United States Patent

Olsen et al.

[15] **3,706,893**

[45] **Dec. 19, 1972**

[54] **NUCLEAR BATTERY**

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[73] Assignee: **McDonnel Douglas Corporation**

[22] Filed: **Sept. 19, 1969**

[21] Appl. No.: **859,266**

[52] **U.S. Cl.** ....**310/3 B**, 310/3, 310/3 A

[51] **Int. Cl.** **G21d 7/00**

[58] **Field of Search** ....310/3, 3 A, 3 B; 317/235

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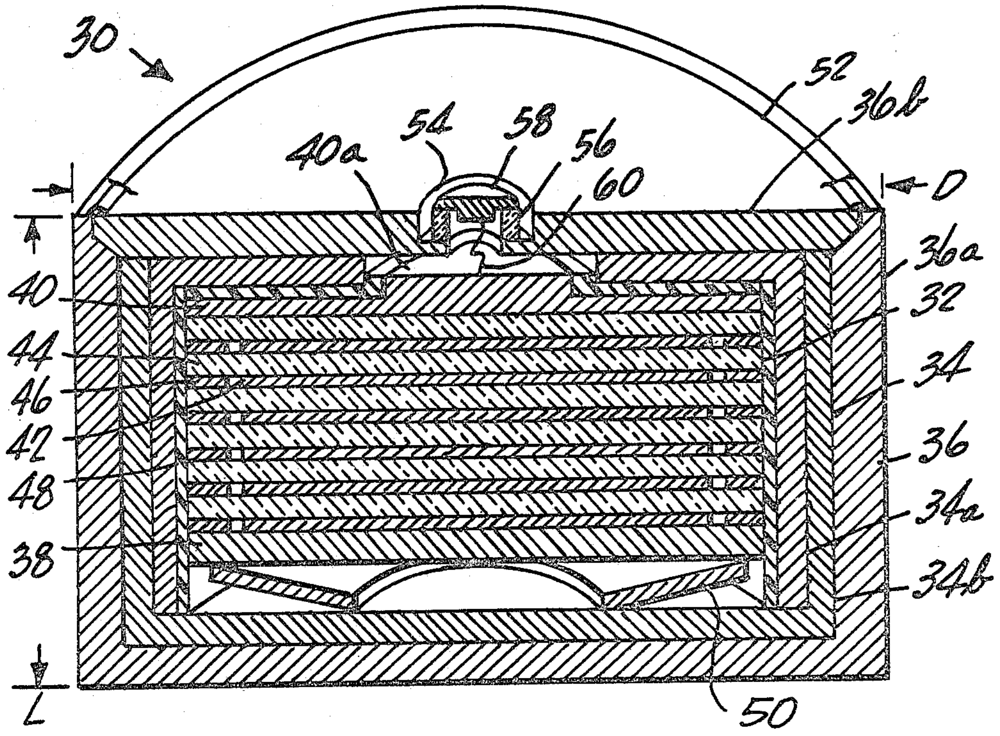
[57] **ABSTRACT**

Nuclear battery including one or more cells each comprising a radioactive fuel element or source and a semiconductor element positioned contiguously to the source and irradiated by it. The fuel element includes a radioactive material which is preferably promethium-147 metal or its oxide, promethia, and the semiconductor element includes a N^+/P or $N^+/P/P^+$ semiconductor wafer which is preferably silicon.

The semiconductor wafer has an energy threshold of radiation damage which is compatible with the maximum energy of the nuclear particles or radiation emitted by the radioactive material, to provide a long-life (minimal radiation damage) cell of optimum power output. Other versions include a nuclear battery utilizing a bi-directional fuel element, and certain compact and useful embodiments utilizing a multiple section cell therein.

