United States Patent [19]

Rason et al.

[11] **3,843,896**

[45] **Oct. 22, 1974**

[54] **RADIOISOTOPIC THERMOINIC CONVERTER**

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[73] Assignee: **McDonnell Douglas Corporation**, Santa Monica, Calif.

[22] Filed: **Feb. 4, 1972**

[21] Appl. No.: **223,691**

Related U.S. Application Data

[63] Continuation of Ser. No. 794,933, Jan. 29, 1969, abandoned.

[52] **U.S. Cl.** **310/4**
[51] **Int. Cl.** **H01j 45/00**
[58] **Field of Search** 310/4

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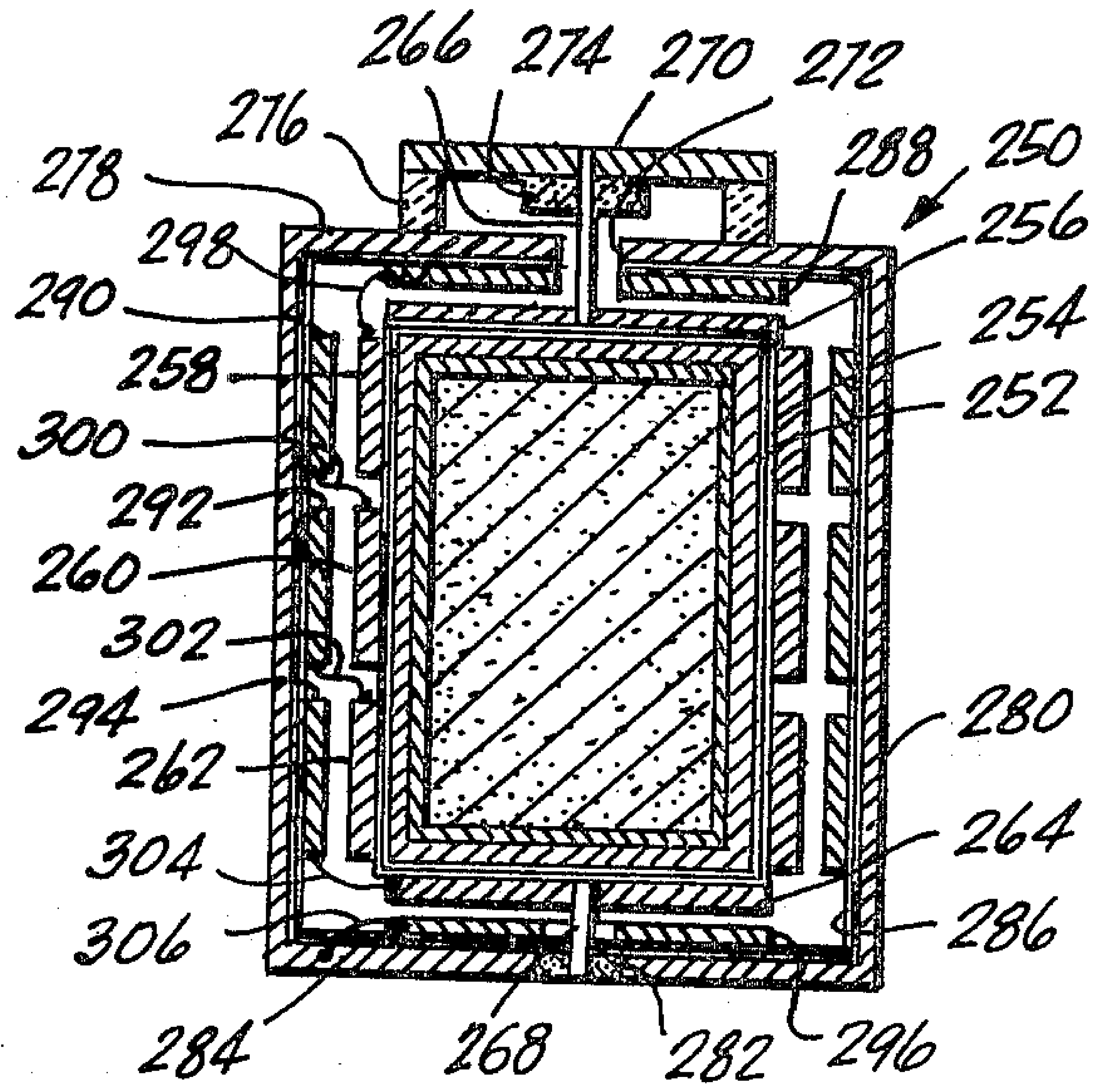
[57] **ABSTRACT**

Atomic diode battery or thermionic converter including a radioisotopic fuel pellet enclosed in a capsule having an emitter surface extending over substantially the entire capsule external area, a housing enclosing the emitter capsule and having an internal collector surface extending over substantially the entire housing internal area and maintained at a predetermined spacing from the emitter surface, a cesium vapor source communicating with the interelectrode space under such low vapor pressure as to effect nominally vacuum mode operation, and emitter and collector connections providing an electrical output from the battery. An optimum relationship established among battery parameters provides maximum energy conversion efficiency at practical electrode temperatures and spacings using available materials.

14 Claims, 19 Drawing Figures



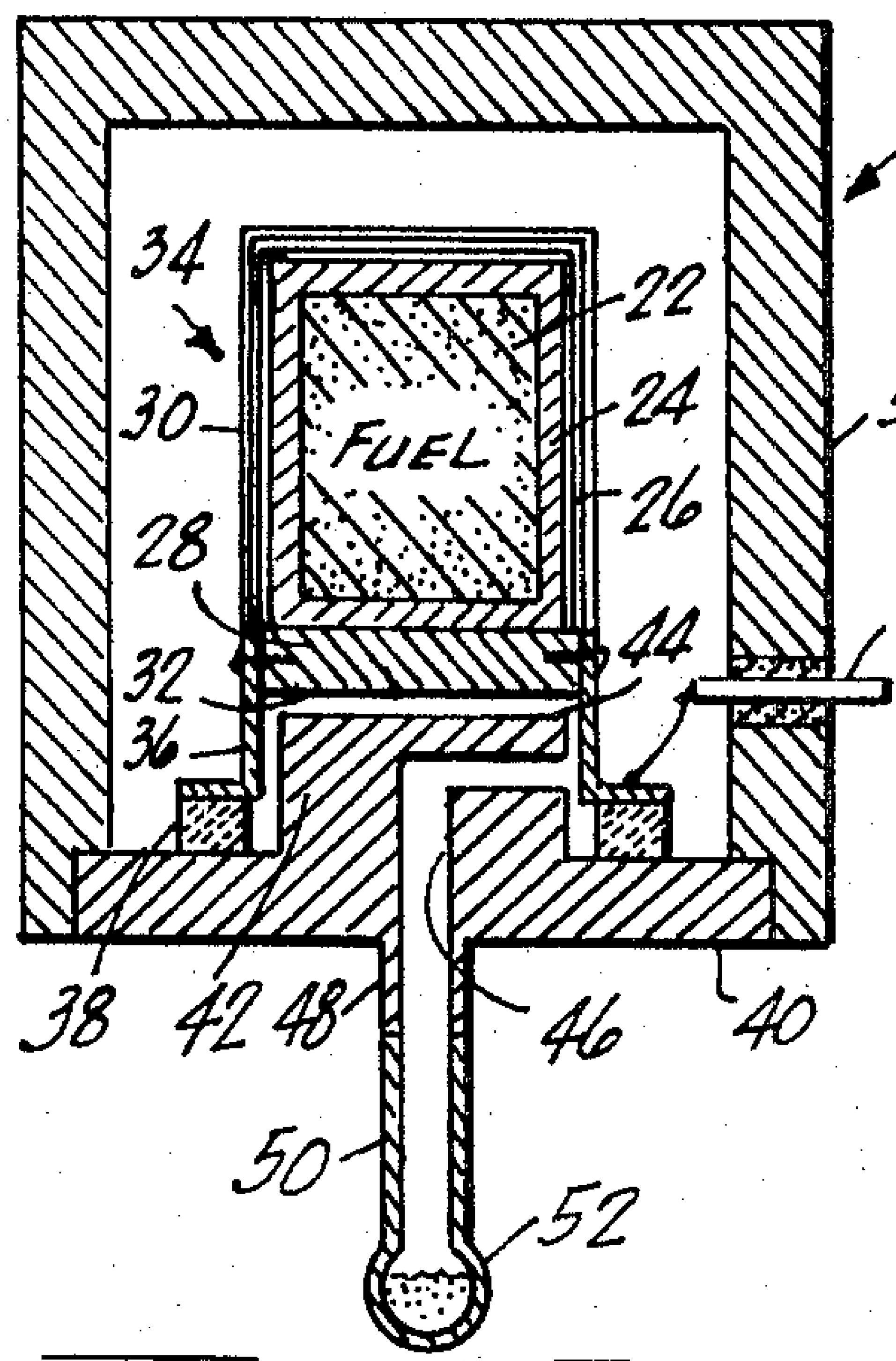


Fig. 1
PRIOR ART

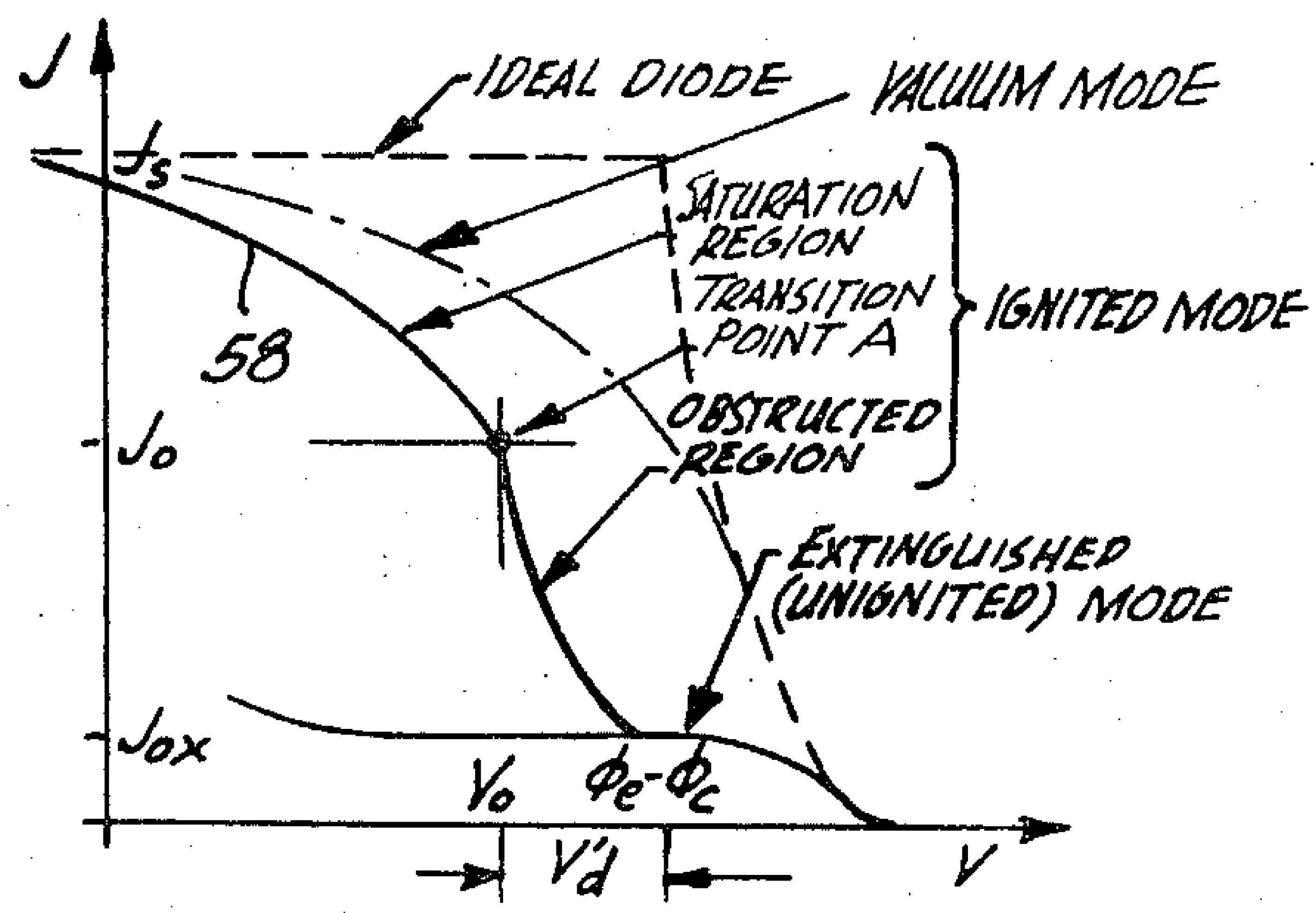


Fig. 3

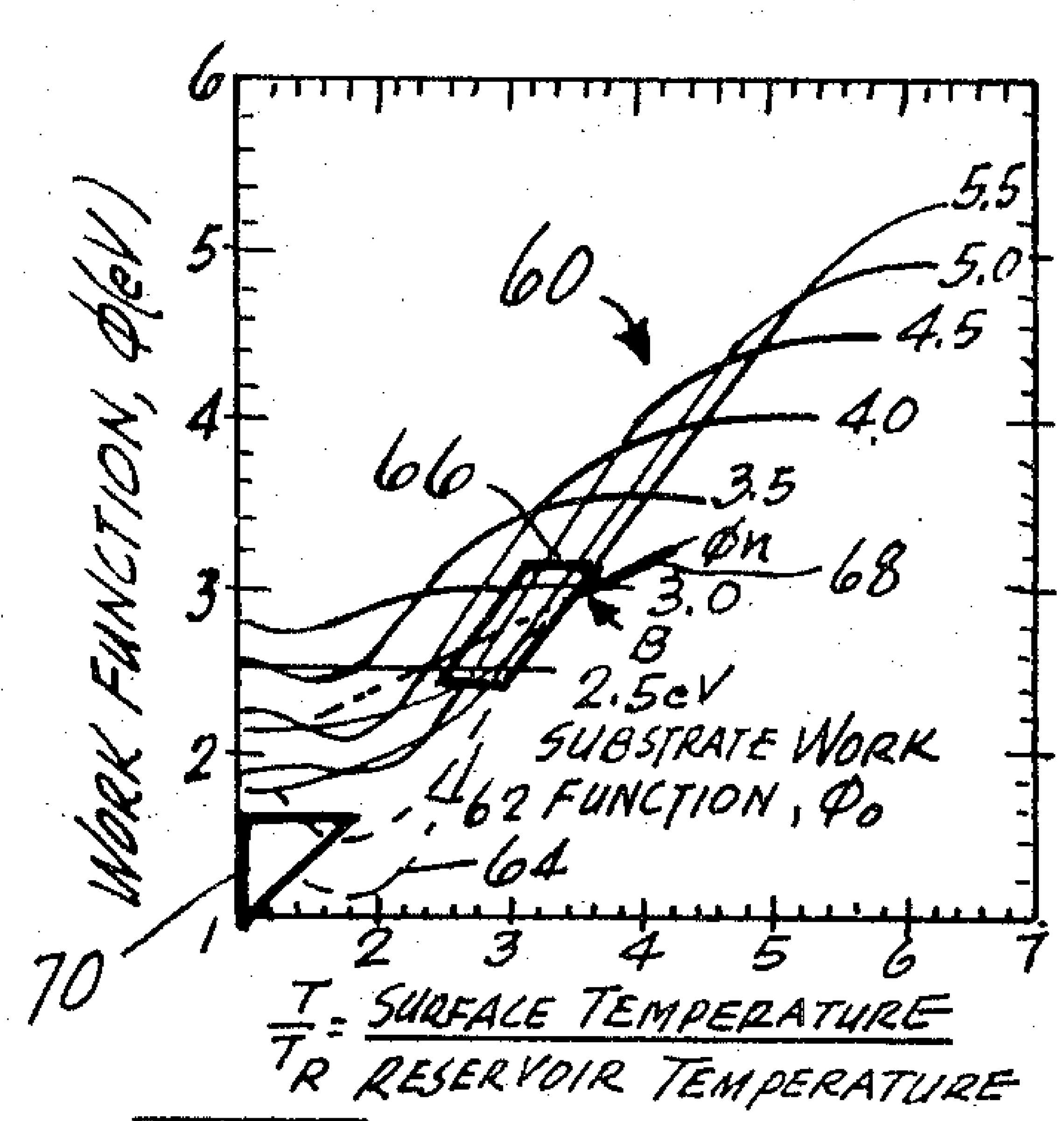
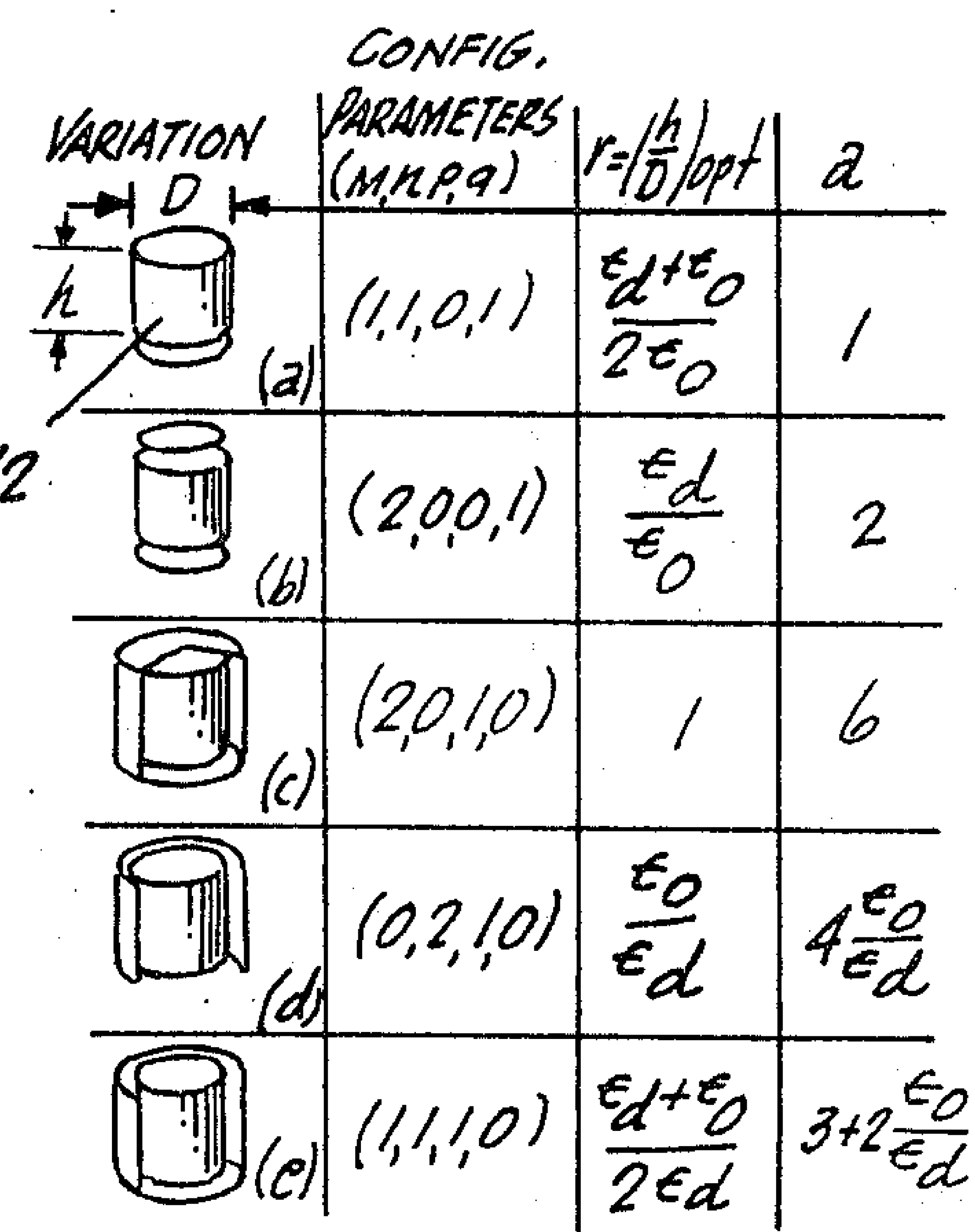


