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MEANS FOR CLOSE PLACEMENT OF ELECTRODE PLATES IN A THERMIONIC CONVERTER

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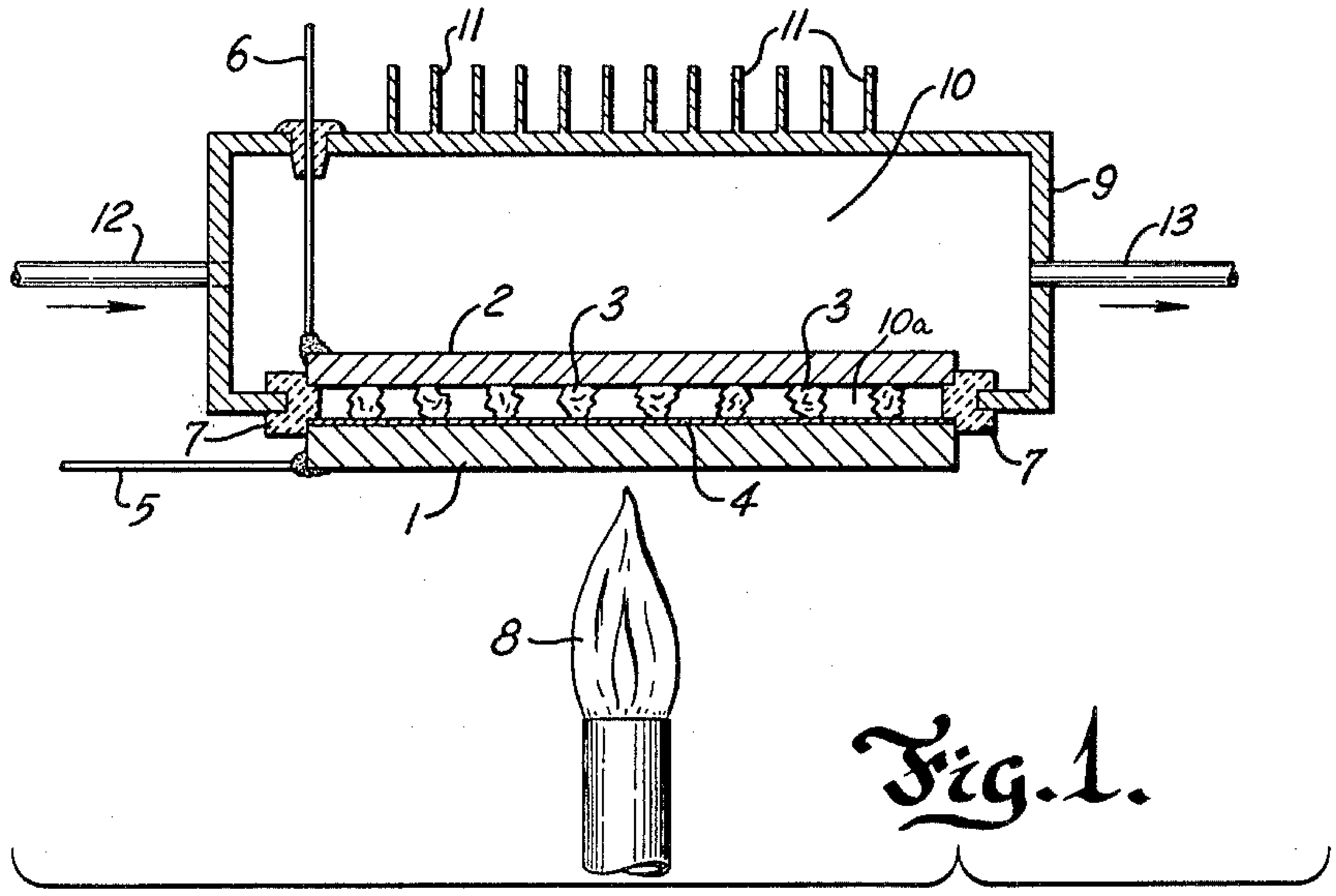

Fig. 1.

Fig. 2.