12 Claims, 24 Drawing Figures



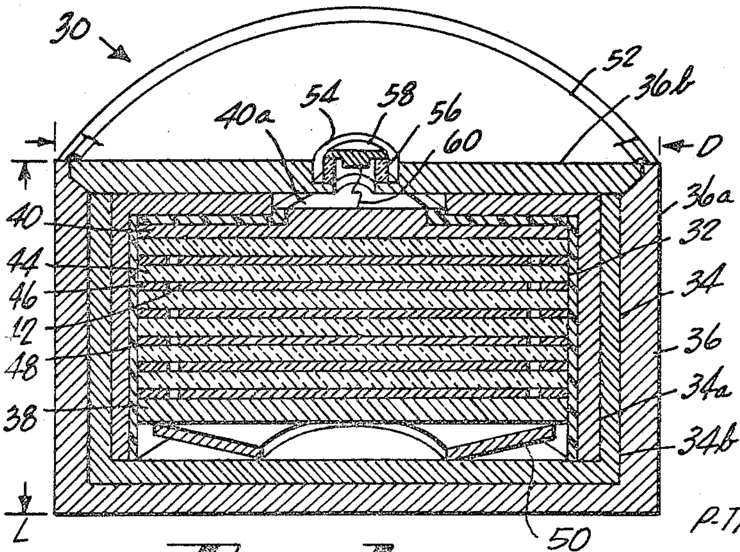


Fig. 1

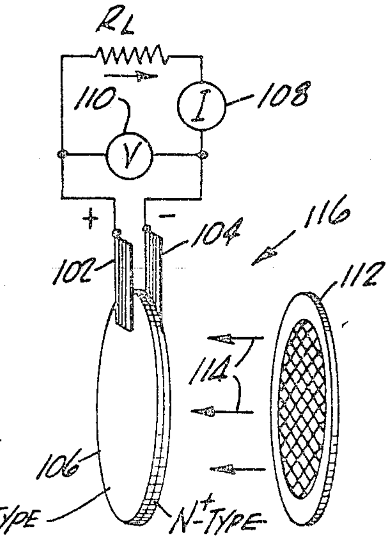


Fig. 5

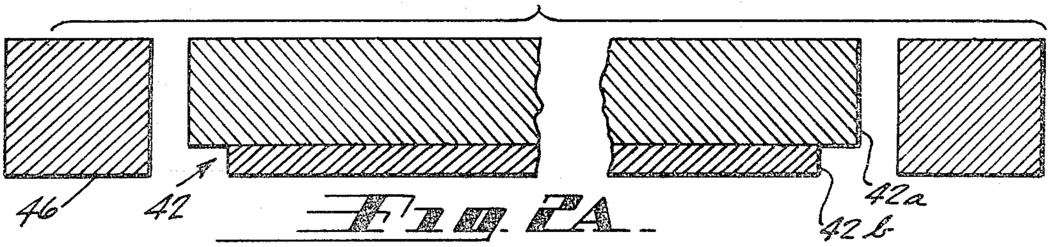


Fig. 2A

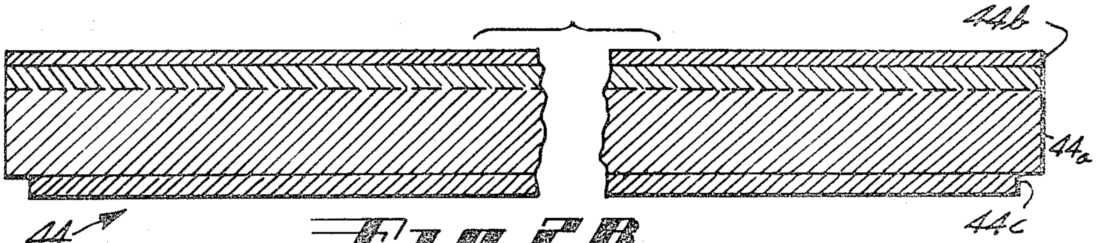


Fig. 2B

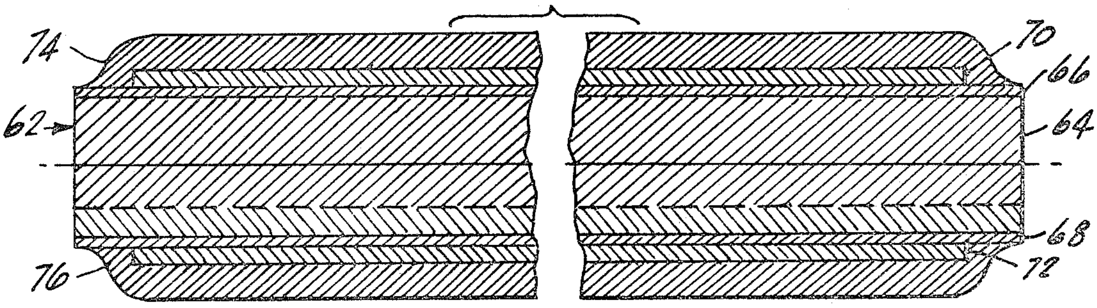


Fig. 3

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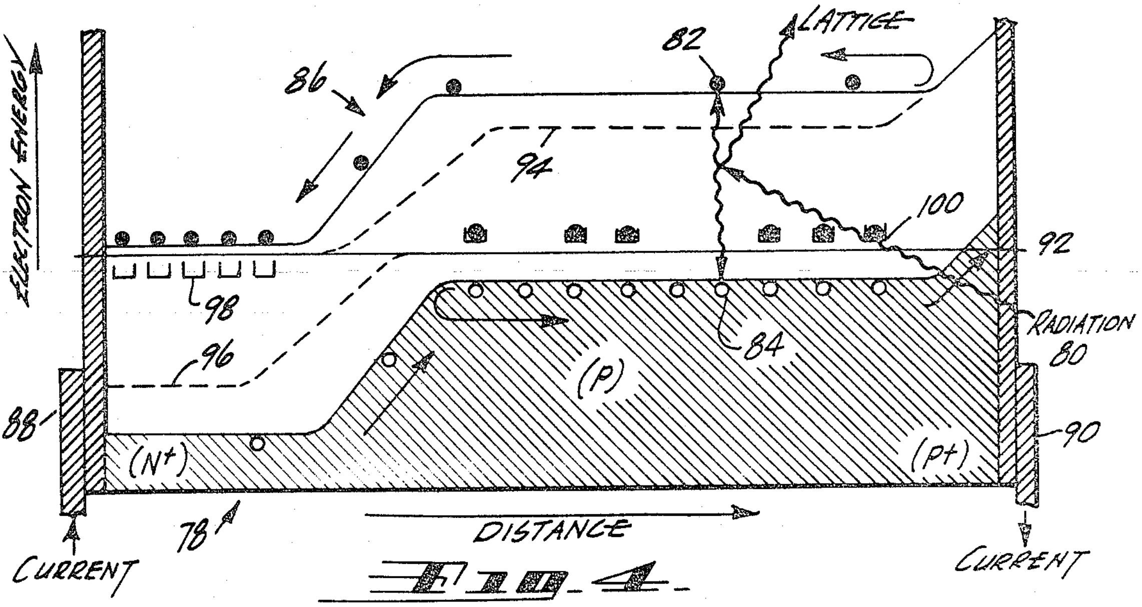

FIG. 4

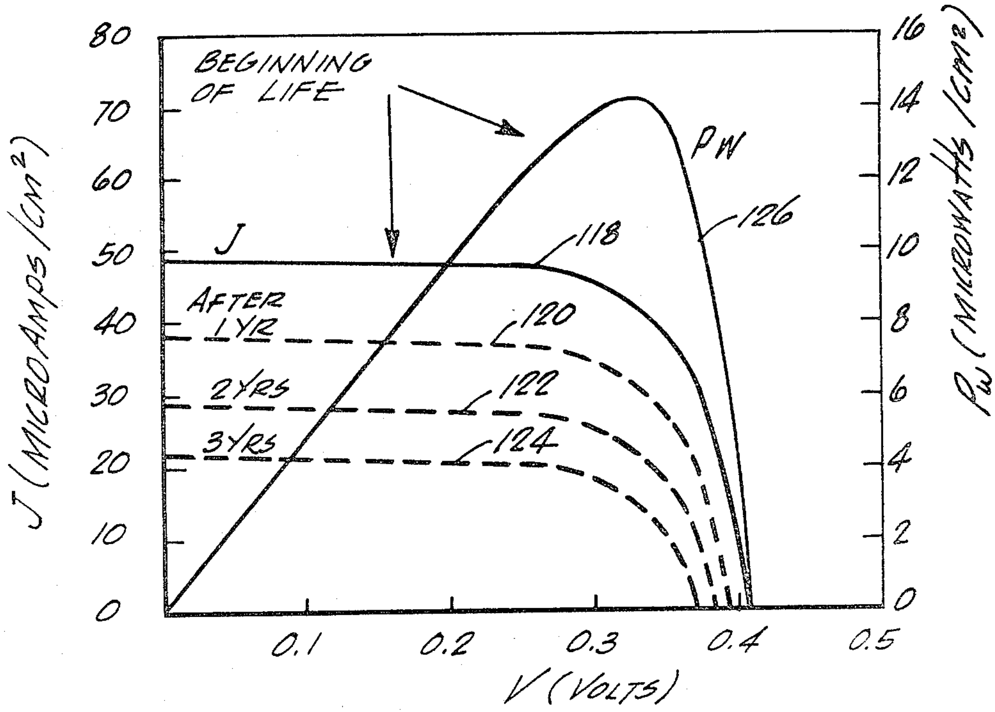

FIG. 7

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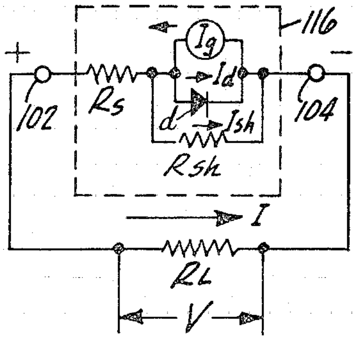

Fig. 6.

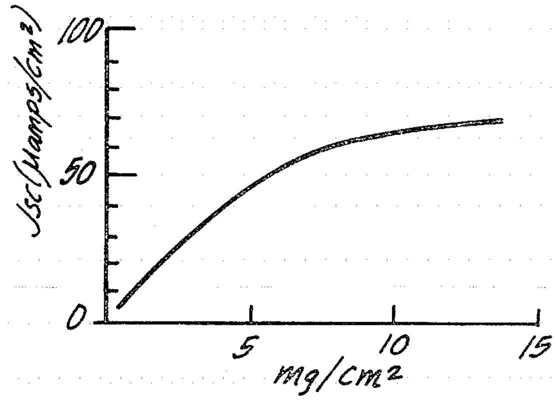

Fig. 8A.

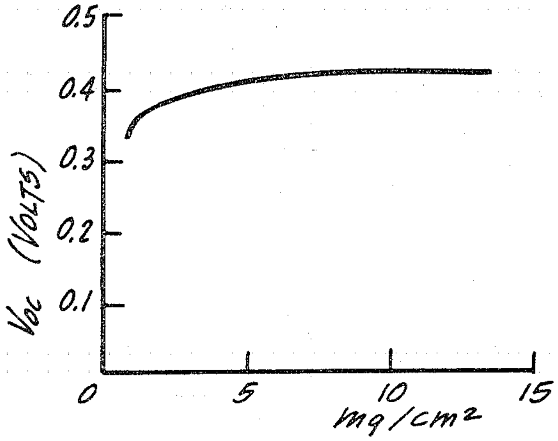

Fig. 8B.

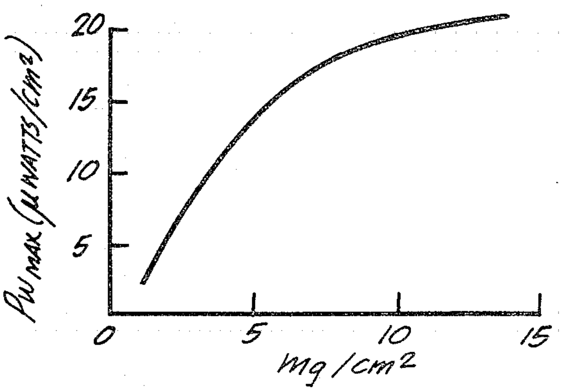

Fig. 8C.

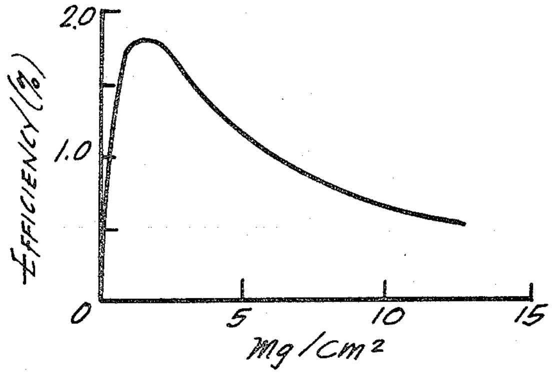

Fig. 8D.

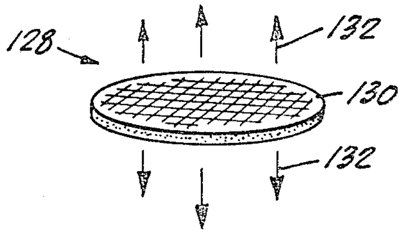

Fig. 7A.

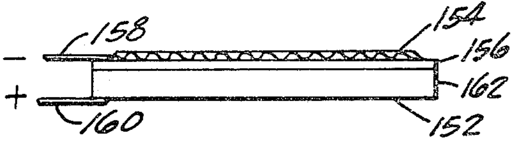

Fig. 11

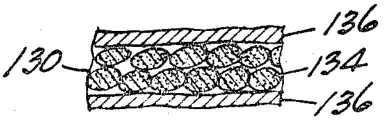

Fig. 7B.