Fig. 4



CONFIGURATIONAL VARIATIONS

Fig. 5

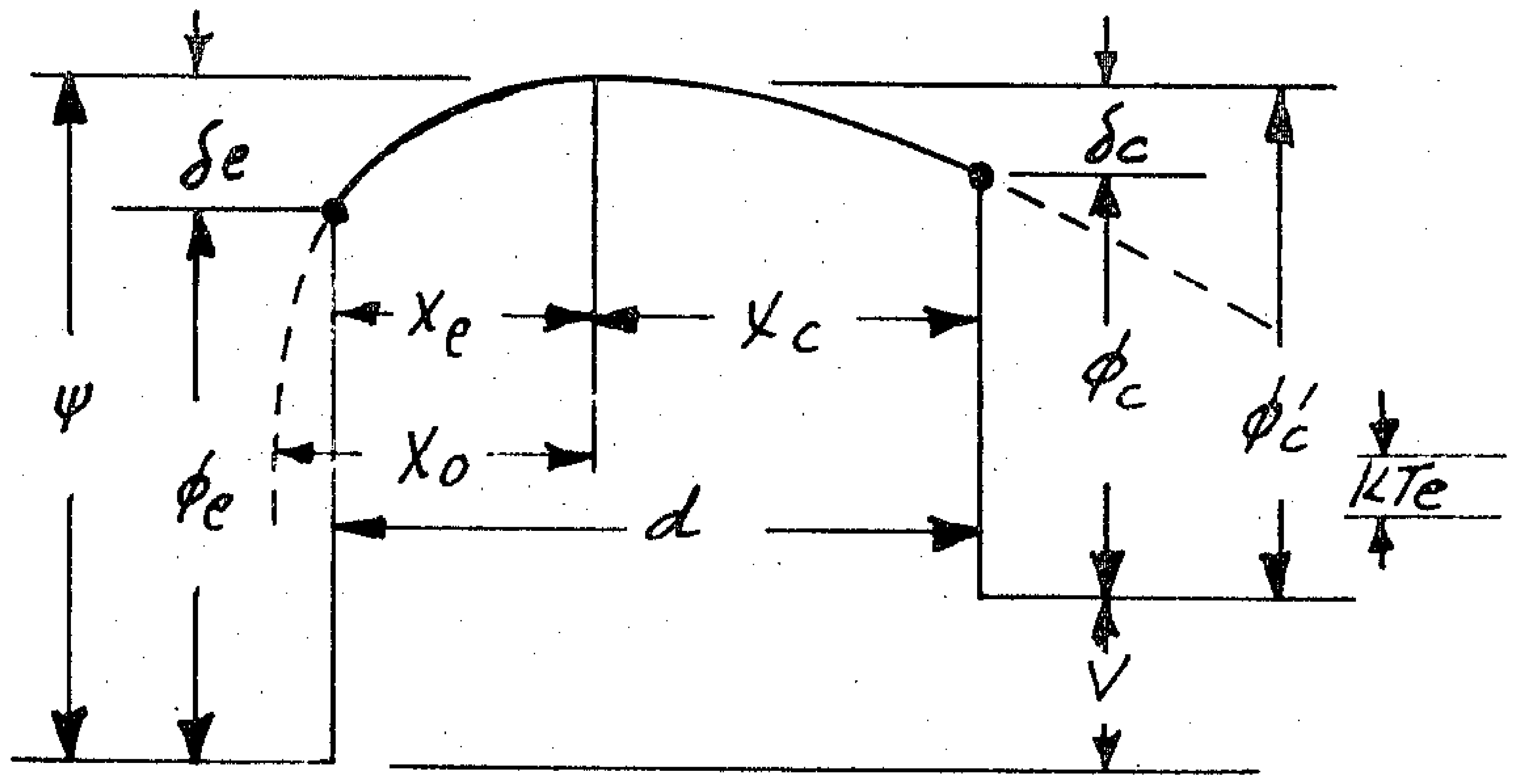


Fig. 6

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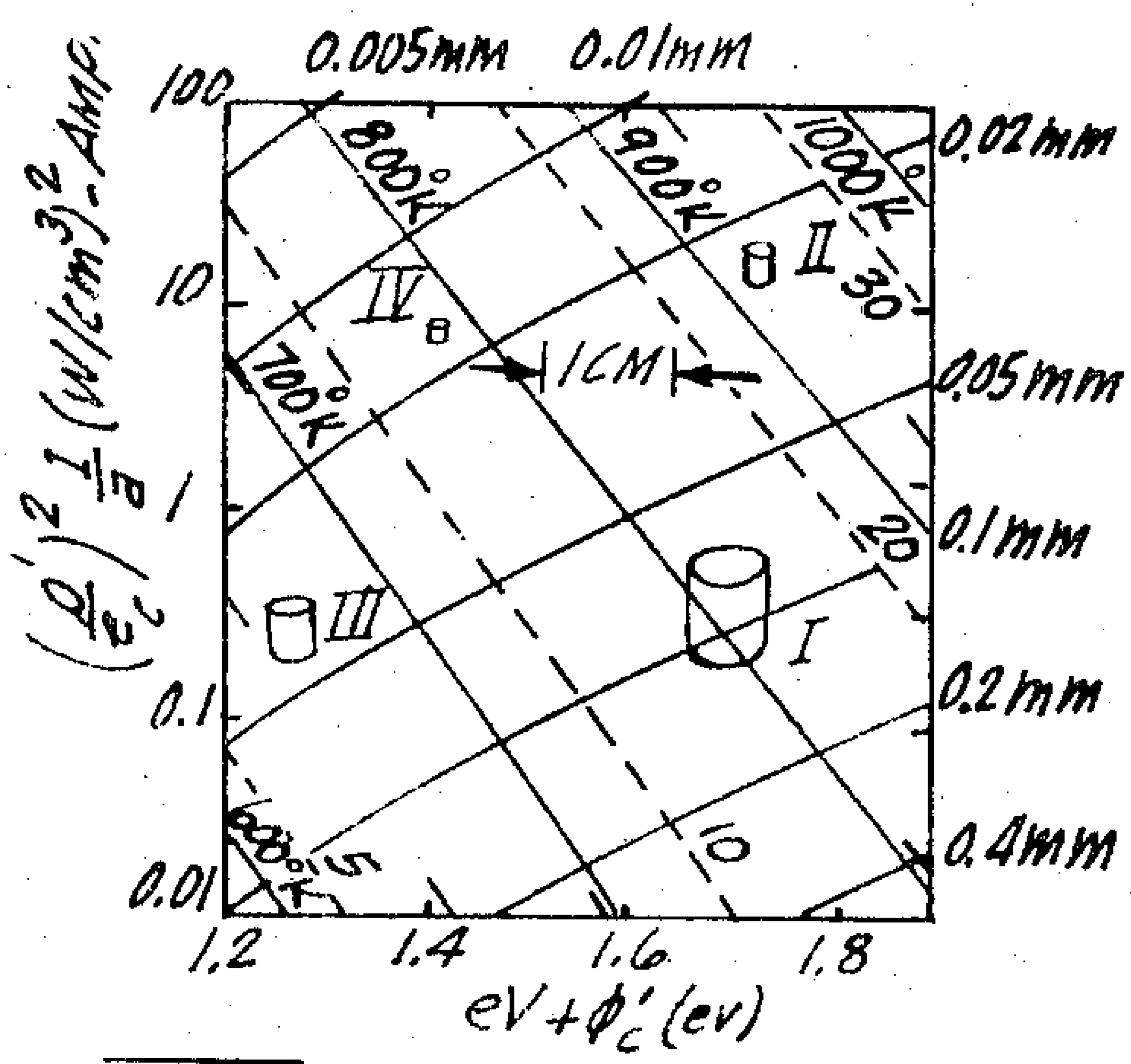

Fig. 7

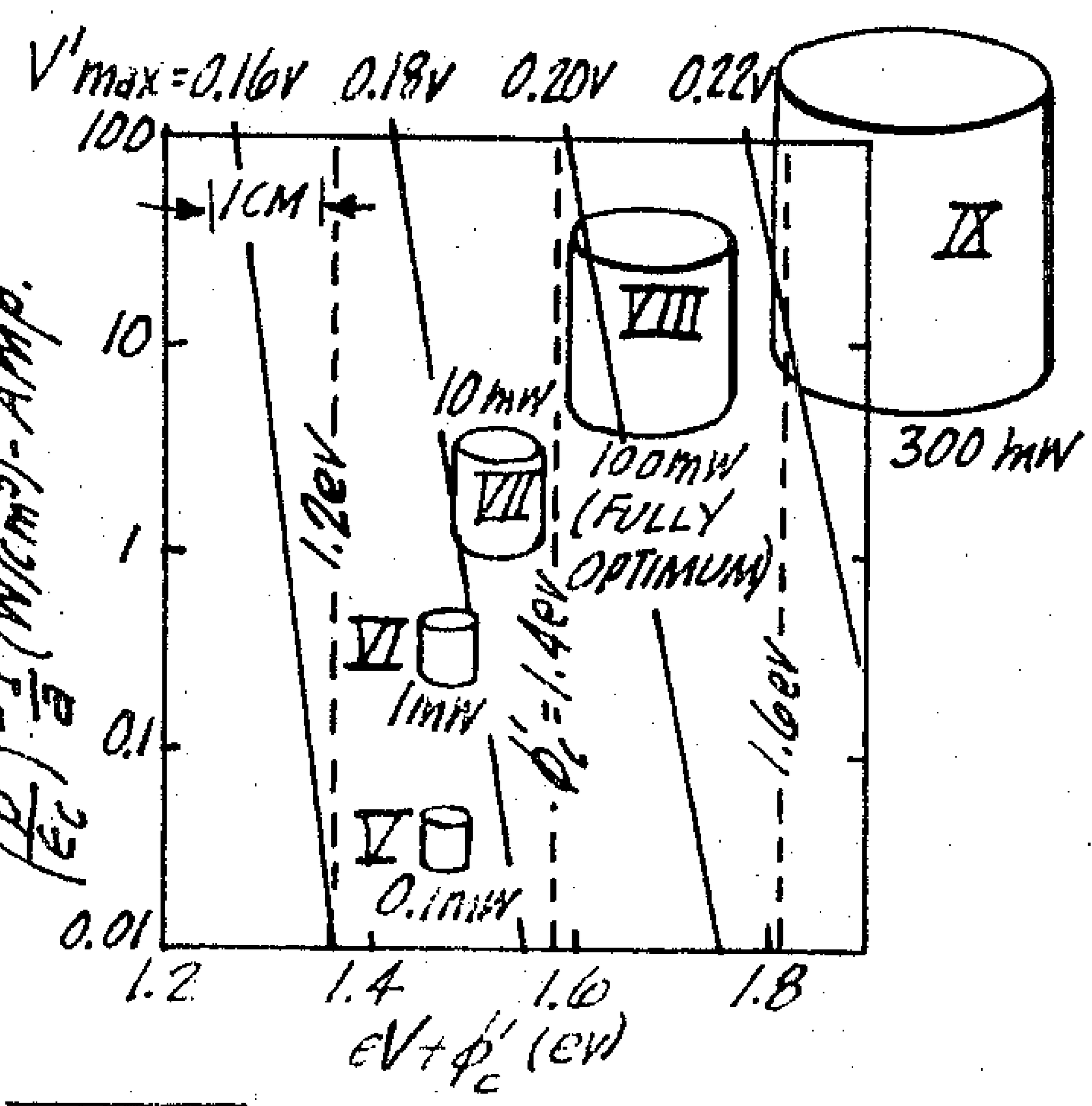

Fig. 8

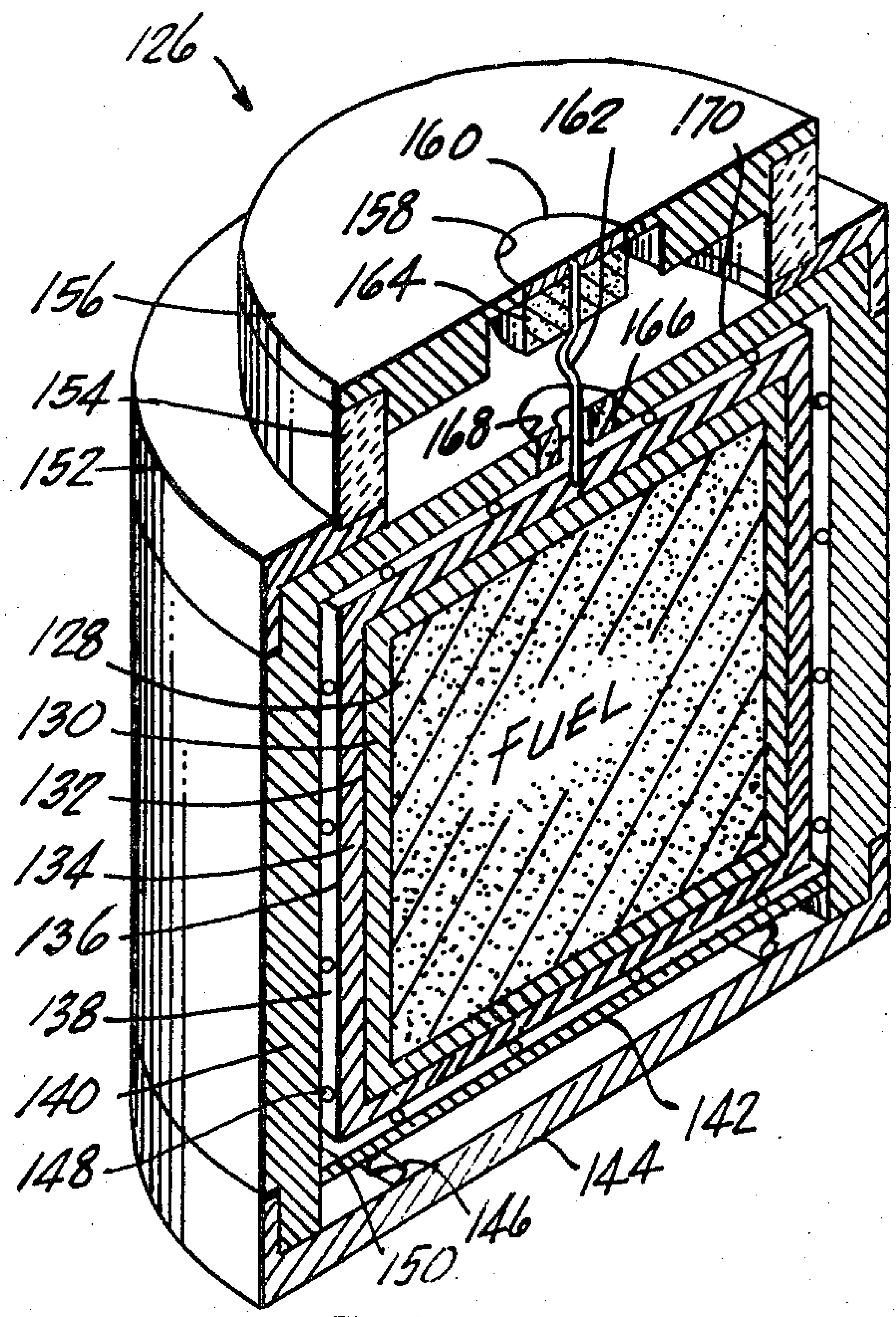

Fig. 11

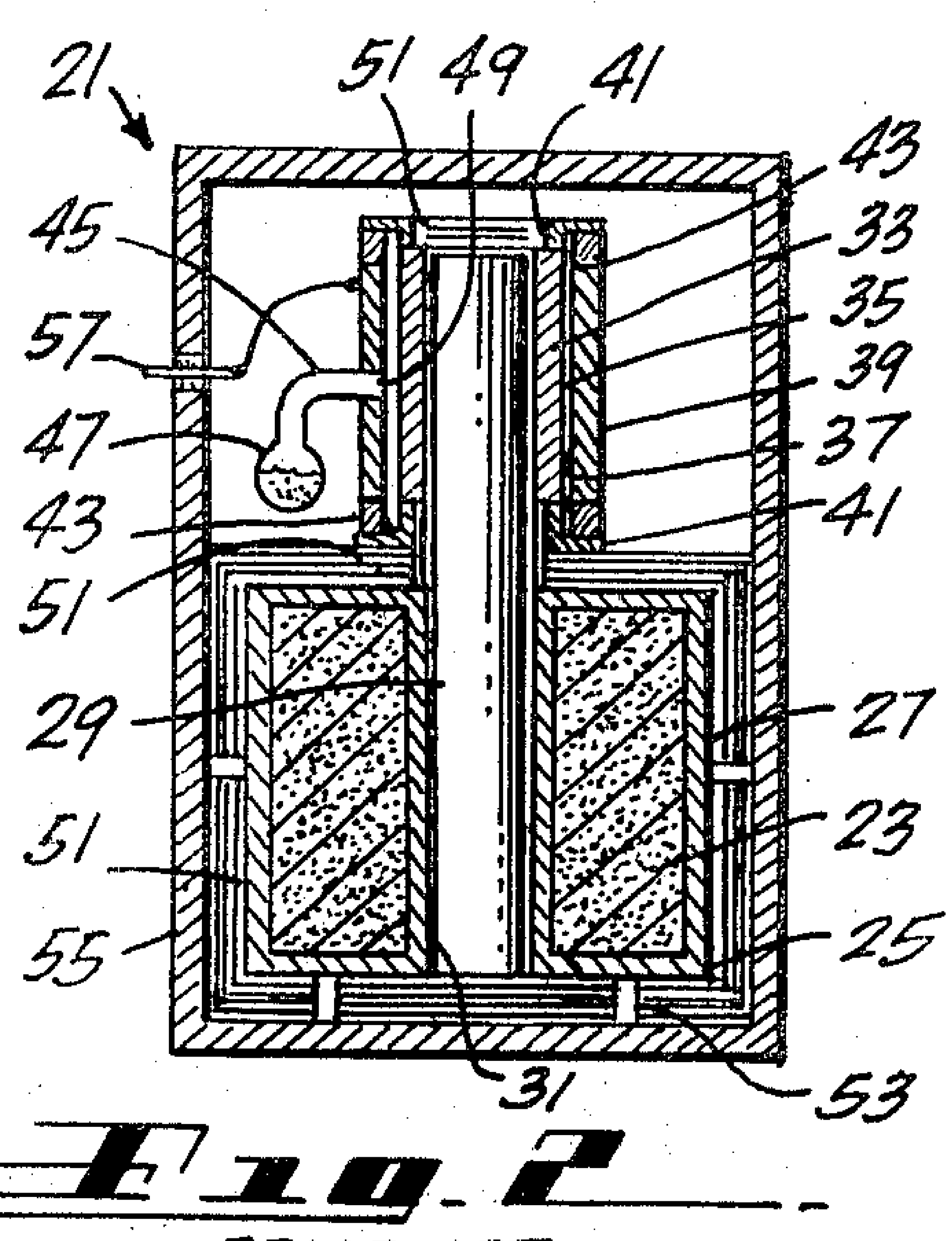

Fig. 2

PRIOR ART

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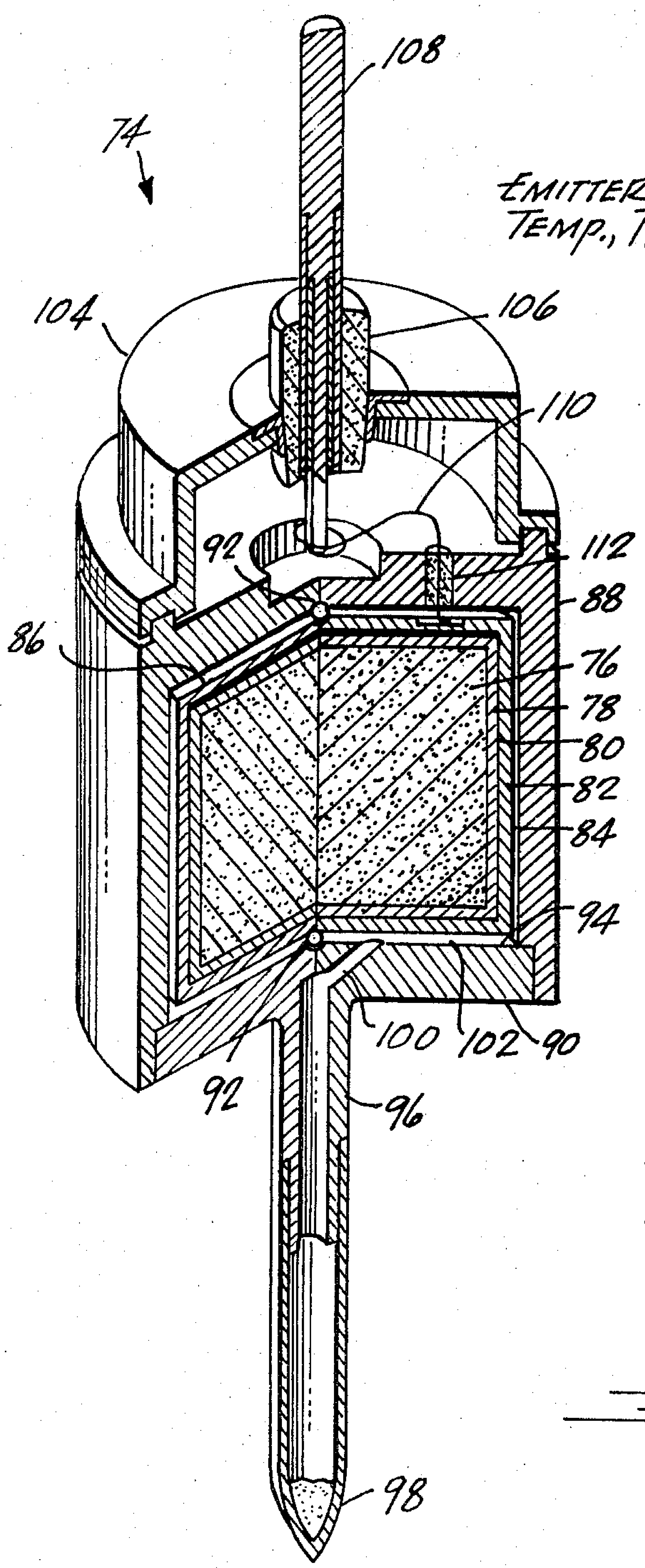