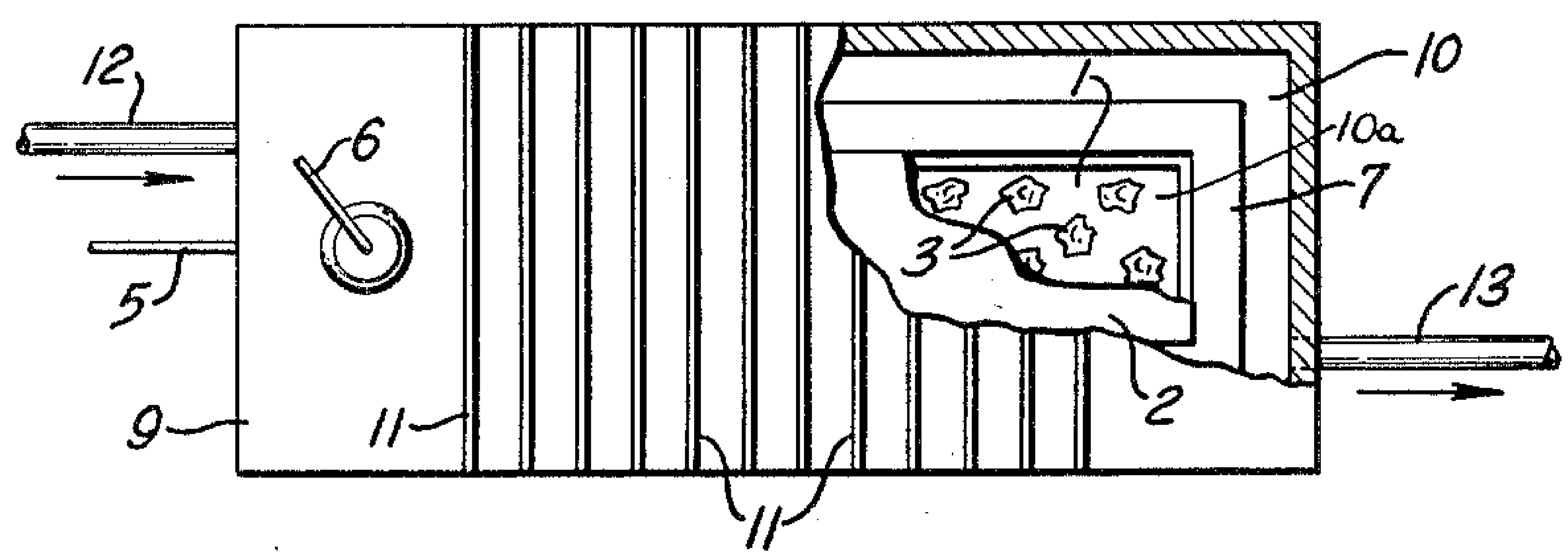

Fig. 3.