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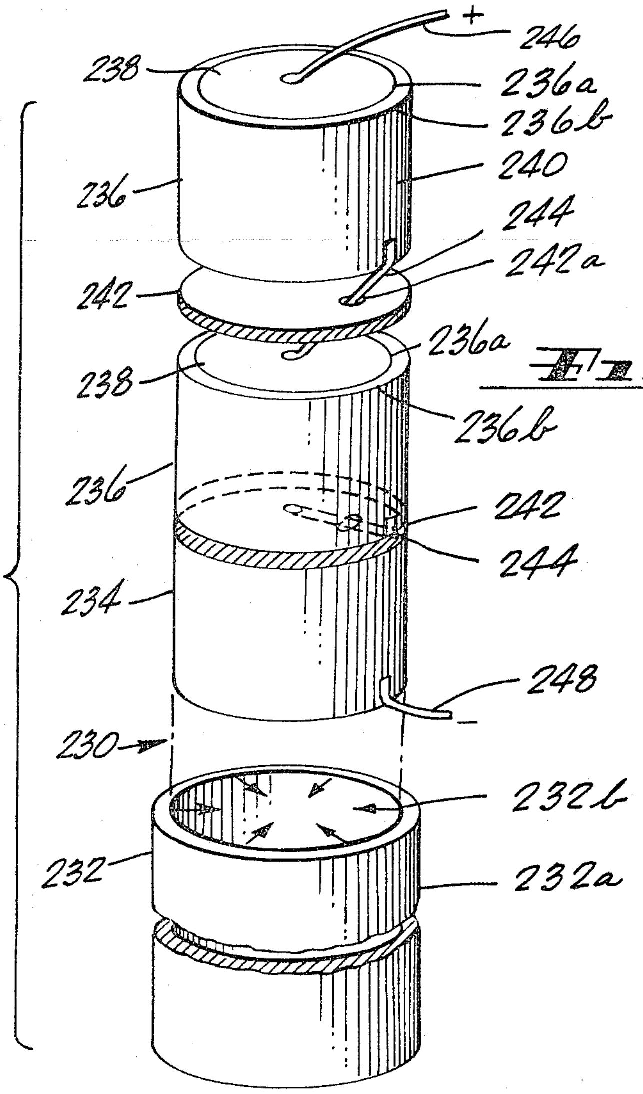

Fig. 13

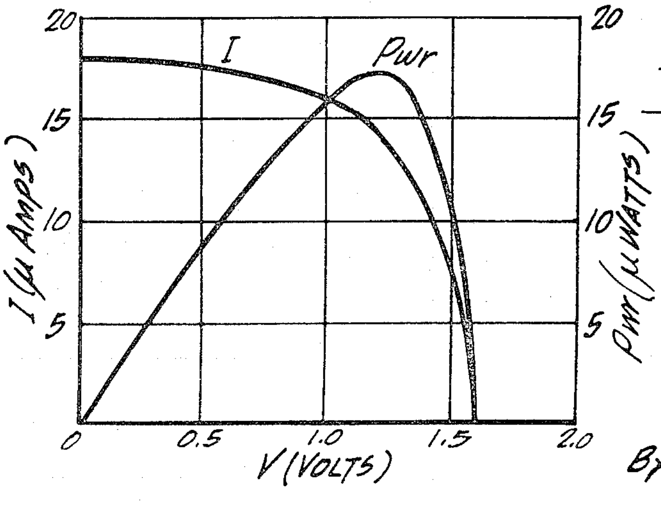

Fig. 14

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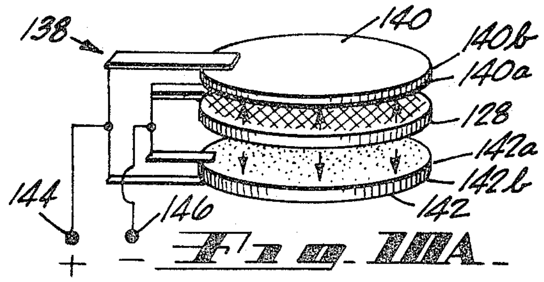

Fig. 11A

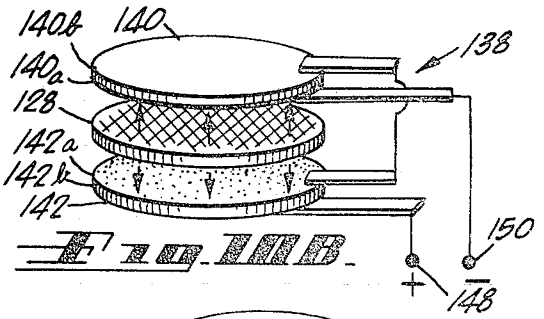

Fig. 11B

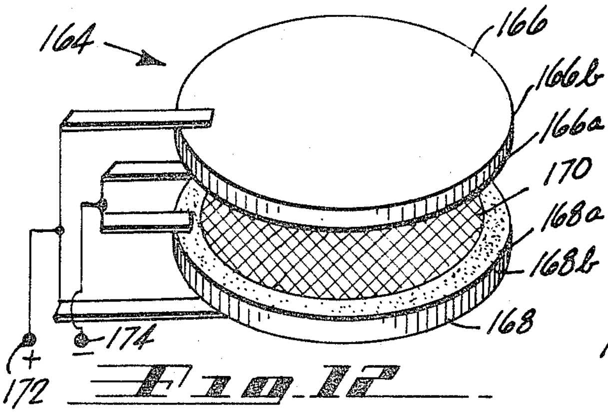

Fig. 12

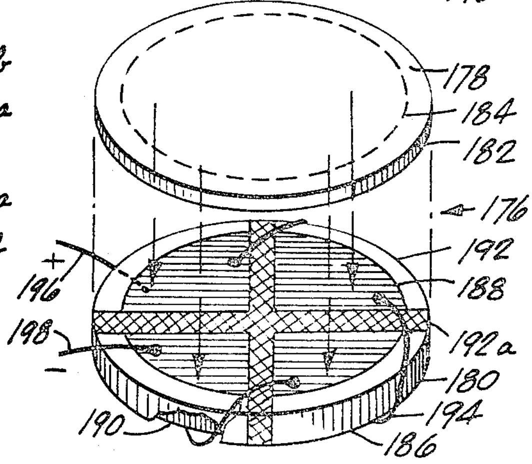

Fig. 13

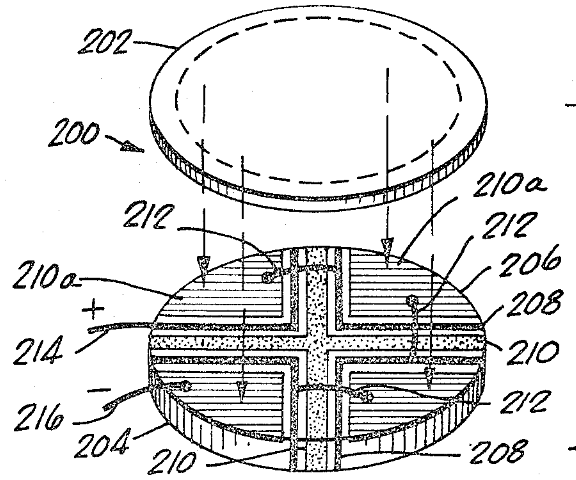

Fig. 15

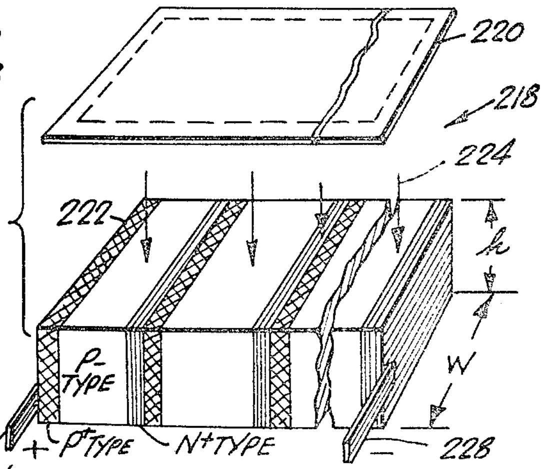

Fig. 16

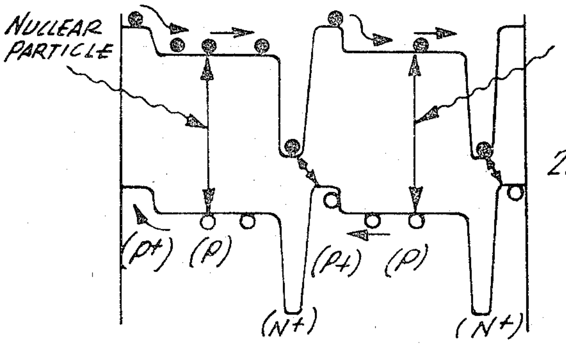

Fig. 17

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NUCLEAR BATTERY

BACKGROUND OF THE INVENTION

Our present invention pertains generally to the field of batteries and more particularly to a nuclear battery wherein nuclear energy is usefully converted into electrical energy.

Generally, prior radioactive or nuclear batteries which involve the concept of coupling a radioactive source with one or more semiconductor elements have utilized a source of high energy radiation to irradiate the semiconductor elements that each include a NP junction therein. The radiation damage created by the high energy particles or radiation in these prior batteries is so great, however, that their useful lifetimes are so short as to render such batteries to be of questionable value.

Further, the power density, maximum output power, maximum output voltage and device efficiencies are relatively quite low for the prior radioactive or nuclear batteries. The various known concepts of radioactive or nuclear batteries do not in most instances appear to be particularly feasible, and all of such concepts are either clearly impractical or are of little useful value. It is, of course, well known that a general purpose nuclear battery other than this invention and of a similar category is not presently and readily available on the commercial market.