Fig. 9

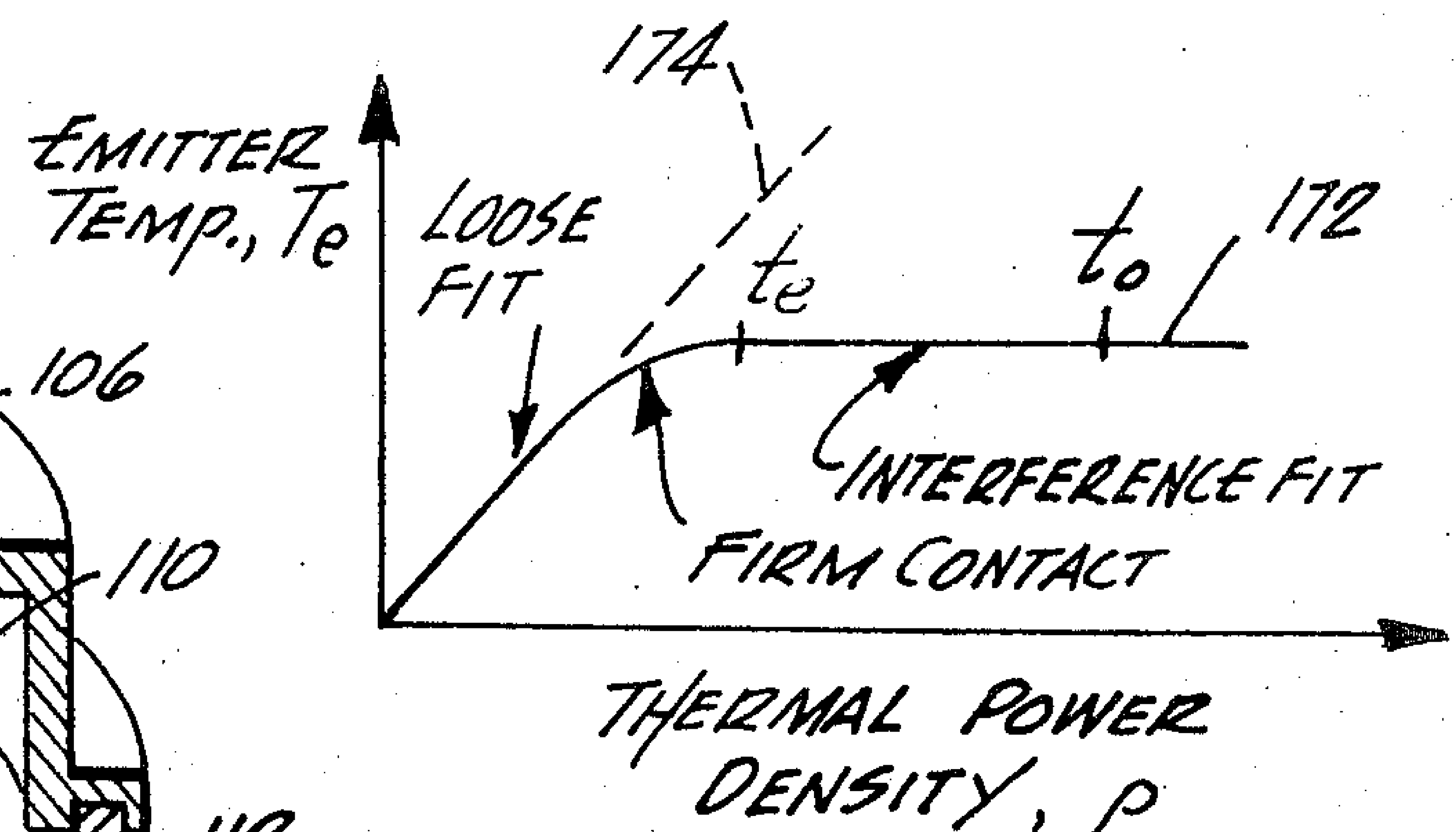

Fig. 12

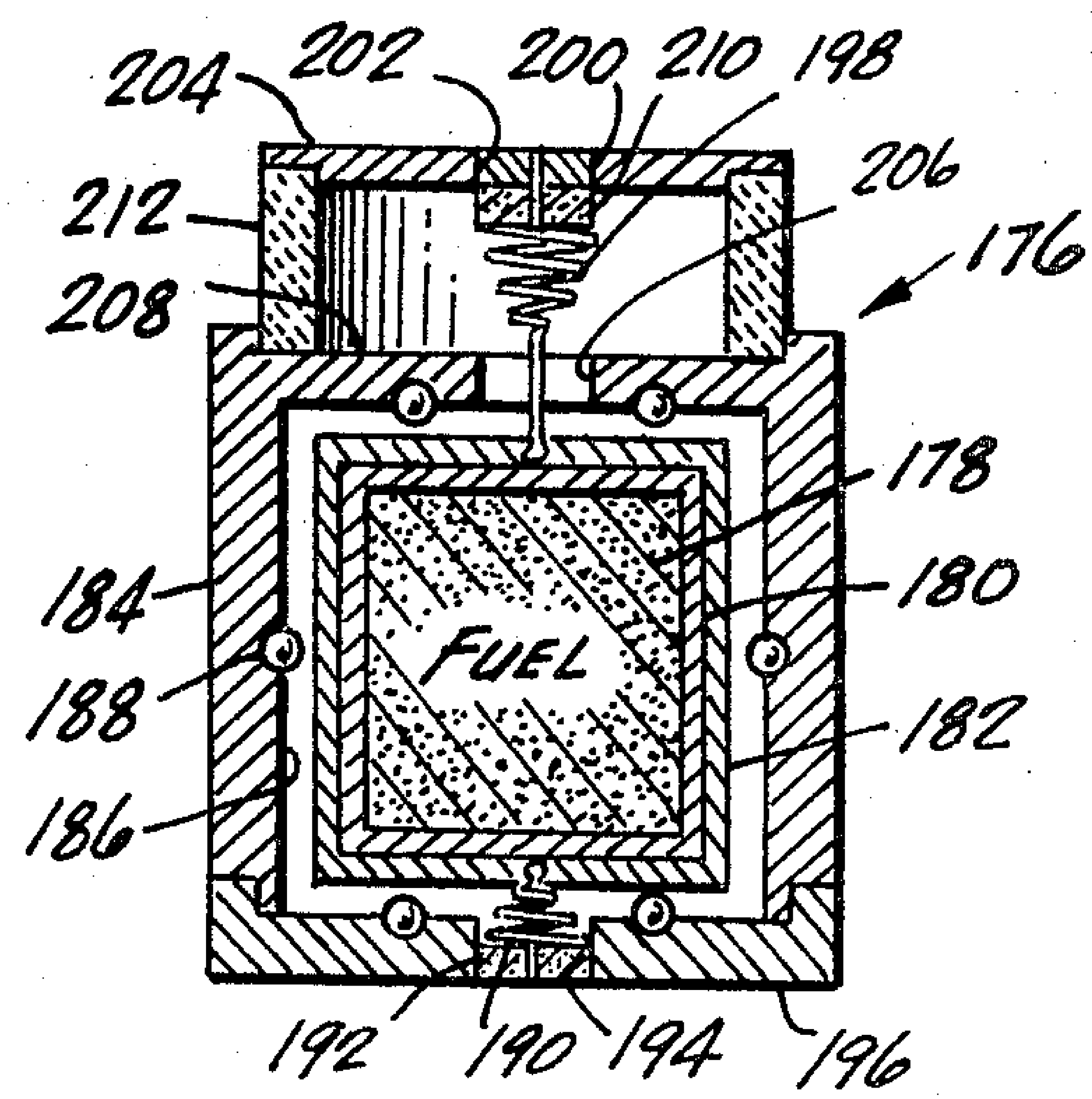

Fig. 13

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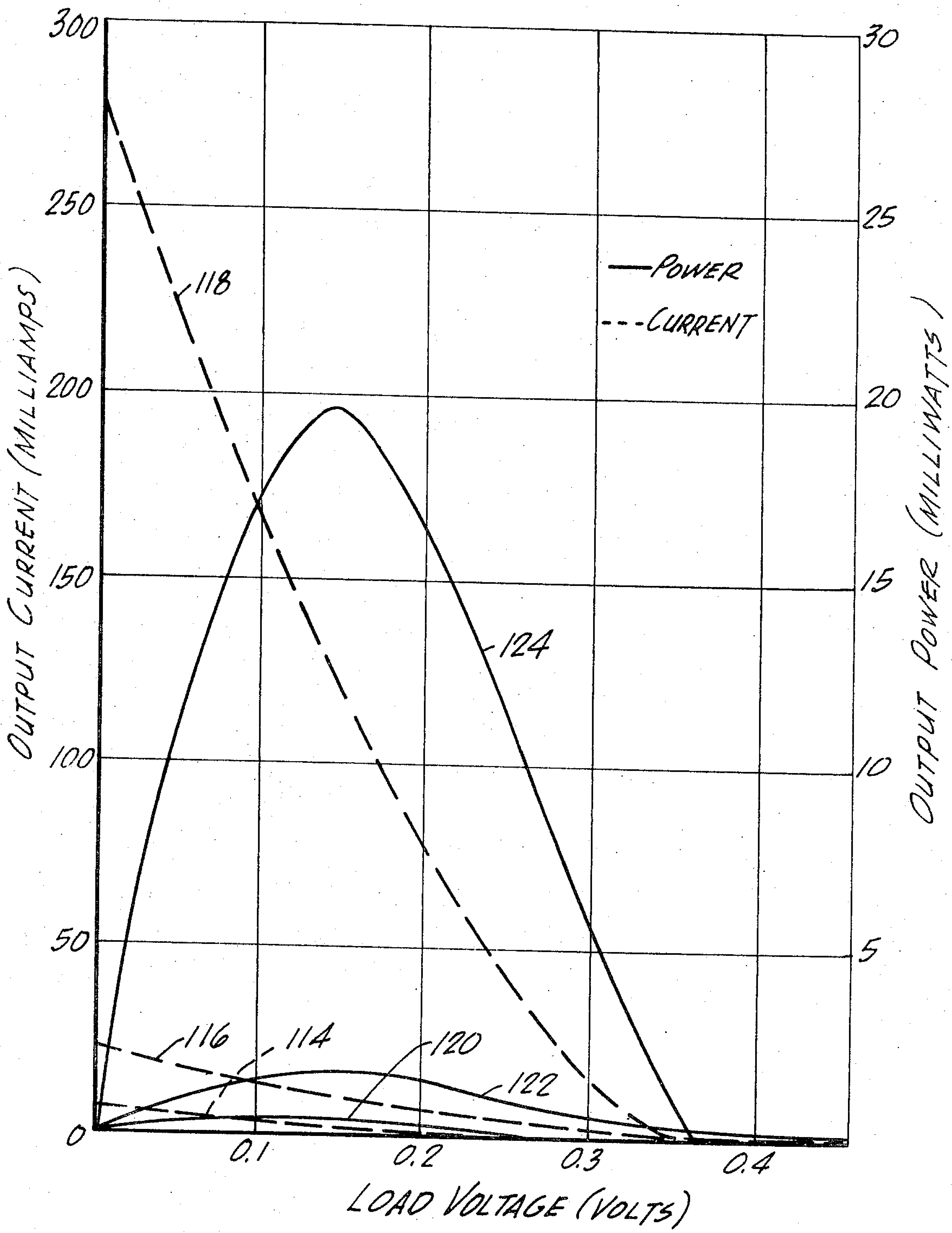

Fig. 10

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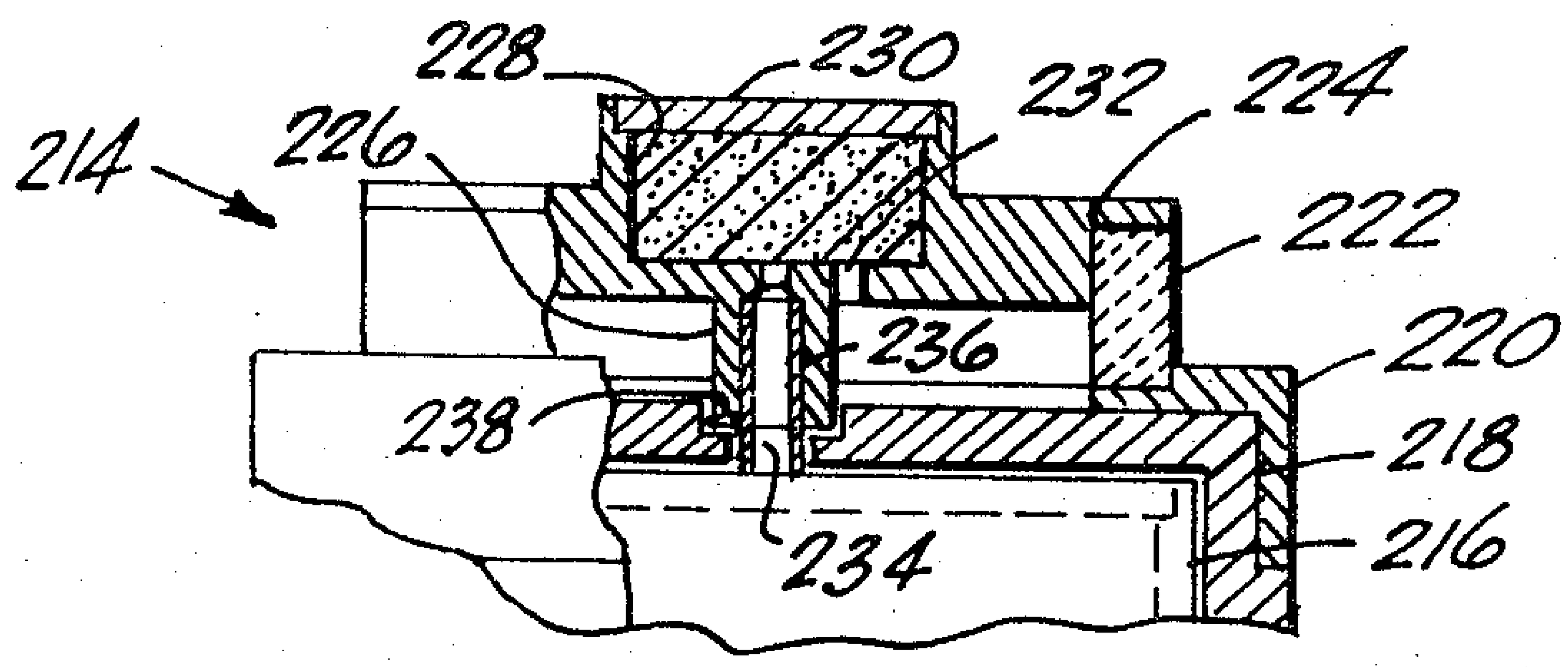