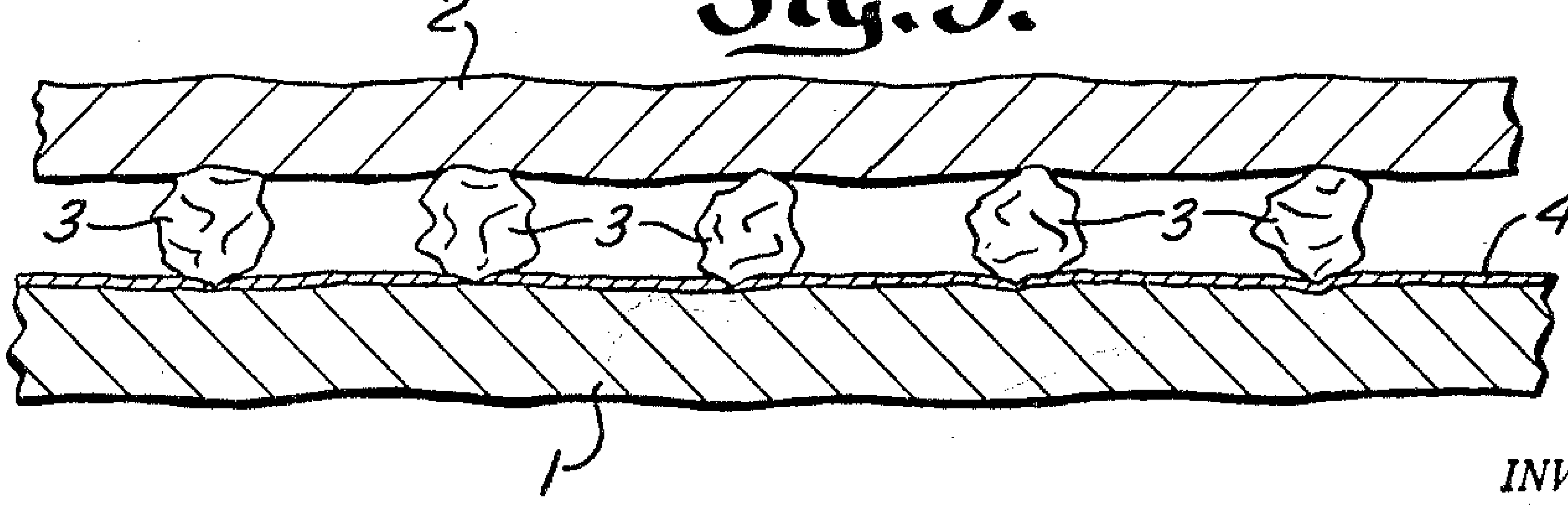

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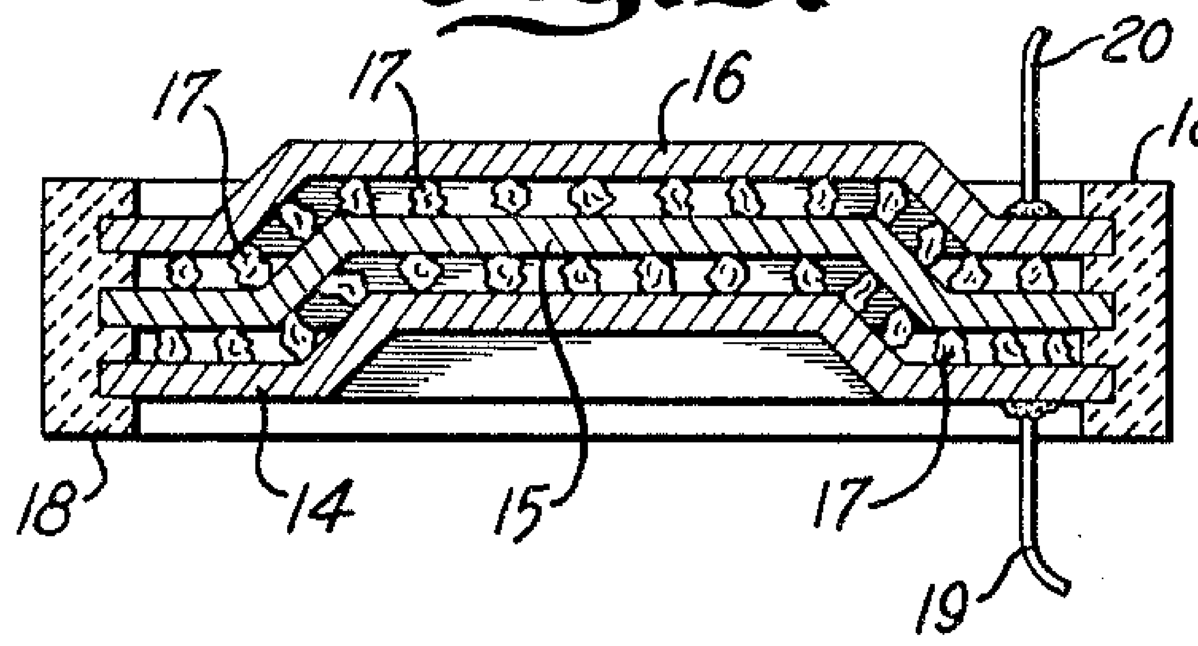
Fig. 4.



