850° C. This arrangement overcomes any difficulty which might occur in the arrangement of Fig. 2 in maintaining a seal between the discs 31 and spacers 33. External leads 56 and 57 pass through the envelope 54 to respective terminals 58 and 59, as in the other arrangements. The entire envelope 54 and its contents are heated to obtain operation similar to that of the Fig. 2 arrangement.

The barrier between successive discs need not necessarily be a vacuum: any suitable electron-permeable material may be used as the barrier.

It should be observed that the action is critically dependent upon the surface conditions of the anodes; for example, if nickel is used for the anodes, they should be preferably hydrogen annealed before being assembled, as the usual oxide surface of nickel, even though it is not apparent, has been found seriously to reduce efficiency.

Although the invention has been mainly described in terms of heat-D. C. converts, clearly it may be used for A. C.-D. C. conversion with heat as an intermediate stage. For example A. C. may be fed to heating resistors provided in and arranged to heat the cathodes of a device in accordance with this invention, or, if the frequency is suitable, the A. C. may be used to heat the cathodes by electro-magnetic induction, being fed to coils suitably arranged and positioned to heat the cathodes by eddy currents set up therein. In the usual case, however, the generators of the invention find their greatest utility in taking as the source of energy the hot gases frequently available as a result of combustion processes, often in constricted exhaust ducts, where it is very convenient to be able to immerse the entire structure in the exhaust flow without attempting to maintain a part of the apparatus relatively hot and other parts relatively cool, as is the case with thermocouple generators and with conventional diode structures using specialized arrangements for heating the cathode.

What is claimed is:

1. An electric generator, comprising: mutually confronting anode and cathode structures, the surface of said anode structure being of a conductive metal and the surface of said cathode structure being of another material having a relatively very high thermionic emission

property at elevated temperatures; means for sealing the space between said anode and cathode structures and for maintaining said space substantially free from substances retarding electron propagation thereacross; means for continuously heating both of said anode and cathode structures to elevated temperatures while maintaining said anode surface at approximately the same temperature as that of said cathode surface; and circuit connections to said anode and cathode structures for utilizing the electromotive force developed therebetween at said elevated temperatures as a result of the net electron flow from said highly emissive surface of said cathode structure to said anode structure.

2. An electric generator, comprising: a plurality of diodes in cascade, each individual diode consisting of a cathode in the form of a highly electron-emissive layer upon one face of a metallic base, the other face of said metallic base constituting the anode of a preceding diode, and of an anode for said individual diode which, except in the case of the last cascaded diode, constitutes the metallic base of a succeeding diode, said metallic base being such that there is developed at the junction with said emissive layer an internal "contact" potential (Peltier E. M. F.) making the anode positive relatively to the cathode, means being provided for heating all of said plurality of diodes so that in each one thereof its anode and its cathode are maintained at substantially the same temperature, the arrangement being such that output current can be taken by means of a load circuit connected between the anode of the last diode and the cathode of the first.

3. A direct-current electric generator comprising a plurality of diodes in cascade, each individual diode consisting of a cathode in the form of an electron-emissive layer of highly emissive oxide upon one face of a metallic base, the other face of said metallic base constituting the anode of a preceding diode, and of an anode for said individual diode which, except in the case of the last cascaded diode, constitutes the metallic base of a succeeding diode, said metallic base being such that there is developed at the junction with said emissive layer an internal "contact" potential (Peltier E. M. F.) making the anode positive relatively to the cathode, means being provided for heating all of said plurality of diodes so that in each one thereof its anode and its cathode are maintained at substantially the same temperature, the arrangement being such that output current can be taken by means of a load circuit connected between the anode of the last diode and the cathode of the first.

4. A direct-current electric generator comprising a plurality of diodes in cascade, each individual diode consisting of a cathode in the form of an electron-emissive layer of metal of low work function upon one face of a metallic base, the other face of said metallic base constituting the anode of a preceding diode, and of an anode for said individual diode which, except in the case of the last cascaded diode, constitutes the metallic base of a succeeding diode, said metallic base being such that there is developed at the junction with said electron-emissive layer an internal "contact" potential (Peltier E. M. F.) making the anode positive relatively to the cathode, means being provided for heating all of said plurality of diodes so that in each one thereof its anode and its cathode are maintained at substantially the same temperature, the arrangement being such that output current can be taken by means of a load circuit connected between the anode of the last diode and the cathode of the first.