Fig. 14A

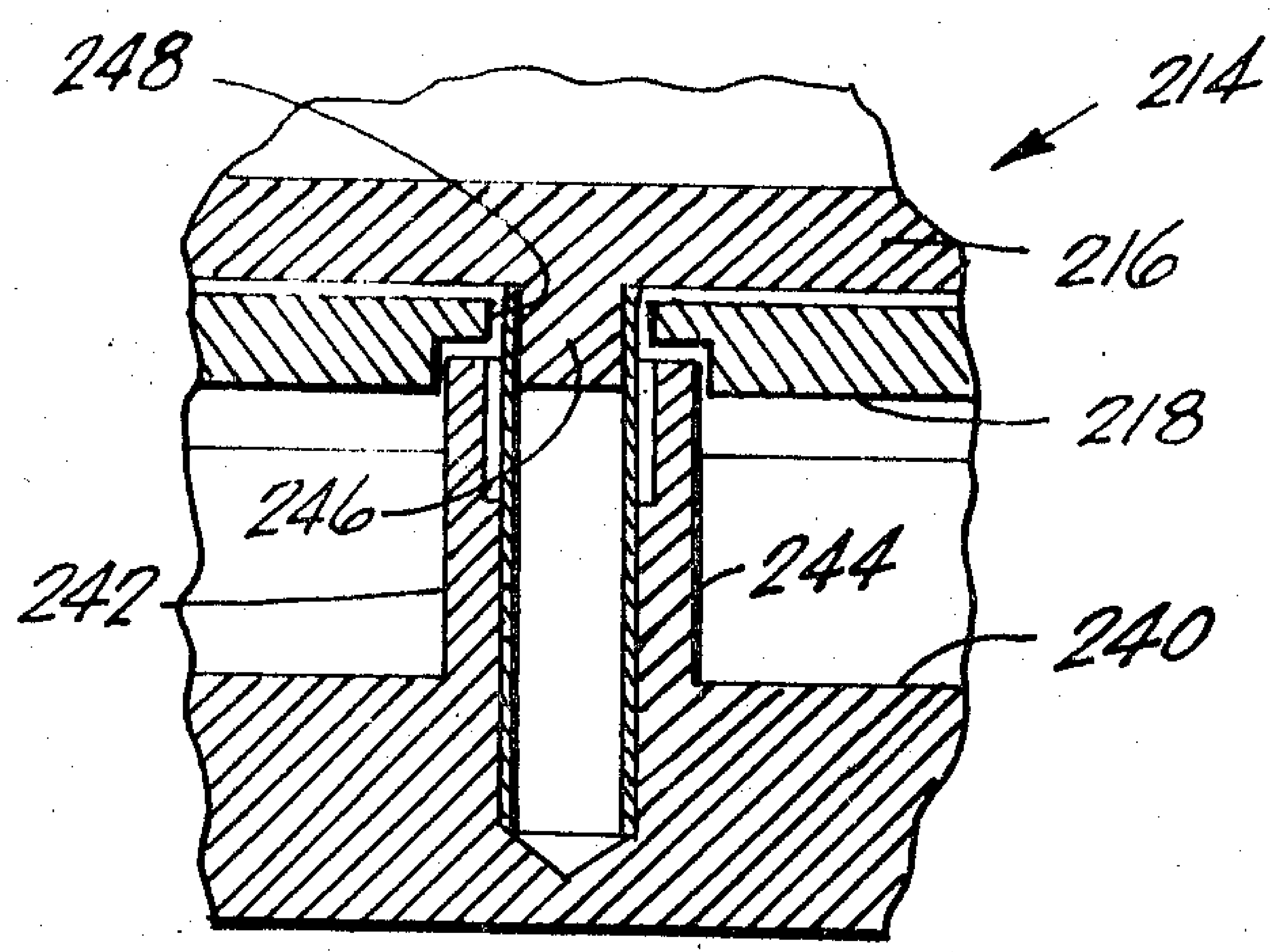

Fig. 14B

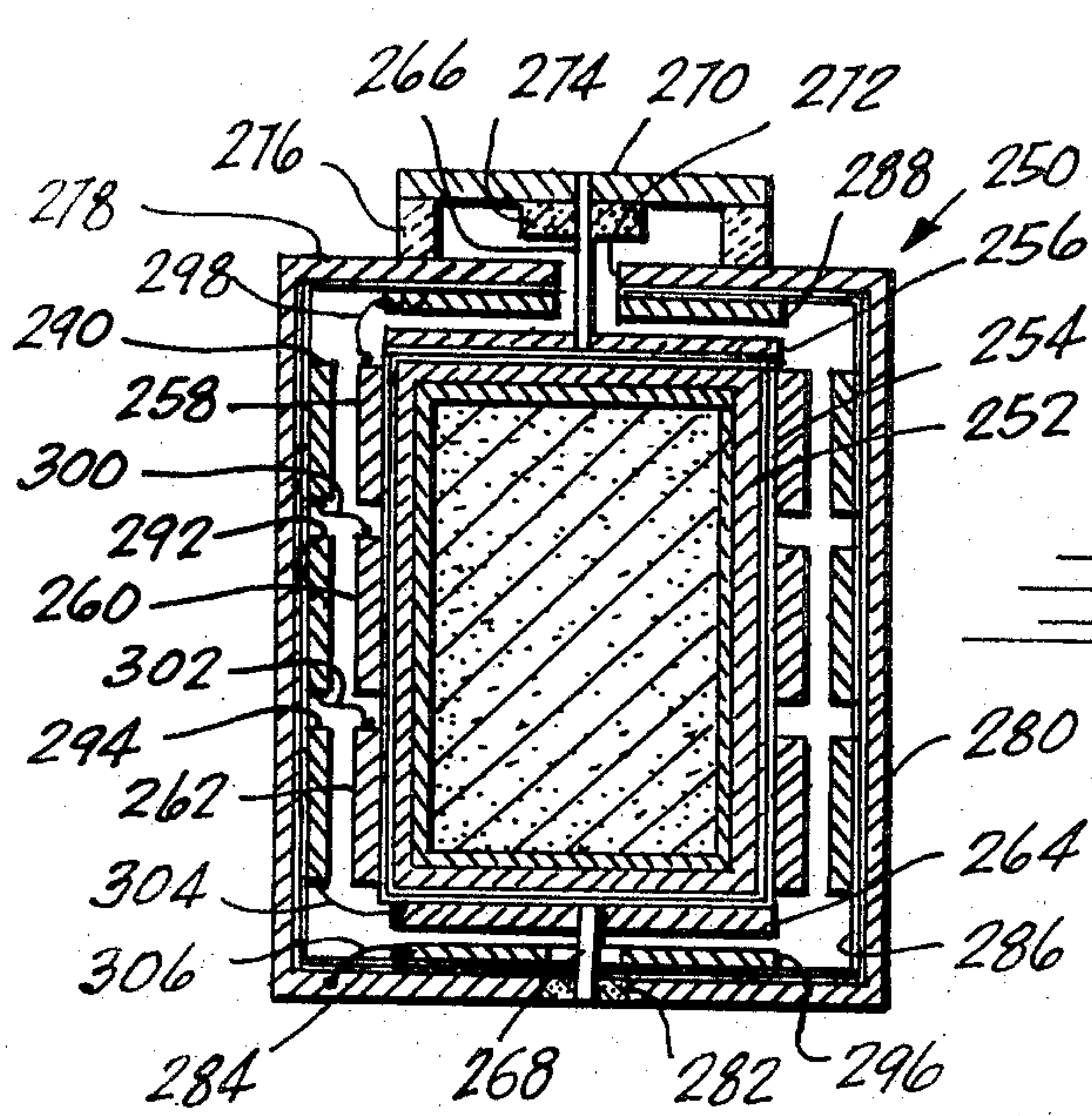

Fig. 15

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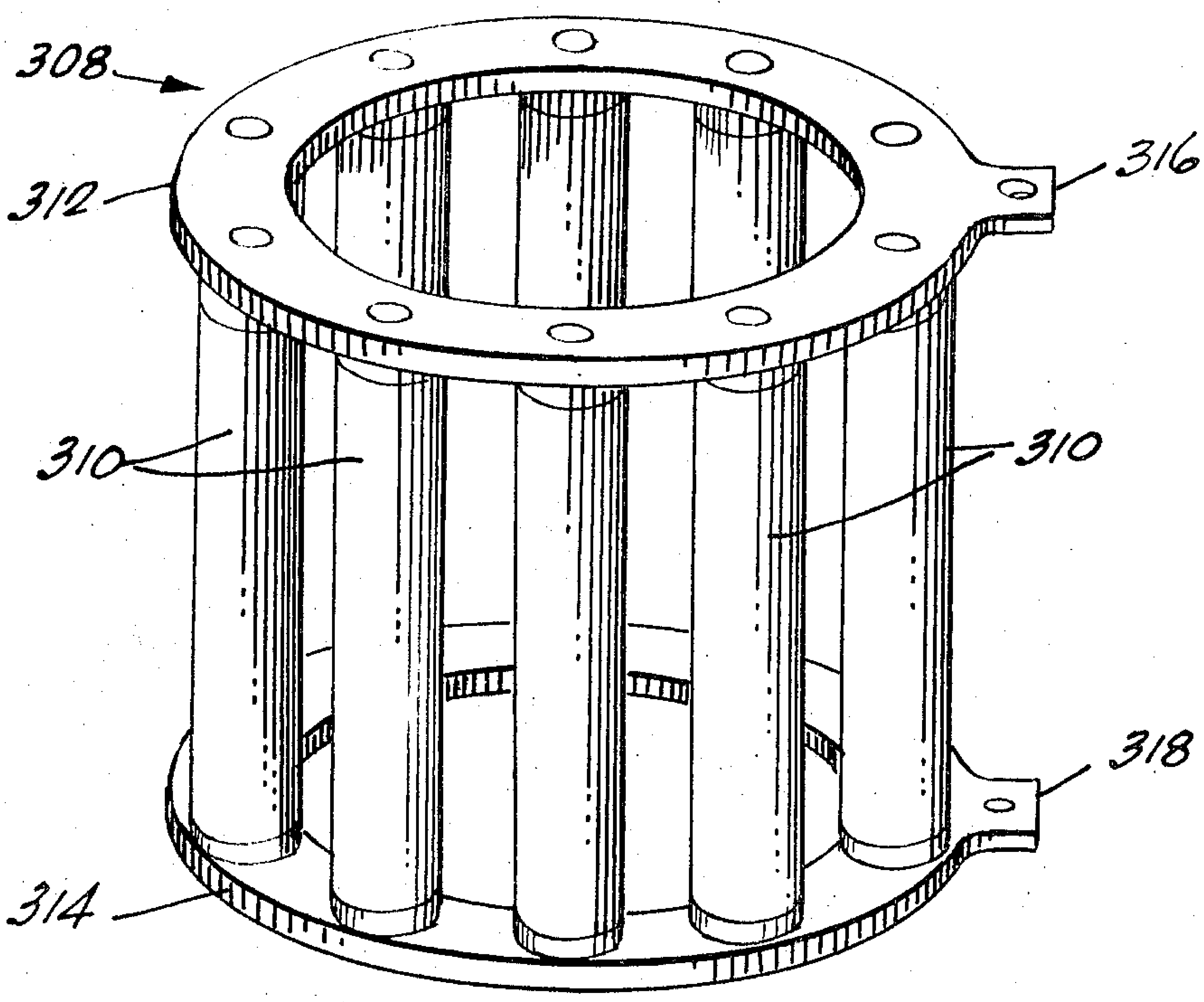

Fig. 16

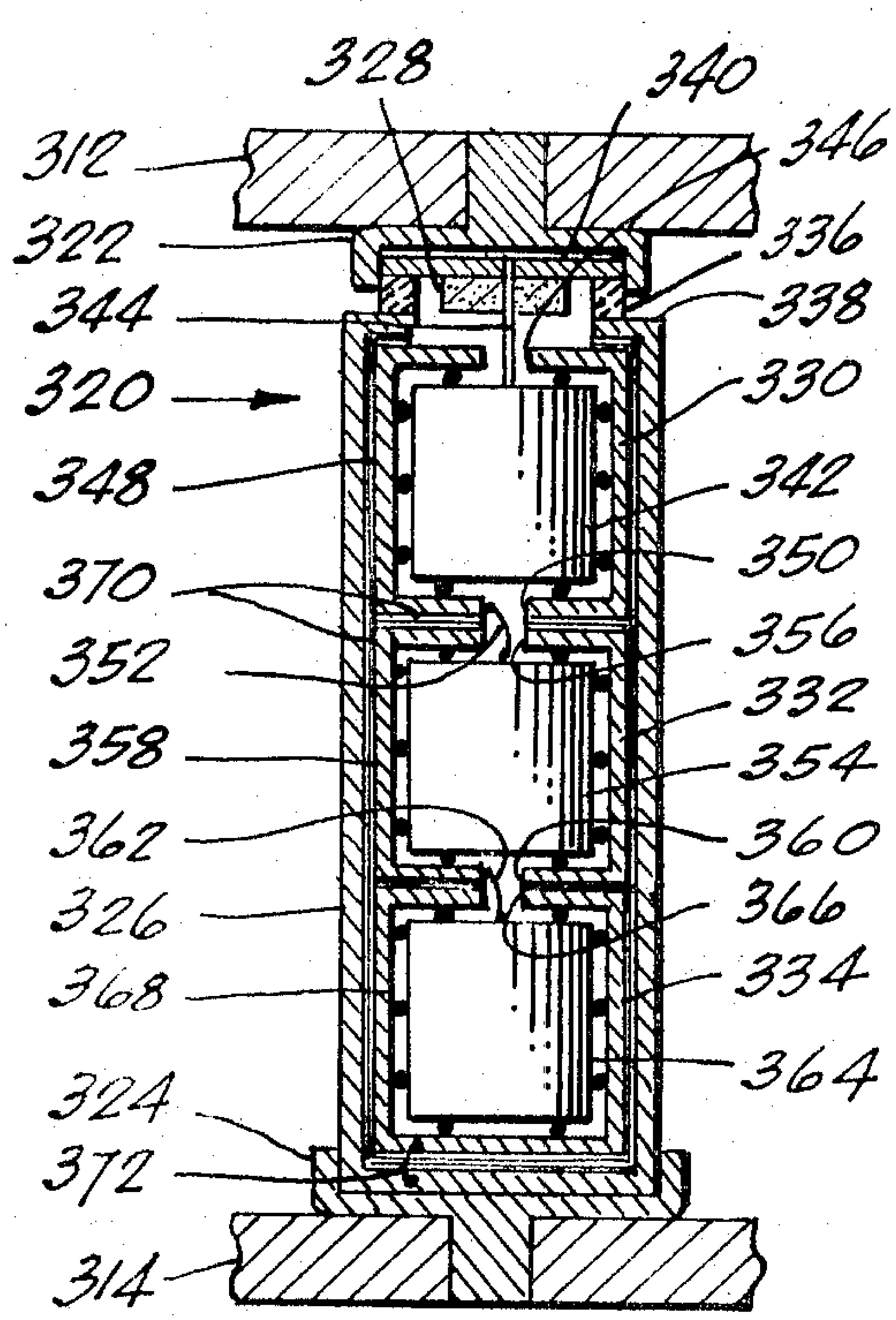

Fig. 17

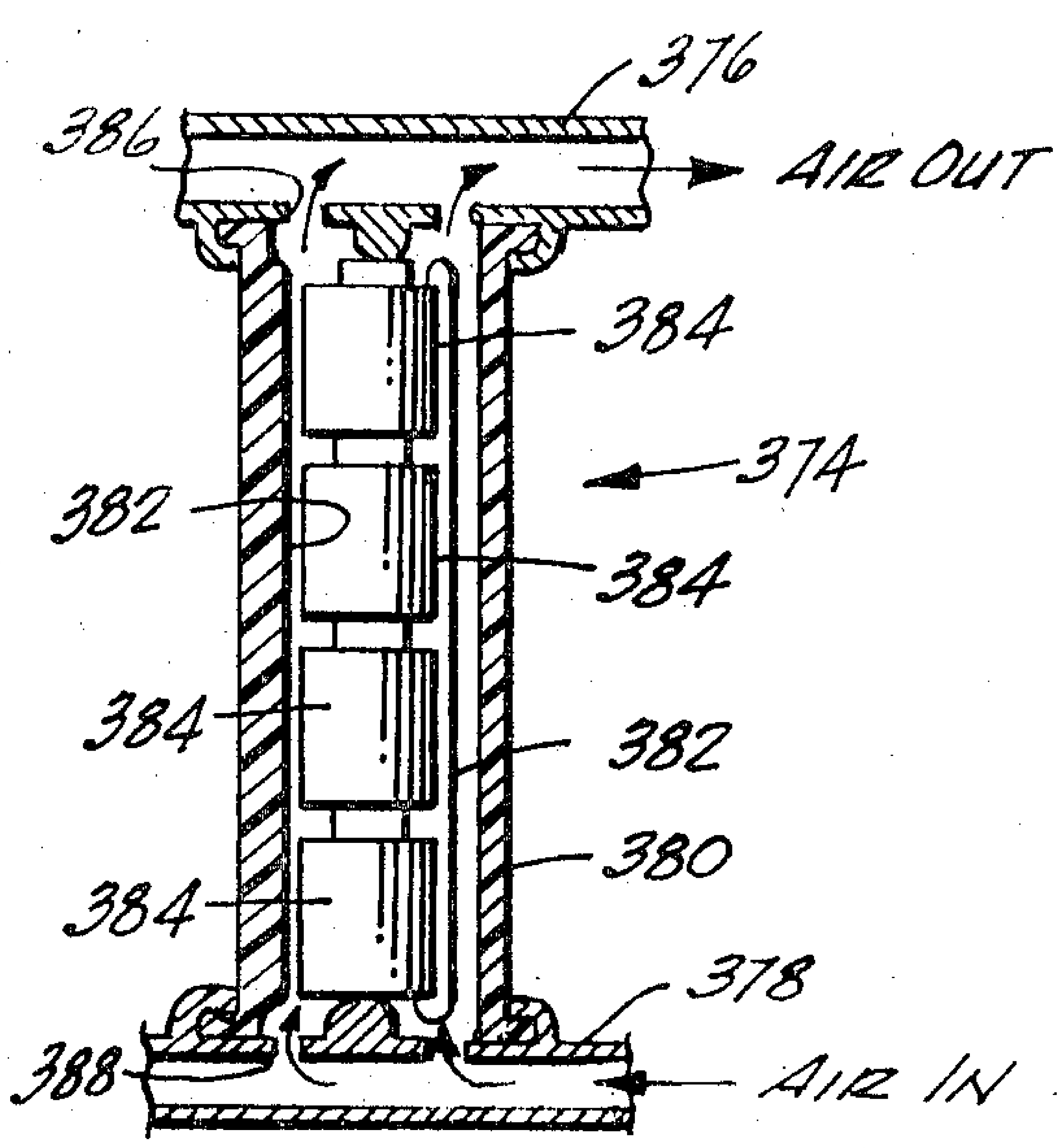

Fig. 18

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RADIOISOTOPIC THERMOINIC CONVERTER

This is a continuation, of application Ser. No. 794,933 filed Jan. 29, 1969 now abandoned.

BACKGROUND OF THE INVENTION

Our present invention pertains generally to the field of thermionic conversion of heat into electrical power, and more particularly to a radioisotope-fueled thermionic energy conversion device.

Radioisotope-fueled thermionic energy conversion devices utilizing conventional diode converters have been designed in the past to operate typically with fuels of a high volume thermal power density (greater than about 10 watts/cm^3), high emitter and collector temperatures (emitter temperature between about 1,600° and 2,100°K, and collector temperature between about 800° and 1,000°K), emitter and collector electrodes which are spaced closely together (between about 0.005 to 0.2 mm), and high current densities (between about 5 to 50 amp/cm^2). The high electrode temperatures employed in these converters prevented the utilization of low vacuum-work-function surfaces which evaporated too rapidly for stable operation over a useful lifetime. Also, the high current densities employed required impractically close electrode spacings to avoid space charge limitation effects for efficient vacuum mode operation. In subsequent designs, high vacuum-work-function electrodes having very low evaporation rates were immersed in cesium vapor, to lower their work function into the range required for operation at high current densities, and to provide positive ions for space charge neutralization. However, the high cesium vapor pressures ($>$ 1 torr) necessary to obtain the required work functions for the high temperature electrodes resulted in large voltage and current losses in the arc, for practical electrode spacings, with a corresponding loss in energy conversion efficiency.

In addition to these fundamental difficulties found in conventional diode converter operation, the high temperatures and high current densities previously employed made it difficult to obtain efficient and stable coupling of the diode portion of the converter to its heat source. To obtain the high current density, it was necessary to conduct or otherwise transport heat from a fuel capsule (heat source) to an emitter having an area much smaller than that of the capsule. This resulted in regions of the isotope fuel material being at much higher temperatures than the emitter, or required the introduction of complex heat transfer loops between the fuel material and emitter but such loops are unreliable at the high emitter temperatures. Furthermore, it was necessary to insulate thermally and electrically the heavy fuel capsule over most of its surfaces, and to support it in rigid contact with the diode portion of the conventional converter, all of which is exceptionally difficult to achieve at the high temperatures employed, especially with the possibility that the resulting structure may also have to withstand mechanical shocks. Since these latter difficulties increase rapidly with increasing capsule size, only the use of high-power-density, highly refractory radioisotopes ($>$10 watts/cm^3) was feasible. Also, the heat losses and mechanical constraints in the prior converters prevented obtaining efficient operation in units of less than about 20 watts total output power. In fact, all these fundamental and practical difficulties have been so severe that no radioisotope-fueled thermionic diode converter in the prior art has operated longer than a few dozen hours as of this date, although millions of dollars have been spent in efforts to do so.

Considerable progress has been made over the past few years in many aspects of the basic understanding and technology of thermionic energy conversion. We have been able to use this new knowledge to obtain a general formulation which permits the choice of optimum operating and design factors for any given application of the radioisotope-fueled thermionic converter. Our present invention is the result of combining several design features, which were impractical under operating conditions used in the prior art, to obtain efficient and stable operation in a previously unrecognized region of practical importance.

SUMMARY OF THE INVENTION

Briefly, and in general terms, our invention is preferably accomplished by providing an atomic diode battery or thermionic converter including a radioisotope fuel pellet or mass which is encapsulated fully to provide a sealed capsule having an emitter surface thereon, an outer housing completely enclosing the emitter capsule and having an internal collector surface spaced a predetermined distance from the emitter surface, a means for precisely maintaining this spacing, a cesium vapor source in communication with the spacing between the emitter and collector surfaces under such low vapor pressure that nominally vacuum mode (quasi-vacuum) operation is effected, and output contact elements electrically connected respectively to the emitter and collector surfaces whereby battery output can be obtained through suitable connections to the contact elements. The cesium vapor does not necessarily generate plasma effects but is present to modify the surface properties of the emitter and collector. Electron conduction in the diode battery between the emitter and collector occurs in the nominally vacuum mode of operation. Of course, there is a wide range of different electrode surfaces, vapor additives and working fluids which can be suitably used in this diode battery. For example, the cesium vapor can be omitted altogether and the cesiated surfaces replaced by alkaline earth oxide coatings on metallic substrates. Without cesium vapor or other vapor additives therein, the battery operates wholly in the vacuum diode (high-vacuum) mode.

The diode battery operates in a previously unrecognized region (at power levels presently in the range of about 10 microwatts to 1 watt) of practical importance for thermionic conversion devices. Much lower emitter current densities (typically about 0.1 to 400 ma/cm^2) are employed than previously considered and these lower current densities allow the use of nominally vacuum mode (quasi-vacuum) operation with practical electrode spacings and low work function surfaces for relatively low temperature emitters (600° to 1,400°K) and collectors (300° to 800°K). The battery is operated at such low current densities that emitter temperatures required to emit such current densities are so low that previously impractical classes of low work function surfaces can be used for the emitter. Cesium vapor pressures required for the emitter surfaces are so low that a class of very low work function (photocell) surfaces can now be used for the collector surfaces which can operate at nearly room temperature. The low temperatures of both emitter and collector electrodes permit the use of surfaces with very low thermal emissivities, low net radiant heat transfer and simple low thermal conductivity supports that were previously impractical and which greatly reduce the heat losses to provide relatively high efficiencies. By defining the optimum interaction of variables for a thermionic conversion device to be operated in this new region, the resulting diode battery configuration based thereupon has a minimum fuel inventory for a given power output so that efficiency is maximized and the required fuel and nuclear shielding is minimized. The size and shape of the emitter, for example, can be optimized to match the thermionic properties of low work function surfaces with the thermal power density and permissible operating temperature for any applicable radioisotope fuel.

Accordingly, the diode battery includes a radioisotope fuel pellet which is suitably encapsulated to provide an emitter capsule that is preferably of the form of a right circular cylinder having an emitter surface extending over substantially the entire external surface of the cylinder (capsule). Low thermal power density radioisotope fuels can, of course, be used in this battery. The capsule is enclosed inside the vacuum-tight and enveloping outer housing which has the collector surface correspondingly extending over substantially the entire internal surface of such housing. The interelectrode spacing between the emitter and collector surfaces is maintained throughout the full extent of these surfaces. This can be accomplished by introducing electrically insulating spacers between the electrodes or by elastic supports at other locations (i.e., not between the electrodes). The insulating spacers can be ceramic rods, balls or grains located within the electrode gap, for example. The elastic supports can be thin tension wires, springs or tubes connected to the capsule and secured to insulating inserts affixed to the collector (housing) or projecting through holes in the collector and secured to exterior insulating structure. In the optimum configuration, the battery output voltage, the product of capsule diameter and the ratio of effective radioisotope thermal power density to emissivity, and the product of battery total output current and this ratio squared are generally unique functions of the interelectrode spacing. Thus, the smallest battery with maximum efficiency is obtained by conforming to the crucial optimum relationship established among the battery parameters including its output voltage, radioisotope thermal power density, capsule diameter, electrode surface thermal emissivity, total output current and electrode spacing, in accordance with our invention.

The atomic diode battery can produce stable and long-life electric power with outputs in the range from 10 microwatts to several watts, approximately. The choice of appropriate radioisotopic fuel allows lifetimes of these devices from months to several tens of years. Our atomic battery is generally superior in size, efficiency, simplicity, versatility and stability to all other forms of atomic batteries in this power range, including those utilizing thermoelectric, beta-voltaic, beta-photovoltaic and direct-collection energy conversion processes. Furthermore, this radioisotope-fueled thermionic conversion device forms a battery with an energy density several orders of magnitude greater than that which can be derived from energy stored in a chemical system. In existing power supplies based on chemical batteries, energy densities have been and probably will continue to be less than 800 watt-sec/gm (100 watt-hr/lb), whereas the heat produced by radioisotope decay provides power sources with practical energy densities of 1,600 to 160,000 watt-sec/gm (200 to 20,000 watt-hr/lb).