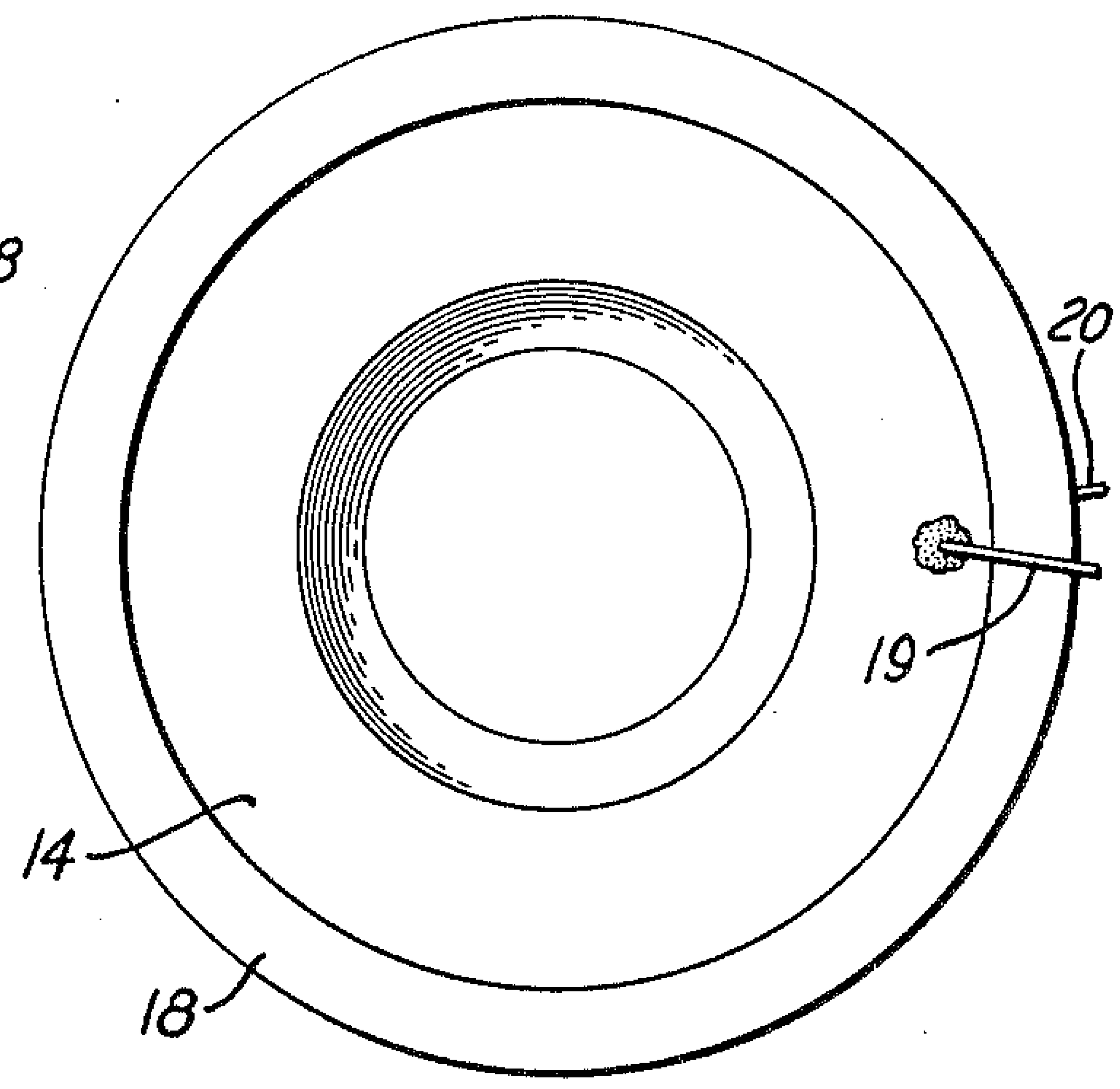
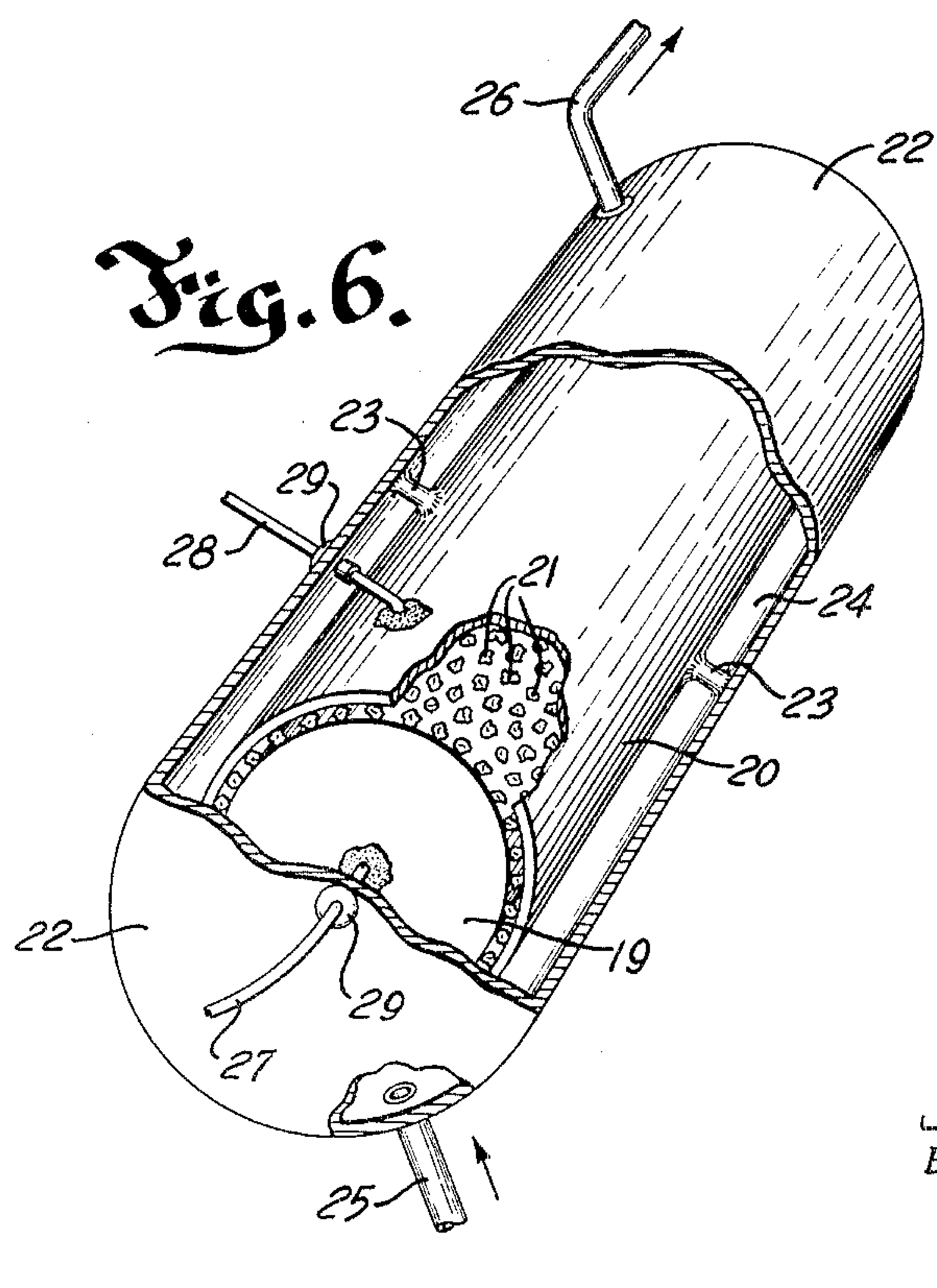


Fig. 5.

Fig. 6.



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MEANS FOR CLOSE PLACEMENT OF ELECTRODE PLATES IN A THERMIONIC CONVERTER

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2 Claims. (Cl. 310—4)

This invention relates to a thermionic converter, and more particularly to the use of uniform, finely divided insulating particles disposed between the electrode plates of a thermionic converter element to effect a very close spacing of the plates which increases the electron flow to the anode, electron emission from the cathode due to reduction of space charge, and thermal efficiency of the device.

There have been numerous attempts in recent years to develop efficient heat-to-electricity converters. Various devices have been created which utilize the phenomena of thermionic emission. The British Patent 741,058, to David Malcolm Johnstone, covers such a device. Basically, thermionic emission is the flow of electrons from a conductor surface subjected to heat. When an electron absorbing or attracting surface, or anode, is placed in close proximity to an electron emitting metal surface, and a complete external circuit is provided, the flow of electrons creates an electrical current through the circuit.