5. A direct-current electric generator comprising a plurality of diodes in cascade, each individual diode consisting of a cathode in the form of a monatomic electron-emissive metallic layer upon one face of a metallic base, the other face of said metallic base presenting a clean, non-layerized metallic surface which constitutes the anode of a preceding diode, and further consisting of an anode

for said individual diode similarly having a clean, non-layerized metallic surface which, except in the case of the last cascaded diode, constitutes the metallic base of a succeeding diode, said metallic base being such that there is developed at the junction with said emissive layer an internal "contact" potential (Peltier E. M. F.) making the anode positive relatively to the cathode, means being provided for heating all of said plurality of diodes so that in each one thereof its anode and its cathode are maintained at substantially the same temperature, the arrangement being such that output current can be taken by means of a load circuit connected between the anode of the last diode and the cathode of the first.

6. A generator in accordance with claim 3 in which, in each of said individual diodes, said highly emissive oxide layer forms said cathode and in which said anode for said individual diode has a monatomic surface layer of low work function.

7. A generator according to claim 2, comprising, within an enclosing envelope, a stack of similar, parallel coaxial nickel discs each coated on one side only with said electron emissive layer, and insulating rings to space the discs closely from one another, the discs all facing the same way so that each said electron-emissive surface is faced by a nickel surface, and said discs extending through the wall of said envelope to provide external fins for the application of heat.

8. A generator according to claim 7, wherein the insulating spacing rings are of vacuum-tight ceramic and form, in conjunction with the annular portions of the discs which are sandwiched between them, the circular wall of a cylindrical envelope whose end walls are constituted by the two end discs, the discs and rings being machined and treated to provide vacuum tight joints.

9. A generator according to claim 8, wherein the envelope is sealed and evacuated.

10. A generator according to claim 8, wherein the envelope is sealed and provided with a suitable inert gas filling.

11. A generator according to claim 8, wherein the envelope is sealed and is provided with an exhaustion tube through which it is adapted to be put in communication with a continuously running exhausting pump.

12. A generator according to claim 3, wherein the anode is provided with a monatomic layer of metal of lower work function than the metallic base.

13. A generator according to claim 2, wherein the metallic base is hydrogen annealed nickel.

14. A generator according to claim 12, wherein the metallic base is hydrogen annealed nickel and the monatomic layer is barium.

15. An electric generator comprising, in combination, an anode structure and a cathode structure having confronting slightly spaced apart surfaces from one another, the surface of the anode structure being of an electrically conductive material and the surface of said cathode structure being of another material having a relatively high thermionic emission property at highly elevated temperatures, the space between said confronting surfaces of the cathode and anode structures being substantially free from substances retarding electron propagation thereacross; means for simultaneously subjecting the anode structure and the cathode structure to highly elevated temperatures to raise the temperature of both structures to approximately the same high temperature; and a circuit having connections to the anode structure and the cathode structure for utilizing the electromotive force developed therebetween while the same are subjected to said elevated temperatures and as a result of the electron flow from said highly emissive surface of the cathode structure to the anode structure.

16. An electrical generator comprising, in combination, a pair of concentrically arranged tubular structures having a narrow annularly shaped space therebetween, one of said structures constituting an anode and having

the peripheral surface thereof facing the other structure formed of electrically conductive material, the other of said structures constituting a cathode and having the peripheral surface thereof facing the anode structure formed of material having a relatively high thermionic emission property at elevated temperatures; means for sealing the annular space between said surfaces of the anode and cathode structures and maintaining the same substantially free of substances retarding electron propagation thereacross; means for directing highly heated gas simultaneously through both the innermost tubular structure and around the outermost tubular structure to

heat said surfaces thereof to substantially the same temperature; and a circuit having connections to the anode structure and to said cathode structure for utilizing the electromotive force developed therebetween, while the same are subjected to the temperatures of said heated gas and as a result of the electron flow from said highly emissive surface of said cathode structure to said anode structure.

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