BRIEF DESCRIPTION OF THE DRAWINGS

Our invention will be more fully understood, and other features and advantages thereof will become apparent, from the description given below of certain exemplary embodiments of the invention. This description of the exemplary embodiments is to be taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a diagrammatic sectional view of a radioisotope-fueled thermionic conversion electrical power source, typically illustrating a prior construction form of thermionic conversion devices;

FIG. 2 is a diagrammatic sectional view of another radioisotope-fueled thermionic conversion electrical power source, illustrating a different prior construction form of thermionic conversion devices;

FIG. 3 is a graph showing the electrical output characteristic of a thermionic diode converter such as the source shown in FIG. 1;

FIG. 4 is a graph showing a plot of work function against the ratio of surface temperature to reservoir temperature, for a cesium vapor thermionic diode converter;

FIG. 5 is a chart depicting the basic reference configuration chosen for this invention and certain configurational variations thereof;

FIG. 6 is an electron motive diagram for a thermionic diode conversion device operated in the vacuum mode;

FIG. 7 is a graph showing the relationship among variables which results in minimum fuel volume for a diode battery operated in the vacuum mode;

FIG. 8 is a graph showing the loci of optimum output voltage and associated effective battery collector work function with negligible electron cooling which yield the smallest diode battery for given values of battery current;

FIG. 9 is a sectionalized perspective view of a diode battery which is constructed in accordance with our invention;

FIG. 10 is a graph showing the output characteristics of three prototype diode batteries;

FIG. 11 is a sectionalized perspective view of another illustrative embodiment of this invention;

FIG. 12 is a graph showing a plot of emitter temperature against radioisotope thermal power density decay in an automatically controlled diode battery construction;

FIG. 13 is a sectionalized elevational view of a miniature diode battery having a basically lead-supported emitter capsule therein;

FIG. 14A is a fragmentary and partially sectional view of the upper portion of a diode battery having an integral (cesium) reservoir and illustrating an elastic tube support for the upper end of the emitter capsule thereof;

FIG. 14B is a fragmentary and enlarged sectional view of the elastic tube support for the lower end of the emitter capsule of the diode battery fragmentarily shown in FIG. 14A;

FIG. 15 is a central sectional view of another version of this invention wherein a battery having diode sections therein provides a higher output voltage by means of a series connection of the diode sections;

FIG. 16 is a perspective view of a unitary battery system wherein a plurality of battery units are connected together in parallel to provide a system having a high total output power;

FIG. 17 is a central sectional view of a battery unit including a plurality of diode batteries connected in series within a single container or casing having a common cesium reservoir therein and mounted as a unit of the system shown in FIG. 16; and

FIG. 18 is a fragmentary sectional view of a unitary battery system, showing a unit thereof containing a plurality of separate diode batteries stacked in series and cooled by circulating air passing through the unit casing.

DESCRIPTION OF THE PRESENT EMBODIMENTS

FIG. 1 is a diagrammatic sectional view of the planar diode type of radioisotope-fueled thermionic conversion electrical power source. Power source **20** typically illustrates the principal type of prior construction of thermionic conversion devices utilizing a radioisotope fuel. A brief description of the source **20** will readily make evident the problems inherently associated therewith. Part of this description will, however, be useful in explaining and understanding certain features of our present invention and the operation thereof. The source **20** is generally symmetrical cylindrically and includes a radioisotope fuel pellet **22** which is suitably encapsulated by liner **24** to form a fully encased fuel capsule **26**. An emitter disc **28** is bonded to the lower surface of the capsule **26** for good thermal contact therewith and a thermal radiation shield **30** is attached to the other surfaces of the capsule. The emitter disc **28** has a suitable emitter surface **32**.

The assembly **34** including fuel capsule **26**, emitter disc **28** and thermal shield **30** is bonded to and supported on the upper end of a generally tubular emitter sleeve **36** having its lower flange end bonded to insulator ring **38**. The ring **38** is bonded to a base disc **40** including a collector structure **42** having an upper collector surface **44** thereon. The collector structure **42** protrudes upwards and the collector surface **44** is positioned in close propinquity to the emitter surface **32**. The space between the emitter and collector surfaces **32** and **44** is connected by the enclosing sleeve **36** and ring **38** to a passageway **46** which extends through the collector structure **42** and a lower collar **48**. A tube **50** of predetermined length connects a cesium (Cs) reservoir **52** to the collar **48** and the passageway **46**. Finally, an outer cap or cover **54** is hermetically attached to the periphery of the base disc **40** and is used to enclose the assembly **34** in a vacuum. The cap **54** provides additional thermal and radiation shielding to the necessary extent, and also mounts an insulated emitter terminal **56** which is electrically connected to the emitter surface **32** through sleeve **36**.

The radioisotope fuel pellet **22** includes, for example, curium-244 (Cm^{244}), actinium-227 (Ac^{227}) or polonium-210 (Po^{210}) fuel material and has a net volume thermal power density typically greater than 10 watts/cm^3. The emitter disc **28** is typically made of tungsten (W), tantalum (Ta) or rhenium (Re). The thermal shield **30** preferably comprises multifoil insulation which is quite fragile and delicate to handle. The collector structure **42** can be made of molybdenum (Mo) or nickel (Ni), for example. The emitter surface **32** is typically spaced from the collector surface **44** at a separation distance of approximately 0.05 – 0.15 mm (0.002 – 0.006 inch) and this must be maintained by the supporting emitter sleeve **36** which is preferably less than about 0.05 mm (0.002 inch) thick since a thicker sleeve would conduct and radiate too much heat. The emitter surface **32** typically has a temperature T_e of approximately 1,700° – 2,000°K and an electrical output power density of from 5 to 20 watts/cm^2. The collector surface **44** has a temperature T_c of approximately 800° – 1,000°K and the cesium reservoir **52** is located at a distance from the collector structure **42** such that its temperature T_R is about 600°K, to provide a cesium vapor pressure of approximately 4 torr for operation of the source **20** in the ignited mode.

FIG. 2 is a diagrammatic sectional view of another prior type of radioisotope-fueled thermionic conversion electrical power source. Power source **21** represented an attempt to alleviate some of the severe problems and limitations encountered in the planar type of source **20** shown in FIG. 1. A brief description of the source **21** will readily make evident the additional problems inherently associated therewith, and will also be useful in explaining and understanding certain features of our present invention and the operation thereof. The source **21** is generally symmetrical cylindrically and includes an annular radioisotope fuel pellet **23** which is encapsulated by liner **25** to form a fully encased fuel capsule **27**. A vapor reflux column **29** (also known as a heat pipe) is inserted into central hole **31** in the capsule **27** and suitably bonded thereto. The protruding upper end of the heat pipe **29** is bonded to the inner surface of a hollow cylindrical emitter tube **33**. The outer surface of tube **33** provides an emitter surface **35**, which is positioned inside and in close propinquity to collector surface **37** that is the inside surface of a hollow cylindrical collector tube **39**. The emitter tube **33** is bonded to and supported by two generally tubular emitter sleeves **41**, one at each end, with their outer flange ends bonded to insulator rings **43**. The rings **43** are, in turn, bonded to respective ends of the collector tube **39** such as to form a vacuum-tight enclosure including the annular gap between the emitter and collector surfaces **35** and **37**. A tube **45** connects a cesium reservoir **47** to a hole **49** extending through the wall of the collector tube **39** and thus with the annular gap in the vacuum-tight enclosure. The entire external surface of the capsule **27** and any exposed surface of the heat pipe **29** must be covered by thermal radiation shielding **51**. Finally, the entire assembly is supported by capsule supports **53** in the vacuum inside hermetically sealed can **55**. The can **55** mounts an insulated collector terminal **57** which is electrically connected to the collector surface **37**. The discussion given for the fuel, electrodes, thermal shield, emitter sleeve and operating conditions for source **20** in FIG. 1 apply equally to source **21** in FIG. 2. Several variants of sources **20** and **21** have been proposed to avoid the severe problems and limitations associated therewith.

The prior radioisotope-fueled thermionic conversion devices **20** and **21** shown in FIGS. 1 and 2 operate in what is known as the ignited mode of converter operation. In order to appreciate fully the unique features of our invention, which does not utilize ignited mode operation, it is necessary to review briefly the factors of plasma and surface physics which distinguish the operation of prior thermionic converters from that employed in the present invention.

FIG. 3 shows a typical electrical output characteristic **58** (current density J versus output voltage V) of a cesium vapor thermionic diode converter, such as source **20** or **21,** operated in its two discharge modes. The curve **58** shown corresponds to the optimum operating condition for such converters; i.e., when the cesium vapor pressure is such that the electron mean free path is approximately one tenth of the electrode spacing. In the mode of operation that prior sources (**20** and **21**) operate, the vapor between the electrodes glows brightly and is called the ignited mode of the discharge. In this mode of operation, the electrons in the interelectrode region are maintained at about twice the temperature of the emitter by a potential drop, known as the arc drop V_d, across such region. This high electron temperature in the glowing region is sufficient to excite and ionize the cesium vapor and thereby maintain the high density plasma necessary for the flow of a large electron current between the electrodes. The potential difference between the electrodes is, therefore, $V=(\phi_e - \phi c) - V_d$ where $(\phi_e - \phi c)$ is the contact potential difference, and ϕ_e and ϕ_c are the work functions of the emitter and collector, respectively.

In most applications, it is desired to obtain the required electrical power output of the diode converter at the highest potential difference consistent with adequate power density since this generally corresponds to maximum efficiency for the converter and minimum losses in the external circuit. In the ignited mode, it has been found that the output current falls rapidly when the arc drop V_d becomes less than the minimum value V_d' required to maintain the plasma; i.e., for V greater than $V_o = (\phi_e - 100_c) - V_d'$ as identified by the transition point A in FIG. **3.** Maximum power output typically occurs near this point A. It has been found that the minimum value of the arc drop V_d' is about 0.4 volt at the optimum product of the electrode spacing and the cesium vapor pressure in the diode converter. Since the cesium vapor pressure is related to the cesium reservoir temperature T_R, the optimum electrode spacing is determined by the cesium reservoir temperature. The cesium vapor pressure and reservoir temperature are those necessary to obtain the emitter work function which will permit emission of the saturation electron emission current density J_s at the given emitter temperature T_e. The optimum potential difference V_o between the emitter and collector electrodes in the ignited mode of operation is, therefore, approximately equal to $(\phi_e - \phi_c - 0.4)$ volts.

It has also been found that at the optimum condition mentioned above, the emission current per unit electrode area, J_o, is equal to about 0.4 of the saturation electron emission current density from the emitter, J_s, which can be determined from the well-known Richardson equation that is given below later. It may, therefore, be seen that a consequence of operation in the ignited mode is a loss of at least 0.4 volt in output potential difference, and a loss of about 60 percent of the current which would otherwise be obtained if no plasma or space charge were present (ideal diode). These losses should be looked upon as the penalty which must be paid when part of the electrical output of the device is consumed in producing and maintaining the high density plasma necessary to conduct a high current density of electrons across the interelectrode gap. As the emitter temperature is lowered, the emitter work function must be lowered to maintain the emitter current. Since ϕ_c is relatively fixed, the output voltage falls rapidly as the emitter temperature is approached where the contact potential $(\phi_e - \phi_c)$ equals the minimum arc drop V_d', which is about 1,400°K. At this point, virtually the entire potential electrical output power is consumed in maintaining the plasma. Therefore, operation is the ignited mode is impractically inefficient below an emitter temperature of about 1,600°K.

In the other discharge mode of operation, called the unignited mode of the discharge, the interelectrode space is dark, i.e., the arc is is extinguished. In this mode of operation, the positive ions required to maintain the plasma are thermionically emitted from the hot emitter electrode. If precisely enough positive ions are emitted to neutralize the electron emission from the emitter, no significant space charge exists. Therefore, since electrical energy is not required to produce the ions, the arc drop V_d can be zero. Thus, the optimum potential difference V_{ox} between electrodes in the unignited mode of operation is approximately equal to $\phi_e - \phi_c$, provided that the emitter work function ϕ_e is chosen to give neutral emission wherein $\phi_e = \phi_n$, which is dependent upon emitter and cesium reservoir temperatures. Therefore, operation in the unignited mode is more efficient than in the ignited mode, since the plasma is maintained by thermal energy instead of electrical energy, However, it is readily shown that the requirement of $\phi_e = \phi_n$ requires high emitter temperatures, excessively high cesium vapor pressures and, therefore, impractically small electrode spacings with known materials for operation at high current densities. Thus, the foregoing operation obviously does not pertain to electron conduction in the nominally vacuum mode of operation.

Emitters with work functions between about 2.2 and 3.2 ev are necessary to operate at the high power densities and temperatures associated with ignited mode converters employed in the prior art. A few elementary materials are known to have vacuum work functions in this range, but they all evaporate too rapidly at the corresponding temperatures to achieve stable operation over a useful lifetime. It appears that there is a fundamental correlation between the rate of evaporation and electron emission which makes the use of this class of elementary emitter materials impractical. Fortunately, however, when immersed in cesium vapor at reasonable pressures, materials with vacuum work functions greater than 4.0 ev such as the refractory metals, adsorb enough cesium on their surfaces to lower their work functions into the range of required values. Since the immersed surface is in equilibrium with the vapor, problems of emitter stability and lifetime are virtually eliminated. Accordingly, essentially all practical thermionic converters have employed refractory metal electrodes with adsorbed cesium. However, the competing requirements on the cesium vapor for plasma maintenance and for work function determination have constrained operation of prior cesium vapor converters to high temperatures, high current density and close electrode spacing in order to obtain practical energy conversion efficiencies.

FIG. **4** is a graph showing a plot of work function ϕ against the ratio of surface temperature T to cesium reservoir temperature T_R or materials immersed in cesium vapor. The interaction leading to the constraints noted above in prior cesium vapor converter operation is best understood by considering this figure. The interaction among electrode materials (work functions), temperatures and spacings (reservoir temperatures) is summarized in the family of curves **60** which correlates the work function of surfaces in cesium vapor with their respective vacuum work functions ϕ_o. Virtually all experimental data for surfaces immersed in pure cesium vapor fall within the envelope defined by this family of curves **60**. The principal exception is in the region below 2.5 ev where such data frequently extends the lower envelope portion down to the broken line curve **62**, although such behavior is often known to be associated with contamination. A cesiated silver oxide surface could, for example, extend the lower envelope portion even farther down to the curve **64**. The upper trapezoid **66** encloses the region of greatest importance to emitters operating in the ignited mode. The upper and lower boundaries correspond to work functions for sufficient electron emission at 1,600°K and 2,100°K, respectively. The left and right boundaries correspond to optimum spacings for the ignited mode of about 0.05 mm (0.002 inch) and 0.5 mm (0.020 inch), respectively.

For high power density operation in the unignited mode, emitters are restricted to the heavy line segment **68** which represents the neutral emission condition ϕ_n for maximum spacings between 0.05 mm (0.002 inch) and 0.5 mm (0.020 inch) corresponding to the left and right ends, respectively, of the line segment **68**. Operation at the left (small interelectrode spacing) terminus B of the unignited mode heavy line segment **68** can be reached by either a bare emitter surface having $\phi_o = 2.9$ ev, or by an emitter surface with adsorbed cesium and having $\phi_o = 5.5$ ev. As far as the diode converter is concerned, both methods give the same output, since the ion and electron emission currents and the cesium vapor pressure are the same for both. The known materials having tese work functions are, however, unattractive for other reasons, primarily that of excessive vaporization during operation. The region of greatest importance to the collector for operation in either of the discharge modes is indicated by the lower triangle **70**. The right boundary of this region is imposed by collector emission at the lowest cesium vapor pressure occurring in the emitter region (**66** and **68**) of the plot, and the upper boundary corresponds to the collector emission limitation for a collector temperature of 1,000°K, which is high enough for most applications.

The foregoing description has described those aspects of the prior art which have been improved by our present invention, and has outlined the basic principles which are common to the prior art and to our invention. The following description describes how we use these basic principles to optimize the performance of the radioisotope-fueled thermionic converter, and introduce formerly impractical design features to obtain a unique and superior result.

FIG. **5** is a chart depicting the basic reference configuration chosen for our invention. Configurational variations including values of certain of their respective parameters are indicated in the chart. The radioisotope fuel capsule **72** is selected to be a right circular cylinder of height h and diameter D, and is suitably fabricated to include the emitters for the various thermionic diodes on its surfaces. The five configurational variations considered are: (a) emission from one planar surface only; (b) emission from both planar surfaces only; (c) emission from all surfaces; (d) emission from the cylindrical surface only; and (e) emission from the cylindrical and one planar surface only.

Optimization of this invention for the reference configuration has shown the interdependence of important design variables. As derived below, a device of the reference configuration is governed by the following variables:

ρ' = effective radioisotope thermal power density (watts/cm³)

ϵ_c = effective net electrode thermal emissivity of the cylindrical region

I = device current (amperes)

T_e = emitter temperature (°K)

d = electrode spacing (cm)

ψ = emitter emission energy barrier (electron volts), $\psi = eV + 100_c'$

where

ϕ'_c = effective collector work function (electron volts)

e = electronic charge (coulomb)

V = output voltage (volts).

At steady state, the rate of heat generation P_g in a fuel capsule of average volume power density ρ is equal to the rate at which heat is lost by thermal radiation P_r, by electron cooling P_e, and by conduction P_c through the emitter lead and supporting structure with thermal conductance G; i.e.,

$$P_g = P_r + P_e + P_c = (\pi D^2/4)\ h\sigma \quad 1.$$

where

$$P_r = \theta(T_e^4 - T_c^4)(m\epsilon_d\ \pi D^2/4 + n\epsilon_o\ \pi D^2/4 + p\epsilon_d\pi Dh + q\epsilon_o\pi Dh) \quad 2.$$

$$P_e = I(eV + \phi_c' + 2kT_e). \quad 3.$$

$$P_c = G(T_e - T_c). \quad 4.$$

T_e and T_c are the respective emitter and collector temperatures, θ is the Stefan-boltzmann constant, k is the Boltzmann constant, and ϵ_d and ϵ_o are the net thermal emissivities of the diode and non-diode regions, respectively. The configurational variations are represented by the set of parameters (m, n, p, q) given for each of the variations (a), (b), (c), (d) and (e) shown in FIG. **5**.

For a given current I, the heat removed by electron cooling and conduction is relatively insensitive to all of the variables. It is convenient, therefore, to define a net heat generation rate $P'_g = P_g - (P_e + P_c)$, with an associated effective or net volume thermal power density

$$\rho' = \rho - 4/\pi\ (P_e + P_c/rD^3) \quad 5.$$

where $r = h/D$ is the height-to-diameter ratio.

Accordingly, to a good approximation, the minimum fuel capsule volume is obtained when $(dP_g' / dh) = 0$ which, from Equations 1 and 2, occurs for the optimum height-to-diameter ratio

$$r = (h/D)_{opt} = ½\ (m\epsilon_d + n\epsilon_o/p\epsilon_d + q\epsilon_o) \quad 6.$$

The value of this optimum ratio for each configurational variation is given in FIG. **5**. Note that a square cylinder ($h = D$) is optimum for all variations if $\epsilon_d = \epsilon_o$. Furthermore, Equations **2** and **6** require that

$$D = 6\theta\epsilon_c\ (T_e^r - T_c^4)\ /\rho' \quad 7.$$

where $\epsilon_c = p\epsilon_d + q\epsilon_o$ is the net electrode thermal emissivity of the cylindrical region.

For negligible collector back emission, Equations 6 and 7, and the well-known Richardson equation

$$J = AT_e^2 \exp(-\psi / kT_e) \quad 8.$$

where

J = electron emission current density (amps/cm^2)

A = the Richardson constant (120 amp/cm^2 - °K^2)

combine to give

$cV+$

$$T_e = \frac{cV + \varnothing_c'}{k \cdot \ln\left[\left(\frac{3\sigma\epsilon_c}{\rho'}\right)^2 \frac{\Lambda \pi a T_c^2}{1} (T_c'' - T_c'')^2\right]} \quad (9)$$

where

$a = m + 4pr$.

The values of the coupling factor configurational parameter $a = m + 4pr$ for each configurational variation are included in FIG. **5.**

FIG. **6** is an electron motive diagram for a vacuum thermionic diode with electrode spacing d, true collector and emitter work functions ϕ_c and ϕ_e, and collector and emitter space charge barriers δ_c and δ_e. The distances to the motive maximum from the collector and from the emitter and x_c and x_e, respectively. It will be assumed that $\phi_e < eV + \phi_c' + 2kT_e$, so that $x_e = x_o$, and to a sufficiently good approximation for present purposes

$\phi_c' = \phi_c + kT_e\,(d/x_o - 1)^2$ 10.

for $d > x_o$

$\phi_c' = \phi_c$ 11.

for $d < x_o$

where

$x_o = b(\pi a/I)^{1/2}\, T_e^{3/4}\, D$ 12.