Other devices which convert heat to electricity are known as thermoelectric couples. These may be used in series to increase the available electromotive force, and are then referred to as thermopiles. Thermopiles and, more specifically thermoelectric couples, are comprised of dissimilar metals or dissimilar (p and n type) semiconductor elements, which are physically connected at one end to form an electrical junction. The open ends of the elements are electrically connected to a resistance load which consumes the generated power. Applying heat to the junction so formed, creates a temperature difference and thermal gradient along each element, giving rise to Seebeck and Thomson potentials. The Seebeck potential is an electromotive force developed if two different homogeneous conductor phases are joined at both ends, and the two junctions are kept at different temperatures. The Thomson potential refers to the thermal gradient within a homogeneous conductor, and since it occurs in a single material it is difficult to measure.

The Seebeck and Thomson potentials created by heating the elements produce a source of electrical energy to power an external load. The higher the temperature differential that can be maintained between the hot and cold junction, the higher will be the electromotive force potential that is available to power an external load. Heat conducted from the hot junction through each element to the cold junction limits the maximum temperature differential that can be maintained, and hence the available power output and thermal efficiency is also limited.

In an effort to reduce thermal conductivity, semiconductor elements are doped with impurity atoms, usually resulting in an undesired increase in element resistivity. Due to the relatively high resistivity and high thermal conductivity of the elements, the output current density and voltage output per couple is inherently low.

A thermionic generator is another thermoelectric device which is similar to the thermo-couple. The thermionic generator has a portion of the thermo-couple circuit replaced with a separated conducting space which may contain an inert gas, an ionized gas, or which may be evacuated. This minute, evacuated or gas filled space serves as an excellent thermal barrier, preventing heat transfer from cathode to anode, while offering very little impedance to the flow of electrons. Radiation losses

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from the hot cathode are practically independent of the anode position or gap spacing. Extremely high temperature differences, or gradients, between the anode and the cathode may be easily maintained and are limited only by the melting points of the cathode, and not by conduction losses, as in the case of a semi-conductor thermo-couple.

The importance of a high cathode temperature is exhibited by the Richardson-Dushman thermionic emission equation for saturation current under zero field conditions. This equation must be modified to include any additional potential fields to which an escaping electron may be subjected. One such force is a retarding space charge field above the cathode. Assuming that the anode temperature is sufficiently low to prevent any current flow from the anode to cathode, the following equation illustrates the temperature dependence of electron flow:

$$J_0 = A_0 T^2 e - (\phi_c + \phi_{sc})/kT$$

where:

J_0 equals electron current density escaping to the anode,
A_0 equals characteristic saturation emission constant of the emitting surface,
T equals cathode emitter temperature,
k equals Boltzmann's constant
ϕ_c equals cathode work function potential (electron volts),
ϕ_{sc} equals space charge potential due to electron-electron interactions and collision scattering.

It can be seen that any appreciable increase in the cathode operating temperature will greatly increase the output current, and hence the overall efficiency of the thermionic converter. More specifically, increasing the cathode temperature has the desired effect of increasing the amplitude of atom vibration and the number of elastic collisions between electrons and atoms, thus increasing the number of electrons which have enough energy to escape from the surface potential barrier of the emitting metal. Once the electrons escape, they are subject to whatever potential fields exist above the cathode surface. Electrons which escape both the potential barrier of the cathode and the retarding space charge potential field, are attracted to the anode due to image charge. In order to trap the maximum number of the free electrons at the anode, it is desirable to place the anode as close in proximity as possible to the cathode, leaving only sufficient space between the cathode and anode plates to prevent electrical shorting. Closer spacing allows a higher current, higher power output and better overall thermal efficiency, although output voltage may be slightly lower. Current and power increase approximately as a function of $1/_{x2}$ where x is the spacing, while the output voltage decreases as only a small linear function of the gap spacing as it is reduced.

In view of the foregoing, it can be seen that a thermionic device, having a minutely separated cathode and anode has greater capacity to perform efficiently when compared to a thermoelectric couple of the same size and materials. Also, more intense heat sources can be used to drive a thermionic converter. Solar energy, atomic energy, and high temperature combustion energy, or a combination thereof, may be used to create direct current electrical energy.

In general, the thermionic converter of the present invention comprises an electron emitting cathode, an electron collecting anode disposed in intimate, spaced relationship to said cathode, and a plurality of finely divided particles of a substance having a high melting point, high resistance to crushing, and high electrical resistance at the working temperature disposed between the opposing surfaces of the anode and the cathode. A ceramic seal is employed around the edges of the anode and the cathode for sealing the chamber therebetween and for electrically separating the members. Electrical conducting leads connect the anode and cathode to a resistance load, thereby utilizing the electrical power generated by thermionic emission.

According to the invention, the minute particles, having a size in the range of .2 to 1000 microns, are formed of a substance such as diamond, metal oxides and the like and are applied to either the cathode or the anode surface by spraying, sputtering, printing, chemical coating process, or electrode deposition.