SUMMARY OF THE INVENTION

Briefly, and in general terms, our invention is preferably accomplished by providing a nuclear battery including one or more cells each comprising a radioactive fuel element or source and a semiconductor element positioned in close proximity or contiguously to the source and irradiated by it.

The semiconductor element is made of a material which has an energy threshold level of radiation damage that is compatible with the maximum energy of the nuclear particles or radiation emitted by the radioactive source. The fuel element includes a radioactive material which is preferably promethium-147 (Pm^{147}) metal or its oxide, promethia (Pm_2O_3), and the semiconductor element includes a N^+/P or $N^+/P/P^+$ semiconductor wafer which is preferably silicon (Si), to provide a long-life (minimal radiation damage) cell of optimum power output. The semiconductor wafer is preferably characterized by having at least a N^+-type layer which has a very high density of conduction electrons. In the three-layer semiconductor wafer, the P^+-type layer has a very high density of "holes," of course. In both instances (N^+ or P^+), the carrier density preferably approaches 10^{20} or 10^{21} carriers/cm^3 in order that maximum voltage be obtained.

The radioactive fuel element and the semiconductor element of a cell are preferably discs of similar sizes. The fuel element is also preferably positioned virtually against the N^+-type layer surface of the semiconductor wafer. The N^+/P and $N^+/P/P^+$ (silicon) semiconductor wafers are preferred because they are more resistant to damage caused by (beta) radiation. However, P^+/N and $P^+/N/N^+$ semiconductors (N-type semiconductor stock) can, of course, be used satisfactorily in this invention.

In the N^+/P semiconductor wafer, the highly doped N^+-type layer face thereof provides a large number of conduction electrons which are available to an external circuit or load. In the $N^+/P/P^+$ semiconductor wafer, both faces thereof are highly doped to have high carrier concentrations such that the resulting N^+-type layer and P^+-type layer faces prevent any bending of the electron bands in the wrong sense and thus generate an electromotive force of the incorrect polarity. These highly doped surfaces essentially "lock" the electron bands in place whereby the semiconductor surfaces can be treated in any manner desired without degrading device performance. In such an arrangement, ohmic contacts can be easily made to the semiconductor faces and, in fact, any adjacent oxide layers formed thereon will not alter the electron band structure to affect the performance of the device. The resulting nuclear batteries can be manufactured with power levels covering a wide range and have long lifetimes (of over three years) with high power densities (of one milliwatt/cm^3 or more).

Other versions of our invention include a two-cell nuclear battery utilizing a bi-directional fuel element or source, a planar multiple section cell nuclear battery embodiment, a laminar multiple section cell nuclear battery configuration and an elongated, cylindrical multiple section cell nuclear battery embodiment. The nuclear battery configurations including a multiple section cell therein are particularly compact and practical forms of our invention, and can supply electrical power at voltages much greater than that available from an equivalent single cell which utilizes only one active area.

BRIEF DESCRIPTION OF THE DRAWINGS

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

FIG. 1 is a central sectional and elevational view, perspectively shown, of a nuclear battery constructed in accordance with our invention;

FIGS. 2A and 2B are enlarged fragmentary and central sectional views of a fuel element and its concentric ring, and a semiconductor element, respectively, of the nuclear battery shown in FIG. 1;

FIG. 3 is an enlarged fragmentary and central sectional view of a directly fueled nuclear battery cell;

FIG. 4 is an electron energy level diagram for a $N^+/P/P^+$ semiconductor device;

FIG. 5 is a circuit diagram showing a resistive load connected to positive and negative electrodes of a N^+/P semiconductor device;

FIG. 6 is a circuit diagram of an equivalent circuit of the semiconductor device shown in FIG. 5 connected to its resistive load;

FIG. 7 is a graph illustrating current density and power density versus output voltage characteristics of a single cell device constructed according to this invention;

FIGS. 8A, 8B, 8C and 8D are graphs which were plotted from experimental results and show typical characteristics of promethia-fueled, silicon semiconductor, betavoltaic single cells as a function of promethia layer thickness;

FIGS. 9A and 9B are respectively a perspective view of a bi-directional fuel element or source, and a fragmentary and enlarged sectional view thereof;

FIGS. 10A and 10B are exploded perspective views of a two-cell betavoltaic energy converter or battery using the bi-directional source of FIG. 9A, wherein the cells are connected respectively in parallel and in series;

FIG. 11 is an elevational view of a N^+/P semiconductor wafer having a promethium coating deposited directly onto the N^+-type layer surface of the wafer;

FIG. 12 is an exploded perspective view of a two-cell betavoltaic battery having a radioactive material coated directly on at least one semiconductor wafer of the cells;

FIG. 13 is an exploded perspective view of a highly compact and practical form of a nuclear battery constructed according to this invention;

FIG. 14 is a graph illustrating the current and power versus voltage characteristics of a nuclear battery such as that shown in FIG. 13;

FIG. 15 is an exploded perspective view of a planar, multiple section, cell embodiment of a nuclear battery;

FIG. 16 is a partially fragmentary and exploded perspective view of a laminar, multiple section, cell configuration of a nuclear battery;

FIG. 17 is an electron energy level diagram for about two sections of the $N^+/P^+/P$ semiconductor device shown in FIG. 15; and

FIG. 18 is an exploded and partly fragmentary perspective view of an elongated cylindrical, multiple section, cell embodiment of a nuclear battery.

DESCRIPTION OF THE PRESENT EMBODIMENTS

FIG. 1 is a central sectional and elevational view, perspectively shown, of a nuclear battery **30** constructed in accordance with our invention. The battery **30** broadly includes a radioactive fuel-semiconductor stack **32**, and inner and outer containers **34** and **36** for suitably enclosing and housing the stack. The stack **32** includes lower and upper metallic discs **38** and **40** which sandwich a number of radioactive fuel elements **42** and semiconductor elements **44** that are contiguously positioned in alternate layers. The diameter of the fuel elements **42** is smaller than that of the semiconductor elements **44**, such that metallic rings **46** having an inner diameter larger than that of the fuel elements and an outer diameter equal to that of the semiconductor elements, can be positioned concentrically around and radially spaced from the semiconductor elements in the same corresponding layers thereof.

The lower metallic disc **38** is in direct contact with the lower fuel element **42** and its concentric metallic ring **46**. The upper metallic disc **40** is in direct contact with the upper semiconductor element **44**. An insulating liner **48** made of radiation resistant rubber or an oxide, for example, is provided around the sides or circumferential surface of the stack **32** and over the upper surface of the metallic disc **40** except for a central area **40*a*** thereof, as shown in FIG. 1. The liner **48** insulates the stack **32** from the inner sleeve **34*a*** of inner container **34** which can be fabricated of tantalum (Ta), for example. The inner container **34** includes an outer sleeve **34*b*** which is closed at its lower end to support the stack **32** through a metallic spring ring **50**. The spring ring **50** also provides an electrical connection between the lower disc **38** and the inner container **34**.

The inner container **34** is enclosed by and in direct contact with the outer container **36** which is preferably a closed stainless steel fire can. The outer container **36** includes a lower can portion **36*a*** and an upper cover portion **36*b*** which can be electron beam welded to the can portion at the juncture **52** thereof. The cover portion **36*b*** has a central and countersunk hole **54** therein. A small insulating sleeve **56** of ceramic or glass, for example, is positioned within the countersunk portion of the hole **54** and supports a closing metallic disc **58** which is electrically connected by lead **60** to the central area **40*a*** of the upper metallic disc **40**. Glass-to-metal seals are, of course, suitably provided at the lower and upper ends of the insulating sleeve **56**. Thus, the disc **58** is one (positive) electrode and the outer container **36** is the other (negative) electrode of the nuclear battery **30**. The battery **30** as shown illustratively in FIG. 1 is cylindrical in configuration; however, it obviously can be made in rectangular or other configurations. The battery **30** has outside or overall dimensions of diameter D and length L.

FIGS. 2A and 2B are enlarged fragmentary and central sectional views of a fuel element **42** and its concentric ring **46**, and a semiconductor element **44**, respectively. In FIG. 2A, the ring **46** can be made of aluminum (Al) and can have an outer diameter of approximately 1 cm, for example. The fuel element **42** includes an aluminum disc **42*a*** and a thin layer **42*b*** of promethia (Pm_2O_3) thereon. The ring **46** can have an inner diameter of approximately 0.95 cm, and the disc **42*a*** can have a diameter of approximately 0.93 cm and a thickness typically of from 3 to 10 mils. This thickness is primarily for strength and handling. Nickel (Ni) or tantalum, for example, can be used instead of aluminum. The disc **42*a*** is preferably sand-blasted on a face first and then the promethia layer **42*b*** can be provided tenaciously thereon by vapor deposition. The promethia layer **42*b*** can be provided on the face with a layer thickness of approximately 5.3 milligram/cm^2, for example. Promethia is preferably used since it is a good and stable source of beta particles or radiation. It is, of course, to be understood that the various types of materials and different dimensions noted herein are given by way of example only and are not intended to be restrictive or limiting on the scope of our invention in any manner.