$b = 1.4 \cdot 10^{-6}\ (\text{amp})^{1/2}/(°\text{K})^{3/4}$

It should be noted that vacuum thermionic diode operation characterized by low current density is possible in a device with cesiated electrodes. This occurs when the cesium is present at low pressures (of much less than 1 torr, for example) and is used as a surface adsorbate without contributing to transport effects between electrodes. Such low pressures are, however, only possible at the low emitter temperatures corresponding to the low current densities employed.

FIG. **7** is a graph showing the unique relationship of T_e and $\rho' D/\epsilon_c$ to the emitter emission energy barrier quantity $eV + \phi_c'$ and normalized current quantity $(\rho'/\epsilon_c)^2\, I/a$, for $T_e >> T_c$. Values of x_o (in mm) are included in FIG. **7.** The appropriate value of ρ' can be found by iteration, using values of T_e, D and $eV + \phi_c'$ attained from FIG. **7** in Equations 3, 4 and 5. The graph of FIG. **7** shows the relationship among the variables imposed by thermal and electron emission constraints, for the optimum height-to-diameter ratio r (Equation 6). The fuel capsule diameter D and the emitter temperature T_e are related to the effective collector work function ϕ_c', the output voltage V, the total output current I, the configurational parameter a (FIG. **5**), the net thermal emissivity of the cylindrical region ϵ_c and the net thermal volume power density ρ' of the fuel capsule. The net power density ρ' is computed from the difference between the heat generated in the fuel capsule (of average power density ρ) and that removed from it by electron cooling and condution through the emitter supports.

The negatively sloping solid lines in FIG. **7** are loci of T_e (in °K), and the positively sloping solid lines are loci of x_o (in mm). The negatively sloping broken lines are loci of $\rho' D/\epsilon_c$ (in watts/cm^2). The fueled emitters of capsules I, II, III and IV, shown in FIG. **7,** are relatively dimensioned (with respect to the 1 cm indicated scale) to represent 1 mw vacuum diode battery devices with operating points at their respective centers. The major objective of atomic battery design is, of course, to minimize the fuel inventory for a given power output so that efficiency η is maximized and the required fuel and shielding is minimized.

The size of capsule I is reduced to that of capsule II if the ratio (ρ'/ϵ_c) is increased by an order of magnitude. This can be accomplished through appropriate power density or emissivity improvement. The capsule I is reduced in size to that of capsule III if $eV + \phi_c'$ is reduced by 0.4 ev, which can be accomplished at a given output voltage by a suitable reduction of the collector work function. Joint improvements in power density or emissivity and in collector work function would reduce the size of capsule I to that of the very small capsule IV. Capsules III and IV illustrate the reduction in size obtained for capsules I and II, respectively, when a feasible lower collector work function is employed. Alternatively, capsules I and II illustrate the change (increase) in size of capsules III and IV, respectively, which would occur if the output voltage were increased from the optimum $V_{max} \approx 0.2$ volt to $V \approx 0.6$ volt. Also, it is apparent from Equation **11** (collector space charge barrier $\delta_c = \mathbf{0}$) that the performance of the vacuum diode battery is independent of electrode spacing for $d < x_o$. However, as can be seen from Equation 10 and FIG. **7,** the battery diameter D for a given current I increases rapidly for a spacing d appreciably greater than $2x_o$. In practice, the diameter-to-spacing ratio D/d often is more closely related to what is practically achievable than is the spacing d alone.

The efficiency of conversion of heat into electrical power, neglecting conduction and lead losses (i.e., letting P_c equal zero) but including electron cooling, is

$\eta = (IV/P_g)\ \alpha\eta'$ 13.

where

$\eta' = 4\ IV/\pi\rho_o D^3 r$

$\alpha = (1 + eV + \phi_c' + 2kT_e/eV \cdot \eta')^{-1}$

$\rho_o = \rho - 4/\pi\ (P_e/rD^3)$

The smallest diode battery is obtained when the efficiency η is maximized. Differentiation of Equation **13** with respect to V, with $T_e >> T_c$, shows that maximum efficiency is obtained for a given current I and effective work function ϕ_c' when the output voltage is

$V_{max} = V_{max}'\ (1 + 7\eta')$ 14.

for

$\eta' < 0.1$

where

$V_{max}' = (\phi_c' + 10kT_e)/11e$.

FIG. **8** is a graph showing values of output voltage V_{max}' which yield the smallest diode battery for given values of I and ϕ_c', with negligible electron cooling. The values of V_{max} for significant electron cooling are somewhat higher than V_{max}', as is apparent from Equation **14.** The loci of optimum output voltage V_{max}' and associated effective collector work function ϕ_c' are indicated in solid and broken lines, respectively. The fueled emitters or capsules V, VI, VII, VIII and IX shown in FIG. **8** are relatively dimensioned (with respect to the 1 cm indicated scale) to represent devices having the various indicated output power levels with (D/d) $\leq$ 300 and $\rho_o = 1$ watt/cm^3. It can be shown that for constant I and D/d, minimum battery size occurs near $V = V_{max}$ for $\eta < 0.05$. Maximization of efficiency η with respect to I, using $V = V_{max}$ in Equation **13,** shows that with a given achievable value of D/d, maximum efficiency occurs when $\phi_c' = 1.09\ \phi_c$, over the range of FIGS. 7 and 8. This leads, in turn, via the previous equations to the notable conclusion that for given values of ρ, ϵ_c, ϕ_c and D/d, there exists an optimum total output power for which the efficiency is a maximum.

For this fully optimized case, $d_{opt} = 2.2\ x_o$, $(\phi_c')_{opt} = 1.09\ \phi_c$, approximately, and the optimum total current is

$$I_{opt} = (3 \cdot 10^{-11}) a T_e^{3/2} (D/d)^2 \text{ amp} \quad 15.$$

Because T_e and V_{max} are insensitive to all variables, the optimum total output power is relatively insensitive to all properties of the device except the diameter-to-spacing ratio D/d.

The preceding discussion for the vacuum thermionic diode battery can be readily applied to both the ignited and unignited discharge modes of the cesium vapor thermionic diode converter. It can be shown, however, that for a given D/d, the efficiency for the vacuum diode battery is greater than that of the cesium diode converter in either the ignited or unignited modes, for emitter temperatures below about 1,400°K. This, in turn, establishes through Equation 15, the maximum total power for which the vacuum diode is superior for a single cell ($\leq$ 1 watt, approximately). We have also computed spacing lines for the ignited and unignited modes and have determined where they intersect the domain shown typically in FIG. 7, allowing the choice of these modes when they are superior at the higher temperatures. It can also be shown that a collector-to-emitter temperature ratio up to $(T_c / T_e) = 0.78$, approximately, will not appreciably affect the electrical output of the optimized battery. However, radiant heat transfer is reduced by a factor of about 0.6 for this condition, which is equivalent to a similar reduction in the value of thermal emissivity ϵ_e in the foregoing results.

Table A, below, summarizes the preceding results through the use of approximations appropriate in the region of variables of FIGS. 7 and 8. Although the relationships in Table A are not precise, they are useful for recognizing the relative importance of the diode battery properties.

Table B, below, summarizes the values of the diode battery properties which already have been achieved in experimental devices of this invention, and those which are obtainable with existing technology.

These spacings ($0.02 \leq d \leq 0.05$ mm, approximately) and diameter-to-spacing ratios ($500 \leq D/d \leq 1000$, approximately) are quite conservative for the relatively low power devices of this invention because of the low temperature and heat flux requirements thereof. The radioisotope fuel is also fully enclosed within a cylindrical emitter as in configurations (c), (d) and (e) of FIG. 5, where $p = 1$ (Equation 2) for a diode cylindrical region, so that $4 < a < 6$ is quite feasible without the use of complex thermal shielding.

Table C, below, summarizes the diode battery properties for the fueled emitters or capsules I through IX shown in FIGS. 7 and 8.

TABLE A

Approximations for Vacuum Diode Operation
(ρ_o in watts/cm³, ϕ_e in ev)

Case	$d \lesssim x_o \cong 10^{-3}(a/I)\ \epsilon_e/\rho'\phi_e^{.5}$ cm	D/d given
I(amp)	Given	$(5 \cdot 10^{-7})\ a\phi_e^{3/2}\ (D/d)^2$ (optimum)
V_{max} (v)	$0.14\ \phi_e$	$0.15\ \phi_e$
Efficiency, η (for $\eta < 0.06$)	$[10^8\ \epsilon_e\phi_e/a\ x_o^2 + 9]^{-1}$	$[(2 \cdot 10^8)\ \epsilon_e^3\ \phi_e^{10}/a\rho_o^2\ (d/D)^2 + 9]^{-1}$

TABLE B

Properties Obtainable with Known Technology
(demonstrated — obtainable)

d	D/d	a	ϕ_e	ϕ_c	ϵ_e	ρ
0.05–0.02 mm	500–1000	6	1.5–1.3 ev	1.3–1.0 ev	0.05–0.02	0.3–100 w/cm³

TABLE C

Summary of Examples Shown in FIGS. 7 and 8
($\epsilon = 0.05$, $a = 6$)

Device or Capsule	Output pwr. (mw)	ϕ_e (ev)	ρ_o (w/cm³)	* V (volt)	T_e (°K)	** η (%)	*** d (mm)	D (cm)
I	1	1.5	1	0.20	810	0.3	0.09	0.74
II			10	0.23	920	1.8	0.02	0.20
III		1.1	1	0.17	650	2.2	0.04	0.40
IV			10	0.35	780	9.6	0.02	0.11
I	3		1	0.60	810	1.0	0.09	0.74
II	2.7		10	0.63	920	5.0	0.02	0.20
V	0.1	1.3	1	0.17	690	0.2	0.20	0.40
VI	1			0.18	730	0.9	0.06	0.52
VII	10			0.23	780	2.4	0.03	0.81
VIII	100			0.27	900	4.4	0.05	1.44
IX	300			0.30	1030	3.0	0.08	2.35

* Optimum; except for 0.60 and 0.63 v in devices I and II
** Does not include lead and support losses
*** Maximum; devices V – IX are for D/d 300

The device or capsule I represents diode battery property values which already have been demonstrated, combined with a fuel power density $\rho_o = 1$ watt/cm^3, which can be achieved with many radioisotopes. These include promethium-147 Pm^{147}) with a half-life of 2.6 years and plutonium-238 (Pu^{238}) with a half-life of 87 years, which would require little or no shielding for most applications. The device or capsule II represents the same diode battery property values as capsule I, but with $\rho_o = 10$ watts/cm^3, such as obtained using polonium-210 (Po^{210}) with a half-life of 0.4 year or curium-244 (cm^{244}) with a half-life of 18 years, requiring minor and moderate shielding, respectively, for biological applications. As can be seen in Table C, the 100 milliwatt device VIII is fully optiumum approximately (maximum efficiency) in accord with the expressions in Table A for a $(D/d) \leqslant 300$. Also, it can be noted that doubling the indicated interelectrode spacing d for any device would increase the diameter D by less than 10 percent for each device. Optimizing the collector temperature T_c would decrease the diameter D by as much as 30 percent and increase the efficiency η by as much as a factor of **2.**

FIG. **9** is a sectionalized perspective view of a diode battery **74** which has been constructed in accordance with this invention. The device or battery **74** is generally symmetrical cylindrically and includes a right circular cylindrical radioisotope fuel pellet **76** which is suitably encapsulated by liner **78** to form a fully encased primary capsule **80.** The primary capsule **80** is, in turn, fully enveloped by an oxygenated tantalum layer **82** to form a secondary capsule **84** having an external emitter surface **86.** The oxygenated tantalum surface **86** is suitably cesiated subsequently at an appropriately low cesium vapor pressure for nominally vacuum diode operation. An outer housing body **88** is fitted over the secondary capsule **84** and is closed by a base plate **90.** The housing body **88** and base plate **90** are spaced from the emitter surface **86** by, for example, small ruby insulating spheres **92.** An internal collector surface **94** is provided by the body **88** and plate **90** surfaces which are opposite to and properly spaced from the emitter surface **86.** In this instance, both emitter and collector surfaces **86** and **94** are preferably identical Ta-O-Cs surfaces to prevent components of the emitter from poisoning the collector. These surfaces would normally operate at a point on the lower portion of the curve **62** (FIG. **4**). A work function range of 1.4 to 1.8 ev at 500 to 900°K has been achieved for the Ta-O-Cs surface, for example.

The base plate **90** has a collar **96** which is joined to evacuation tube and cesium reservoir **98.** Passageway **100** in the plate **90** connects the reservoir **98** to the space **102** between the emitter and collector surfaces **86** and **94.** Cap **104** is secured at its lower end to the upper peripheral edge of the housing body **88.** The cap **104** supports a feedthrough insulator **106** which mounts emitter terminal **108.** The lower end of the terminal **108** is connected to the emitter surface **86** by an emitter current lead **110.** The lead **110** is passed through a metal-to-ceramic seal **112** which insulates it from the collector housing body **88** and maintains the low cesium vapor pressure in the closed housing body. Cesium reservoir **98** can be omitted in this invention when a suitable charge of cesium has been properly injected into the interelectrode space. However, the normal operating lifetime of the battery **74** may be somewhat reduced from that obtainable using the reservoir **98.** Vacuum diode batteries such as battery **74** have been successfully operated well in excess of 9,000 hours in continuing tests with no observed degradation beyond that expected due to radioisotope decay. By adjusting the initial operating parameters off-optimum (for example, cesium reservoir and collector temperatures set too high), then the battery power output can be maintained relatively constant over more than one radioisotope half-life.

Table D, below, summarizes the operating parameters for three prototype devices X, XI and XII which, among others, have been constructed and successfully tested.

TABLE D

Operating Parameters for Diode Battery Devices

Parameter	Device X	Device XI	Device XII
Total heat input, P_g, thermal watts	1.5 w $^{147}Pm_2O_3$	3.8 w $^{147}Pm_2O_3$	3.6 w $^{147}Pm_2O_3$
Fuel capsule effective thermal power density, ρ, watts/cm^3	0.28	0.68	0.82
Fuel capsule diameter, D, cm	1.78	1.93	1.78
Emitter area, cm^2	16.9	17.6	16.9
Interelectrode spacing, d, mm	0.25	0.17	0.25
Net thermal emissivity, ϵ_e	0.05	0.05	0.05
Emission energy barrier, ψ_{opt}, ev	1.60	1.90	1.62
Estimated emitter temperature, T_e, °K	573	865	870
Collector temperature, T_c, °K	474	556	703
Maximum output power, mw	0.18 at 0.09 v	1.6 at 0.14 v	20 at 0.15 v
Efficiency η	.01%	0.04%	0.55%
Total volume, cm^3	11.5	13.6	8.20
Total weight, gm	150	150	87

Another device (4 mw output) with characteristics similar to those of device XII was not radioisotope-fueled but simulated the use of a higher power density fuel by thermal energy storage in the emitter capsule. This device was built with an intergral reservoir including a cesium graphite compound ($C_{10}Cs$) operating at collector temperature. The main reason that the efficiencies of these devices X, XI and XII are much lower than would be expected (as from Table C, for example) was due to the effect of lead and support losses which were neglected (in Equation 13 and Table C). The lead and support losses were of the same order as the thermal radiation component. The relatively large conduction loss caused by the lead and support structure in the prototypes is amenable to significant reduction. The effective power density of the promethia ($^{147}Pm_2O_3$) fuel form was reduced to as much as a tenth of its bulk value by the large conduction loss and the heavier-than-necessary capsules. Better support and capsule design will lead directly to device efficiencies indicated in Table C. Reduction of electrode work function will result in smaller devices, improved efficiency and increased output voltage at a given power level. Steady progress and refinement of these devices is evident in the comparison of performance shown in Table D.

FIG. **10** is a graph which shows the output characteristics of the three prototype devices X, XI and XII. Curves **114, 116** and **118** are plots of output current (in milliamps) against output voltage (in volts) for the devices X, XI and XII, respectively. Similarly, curves **120, 122** and **124** are plots of output power (in milliwatts) versus output voltage (in volts) for the devices X, XI and XII, respectively.

FIG. **11** is a sectionalized perspective view of another illustrative embodiment of this invention. Diode battery **126** includes a radioisotope fuel pellet **128.** The fuel pellet **128** is in the form of a right circular cylinder and can comprise a fuel such as Pm^{147}, Pu^{238} or Po^{210}, for example, among other appropriate radioisotopes. The fuel pellet **128** is fully encapsulated by liner **130** of either tungsten (W) or rhenium (Re) to form a fully encased primary capsule **132.** The primary capsule **132** can, in turn, be fully enveloped by either an oxygenated tantalum or oxygenated tungsten layer **134** to form a secondary capsule **136** having an external emitter surface **138.** An outer housing body **140** is fitted over the secondary capsule **136** and is substantially closed by base disc **142.** An outer base plate **144** mounting a circular ring spring washer **146** is secured to the lower end of the housing body **140** as by electron beam welding or copper brazing. The spring washer **146** is made of Inconel X-750 alloy, for example, and is suitably formed to provide a proper spring action on the disc **142** and hence a reasonably resilient (shock cushioned) system. The housing body **140** and base disc **142** are spaced from the emitter surface **138** by spacer grains **148** of aluminum oxide (Al_2O_3), for example. An internal collector surface **150** is provided by the body **140** and disc **142** surfaces which are opposite to and properly spaced from the emitter surface **138.** The housing body **140** and base disc **142** can be made of oxygenated tantalum (subsequently cesiated internally), or oxygenated tantalum having a cesiated silver oxide (Ag-O-Cs) internal collector surface **150.** A cesiated silver oxide surface would operate at, for example, a point on the lower portion of the curve **64** (FIG. **4**).

A corner flange ring **152** is suitably secured to the upper peripheral edges of the housing body **140** and supports a radially smaller insulator ring **154** at its inner edge as shown in FIG. **11.** The insulator ring **154,** in turn, supports a disc cap **156** having a central opening **158** therein. An emitter electrode disc plate **160** fits in the opening **158** and is connected to the upper end of emitter lead **162.** The flange ring **152** can be electron beam welded or copper brazed to the upper corner of the housing body **140,** and the disc plate **160** can be similarly secured to the edges of the opening **158.** The emitter lead **162** extends through a cesium vapor source **164** which can be a porous metal disc with adsorbed cesium or soaked with liquid cesium and suitably secured to the lower surface of the disc plate **160.** The melting point of cesium is approximately 26°C (79°F). The cesium source disc can be porous or powered molydenum, iron, copper, steel, tungsten, rhenium, tantalum or nickel, among others, with adsorbed cesium or soaked with liquid cesium. A graphite compound with absorbed cesium can also be used for the source **164.** Other sources of alkali vapors and alkaline earth vapors are suitable for use in the device **126.** The source **164** is an integral reservoir which replaces the liquid reservoir **98** shown in FIG. **9** and can function in a higher temperature environment than a liquid reservoir. Of course, the integral reservoir (source **164**) can be omitted if a suitable charge of cesium has been properly injected into the interelectrode space of battery **126** which must then be carefully sealed hermetically. The ring **152,** cap **156** and plate **160** can be made of niobium (Nb) and the insulator ring **154** can be made of aluminum oxide (Al_2O_3). The ring **152** and the plate **160** can be electron beam welded or copper brazed to the body **140** and cap **156,** respectively, and the insulator ring **154** can be copper brazed to the edges of the flange ring **152** and disc cap **156.**

The emitter lead **162** can be made of tantalum or tungsten, and passes through the passageway of an insulating sleeve **166** to connect with the emitter surface **138.** The sleeve **166** is suitably secured to the sides of a central hole **168** in upper wall **170** of the housing body **140.** The sleeve **166** can be made of aluminum oxide, for example, and the lead **162** can be elastically convoluted axially in the space below the lower surface of the cesium source **164** and above the upper surface of the wall **170.** The insulating sleeve **166** can, of course, be omitted if the hole **168** is made sufficiently large so that the lead **162** would not contact the sides thereof under any operating conditions (as may be due to shocks, vibrations, etc.). The spacer grains **148** are sandlike particles which are engaged between the emitter and collector surfaces **138** and **150** in a relatively tight interference fit at operating temperature. This provides automatic temperature control with radioisotope power decay whereby emitter temperature is maintained substantially constant through the designed lifetime of the diode battery **126.**

FIG. **12** is a graph showing a plot of controlled emitter temperature T_e against radioisotope thermal power density ρ which generally decreases with decay. Curve **172** indicates that the emitter temperature T_e rises fairly linearly in a normal manner with radioisotope thermal power density ρ when the spacer grains **148** have a relatively loose fit between the emitter and collector surfaces **138** and **150.** The emitter capsule **136** expands, of course, with a higher emitter temperature and progressively produces firmer and greater contact of the grains **148** against both the emitter and collector surfaces **138** and **150.** When a relatively firm contact of the grains **148** between the two surfaces **138** and **150** is reached, the curve **172** departs from the slope indicated by the broken line **174** to flatten out into a generally horizontal condition. This result is due to the thermal expansion of the emitter capsule **136** with a higher temperature to produce tighter and greater contact of the spacer grains **148** with the emitter and collector surfaces **138** and **150,** which causes increased thermal conduction of the grains **148** between the two surfaces.