The thermionic converter has no moving parts, utilizes high temperature heat sources, and produces electricity directly from heat energy at improved efficiency because of the novel cathode and anode spacing means. Other objects and advantages of this invention will appear in the course of the following description.

The drawings illustrate the best mode presently contemplated for carrying out the invention.

In the drawings:

FIGURE 1 is a vertical section of a thermionic converter with a cooling jacket surrounding the anode plate;

FIG. 2 is a top view of the device shown in FIGURE 1, with the respective layers broken away to show the random distribution of the particles and the relationship of the cooling jacket to the anode plate;

FIG. 3 is a greatly enlarged sectional view showing the jagged particles imbedded in the cathode and anode plate surfaces;

FIG. 4 is a sectional view of a modified form of the invention showing a series of electrode plates in thermal cascade;

FIG. 5 is a bottom view of the thermal cascade device of FIG. 4; and

FIG. 6 is a perspective view with parts broken away to show internal details of construction of a second modified form of the invention showing a thermionic converter element in an atomic reactor.

FIGURES 1–3 illustrate a thermionic converter comprising a cathode plate **1** and an anode plate **2** which are spaced apart by a plurality of minute, uniform size particles **3**.

A cathode **1** is a thin, rectangular plate formed of a metal, a metallic oxide or a "cermet" having good thermionic emission properties, and which will remain in the solid state at the operating temperature range, which may be up to 4000° K. A "cermet" is a combination of a refractory metal and a highly emissive oxide and most of the "cermet" have high melting points and can be used as a cathode material at the higher operation temperature ranges up to about 3500° K.

A surface coating **4** may be added to the cathode **1** as shown in FIGURE 1. The surface coating **4** is a crystal complex of barium oxide and strontium oxide (BrO·SrO) from one to several monolayers thick, and it substantially covers the top surface of the cathode **1**. The surface coating **4** increases electron emission of the cathode **1**.

An anode **2** is a thin, rectangular plate and complements the cathode **1** in size and shape. The anode **2** is disposed parallel to, and in close relationship to the cathode **1**, being spaced apart therefrom at a distance in the range from .2 to 1000 microns by particles **3**. The anode **2** is formed of a metal such as nickel, and serves to collect the electrons emitted from the cathode **1**.

The particles **3** are a substance having a high melting point, high resistance to crushing, and high electrical resistance. The melting point of the particles **3** is in the range from 1000° K. to 4000° K. and the particular operating temperature of the thermionic converter determines the material selected for use as particles **3**, since it is desirable that the particles **3** have a melting point more than 200° K. above the operating temperature to insure permanent spacing of the cathode **1** from the anode **2**.

The particles **3** should have a thermal conductivity less than 1.25 cal.-cm./cm.^{2}/° C./sec. Assuming the effective projected area of the grains does not exceed 10% of cathode emissive area, and that maximum permissible leakage is to be no more than 1% of the output current per unit of area of the cathode **1**, the electrical resistivity of the particles **3** should be no less than 1×10^5 ohm-cm.

The compressive strength of the particles at the operating temperature should be greater than 150 p.s.i. assuming a maximum of 10% coverage of the emissive surface of the cathode **1**. A greater degree of particle coverage may be used, but will decrease the efficiency of the device. The compressive strength requirements will depend upon the total external load to which the particles **3** are subjected and is a function, also of particle distribution density on the cathode **1**. Approximate requirements are as follows:

External Load	Particle Distribution Density	Minimum Compressive Strength, p.s.i.
14.7 p.s.i.	1% of cathode surface	1,470
14.7 p.s.i.	10% of cathode surface	147

When the external load increases, the compressive strength of the particles **3** must be higher, by the proportion factor of 100 times greater compressive strength per p.s.i. increase, in the situation of 1% particle density on the cathode surface. Where particle density is 10% of the cathode surface, then compressive strength of the particles **3** must be increased 10 times for each additional p.s.i. of external load.

The particles **3** may be any of the following compounds: MgO; $CaO \cdot MgO \cdot SiO_2$; $MgO \cdot SiO_2$ (steatite); $2MgO \cdot SiO_2$ (bosterite); $ZrO_2 \cdot SiO_2$ (zircon); $MgO \cdot 2Al_2O_3$; $5SiO_2$ (cordierite); crystal forms of Al_2O_3 including alumina or Alundum; ruby; corundum; sapphire; diamond; mixtures of compounds which contain relatively large amounts of Al_2O_3, including mullite, sillimanite and firebrick (53% SiO_2, 43% Al_2O_3); glass, including fused quartz, Vycor, porcelain, agate and amethyst; zirconium compounds, including ZrN, $ZrBr_2$, ZrO_2 (white) and baddeleyite (yellow or brown ZrO_2); and the like.

The particles **3** have a size in the range of 0.2 to 1000 microns and serve to space apart the cathode **1** and the anode **2** at a fixed distance. The cathode **1** and the anode **2** may be very thin metal plates, because the particles **3** also provide internal mechanical support in the chamber formed by the cathode **1** and the anode **2**, preventing buckling due to external pressure and thermal expansion.

The cathode **1** and anode **2** are connected in an electrical circuit with a resistance load, not shown, by conductor leads **5** and **6**, which are connected to the cathode and anode, respectively. The resistance load may be an electric motor, a transistorized television receiver (which operates on direct current), storage batteries for domestic and industrial use, or any other electrically driven appliance or device.