In FIG. 2B, the semiconductor element **44** has an outer diameter which is preferably equal to the outer diameter of the ring **46** (FIG. 2A). The semiconductor element **44** includes a N^+/P silicon (Si) wafer **44*a***, a thin metallic upper layer **44b** and a thin metallic lower layer **44*c***. The wafer **44*a*** can have a thickness of from 3 to 15 mils, for example. This wafer **44*a*** can be, if desired, a $N^+/P/P^+$ silicon wafer in accordance with this invention. The upper and lower layers **44*b*** and **44*c*** can be of aluminum, and the upper layer **44*b*** provides an electrical ohmic contact from the N^+-type surface of wafer **44*a*** to the lower surface of (an upper) ring **46** while the lower layer **44*c*** provides an electrical ohmic contact from the P-type surface of wafer **44a** to the upper surface of (a lower) ring **46** and, incidentally, to the upper surface of (a lower) disc **42*a***. The upper layer **44*b*** is, of course, sufficiently thin (less than 2 microns thick, for example) to permit adequate penetration thereof by the beta radiation from the contiguous promethia layer *42b* above it. In one particular embodiment, the upper layer *44b* is actually in the form of a grid (generally similar to a wire screen) wherein each mesh or enclosed space allows free passage of the beta particles or radiation therethrough. The upper and lower layers *44b* and *44c* can be of silver (Ag) instead of aluminum, and are preferably vapor deposited or plated on the wafer *44a*. The lower layer *44c* can be 1 mil thick although 2 microns would be adequate.

The thin metallic layer and grid are both distributed or extended electrode forms which provide good ohmic contact with the full lower and upper surfaces of the semiconductor wafer *44a*. A grid providing an ohmic contact to a given semiconductor surface (unit reference) area has a certain fractional ohmic contact area and a remaining fractional open area for passage of beta particles or other radiation. A thin metallic layer obviously provides maximum (lowest resistance) contact over the full semiconductor surface with, however, a zero fractional open area for free passage of the beta particles or radiation. Of course, the distributed ohmic contact area of a grid or any other such extended electrode form with a given semiconductor surface area must be adequate to achieve a suitable balance between the fractional open area obtainable for free passage of the beta particles or radiation commensurate with maintaining a sufficiently extensive and good (low resistance) ohmic contact for the entire semiconductor surface area. In this respect, a minimum distributed ohmic contact area is required with a highly conductive (high carrier concentration) semiconductor surface.

In our invention, beta radiation is preferably coupled with either a N^+/P or $N^+/P/P^+$ silicon wafer. The N^+/P silicon wafer is a two-layer silicon system including a N^+-type layer characterized by a phosphorus (P) concentration of approximately 10^{19} to 10^{20} atoms/cm^3 and a P-type layer characterized by a boron (B) concentration of approximately 10^{16} atoms/cm^3 (or a P-type layer having a resistivity of approximately 1 ohm-cm). The $N^+/P/P^+$ silicon wafer can be produced from a N^+/P silicon wafer by diffusing a suitable amount of boron into the lower surface of the P-type layer or region of the silicon wafer to produce a P^+-type layer therein. The $N^+/P/P^+$ silicon wafer is a three-layer silicon system including N^+-type and P-type layers as in the above N^+/P silicon wafer, and a P^+-type layer characterized by a boron concentration of approximately 10^{19} to 10^{20} atoms/cm^3. In both of these types of silicon wafers, arsenic (As), antimony (Sb) or bismuth (Bi) can be substituted for phosphorus, and aluminum, gallium (Ga), indium (In) or thallium (Tl) can be substituted for boron. Germanium (Ge), cadmium sulfide (CdS) and gallium arsenide (GaAs) semiconductors, among others, can be used instead of silicon. However, more power can be obtained from silicon cells than from the others. For example, roughly five times more power can be usually derived from a silicon cell than from a generally similar germanium cell.

FIG. 3 is an enlarged fragmentary and central sectional view of a directly fueled nuclear battery cell **62**. A N^+/P (or $N^+/P/P^+$) semiconductor wafer **64** of silicon, for example, has both upper and lower surfaces coated with thin metallic layers **66** and **68**, respectively, which can be of aluminum, nickel or silver. Suitably deposited thereon are respective layers **70** and **72** of a source of beta radiation material such as promethia or promethium-147 (Pm^{147}) metal. The radioactive layers **70** and **72** are smaller in diameter than that of the semiconductor wafer **64**, as illustrated. The radioactive layers **70** and **72** are then fully covered by outer metallic layers **74** and **76**, respectively, which can be of aluminum or silver and are for electrical contact.

The radially outer circumferential (lower) surface portion of the upper cover layer **74** contacts the corresponding portion of the thin metallic layer **66** which is in contact with the surface of the P-type layer of the semiconductor wafer **64**. Similarly, the radially outer circumferential (upper) surface portion of the lower cover layer **76** contacts the corresponding portion of the thin metallic layer **68** which is in contact with the surface of the N^+-type layer of the wafer **64**. Thus, the upper cover layer **74** is of positive polarity and the lower cover layer **76** is of negative polarity for the battery cell element **62**. The cell elements **62** can be readily stacked in series for a higher output voltage and, of course, the stacks can also be suitably connected in parallel as may be desired or required.

FIG. 4 is an electron energy level diagram for a $N^+/P/P^+$ semiconductor wafer **78**. Nuclear-voltaic effects are initiated when radiation **80** enters the semiconductor **78** and creates electron **82** and hole **84** pairs. A large number of these carriers (electrons and holes) diffuse to the vicinity of the abrupt (N^+P) junction **86** where the junction electric field accelerates them to device terminals **88** and **90**. By suitably adjusting the device parameters, most of the carriers produced are collected under short circuit conditions. The electrochemical potential or Fermi level of the device under equibrium conditions is indicated by full line **92**, and broken lines **94** and **96** represent the electrochemical potentials for electrons and holes, respectively, resulting from electron and hole pair production of the device under radiation excitation. Brackets **98** shown near the line **92** represent donor impurity atoms which have donated their excess valence electrons to the conduction band above the energy gap of the forbidden region. Similarly, brackets **100** shown near the line **92** represent acceptor impurity atoms which have captured extra electrons from the valence band below the forbidden energy gap. It can also be seen that the P^+-type layer acts as a reflector of the free electrons.

Nuclear-voltaic energy conversion involves collecting electrons and holes at the terminals of an inhomogeneous semiconductor or metallic wafer. The electrons and holes result from electron-hole pair creation by the absorption of nuclear particles within the material. These charge carriers are accelerated to the device terminals as a result of an internal electric field which exists because of the inhomogeneous nature of the medium. Electrons and holes live longer in semiconductors than in metals. Thus, the most practical approach to nuclear-voltaic energy converters involves the use of a semiconductive material for at least part of the system. For example, a two-electrode system can contain one layer of semiconductive material and another layer characterized as (1) the same kind of semiconducting material but with a different electrochemical potential as can be obtained by doping the layer differently than the first layer, (2) a different kind of semiconductor, or (3) a metal. The first approach is, of course, followed in accomplishing this invention.

Radiation employed in the various embodiments of this invention is preferably beta nuclear particles supplied by a source of promethia or promethium-147 metal. A flux of approximately $5 \cdot 10^{10}$ betas/cm^2/sec can be obtained from a layer of promethia of about 0.001 cm thickness and approximately 10^{11} betas/cm^2/sec in the case of a layer of promethium-147 metal of about the same thickness. The energy spectrum of beta particles emitted from a radioactive promethium source (the metal or its oxide) is such that very little radiation damage is caused in silicon semiconductors. The thickness of the semiconductor wafer is selected so that most of the radiation is absorbed by the semiconducting medium. Where promethium-147 metal or its oxide is used in conjunction with a N^+/P or $N^+/P/P^+$ silicon semiconductor wafer, the thickness of the wafer need only be approximately 0.01 cm, for example.

Beta sources other than promethium include the isotopes of tritium (H^3), nickel-63 (Ni^{63}), and strontium-90 and yttrium-90 (Sr^{90}—Y^{90}). Such other beta sources as these, however, are used in this invention largely for special applications. More power can be obtained from promethium-147 metal or its oxide than with H^3 and Ni^{63}. For example, tritium may be preferred under certain circumstances because of its longer half-life. Similarly, the available energy in strontium-90 and yttrium-90 sources greatly exceeds that of Pm^{147} sources, and this is useful for certain applications even though such high energy beta particles would cause greater radiation damage in the semiconductor than the lower energy beta particles emitted from the other sources.

Beta particles emitted by a promethium source have a maximum energy of approximately 0.230 million electron volts (mev), approximately 0.0186 mev from tritium, and approximately 0.54 and, 2.26 mev from strontium-90 and yttrium-90 (Sr^{90} and Y^{90} are in secular equilibrium and cannot be separated due to the short half-life of Y^{90}, as is well known). Radiation damage in P-type silicon starts at about 0.20 mev so that a promethium source coupled with a silicon N^+/P or $N^+/P/P^+$ cell is almost ideal and provides optimum power output. Germanium has a higher threshold level (of about 0.4 mev) for the start of radiation damage than silicon but the power obtainable from silicon is about five times better. Other nuclear particles or radiation such as alpha, neutrons or gamma can be used besides beta in this invention. However, use of such other particles or radiation is limited to other specific purposes and is not particularly practical for the purpose of a nuclear battery. For example, the most energetic alpha particles from radionuclides lose all their energy within several microns in silicon or other semiconducting materials.