The increased contact and conduction of the grains **148** would, of course, reduce the normal emitter temperature for the corresponding thermal power density and maintain a fairly constant emitter temperature. Thus, by having a relatively tight interference fit wherein the comparatively hard grains **148** are strongly impressed against or partly into the emitter and collector surfaces **138** and **150** at an initial time t_o when the radioisotope thermal power density is high, the emitter temperature normally corresponding thereto is reduced by the increased conduction of the grains between the emitter surface **138** and the cooler collector surface **150.** As the radioisotope decays, its temeprature also tends to drop and the emitter capsule **136** contracts in size to decrease the conduction of the grains **148** between the surfaces **138** and **150.** The interference fit is correspondingly reduced such that conduction of the grains **148** is decreased an amount whereby the emitter temperature remains essentially the same as before. This continues until time t_e which is the end of the designed lifetime of the diode battery **126.** It can be seen from the curve **172** of FIG. **12** that emitter temperature T_e is controlled to be substantially constant throughout the designed lifetime of the battery **126.**

FIG. **13** is a sectionalized elevational view of a miniature diode battery **176** which illustratively depicts another version of this invention. The battery **176** includes a radioisotope fuel pellet **178** which is in the form of a right circular cylinder as in the version of FIG. **11.** The fuel pellet **178** is similarly encapsulated doubly to provide a fully and safely encased emitter capsule **180** having an external emitter surface **182.** An outer housing body **184** having an internal collector surface **186** is fitted over the capsule **180** and includes a few carefully embedded spacer grains **188** which normally do not contact the emitter surface **182.** This is in contrast to the larger number of spacer grains **148** utilized in the diode battery **126** of FIG. **11** wherein the grains **148** can be almost randomly scattered evenly over the emitter surface **138** in contact therewith and with the collector surface **150.** Only a few spacer grains **188** are needed and used in the miniature diode battery **176** because of the method of supporting the emitter capsule **180.**

The capsule **180** is essentially supported axially under tension between slightly elastic leads (springs) wherein one can be a conductive emitter lead. The lower center of the emitter surface **182** is connected by elastic lead **190** to insulator disc **192** affixed within a central hole **194** in the outer base plate **196** which is suitably accured to the lower edges of the housing body **184.** The upper center of the emitter surface **182** is connected by elastic emitter lead **198** to a disc plate **200** which is secured in an opening **202** in disc cap **204.** The emitter lead **198** first passes through a central hole **206** in upper wall **208** and then extends through a cesium vapor source **210** to the disc plate **200.** The source **210** can be a porous metal disc with adsorbed cesium or previously soaked with liquid cesium and suitably secured to the lower surface of the disc plate **200** as in the diode battery **126** of FIG. **11.** The disc cap **204** is supported on and secured to the upper surface of an insulator ring **212** which is, in turn, supported on and secured at its lower surface to the radially outer surface portion of the upper wall **208** of the housing body **184.** The emitter capsule **180** is basically supported between the elastic supports **190** and **198** which provide additional spring action essentially only in response to shocks, vibration, etc. on the battery **176.** In several early models constructed and successfully operated, thin wall metal tubings were used for the elastic supports instead of the springs **190** and **198.**

FIG. **14A** is a fragmentary and partially sectional view of the upper portion of a diode battery **214.** The battery **214** includes an emitter capsule **216** suitably spaced from collector housing **218.** A corner flange ring **220** mounts an insulator ring **222** which, in turn, supports a cap disc **224.** The cap disc **224** has a dependent collar **226** and an upper cavity **228.** The cavity **228** contains, for example, a cesium compound of expanded pyrolitic graphite ($C_{10}Cs$) and is sealed with a cover disc **230.** A passageway **232** connects the cavity **228** to the space enclosed by the insulator ring **222** below the cap disc **224.** The emitter capsule **216** has a central protruding stem **234** on which is press-fitted the lower portion of a thin-walled tube **236.** The upper portion of the tube **236** is press-fitted into the collar **226** and, thus, supports the upper end of the emitter capsule **216.** The collector housing **218** has a central opening **238** which provides clearance and access for the tube **236** to the emitter capsule stem **234.** The opening **238** also permits entry of cesium vapor from the cesium compound in the cavity **228** (after passing through the passageway **232**) to the emitter surface of the capsule **216.**

FIG. **14B** is a fragmentary and enlarged view of the support for the lower end of the emitter capsule **216.** The battery **214** has a lower cap disc **240** which is similar to the upper cap disc **224.** The lower cap disc **240** is similarly supported or attached to an insulator ring (not shown) which is suitably bonded to the lower corner flange ring (also not shown) that is welded to the lower corner of the collector housing **218.** The lower cap disc **240** has a collar **242** into which is press-fitted the lower portion of a thin-walled tube **244** similar to the tube **236.** The emitter capsule **216** has a central protruding lower stem **246** around which the upper portion of the tube **244** is press-fitted. A lower central opening **248** in the collector housing **218** provides clearance and access of the tube **244** to the emitter capsule stem **246.** The tubes **236** and **244** each has an outer diameter of 0.040 inch, a 0.0015 inch thick wall, a length of 0.175 (+ 0.000 − 0.001) inch and is made of kovar, for example. The tubes **236** and **244** support the emitter capsule **216** and maintain its external emitter surface at the proper distance or spacing from the internal collector surface of the housing **218.**

FIG. 15 is a central sectional view of another version of this invention. Battery **250** includes a fuel capsule **252** which can be doubly encapsulated and then further encapsulated by an insulating layer **254** of a suitable ceramic, for example. Emitters **256, 258, 260, 262** and **264** are suitably bonded to the insulating layer **254**. The emitters **256** and **264** are in the form of discs, and the emitters **258, 260** and **262** are in the form of cylinders. The capsule **252** is supported at its upper and lower ends respectively by tension wires (or tubes) **266** and **268**. As can be seen, the wire **266** is secured at its lower end centrally to emitter **256** and at its upper end centrally to disc cap **270** after passing through clearance opening **272** and an integral cesium reservoir or source **274**. The disc cap **270** is supported by insulator ring **276** which, in turn, is supported by the upper wall **278** of outer housing **280**. Similarly, the wire **268** is secured at its upper end centrally to emitter **264** and at its lower end centrally to an insulator disc insert **282** in the lower wall **284** of the housing **280**.

The internal surface of housing **280** is coated with an insulating layer **286** of a suitable ceramic, for example, and has collectors **288, 290, 292, 294** and **296** bonded thereto. These collectors **288, 290, 292, 294** and **296** form diode sections with their associated emitters **256, 258, 260, 262** and **264**, respectively. Wire **266** electrically connects the disc cap **270** to emitter **256**, wire **298** connects collector **288** to emitter **258**, wire **300** connects collector **290** to emitter **260**, wire **302** connects collector **292** to emitter **262**, wire **304** connects collector **294** to emitter **264**, and wire **306** connects collector **296** to the outer housing **280**. Thus, the five diode sections are connected in series to provide a higher battery output voltage. Of course, the diode sections in such a battery **250** can be connected variously in parallel or in series and parallel, as desired or required.

Low output voltage (generally less than 1 volt) is inherent in a diode battery formed by one pair of thermionic electrodes. However, a system of interconnected series and/or parallel diode batteries can be formed easily in a single envelope to increase the output voltage and total electrical output power. Also, a suitably interconnected system of series stacked and parallel clustered stacks of diode battery elements can be easily formed to provide any desired total output power. Moreover, each module or element of such a system requires a radioisotopic fuel capsule which must provide only a relatively low thermal input therefor (e.g., a 10 watt thermal power capsule for each module having 1 watt of electrical energy output). Problems of fabricating and handling large radioisotope capsules are thereby reduced proportionately. Voltage amplification of the output voltage of a diode battery is, of course, possible with suitable external electronic means. For example, power conditioning efficiencies from 25 to 40 percent have been achieved with a tunnel diode circuit used to amplify the 0.14 volt output of the device XI (Table D) to the 1 volt level.

FIG. 16 is a perspective view of a unitary battery system **308** including a plurality of battery units **310** connected in parallel to provide a high capacity power system having any desired total output power selectable over a wide range. The units **310** are connected in parallel by means of bus bars **312** and **314** which have positive and negative output terminals **316** and **318**, respectively. Shorter (lower voltage) or longer (higher voltage) units **310** can be installed between the bus bars **312** and **314**, of course. Also, a greater or lesser number of units **310** can be used in the system **308**. The illustrated system **308** is only representative of the different configurations of a unitary battery system which can be produced. A great deal of design flexibility is available and linear, planar, cylindrical, etc., arrays of battery units can be formed following the disclosed example.

FIG. 17 is a central sectional view of a battery unit **320** mounted between the bus bars **312** and **314** of the system **308** shown in FIG. 16. The unit **320** is connected at its upper end to bus bar **312** through connector **322** and at its lower end to bus bar **314** through connector **324**. The unit **320**, in this instance, is similar to three of the batteries **126** (shown in FIG. 11) stacked in series with the differences that a unitary outer casing **326** is used and only a single cesium source **328** is required. Since the diode batteries **330, 332** and **334** of the unit **320** are basically similar to the battery **126** of FIG. 11, a detailed description of the batteries **330, 332** and **334** need not be given.

Generally, an insulator ring **336** attached to the upper wall **338** of casing **326** supports disc cap **340**, and the cap **340** is connected to upper emitter capsule **342** by lead **344**. The lead **344** passes through cesium source **328** and opening **346** in upper collector housing **348**. Collector housing **348** has a lower opening **350**, and a lead **352** connects the collector housing **348** to the middle emitter capsule **354** through upper opening **356** in the middle collector housing **358**. Collector housing **358** also has a lower opening **360**, and a lead **362** connects the collector housing **358** to lower emitter capsule **364** through upper opening **366** in the lower collector housing **368**. An insulating layer **370** electrically isolates the casing **326** and the collector housings **348, 358** and **368** from each other. Finally, a lead **372** connects the lower collector housing **368** to the casing **326**. Thus, the batteries **330, 332** and **334** are connected in series to provide a higher output voltage between disc cap **340** and the casing **326**.

FIG. 18 is a fragmentary sectional view of a unitary battery system wherein a unit **374** is suitably connected between the hollow bus bars **376** and **378**. The unit **374** includes an insulating casing **380** having longitudinal support ribs or ridges **382** extending radially inwardly from the inner surface of the casing **380**. The ridges **382** support four diode batteries **384** stacked in series in the casing **380**. Of course, a shorter (lower voltage) or longer (higher voltage) casing **380** can be used between the bus bars **376** and **378** to contain less or more batteries than the four illustratively shown. The bus bar **376** has a series of holes **386** therein which normally communicate with the upper end opening of the casing **380**. Similarly, the bus bar **378** also has a series of holes **388** therein which normally communicate with the lower end opening of the casing **380**. A cooling source such as a blower (not shown) can be suitably connected to the hollow bus bar **378** to circulate air through the holes **388**, casing **380**, holes **386** and out the hollow bus bar **376** to keep the batteries **384** cool in the casing **380**. Actually, ordinary environmental heat dissipation to the surrounding atmosphere is adequate for most unitary battery systems (except for the very high power ones) and a cooling source is usually unnecessary.

One of the most important advantages of our invention is its high conversion efficiency as compared with previous miniature atomic batteries. Efficiencies up to 10 percent in the vacuum operational mode can be obtained in the fractional wattage power range, and these relatively high efficiencies significantly reduce required fuel inventory and shielding thickness. The radioisotope fuel pellet is shielded and effectively encapsulated by an inner liner, an emitter layer and a surrounding collector housing body. This 4π (fully enclosed) configuration is simple to fabricate and is the safest geometry for containing a radioactive source. This design produces the most efficient coupling of heat source and converter without the use of liquid metal loops or other theremal flux concentrating devices and eliminates large thermal gradients between the center region of the fuel and emitter surface. Because each of the inner and outer cylindrical bodies is a fully closed, relatively thick-walled refractory metal body, the devie is mechanically strong. Compensation for the effects of radioisotope decay can be achieved by adjusting the thermionic operation conditions in different ways to produce substantially or nearly constant power output over the operative portion of the fuel half-life period. Of course, thermionic characteristics of the diode battery can be designed to match a wide range of available fuel power densities.

Each diode battery can be easily fabricated and is a safer unit because of the lower operating temperatures normally utilized or required in these devices. Because they are operated at relatively low current densities, the vacuum diode mode of operation can be used together with readily achievable interelectrode spacings, thus eliminating the plasma (arc drop) losses in the prior devices which operated in the ignited mode. Low work function surfaces can be employed at relatively low temperatures which are not practical in existing high power density diode converters. In turn, low temperatures allow stable component life many times that of high temperature devices, long term compatibility between metal, ceramic and vapor components and hence permit a much greater choice of construction materials. Electrode surfaces on early models of the diode batteries have shown stable performance for over 9,000 hours in continuing life tests. Electrode surface stability is expected to last over a time span of several decades since both electrodes in each of the early diode battery models are refractory metal based and operate at less than half the emitter temperature typical of the existing high power converters.

At low emitter operating temperatures and current densities, the required emitter work function ϕ can be obtained with conventional refractory metals immersed in cesium vapor at pressures so low that negligible electron scattering occurs (vacuum mode operation). The emitter operates near the work function minimum where the collectors of conventional diode converters usually operate. Furthermore, very low work function photocell surfaces can be used as the collector. Similarly, a lower value of radiant thermal emissivity ϵ can be maintained at the lower temperatures employed in this invention. Also, the relatively low temperatures and small size of the fuel capsule used in the present invention greatly suppress or reduce problems of materials compatibility and containment of radioisotope-generated helium, as have arisen in certain previous thermionic conversion devices employing a radioisotope fuel.

In a thermionic conversion device, part of the total fuel heat is lost through the emitter supports and by electron cooling. This reduces the effective power density of the fuel capsule. The effective power density ρ_o (defined in Equation **13**) takes into account the reduction in ρ caused by electron cooling in the absence of lead and support losses. Because of the relatively low temperatures involved, and due to the lack of the thermal insulation or radiation shields (as required in the source **20** of FIG. **1**), a wide variety of materials and methods can be used to reduce greatly the heat losses previously occurring through the lead and the capsule and emitter supports.

Basic configurational variations including valves of certain of their respective parameters have been shown in FIG. **5**, Equations 7, 9, 14 and 15 generally establish a crucial optimum relationship among parameters of our diode battery. For a fully enclosed emitter capsule configuration, a diode battery of maximized efficiency is obtained by conforming to the crucial optimum relationship established among the parameters of fuel capsule diameter D (cm), emitter temperature T_e (°K), collector temperature T_c (°K), electrode thermal emissivity ϵ_c, effective fuel capsule thermal power density ρ', true collector work function ϕ_c (eV), electrode spacing d (cm), output current I(amp) and output voltage V (volts), and given approximately by the following simultaneous equations:

$$D = 6\ \theta\epsilon_c\ (T_e^4 - T_c^4)\ /\rho'$$

$$T_e = (eV + 1.1\ \phi_c)\ /\ k \cdot \ln\ (3\ \pi A T_e^2\ D^2\ /\ 2\ I)$$

$$V = (1.1\ \phi_c + 10\ kT_e)\ (1 + 2 \cdot 10^{-6}/\epsilon_c\ \phi_c\ d^2)\ /\ 11e$$

$$I = (1.8 \cdot 10^{-10})\ T_e^{3/2}\ (D/d)^2$$

where

k is the Boltzmann constant

A is the Richardson constant

θ is the Stefan-Boltzmann constant

e is the electronic charge.

The first of the above simultaneous equations is, of course, Equation 7. The second of the simultaneous equations is derived by substituting in Equation 9, $\phi_c' = 1.1\ \phi_c$, $a = 6$, and $(T_e^4 - T_c^4) = \rho' D/6\theta\epsilon_c$. The third of the simultaneous equations is obtained by substituting in Equation 14, $V_{max}' = (1.1\ \phi_c + 10\ kT_e)\ /\ 11e$ and $\eta' = (10^8\ \epsilon_c\ \phi_c\ x_o^2\ /\ a)^{-1}$. In the range of interest, $\eta' = \eta$. Thus, from Table A, second column and last row, the expression for η' is obtained by substituting η' for η and dropping the numeral "9" in comparison with the "10^8" quantity. In the optimum, $x_o = d\ /\ 2.2$ and, since $a = 6$, these further substitutions would result in the third of the simultaneous equations. Finally, the last of the above simultaneous equations is obtained from Equation 15 with the substitution of $a = 6$ therein.

All prior thermionic converters required an emitter support structure which performed a multitude of functions. The emitter support had to conduct the emitter current simultaneously, serve as a heat dam between emitter and collector to prevent excessive thermal loss, function as part of the total structure forming the vacuum envelope of the converter, and maintain the critical spacing between the electrodes, The design of the emitter support structure for all previous converter configurations was thus a compromise to suit the conflicting requirements of these functions, and resulted in a fragile structure susceptible to deformation under stress of loads transmitted to the emitter, and to metallurgical deterioration and to corrosion from impurities released by the cesium vapor source and by other parts of the structure during its high temperature operation.

Since, in our invention the only function of the emitter lead is to carry the output current, it can be a simple wire with the optimum length-to-diameter ratio for maximum efficiency. Also, since in our invention the emitter support structure is not required to contain the cesium vapor as in previous cesium diode converters, heat losses can be minimized by using ceramic (insulator) supports which contact the fuel capsule at only a few discrete points, or by supporting it by thin tension wires, springs or tubes. The insulator supports can be sphere-shaped insulating elements separating collector and emitter surfaces, or rod-shaped insulating elements used axially or circumferentially (diametrically) to separate such surfaces. Both of the insulator separating or lead mounting methods of support are much more capable of withstanding mechanical shock, and both permit construction of efficient devices in much smaller sizes than heretofore possible.

The invention can be used to power electric watches (10 microwatts), biomedical sensors and stimulators including cardiac pacemakers (0.1 to 1 milliwatt) and various ecological, geophysical and military telemetry units (1 to 1000 milliwatts). For example, ecological studies can be made of the movements of fish, birds and wild animals by tagging them with very small instrumented packages. Power for remote-site weather instrumentation, navigation aids and cable repeater units can be provided with unusually long life and reliability by this invention. In addition, multiple cell or element, nominally vacuum mode, thermionic diode batteries (0.1 to 1 watt/cell) can compete favorably in size and weight with the conventional radioisotope-fueled devices up to at least several tens of watts. Furthermore, modular encapsulation and the much lower operating temperatures for each cell in a suitably interconnected system of diode batteries greatly reduce crucial fuel handling and containment problems.

While certain dimensions and types of materials have been mentioned in the foregoing description, such dimensions and types of materials have been given by way of example only. It is to be understood that we do not desire to be limited in our invention to the exact details of construction shown and described, for obvious modifications will occur to persons skilled in the art.

We claim:

1. A radioisotopic thermionic converter comprising:

an emitter capsule including a radioisotope fuel mass source of thermal power, at least one layer of material encapsulating and shielding said fuel mass, and an external emitter surface on said layer of material energized by said fuel mass;

an outer housing including an internal collector surface, said housing enclosing said emitter capsule and providing further shielding for said encapsulated fuel mass, said housing providing a vacuum envelope and maintaining a low pressure condition therein to effect a nominally vacuum mode of operation of said converter;

means for mounting said emitter capsule in said housing and maintaining said emitter surface normally at a substantially predetermined spacing from said collector surface, said mounting means including elastic means connecting respective ends of said emitter capsule to corresponding ends of said housing whereby said emitter capsule is supported substantially at its ends; and

output means adapted to connect respectively with said emitter and collector surfaces, for providing an electrical output from said converter, at least one of said elastic means simultaneously serving as the one of said output means connecting with said emitter surface,

whereby direct containment of fuel within said emitter capsule effects the most efficient thermal coupling of heat source and diode conversion portion of said converter and the maximum temperature of any portion of said fuel mass does not differ significantly from the temperature of said emitter surface.

2. In a radioisotopic thermionic converter including an emitter capsule containing a spontaneously and naturally decaying radioisotope fuel and having an external emitter surface, an outer housing enclosing said emitter capsule and having an internal collector surface, said housing maintaining a low pressure condition therein to effect a nominally vacuum mode of operation of said converter, and output means adapted to connect respectively with said emitter and collector surfaces for providing an electrical output from said converter, mounting means comprising:

first elastic means connecting a first end of said emitter capsule to a corresponding first end of said housing; and

second elastic means connecting a second end of said emitter capsule to a corresponding second end of said housing whereby said emitter capsule is supported substantially at its ends in said housing and said emitter surface is maintained normally at a substantially predetermined distance from said collector surface, at least one of said first and second elastic means simultaneously serving as the one of said output means connecting with said emitter surface.