Inherently, each cell of a thermionic device is a high current, low voltage source of electric power. Individual thermionic cells may be electrically connected in series or parallel to produce voltage-current combinations for specific uses. Auxiliary equipment such as rotary inverters, vibrators and transformer-rectifier combinations may be used to produce voltage or current combinations of A.C., or high voltage D.C.

A seal **7** is located between the periphery of the cathode **1** and the anode and around the conductor lead **6** where it leaves the cooling jacket **9**. The seal **7** is an insulating ceramic material which has very low thermal conductivity and high electrical resistivity. Many of the materials described above for use as particles **3** would also be suitable for use as the seal **7**. Specific materials which may be used for the seal **7** are aluminum oxide, fused silica or quartz. The cathode **1** and the anode **2** are bonded or fused to the seal 7, so that the chamber therebetween may be evacuated. The seal 7 electrically separates the cathode 1 and the anode 2, and serves to complete the walls of the sealed chamber of the thermionic device. The seal 7 on the conductor lead 6 serves the same purpose also.

Energy is applied to the device by a heat source 8 which is located with its focal point on the outer surface of the cathode 1. The heat source 8, as shown in FIGURE 1, is a gas burner, but the heat source may also take the form of heat of combustion, focused solar heat, heat of a thermonuclear reaction, or chemical heat other than combustion. The heat source may attain temperatures in the range from 1000° K. to 4000° K. The normal range of the combustion heat source 8 shown in FIGURE 1 is 1000° K. to 2000° K., but solar heat sources operate at temperatures closer to 4000° K.

A cooling jacket 9 surrounds the outer surface of the anode 2 and serves to increase the temperature differential between the cathode and anode. The jacket 9 is connected to the seal 7 or anode 2 by brazing or fusion welding and completely encloses the outer surface of the anode 2. The cooling jacket 9 may be formed of any metallic material which readily conducts away heat and defines a chamber 10 which contains a cooling medium. Circulating means may be provided for the liquid or gas coolant with an inlet 12 and an outlet 13 on the cooling jacket 9. To increase the heat transfer, the cooling jacket 9 may be equipped with cooling fins 11. The cooling fins 11 increase the total heat transfer surface, and further aid in cooling the anode 2. Alternately, in a modified form of this device which does not have a cooling jacket, the cooling fins 11 may be fitted directly to the back of the anode 2. The cooling medium in chamber 10 serves to increase the temperature differential between the cathode 1 and the anode 2, thereby increasing thermionic efficiency.

The thermionic device shown in FIGURES 1–3 may be assembled in the following manner. The cathode 1 is first coated on one surface with a thin film of the BaO·SrO coating 4. The particles 3 may then be applied to the coated surface of the cathode 1 by spraying, sputtering, brushing or vacuum deposition.

The anode 2, which complements the cathode 1 in size and shape, is then placed over the coated surface in substantial alignment therewith and pressure is applied from outside both the anode 2 and the cathode 1, forcing their opposing surfaces into close proximity in spaced relationship, and causing the edges of the particles 3 to embed in the opposing surfaces of the anode and the cathode. As shown in FIG. 3, the surface of the particles is irregular and the edges of the particles 3 penetrate through the thin film coating 4 on the cathode 1. A resilient clamping means, such as a rubber cushioned vise, is used to force the anode and cathode together.

The seal 7 is then inserted between the peripheral edges of the anode and cathode, electrically separating these elements and forming a chamber 10*a* therebetween. A small opening is left in the seal 7 for evacuating the chamber 10*a*. The ceramic-to-metal seal may be accomplished by a brazing method such as described in U.S. Patent 2,836,885 to MacDonald.

Conductor leads 5 and 6 are then connected to the cathode 1 and the anode 2, respectively, by such means as soldering, fusion welding or minute bolts. The chamber 10*a* is then evacuated by means such as a high vacuum pump through the opening left for this purpose in the seal 7.

Evacuation of the chamber 10*a* causes the cathode 1 and the anode 2 to further bear against the particles 3, permanently disposing the particles in fixed positions between the opposing surfaces of the cathode 1 and the anode 2. The small opening in the seal 7 is then permanently sealed and the structure is removed from the resilient clamping means.

The cooling jacket 9 having a small diameter opening to allow for the passage of the conductor lead 6 from the cooled anode 2 is then disposed around anode 2. The conductor lead 6 is passed through the opening and drawn up tight and the peripheral edges of the cooling jacket are connected to the seal 7 by means such as the brazing method previously cited.

In some cases, the chamber 10*a* is filled with an inert gas or a plurality of ionizable gases. Such gases generally have low vapor pressure, and an external insulated clamping means may be added to hold the cathode 1 and the anode 2 in close spaced relationship.

In operation, thermal energy is applied from the heat source 8 to the cathode 1, bringing its temperature up to the operating range, 1000° K. to 4000° K. The heated cathode 1 emits electrons from its upper surface, aided by the effect of the coating 4. Emitted electrons are collected by the anode 2, and an E.M.F. builds up across the chamber 10*a*. Electric energy flows from the anode 2 through the conductor lead 6 to the resistance load which uses the generated electricity to function. As previously mentioned, a thermionic device has no moving parts, and is inherently a source of D.C. electricity having low voltage and high amperage. The closely spaced relationship of the opposing surfaces of the anode 2 and the cathode 1 improves the thermionic efficiency of this device by reducing the major obstacles to high density electron flow.

Another form of a thermionic device is shown in FIG. 4. A cathode plate 14, an anode-cathode plate 15, and an anode plate 16 are placed in thermal cascade to increase efficiency by utilizing excess thermal energy, which passes through the cathode plate 14 to heat the anode-cathode plate 15. The plates 14, 15 and 16 are spaced apart by a plurality of particles 17, similar in composition and function to the particles 3 of the first embodiment. As shown in FIG. 5, the cascaded device is preferably circular, and the succeeding plates are progressively larger in surface area, as shown in FIG. 4, to maintain uniform current output per cell. The combination anode-cathode plate 15 serves a dual function in operation for its lower surface collects electrons emitted from the cathode plate 14, and its upper surface emits electrons which are collected by the anode plate 16. A seal 18 similar to the seal 7 in material and function separates and seals the edges of the plates and conductor leads 19 and 20 are connected only to the cathode plate 14 and the anode plate 16, respectively, and function as do the conductor leads 5 and 6 of the first embodiment. Assembly of this device is substantially as described above in connection with FIGURE 1, except the particles 17 are applied to both sides of the anode-cathode plate 15, before assembling the anode plate 16 and the cathode plate 14 on the opposite surfaces of the anode-cathode plate 15.

FIG. 6 shows a second modified form of the invention in which the thermionic device has a radioactive cathode. A cylindrical radioactive cathode 19 is employed and is formed of a substance such as an uranium compound which readily generates heat when bombarded by neutrons, and emits electrons at a high rate. A cylindrical anode 20 is spaced outwardly of the radioactive cathode 19 and is formed of a metal, such as aluminum, which freely allows passage of neutrons through to the cathode 19. The anode 20 functions in a manner similar to the anode 2 of the first embodiment. A plurality of particles 21 in the size range from .2 to 1000 microns and substantially similar to the particles 3, are distributed between the opposing surfaces of the cathode 19 and the anode 20. A cylindrical jacket 22 surrounds the device, and is formed of an insulating material. A series of supporting members 23 position the cooling jacket 22 around the anode 20 and are fabricated from a material similar to that of cooling jacket 22. An oil coolant is introduced into the chamber 24 between jacket 22 and anode 20 through an inlet and is withdrawn through outlet 26 during operation.

Conductor leads 27 and 28 are connected to the cathode 19 and the anode 20, respectively. The conductor leads 27 and 28 are insulated from the cooling jacket 22 by means of seals 29, which are substantially similar to the seal 7 of the first embodiment.

In operation, the thermionic device shown in FIG. 6 is placed in the core of an atomic reactor. Neutrons from the reactor bombard the radioactive cathode 19, passing through the cooling jacket 22 and the anode 20, which are both neutron "windows." Neutron bombardment causes the cathode 19 to heat up and emit electrons, which are then collected by the closely spaced anode 20. This device effectively bypasses the intermediate step performed by turbines in the present conversion of nuclear power to electricity. It also eliminates the shielding problems inherent in turbines which use radioactive steam. This device also has the advantages described above in connection with the first embodiment, that is, it has no moving parts and inherently produces low voltage, high amperage current.

Various modes of carrying out the invention are contemplated as within the scope of the following claims particularly pointing out and distinctly claiming the subject matter which is regarded as the invention.

I claim:

1. A thermionic converter, comprising an electron emitting cathode, an electron collecting anode disposed in spaced relation to said cathode, means for heating the cathode, a plurality of finely divided particles disposed between the opposing surfaces of the anode and cathode, said particles being haphazardly arranged between said opposing surfaces and having irregular edges penetrating and imbedded in conforming irregular openings in said surfaces to provide a substantially uniform spacing in a range from 0.2 to 1000 microns between said opposing surfaces, said particles having a melting point in

the range of 1000° K. to 4000° K. and having a high resistance to crushing and having electrical resistivity sufficiently high to maintain electrical current losses through said particles at a minimum, and means for electrically connecting said anode and cathode in an operating circuit whereby the electrical energy generated by thermionic emission is utilized.

2. In a thermionic converter, comprising an electron emitting cathode, an electron collecting anode, heating means for heating the electron emitting cathode, cooling means for cooling the electron collecting anode to maintain a temperature differential between said anode and cathode, spacing means disposed between and in contact with the opposing surfaces of the cathode and the anode, said spacing means comprising finely divided particles of a substance selected from the group of metallic oxides consisting of Al_2O_3, ZrO_2, SiO_2, MgO, BeO and mixtures thereof and having a size in the range of 0.2 to 10 microns, said particles being randomly distributed between the opposing surfaces, being of irregular shape and having jagged edges penetrating and imbedded in the opposing surfaces of said anode and cathode, whereby the thermal efficiency of the thermionic converter is substantially increased by decreasing the electric potential barriers to electron flow from the electron emitting cathode to the electron collecting anode.

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