FIG. 5 is a circuit diagram showing a resistive load R_L connected to positive and negative terminals **102** and **104** of a N^+/P (or $N^+/P/P^+$) semiconductor wafer **106**. The terminals **102** and **104** connect respectively with thin metallic coatings on the faces of the wafer **106**. The thin, low resistance, metallic coatings are only needed to cover large area faces, of course. An ammeter **108** is connected in series with the load R_L and a voltmeter **110** is connected across the terminals **102** and **104**. The wafer **106** is operatively associated with fuel element **112** which is a radioactive source providing a nuclear particle flux **114** (of beta radiation) to the wafer. The fuel element **112** is, of course, normally positioned substantially against the wafer **106** to form a battery cell **116**. A current I will flow through the load R_L and can be measured by the ammeter **108**. Similarly, the voltage V across the load R_L can be measured by the voltmeter **110**.

FIG. **6** is a circuit diagram showing an equivalent circuit for the single cell **116** (FIG. **5**) having its terminals **102** and **104** connected across the resistive load R_L. The voltage-current characteristics of the cell **116** are well described by the following relationship:

$$I = I_g - (V/R_{sh}) - I_o\,[\exp(V - R_s I/AkT) - 1] \qquad \text{[Eq. 1]}$$

$$[= I_g - I_{sh} - I_d]$$

where I = Current through resistive load R_L

V = Voltage across R_L

R_s = Series resistance of nuclear-voltaic cell resulting from imperfect terminal contacts to cell surfaces

R_{sh} = Effective shunt resistance of cell

I_o = Reverse current of semiconductor wafer

A = Parameter characterizing N^+P junction

I_g = Generation current

k = Boltzmann's constant

T = Absolute temperature

The diode d in FIG. **6** represents the N^+P junction, and the series contact resistance R_s is usually negligible and it can be henceforth considered that $R_s = 0$. In that case, the short circuit current I_{sc} (I measured when $V = 0$) is equal to I_g. On a per-unit-area basis, the current density of a single cell is given by the following equation:

$$J = J_{sc} - J_o\,[\exp(V/AkT) - 1] - G_{sh}V \qquad \text{[Eq. 2]}$$

where $I_{sc} = I_g$

J = Current (I) per unit area of single cell

J_{sc} = Short circuit current (I_{sc}) per unit area of single cell

G_{sh} = Effective shunt conductance per unit area of single cell [$= 1/(R_{sh} \cdot \text{area})$]

The open circuit voltage V_{oc} of a single cell is given by the following equation:

$$V_{oc} = AkT \cdot \log\,[J_{sc} + J_o - G_{sh}V_{oc}/J_o] \qquad \text{[Eq. 3]}$$

The reverse current density J_o can be appropriately denoted as a "leakage current parameter" and the proper value of J_o to use when describing betavoltaic results is that value obtained when the N^+P junction is subjected to a forward bias voltage of about 0.0 to 0.4 volt. When reverse bias conditions are used to determine J_o, an improper result is generally obtained.

The short circuit current is determined primarily by the diffusion length (which is related to lifetime) of the minority carriers and the generation rate of those carriers. The latter depends on how effectively beta particles are absorbed in the semiconducting medium and upon the average energy of the beta particles. The generation rate is directly proportional to the beta particle average energy; however, radiation damage effects to the semiconductor must also be considered in selecting a suitable beta source. The parameters J_o and

A are tightly coupled, and these parameters reflect the quality of the semiconductor element or device. In the case of an ideal silicon NP junction, J_o is about 10^{-11} amp/cm^2 and A = 1.0. In real devices, however, defects on the surface and near the junction change these values considerably. For example, in the voltage range of interest, typical commercial silicon solar cells are characterized by values of J_o of the order of 10^{-6} amp/cm^2 and A of approximately 2.5.

The net effect of the change in values from the ideal case is that V_{oc} of the device is considerably lowered, and the maximum power is also lowered. The existence of defects in the junction region causes electron-hole recombination currents —or leakage currents— that subtract from the available output current. Surface defects also account for losses, but the junction recombination currents are the primary reason for solar cells not behaving as ideal cells under low bias voltage conditions. The parameter G_{sh} takes into account current shunting paths which are, of course, sources of loss in a betavoltaic energy converter. The paths can arise from inhomogeneities in the planar junction, or defective regions near the edge of the device. Commercial silicon solar cells have values of G_{sh} of about 10^{-5} ohm^{-1} cm^{-2}. Thus, if the effective area of such a cell is 1 cm^2, the shunt resistance, $R_{sh} = 1/(G_{sh} \cdot \text{area})$, would be about 10^5 ohms.

FIG. 7 is a graph illustrating the J–V and Pw–V characteristics of a single cell constructed according to our invention. The cell had a planar junction area of 2.85 cm^2 and was fueled with a promethium-147 radioisotope, by utilizing a promethia source having an area of 2.38 cm^2 and a layer thickness of approximately 5.3 mg/cm^2. Promethia activity was approximately 678 curies/gm such that a total source strength of 1288 microwatts/cm^2 was available. Such cells or devices are much more suited to betavoltaic energy conversion than the solar cells mentioned above. Devices of the nature as that having the typical betavoltaic data of FIG. 7 are characterized by the following parameters: $J_o \cong 10^{-9}$ amp/cm^2, $A \cong 1.5$ and $G_{sh} \cong (0.5 \cdot 10^{-6})$ ohm^{-1} cm^{-2}. With the promethium-147 radioisotope fuel, the energy spectrum of beta particles emitted therefrom is such that very little radiation damage occurs in silicon devices.

The J–V characteristic of the single cell fueled with promethium-147 is shown at the "beginning of life" by a full line **118** in FIG. 7, and is shown by broken lines **120**, **122** and **124** after 1, 2 and 3 years, respectively. The beginning of life output power density (Pw) available from a single cell (output power per unit area of its active area) is shown by a full line **126**. The short circuit current density J_{sc} generally decays as does the promethium-147 radioisotope (of 2.6 years half-life). Further, the single cell open circuit voltage V_{oc} decays as follows:

$$V_{oc} = (V_{oc})_{t=0} - (0.0067)At \qquad \text{[Eq. 4]}$$

where t = Elapsed time (years)

The net effect on the value of maximum power (P_{max}) is that it also decays, with a half-life of $(t_{1/2})_P \cong 2.13$ years. At the maximum power point in FIG. 7, efficiency of the exemplary cell is 1.1 percent. The efficiency is based on the total amount of power available from the promethia source.

FIGS. **8A**, **8B**, **8C** and **8D** are graphs which were plotted from experimental results and show typical characteristics of a promethia-fueled, silicon, betavoltaic single cell as a function of promethia layer thickness. The cell included a N$^+$/P/P$^+$ silicon wafer with a resistivity $\rho_P \cong 0.3$ ohm-cm, A = 1.5, $J_o = 8.8 \cdot 10^{-10}$ amp/cm^2 and the promethia activity was **678** curies/gm. In FIG. **8A**, the short circuit current density J_{sc} (microamps/cm^2) is plotted as a function of promethia layer thickness (milligrams/cm^2). Similarly, in FIGS. **8B**, **8C** and **8D**, the open circuit output voltage V_{oc} (volts), the maximum output power density Pw_{max} (microwatts/cm^2) and device or cell efficiency (%) are respectively plotted as a function of promethia layer thickness (mg/cm^2). This data is used to determine the optimum layer thickness promethia source for a given application. For example, if device efficiency is the dominating factor in any consideration, it is apparent from FIG. **8D** that promethia sources having a layer thickness of about 1 or 2 mg/cm^2 should be used; however, where power output is the dominating factor, it can be seen from FIG. **8C** that promethia sources having a layer thickness of the order of 10 mg/cm^2 should be used.

FIGS. **9A** and **9B** are respectively a perspective view of a bi-directional fuel element or source **128**, and a fragmentary and enlarged sectional view thereof. The fuel element **128** is preferably a thin disc **130** as shown in FIG. **9A**, and emits nuclear particles in two directions as indicated by arrows **132**. Radioisotopic fuel material is, for example, held and supported in a suitable matrix. In this instance, small grains **134** of promethia are used to form a disc and then these grains are thinly coated with approximately 1 micron of metal **136** to hold them together as indicated in FIG. **9B**. The metal **136** is preferably aluminum; however, nickel, copper (Cu) or tantalum can also be satisfactorily used. The metal **136** can be deposited on the grains **134** by vapor deposition or sputtering. The disc **130** can alternatively be made of promethium-147 metal. However, such a metal disc cannot be much greater than 10 microns in thickness if the device efficiencies of the improved later models are to be maintained. It appears that promethium-147 metal cannot presently be rolled-out much thinner than 50 to 75 microns, and direct depositing of the metal is required.

FIGS. **10A** and **10B** are exploded perspective views of a two-cell betavoltaic energy converter **138** using the bi-directional source **128** (FIG. **9A**), wherein the cells are connected respectively in parallel and in series. A cell is, of course, a unit including a fuel element or source and an associated N$^+$/P or N$^+$/P/P$^+$ semiconductor element or wafer. The source and wafer are preferably promethium (metal or its oxide) and silicon, respectively. Thus, the bi-directional source **128** in FIGS. **10A** and **10B** is a mutual source for the wafers **140** and **142**. The source **128** is normally positioned contiguously to the N$^+$-type layers **140***a* and **142***a* of the wafers **140** and **142**. As shown in FIG. **10A**, the P-type layers **140b** and **142***b* (with thin metallic coatings thereon) are both connected to positive terminal **144**, and the N$^+$-type layers **140***a* and **142***a* (with thin metallic coatings or grids thereon) are both connected to negative terminal **146**. In FIG. **10B**, however, the P-type layer **142***b* is connected to positive terminal **148**, the N$^+$-type layer 142*a* is connected to the P-type layer 140*b* and the N$^+$-type layer 140*a* is connected to negative terminal 150.

FIG. 11 is an elevational view of an N$^+$/P (or N$^+$/P/P$^+$ semiconductor wafer 152 having a coating 154 of promethium-147 metal or promethia deposited directly onto the N$^+$-type layer 156 of the wafer 152. The promethium coating 154 can be deposited directly onto the surface of the N$^+$-type layer 156 either by vapor deposition, sputtering or electroplating techniques. Negative electrode strip 158 is bonded to the N$^+$-type layer 156 at its peripheral margin (which has a thin metallic coating thereon), and positive electrode strip 160 is bonded to the (thinly metal coated) P-type (or P$^+$-type) layer 162 at its peripheral margin as illustrated. The surface of the N$^+$-type layer 156 provides direct support for the promethium coating 154, and an intervening conductive metal coating or grid is not used. The advantages include greater simplicity of construction and significantly increased efficiency.

FIG. 12 is an exploded perspective view of a two-cell betavoltaic energy converter 164 having a radioactive material coated on at least one semiconductor wafer. The converter 164 includes N$^+$/P of an enclosing pair, (or N$^+$/P/P$^+$) semiconductor wafers 166 and 168. The N$^+$-type layer 168*a* of the wafer 168 has a coating 170 thereon of promethium-147 metal or promethia, for example, just as the wafer 152 (FIG. 11). The wafer 166 need not have a radioactive coating thereon and is normally positioned with its N$^+$-type layer 166*a* contiguous to the coating 170 to take advantage of its emitted nuclear particles. Of course, the N$^+$-type layer 166*a* can have a coating thereon similar to the coating 170. In this instance, each of such coatings can be formed with a significantly lower layer thickness. The two cells of the converter 164 are shown connected in parallel to the positive and negative terminals 172 and 174; however, it should be clear that the cells can be readily connected in series to the terminals 172 and 174. Of course, the faces of the P-type (or P$^+$-type) layers 166*b* and 168*b* have thin metallic coatings thereon, and the marginal ring areas of the N$^+$-type layers 166*a* and 168*a* also have such coatings thereon.

FIG. 13 is an exploded perspective view of a highly compact and practical form of a nuclear battery 176. Most applications require several cells in a nuclear battery. The voltage requirements determine the number of cells to be connected in series, while the current requirements determine the cell areas and/or the number of cells to be connected in parallel. The final design, therefore, includes one or more cells combined in a series and/or parallel network to meet required specifications. For example, the nuclear battery 30 embodiment shown in FIG. 1 is a series connection of cells, and certain models (DL-10A-2 and DL-100A-1) thereof meet the following specifications.

Model	DL-10A-2	DL-100A-1
Maximum power, P_{max} (microwatts)	43	212
Voltage at P_{max} (volts)	1.35	3.35
Open circuit voltage, V_{oc} (volts)	1.79	4.75
Short circuit current, I_{sc} (microamps)	44.0	77.0
Length of cylindrical envelope, L (cm)	0.57	1.22
Diameter of cylindrical envelope, D (cm)	1.18	1.55
Device efficiency (%)	1.04	0.84

The planar, multiple section, cell embodiment of the nuclear battery 176 can meet the above specifications (taken on a per-cell basis) with relatively greater compactness and, certainly, with a simpler construction than that of the battery 30. The battery 176 includes a fuel element 178 and a multiple section N$^+$/P/P$^+$ semiconductor element 180. The fuel element 178 comprises a disc 182 and a thin coating 184 of radioactive material thereon. The disc 182 is made of aluminum and the coating 184 is of promethia, for example. The semiconductor element 180 can be made by first diffusing phosphorus into the upper surface active areas of a P-type silicon wafer 186 using a suitable mask (not shown) to produce a N$^+$-type layer 188 thereon. Boron is then similarly diffused into the lower surface active areas of the wafer 186 to produce a P$^+$-type layer 190 thereon. The wafer 186 is next cut into appropriate sectors 192 which are suitably cemented back together in disc form to an electrically insulating cross 192a made of material such as ceramic. In one construction, the sectors 192 were cemented directly on the surface of a ceramic substrate plate so that the cross 192*a* was of air. The sectors 192 were connected in series by (three) leads 194 which connect a N$^+$-type layer 188 of one sector to the P$^+$-type layer 190 of a succeeding sector in a clockwise direction. Positive output lead 196 is connected to the P$^+$-type layer of the first (upper left) sector, and negative output lead 198 is connected to the N$^+$-type layer of the last (lower left) sector of the semiconductor element 180. As in the other versions of this invention, the surfaces of the N$^+$-type and P$^+$-type layers 188 and 190 of each sector 192 have a thin metallic coating provided thereon.

FIG. 14 is a graph of the current (I) and power (Pwr) versus voltage (V) characteristics of a planar, four section cell, nuclear battery embodiment similar to that shown in FIG. 13. The semiconductor element was coupled to a promethia fuel element or source wherein the fuel disc is coated with promethia at a layer thickness of approximately 8 mg/cm^2 and having an activity of about 660 curies/gm. It can be noted that maximum power occurs at a relatively high voltage, for a single cell configuration.

FIG. 15 is an exploded perspective view of a planar, multiple section, cell embodiment of a nuclear battery 200 which is superior from a fabrication point of view than the battery 176 of FIG. 13. The battery 200 includes fuel element 202 and a multiple section N$^+$/P/P$^+$ semiconductor element 204. In this configuration, P-type (silicon) wafer 206 need not be cut into sectors since P$^+$-type layers 208 and N$^+$-type layer 210 are formed by deep diffusion or ion implantation (ion beam directed into material) techniques in the wafer as axial guard and isolating walls, respectively, and completely separate and isolate each cell section. The P$^+$-type wall layers 208 are located between the planar N$^+$-type layers 210*a* and the N$^+$-type wall layer 210. The wall layer 210 can be ceramic but this would require cutting of the wafer 206. The cell sections can be connected in series by (three) leads 212, and positive and negative output leads 214 and 216 are connected to the first and last sections as illustrated. The exposed surfaces of the guard layers 208 and of the planar layers 210a are, of course, plated with a thin metallic low resistance coating. It may be noted that a single cell including a promethia source and a silicon N^+P or $N^+/P/P^+$ wafer, and which utilizes only one active area or section, supplies electrical power characteristically at voltages of about 0.3 volt. Thus, multiple section cell embodiments of nuclear batteries are highly desirable to obtain much higher output voltages from a relatively compact device.

FIG. 16 is a partially fragmentary and exploded perspective view of a laminar, multiple section, cell configuration of a nuclear battery 218. The battery 218 includes a fuel element 220 and a multiple section $N^+/P/P^+$ semiconductor element 222. The illustrated structure is believed to be self-explanatory in view of the preceding description on multiple section cell embodiments. The laminar, multiple section battery 218 may at first sight appear to be equivalent to the planar devices of FIGS. 13 and 15. It is not, however. The nuclear particle flux 224 is parallel to the main N^+P^+ junctions in this embodiment. The silicon semiconductor element 222 preferably has, for example, a height h greater than approximately 100 microns and a width w of the order of 1 cm. These dimensions can be varied by using another fuel element similar to the fuel element 220 on the opposite (lower) side of the semiconductor element 222, and also on the front and rear sides thereof. One of the advantages of this battery (218) configuration is that very high voltage devices can be easily made by having any desired number of lateral cell sections. The lateral end surfaces have, of course, metallic coatings deposited thereon to which are soldered the positive and negative electrode strips 226 and 228.

FIG. 17 is an electron energy level diagram for about two sections of the $N^+/P/P^+$ semiconductor element 222 shown in FIG. 16. Its operation under exposure to radiation is indicated in the diagram. It can be seen from the diagram that the main junctions are those between the N^+-type and P^+-type layers. Current flows from the electrode strip 226 (FIG. 16) attached to the coated left end P^+-type layer and to the electrode strip 228 attached to the coated right end N^+-type layer when a load is connected between the electrode strips.

FIG. 18 is an exploded and partly fragmentary perspective view of a "needle-like" or elongated cylindrical, multiple section, cell embodiment of a nuclear battery 230. The battery 230 is fabricated in a manner generally similar to that of the planar battery 176 of FIG. 13. The battery 230 includes a fuel element 232 and a multiple section N^+/P (or $N^+/P/P^+$) semiconductor element 234. In this instance, however, the fuel element 232 comprises a thin cylindrical shell 232a of, for example, aluminum foil having a promethia layer 232b deposited on its inner surface. The semiconductor element 234 is fabricated by diffusing phosphorus circumferentially into a P-type cylinder of semiconductor material. The cylinder is then cut into uniform sections 236 having a P-type core 236a and a surrounding N^+-type outer layer 236b. The normally upper surface of the P-type core 236a is covered with a metallic coating or sheet 238 which can be aluminum, and the circumferential surface of the N^+-type layer 236b is covered with a metallic grid or thin metallic coating 240 which can also be of aluminum. The periphery of the coating or sheet 238 covering the normally upper surface of the P-type core 236a is, of course, spaced from the N^+P junction so that there is no interaction therewith. For a $N^+/P/P^+$ semiconductor, the coating 238 would be deposited on top of a central P^+-type cylinder formed axially in the P-type core 236a.

The sections 236 are separated by insulator discs 242 which are preferably made of ceramic. Each disc 242 has a hole 242a through which passes a lead 244 connecting a P-type core 236a of one section 236 to the N^+-type layer 236b of an adjacent upper section. The sections 236 are thus connected in series with a positive output lead 246 and a negative output lead 248. The insulator discs 242 can be cemented or suitably secured to adjacent sections 236, and then inserted and positioned in the cylindrical fuel element 232 shell. While a cylindrical junction surface is utilized in obtaining the elongated cylindrical battery 230, it is apparent that other configurations of nuclear batteries can be obtained so long as a suitable junction can be formed therein.

It is to be understood that the exemplary embodiments of this invention are merely illustrative of, and not restrictive on, our broad invention and that various changes in design, structure and arrangement may be made therein without departing from the true spirit and scope of the invention.

We claim:

1. In a nuclear battery, a cell comprising:

a fuel element including a radioactive source of nuclear particles having a known maximum energy, said radioactive source comprising a source of beta particles; and

a semiconductor element positioned in at least close proximity to said fuel element and irradiated by the same, said semiconductor element including a semiconductor wafer and relatively thin, electrically conductive, distributed ohmic contact members provided on respective faces of said wafer, and said wafer comprising a system of at least a high carrier concentration first-type layer and a lower carrier concentration second-type layer of semiconductor material having respectively different electrochemical potentials and having an energy threshold level of radiation damage compatible with, and at least of the same order as, the maximum energy of said nuclear particles, said layers having a junction therebetween and said fuel element being positioned operatively close to said junction adjacent to said high carrier concentration first-type layer, at least said ohmic contact member adjacent to said fuel element providing a relatively large fractional open area for passage therethrough of said nuclear particles whereby a long life cell of maximum output voltage and high power output is obtained.

2. The invention as defined in claim 1 wherein said fuel element includes a unitary radioactive source member, and said wafer system further comprises a high carrier concentration layer of said second-type electrochemical potential material, said latter layer serving primarily as a reflector barrier whereby a long life cell of maximum output voltage and high power output is obtained.

3. The invention as defined in claim 2 wherein said source member includes a backing disc having a layer of radioactive material provided on a surface thereof and which is a promethium source of beta particles, and said system includes a silicon system of N^+-type, P-type and P^+-type layers of different electrochemical potential material and having carrier concentrations of the order of approximately 10^{19}, 10^{16} and 10^{19} atoms/cm^3, respectively, said N^+-type and P-type layers having said junction therebetween, said P^+-type layer serving primarily as said reflector barrier and said fuel element being positioned operatively close to said junction adjacent to said N^+-type layer.

4. The invention as defined in claim 1 wherein said fuel element includes a bi-directional source which is a unitary radioactive disc member comprising promethia and a matrix to hold and support said promethia, and said semiconductor element is positioned in at least close proximity to one side of said bi-directional source, and further comprising another similar semiconductor element positioned symmetrically to the other side of said bi-directional source.

5. The invention as defined in claim 2 wherein said fuel element is of a planar form, and said semiconductor element is of a correspondingly similar planar form and having multiple sections which are insulated from each other and operatively connected in at least a partially series arrangement to provide an output voltage higher than that available from a commensurate cell having a unitary semiconductor element.

6. The invention as defined in claim 2 wherein said fuel element is of a planar form, and said semiconductor element is of a laminar form having laterally disposed multiple sections with planes oriented perpendicularly to the plane of said fuel element, said sections being operatively coupled in series to provide an output voltage higher than that available from a commensurate cell having a unitary semiconductor element.

7. The invention as defined in claim 1 wherein said fuel element is of an elongated and hollow cylindrical form, and said semiconductor element is of a correspondingly elongated and solid cylindrical form positioned concentrically within said fuel element and having axially disposed multiple sections which are insulated from each other and operatively connected in at least a partially series arrangement to provide an output voltage higher than that available from a commensurate cell having a unitary semiconductor element.

8. The invention as defined in claim 1 wherein said fuel element includes a unitary radioactive source member comprising a backing disc having a layer of radio-active material provided on a surface thereof and which is a promethium source of beta particles, and said system includes a silicon system of N^+-type and P-type layers of different electrochemical potential material and having carrier concentrations of the order of approximately 10^{19} and 10^{16} atoms/cm^3, respectively, said N^+-type and P-type layers having said junction therebetween and said fuel element being positioned operatively close to said junction adjacent to said N^+-type layer.

9. A nuclear battery comprising:

a plurality of cells arranged in a series stack, each of said cells including

a fuel element comprising a radioactive source of nuclear particles having a known maximum energy, said fuel element including a unitary radioactive source member, and

a semiconductor element positioned in at least close proximity to said fuel element and irradiated by the same, said semiconductor element comprising a semiconductor wafer and relatively thin, electrically conductive, distributed ohmic contact members provided on respective faces of said wafer, and said wafer including a system of at least a high carrier concentration first-type layer and a lower carrier concentration second-type layer of semiconductor material having respectively different electrochemical potentials and having an energy threshold level of radiation damage compatible with, and at least of the same order as, the maximum energy of said nuclear particles, said layers having a junction therebetween and said fuel element being positioned operatively close to said junction adjacent to said high carrier concentration first-type layer;

a plurality of electrically conductive ring members corresponding in number to said cells and positioned concentrically about said fuel elements, respectively;

electrically conductive end members sandwiching said cells of said stack, said ring members axially contacting said end members and said ohmic contact members of said wafers and providing a series connection from one of said end members through said semiconductor elements of said cells to the other of said end members;

spring means for biasing and maintaining said end members and cells of said stack in effective series contact throughout the same; and

a pair of electrode terminals adapted to be connected respectively to said end members, whereby a long life battery of maximum output voltage and high power output is obtained.

10. A nuclear battery comprising:

a fuel element including a radioactive source of nuclear particles having a known maximum energy, said fuel element being of a planar form; and

a semiconductor element positioned in at least close proximity to said fuel element and irradiated by the same, said semiconductor element being of a correspondingly similar planar form to said fuel element and including multiple sections which are insulated from each other and electrical leads operatively connecting said sections in at least a partially series arrangement to provide a higher output voltage therefrom, each of said sections comprising a semiconductor wafer and relatively thin, electrically conductive, distributed ohmic contact members provided on respective faces of said wafer and connecting with said leads, and said wafer including a system of at least a high carrier concentration first-type layer and a lower carrier concentration second-type layer of semiconductor material having respectively different electrochemical potentials and having an energy threshold level of radiation damage compatible with, and at least of the same order as, the maximum energy of said nuclear particles, said layers having a junction therebetween and said fuel element being positioned operatively close to said junction adjacent to said high carrier concentration first-type layer whereby a long life battery of maximum output voltage and high power output is obtained.

11. The invention as defined in claim **9** wherein said source member includes a backing disc having a layer of radioactive material provided on a surface thereof and which is a promethium source of beta particles, at least said ohmic contact member adjacent to said fuel element provides a relatively large fractional open area for free passage therethrough of said nuclear particles, said system includes a silicon system of at least N$^+$-type and P-type layers of different electrochemical potential material and having carrier concentrations of the order of approximately 10^{19} and 10^{16} atoms/cm^3, respectively, said N$^+$-type and P-type layers having said junction therebetween and said fuel element being positioned operatively close to said junction adjacent to said N$^+$-type layer, and said spring means includes an electrically conductive spring ring for axially biasing uniformly over a wide base against one of said end members of said stack, and further comprising a shielding container for containing and primarily providing radiation protection containment of said stack, and a fire container for containing said shielding container and primarily providing high temperature protection containment of said stack, one of said electrode terminals being mounted on and insulated from said fire container and said spring ring electrically connecting the one of said end members to said shielding container which is in electrical contact with said fire container serving as the other of said electrode terminals.

12. The invention as defined in claim **10** wherein said fuel element includes a unitary radioactive source member which is a promethium source of beta particles, at least said ohmic contact member adjacent to said fuel element provides a relatively large fractional open area for free passage therethrough of said nuclear particles, and said system includes a silicon system of at least N$^+$-type and P-type layers of different electrochemical potential material and having carrier concentrations of the order of approximately 10^{19} and 10^{16} atoms/cm^3, respectively, said N$^+$-type and P-type layers having said junction therebetween and said fuel element being positioned operatively close to said junction adjacent to said N$^+$-type layer.

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