3. In a radioisotopic thermionic converter including an emitter capsule containing a radioisotope fuel and having an external emitter surface, and an outer housing enclosing said emitter capsule and having an internal collector surface, said housing maintaining a low pressure condition therein to effect a nominally vacuum mode of operation of said converter, mounting means comprising:

first elastic means connecting a first end of said emitter capsule to a corresponding first end of said housing; and

second elastic means connecting a second end of said emitter capsule to a corresponding second end of said housing whereby said emitter capsule is supported substantially at its ends in said housing and said emitter surface is maintained normally at a substantially predetermined distance from said collector surface, said first and second elastic means including first and second thin-walled tubes longitudinally connected to support said emitter capsule axially at its ends.

4. A radioisotopic thermionic converter assembly comprising:

a plurality of emitter capsules each including a spontaneously and naturally decaying radioisotope fuel source of relatively low predetermined thermal power density not greater than the order of 10 watts/cm^3, at least one layer of material fully encapsulating and shielding said radioisotope fuel, and an external emitter surface of predetermined work function on said layer of material energized by said radioisotope fuel;

a plurality of outer housings each including an internal collector surface of predetermined work function, said housings respectively enclosing said emitter capsules and providing further shielding for said encapsulated radioisotope fuel;

means for mounting said emitter capsules respectively in said housings and maintaining said emitter surfaces normally at a substantially predetermined spacing respectively from said collector surfaces, said mounting means including electrically insulating spheres positioned between said emitter and collector surfaces, a plurality of converters being thereby formed;

a predetermined charge of an additive vapor loaded in said predetermined spacings between said emitter and collector surfaces, said additive vapor being provided at a predetermined low pressure and used essentially only as a surface adsorbate to modify said predetermined work functions of said emitter and collector surfaces without generating plasma contributing electron scattering effects therebetween;

output means adapted to connect respectively with said emitter and collector surfaces, for providing a plurality of electrical outputs from said converters; and

a casing enveloping said converters in a unit and maintaining said predetermined low pressure in the approximate range from 10^{-3} to 0.1 torr, said converters characterized by operating at low emitter current densities established by said thermal power density of said radioisotope fuels and said predetermined work function of said emitter surfaces in the approximate range of 0.1 to 400 ma/cm^2 in a nominally vacuum mode of operation established by the operating temperature of said emitter and collector surfaces, said predetermined spacings and said predetermined low pressure, with negligible ion neutralization of space charge and negligible plasma contributing electron scattering effects, said emitter and collector surfaces having relatively low oeprating temperatures in the approximate ranges of 600° to 1,400°K and 300° to 800°K, respectively, and each of said converters operating thermionically as a space charge limited device having an electron motive diagram wherein a motive maximum is located intermediate to said emitter and collector surfaces thereof whereby an output voltage higher than the difference of said predetermined work functions of said emitter and collector surfaces is obtained from each of said converters, said output means of said converters being interconnected to provide an output for said unit at useful efficiency.

5. The invention as defined in claim **4** further comprising an additive source communicating with said predetermined spacings between said emitter and collector surfaces of said converters, said source providing supplemental additive vapor which can be used to supplement said predetermined charge of additive vapor and functions essentially only as a surface adsorbate to modify said predetermined work functions of said emitter and collector surfaces with negligible ion neutralization of space charge and without generating plasma contributing electron scattering effects therebetween, and each of said converters operating thermionically as said space charge limited device to provide an output voltage higher than the difference of said predetermined work functions of said emitter and collector surfaces thereof.

6. A radioisotopic thermionic converter comprising:

an emitter capsule including a spontaneously and naturally decaying radioisotope fuel source of relatively low predetermined thermal power density not greater than the order of 10 watts/cm^3, at least one layer of material fully encapsulating and shielding said radioisotope fuel, and an external emitter surface of predetermined work function on said layer of material energized by said radioisotope fuel;

an outer conductive housing including an internal collector surface of predetermined work function, said housing enclosing said emitter capsule and providing further shielding for said encapsulated radioisotope fuel;

means for mounting said emitter capsule in said housing and maintaining said emitter surface normally at a substantially predetermined spacing from said collector surface, said mounting means including elements installed between said emitter and collector surfaces and transmitting lost heat energy very much smaller compared to useful heat energy transmitted by said emitter and collector surfaces;

output means for providing an electrical output from said converter, said output means including a conductive collector contact electrically connected to said collector surface and a conductive emitter contact electrically connected to said emitter surface, said collector contact being a contact portion of said housing and said emitter contact being an insulated contact portion thereof, whereby said capsule is supported and spaced from said collector surface by said mounting means and said housing provides a vacuum envelope for said converter,

a quasi-vacuum condition being provided in, and maintained by, said housing of a predetermined low pressure and said converter is characterized by operating at low emitter current densities established by said thermal power density of said radioisotope fuel and said predetermined work function of said emitter surface in the approximate range of 0.1 to 400 ma/cm^2 in a nominally vacuum mode of operation established by the operating temperatures of said emitter and collector surfaces, said predetermined spacing and said predetermined low pressure, with negligible ion neutralization of space charge and negligible plasma contributing electron scattering effects together with practically large spacings and low work function materials for said emitter and collector surfaces, said emitter and collector surfaces having relatively low operating temperatures in the approximate ranges of 600° to 1400°K and 300° to 800°K, respectively, providing a converter module with useful efficiency and which operates thermionically as a space charge limited device having an electron motive diagram wherein a motive maximum is located intermediate to said emitter and collector surfaces whereby an output voltage higher than the difference of said predetermined work functions of said emitter and collector surfaces is obtained from said converter; and

an additive material loaded in said predetermined spacing between said emitter and collector surfaces, said additive material including a predetermined charge of additive vapor used essentially only as a surface adsorbate to modify said predetermined work functions of said emitter and collector surfaces without generating significant plasma contributing electron scattering effects therebetween at said operating temperatures of said emitter and collector surfaces, said predetermined spacing between said emitter and collector surfaces and said predetermined low pressure maintained within said housing, said pressure being in the approximate range from 10^{-3} to 0.1 torr and said converter operating thermionically as said space charge limited device.

7. The invention as defined in claim **6** further comprising an additive source communicating with said predetermined spacing between said emitter and collector surfaces, said source providing supplemental additive vapor which can be used to supplement said predetermined charge of additive vapor and functions essentially only as a surface adsorbate to modify said predetermined work functions of said emitter and collector surfaces with negligible ion neutralization of space charge and without generating plasma contributing electron scattering effects therebetween, and said converter module operating as said space charge limited device to provide an output voltage higher than the difference of said predetermined work functions of said emitter and collector surfaces thereof.

8. The invention as defined in claim **7** wherein said emitter surface extends substantially over the entire external surface of said emitter capsule and said collector surface extends substantially over the internal surface of said housing which fully encloses said emitter capsule, said emitter capsule having a significant lateral dimension relative to its axial dimension whereby said emitter surface also provides a significant amount of emission in a generally axial direction to correspondingly opposite portions of said collector surface, and said mounting includes electrically insulating elements installed in respective pairs of opposing recesses in said emitter and collector surfaces, said insulating elements comprising first and second spheres which axially and centrally support respective ends of said emitter capsule and maintain said emitter surface normally at said substantially predetermined spacing from said collector surface.

9. The invention as defined in claim **6** wherein said emitter surface extends substantially over the entire external surface of said emitter capsule and said collector surface extends substantially over the internal surface of said housing which fully encloses said emitter capsule, said emitter capsule having a significant lateral dimension relative to its axial dimension whereby said emitter surface also provides a significant amount of emission in a generally axial direction to correspondingly opposite portions of said collector surface, and said mounting means includes electrically insulating elements installed in respective pairs of opposing recesses in said emitter and collector surfaces, said insulating elements comprising first and second spheres which axially and centrally support respective ends of said emitter capsule and maintain said emitter surface normally at said substantially predetermined spacing from said collector surface.

10. A radioisotopic thermionic converter comprising:

an emitter capsule including a spontaneously and naturally decaying radioisotope fuel source of thermal power, at least one layer of material encapsulating and shielding said radioisotope fuel, and an external emitter surface on said layer of material energized by said radioisotope fuel;

an outer housing including an internal collector surface, said housing enclosing said emitter capsule and providing further shielding for said encapsulated radioisotope fuel;

means for mounting said emitter capsule in said housing and maintaining said emitter surface normally at a substantially predetermined spacing from said collector surface, said mounting means including means connecting respective ends of said emitter capsule to corresponding ends of said housing whereby said emitter capsule is supported substantially at its ends, said connecting means comprising coiled spring elastic means; and

output means adapted to connect respectively with said emitter and collector surfaces, for providing an electrical output from said converter, said housing including a conductive collector contact electrically connected to said collector surface, and said output means including said collector contact and a conductive emitter contact electrically connected to said emitter surface, whereby said capsule is supported and spaced from said collector surface by said mounting means, said housing provides a vacuum envelope for said converter, and said emitter contact provides an electrical connection to said emitter surface,

a quasi-vacuum condition being provided in, and maintained by, said housing of such low pressure that said converter is characterized by operating at low emitter current densities in the nominal range of 0.1 to 400 ma/cm^2 in a nominally vacuum mode of operation with negligible contributing electron scattering effects together with practically large spacings and low work function materials for said emitter and collector surfaces, said emitter and collector surfaces having relatively low operating temperatures in the nominal ranges of 600° to 1,400°K and 300° to 800°K, respectively, providing a converter module with useful efficiency.

11. A radioisotopic thermionic converter comprising:

an emitter capsule including a radioisotope fuel mass source of thermal power, at least one layer of material encapsulating and shielding said fuel mass, and an external emitter surface on said layer of material energized by said fuel mass;

an outer housing including an internal collector surface, said housing enclosing said emitter capsule and providing further shielding for said encapsulated fuel mass, said housing providing a vacuum envelope and maintaining a low pressure condition therein to effect a nominally vacuum mode of operation of said converter;

means for mounting said emitter capsule in said housing and maintaining said emitter surface normally at a substantially predetermined spacing from said collector surface, said mounting means including means connecting respective ends of said emitter capsule to corresponding ends of said housing whereby said emitter capsule is supported substantially at its ends and said connecting means includes thin-walled tubes; and

output means adapted to connect respectively with said emitter and collector surfaces, for providing an electrical output from said converter,

whereby direct containment of fuel within said emitter capsule effects the most efficient thermal coupling of heat source and diode conversion portion of said converter and the maximum temperature of any portion of said fuel mass does not differ significantly from the temperature of said emitter surface.

12. A radioisotopic thermionic converter comprising:

an emitter capsule including a spontaneously and naturally decaying radioisotope fuel source of relatively low predetermined thermal power density not greater than the order of 10 watts/cm^3, at least one layer of material fully encapsulating and shielding said radioisotope fuel, and an external emitter surface of predetermined work function on said layer of material energized by said radioisotope fuel;

an outer housing including an internal collector surface of predetermined work function, said housing being fabricated of a conductive material electrically connected to said collector surface and enclosing said emitter capsule and providing further shielding for said encapsulated radioisotope fuel, and said emitter surface extends at least over the major portion of the external surface of said emitter capsule and said collector surface extends at least over the corresponding major portion of the internal surface of said housing;

means for mounting said emitter capsule in said housing and maintaining said emitter surface normally at a substantially predetermined spacing from said collector surface, said mounting means including first and second electrically insulating spheres installed in respective pairs of opposing recesses located axially and centrally in said emitter capsule and collector housing surfaces to support said emitter capsule axially and centrally at its ends;

output means adapted to connect respectively with said emitter and collector surfaces, for providing an electrical output from said converter, said output means including a collector contact portion of said housing, and an emitter contact portion thereof electrically connected to said emitter surface and located externally of the main part of said housing and insulated therefrom, whereby said capsule is supported and spaced from said collector surface by said mounting means and said housing provides a vacuum envelope for said converter,

a quasi-vacuum condition being provided in, and maintained by, said housing of a predetermined low pressure and said converter is characeterized by operating at low emitter current densities established by said thermal power density of said radioisotope fuel and said predetermined work function of said emitter surface in the approximate range of 0.1 to 400 ma/cm^2 in a nominally vacuum mode of operation established by the operating temperatures of said emitter and collector surfaces, said predetermined spacing and said predetermined low pressure, with negligible ion neutralization of space charge and negligible plasma contributing electron scattering effects together with practically large spacings and low work function materials for said emitter and collector surfaces, said emitter and collector surfaces having relatively low operating temperatures in the approximate ranges of 600° to 1400°K and 300° to 800°K, respectively, providing a converter module with useful efficiency which operates thermionically as a space charge limited device having an electron motive diagram wherein a motive maximum is located intermediate to said emitter and collector surfaces whereby an output voltage higher than the difference of said predetermined work functions of said emitter and collector surfaces is obtained from said converter;

an additive material loaded in said predetermined spacing between said emitter and collector surfaces, said additive material including a predetermined charge of additive vapor; and

an additive source communicating with said predetermined spacing between said emitter and collector surfaces, said source providing supplemental additive vapor which can be used to supplement said predetermined charge of additive vapor, said supplemental and predetermined charge of additive vapors functioning essentially only as a surface adsorbate to modify said predetermined work functions of said emitter and collector surfaces without generating significant plasma contributing electron scattering effects therebetween at said operating temperatures of said emitter and collector surfaces, said predetermined spacing between said emitter and collector surfaces and said predetermined low pressure maintained within said housing, said pressure being in the approximate range from 10^{-3} to 0.1 torr and said converter operating thermionically as said space charge limited device.

13. A plurality of radioisotopic thermionic converters;

series-forming means for positioning said converters in separate series stacks; and

parallel-forming means for connecting said stacks together in parallel whereby a power supply system of a desired total output power can be obtained, said series-forming means comprising a plurality of insulating tubular casings each mounting a plurality of converters in a series stack therein and passing a coolant therethrough, and said parallel-forming means comprising lower and upper hollow bus bars respectively engaging lower and upper ends of each of said converter series stacks and conveying said coolant to and from said casings,

each of said converters comprising

an emitter capsule including a spontaneously and naturally decaying radioisotope fuel source of thermal power, at least one layer of material encapsulating and shielding said radioisotope fuel, and an external emitter surface on said layer of material energized by said radioisotope fuel,

an outer housing including an internal collector surface, said housing being fabricated of a conductive material electrically connected to said collector surface and fully enclosing said emitter capsule and providing further shielding for said encapsulated radioisotope fuel, and said emitter surface extends at least over the major portion of the external surface of said emitter capsule and said collector surface extends at least over the major portion of the internal surface of said housing,

means for mounting said emitter capsule in said housing and maintaining said emitter surface normally at a substantially predetermined spacing from said collector surface, said mounting means including small insulating spheres positioned between said emitter and collector surfaces,

output means adapted to connect respectively with said emitter and collector surfaces, for providing an electrical output from said converter, said output means including a contact portion of said housing, and an emitter contact electrically connected to said emitter surface and located externally of said housing and insulated therefrom, whereby said capsule is supported and spaced from said collector surface by said mounting means and said housing provides a vacuum envelope for said converter, a quasi-vacuum condition being provided in, and maintained by, said housing of such low pressure that said converter is characterized by operating at low emitter current densities in the nominal range of 0.1 to 400 ma/cm^2 in a nominally vacuum mode of operation with negligible contributing electron scattering effects together with practically large spacings and low work function materials for said emitter and collector surfaces, and

an additive source communicating with the spacing between said emitter and collector surfaces, said source providing an additive vapor used as a surface adsorbate to modify surface properties of said emitter and collector surfaces without generating significant plasma contributing electron scattering effects therebetween at said low pressure maintained within said housing, said pressure being substantially less than 1 torr.

14. In a radioiostopic thermionic converter including an emitter capsule containing a spontaneously and naturally decaying radioisotope fuel and having an external emitter surface, an outer housing enclosing said emitter capsule and having an internal collector surface, said housing maintaining a low pressure condition therein to effect a nominally vacuum mode of operation of said converter, and output means adapted to connect respectively with said emitter and collector surfaces for providing an electrical output from said converter, mounting means comprising:

first elastic means connecting a first end of said emitter capsule to a corresponding first end of said housing; and

second elastic means connecting a second end of said emitter capsule to a corresponding second end of said housing whereby said emitter capsule is supported substantially at its ends in said housing and said emitter surface is maintained normally at a substantially predetermined distance from said collector surface.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,843,896

DATED : October 22, 1974

INVENTOR(S) : Ned S. Rasor et al.

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Front page, left column, in the heading, the inventor's name "Rason et al." should read --Rasor et al.--; Code [54], in the invention title, the word "THERMOINIC" should read --THERMIONIC--; and Code [75], in the Inventors' data, "Ned S. Rason" should read --Ned S. Rasor--, and "John G. De Steese" should read --John G. DeSteese--. Column 1, line 1, the word "THERMOINIC" should read --THERMIONIC--. Column 2, line 20, "radioisotope" should read --radioisotopic--. Column 5, line 60, "radioisotope" should read --radioisotopic--. Column 7, line 24, the equation term reading "øc" (first and second occurrence) should read --ϕ_c-- (first and second occurrence); and line 36, the equation portion reading "100_c" should read --ϕ_c--. Column 8, line 15, "is" (third occurrence) should be deleted. Column 9, line 1, "or" should read --for--; and line 41, "tese" should read --these--. Column 10, line 20, the equation "$\psi = eV + 100'_c$" should read --$\psi = eV + \phi'_c$--; line 32, the equation portion reading "$(\pi D^2/_4)\ h\sigma$" should read --$(\pi D^2/_4)\ h\rho$ --; line 36, the equation portion reading "$P_e = \Pi$" should read --$P_e = I$--; line 39, "Stefan-boltzmann" should read --Stefan-Boltzmann--; line 57, should have a period --.-- at the end of the equation; and line 62, the equation portion reading $6\theta\epsilon_c\ (T_e^r - T_c{}^4)$ should read --$6\sigma\epsilon_c\ (T_e^4 - T_c^4\ )$--.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,843,896

DATED : October 22, 1974

INVENTOR(S) : Ned S. Rasor et al.

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 11, lines 5 through 10, Equation 9,

"

cV +

$$T_e = \frac{cV + \not{0}'_c}{k \bullet \ln \left[\left(\frac{3\sigma\epsilon_c}{p'} \right)^2 \frac{\Lambda \pi a T_c^2}{1} \left(T''_c - T''_c \right)^2 \right]}$$

"

should read

$$-- \; T_e = \frac{eV + \not{0}'_c}{k \bullet \ln \left[\left(\frac{3\sigma\epsilon_c}{\rho'} \right)^2 \frac{A \pi a T_e^2}{I} \left(T_e^4 - T_c^4 \right)^2 \right]} \; --;$$

line 21, "and" should read --are--; and line 60, "condution" should read --conduction--.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,843,896

DATED : October 22, 1974

INVENTOR(S) : Ned S. Rasor et al.

It is certified that error appears in the above–identified patent and that said Letters Patent are hereby corrected as shown below:

Columns 13 and 14, Table A, in the second row, the equation portion reading

"10^{-3} (a/I) ϵ_c"

should read

--10^{-3} $(a/I)^{1/2}$ ϵ_c --; and

in the fourth row, "V_{mas} (v)" should read --V'_{max} (v)--.

Table B, in the second row, the term "$\emptyset_c$" (first occurrence) should read --$\emptyset_e$--.

Table C, in the row labeled "VIII," the number "4.4" should read --4.2--; and in the last footnote, "D/d 300" should read --D/d $\leq$ 300--. Column 15, line 12, "(cm^{244})" should read --(Cm^{244})--; and line 15, "optiumum" should read --optimum--.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,843,896 Page 4

DATED : October 22, 1974

INVENTOR(S) : Ned S. Rasor et al.

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 19, line 29, "temepra-" should read --tempera- --. Column 20, line 1, "accured" should read --secured--. Column 23, line 15, "theremal" should read --thermal--; line 19, "devie" should read --device--; line 53, "$\emptyset$" should read --$\emptyset_e$--; and line 61, "ϵ" should read --ϵ_c--. Column 24, line 31, the equation portion reading "$6\theta\,\epsilon_c$" should read --$6\sigma\,\epsilon_c$--; line 38, "θ" should read --σ--; and line 43, the equation portion reading "$\rho' D/6\theta\,\epsilon_c$" should read --$\rho' D/6\sigma\,\epsilon_c$--. Column 27, lines 47 and 48, "oeprating" should read --operating--. Column 31, line 64, "characeterized" should read --characterized--. Column 34, line 12, "radioiostopic" should read --radioisotopic--.

Signed and Sealed this

fourteenth **Day of** *October 1975*

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,843,896 Dated October 22, 1974

Inventor(s) Ned S. Rasor et al.

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Table C, in the first row, "(ε = 0.05, a=6)" should read -- (ε_c = 0.05, a=6)---.

Signed and Sealed this

second **Day of** *March 1976*

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks