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Pm¹⁴⁷-SILICON BETAVOLTAIC BATTERY FEASIBILITY

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ABSTRACT

This report summarizes betavoltaic battery work and presents expected characteristics of optimized Pm¹⁴⁷-Si betavoltaic batteries. Pm¹⁴⁷ source output calculations and data on experimental batteries are presented.

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Pm¹⁴⁷-SILICON BETAVOLTAIC BATTERY FEASIBILITY

Introduction

The concept and theory of betavoltaic batteries have been described extensively in the literature.¹⁻⁷ Work on experimental batteries has been reported^{6, 7} in which Pm¹⁴⁷ was used as the β source and Si used as the semiconductor.

The betavoltaic battery operation is analogous to the familiar photovoltaic battery (solar battery), the ionization of the atoms of the semiconductor being generated in the former case by beta (rather than photon) bombardment. Although the principle is analogous, the required parameters of the semiconductors used in the two types of batteries are quite different.

With the continuing advances in low power semiconductor devices and circuits, the Pm¹⁴⁷-Si betavoltaic battery should find applications in many places. Some very low power circuitry have been suggested and tested;⁵ however, many others could doubtless be designed to serve many unique applications. The betavoltaic battery will be used in those unique applications requiring continuous low power (<500 μ w) for long periods of time (up to approximately 5 years).

This report is intended to summarize betavoltaic battery work and to discuss the expected characteristics of optimized Pm¹⁴⁷-Si betavoltaic batteries. The source and semiconductor will first be considered independently. That is, the source will be considered to deposit energy in the semiconductor independent of the properties of the p-n junction, and the electrical output of the semiconductor will be considered independent of the origin of the energy deposited. Consideration will then be given to the performance of a complete battery, for which a partial cross section is shown in Figure 1.

Beta Source

Promethium-147 decays to Samarium-147, by what is probably a once forbidden β transition having a characteristic energy⁸ of 223 Kev with a half-life of 2.62 years. Experimental determinations of the Pm¹⁴⁷ β spectrum^{8, 9} have given linear Fermi-Kurie plots down to very low energies (~10 Kev). Curves¹⁰ for the ratio of the average energy to the maximum energy of beta spectra having an allowed shape (linear Fermi-Kurie plot) indicate an average energy for Pm¹⁴⁷ of 62 Kev. This energy is very slightly higher than the 60.54 Kev resulting from the recent calorimetric determination of the decay energy.¹¹ The theoretical specific activities of Pm¹⁴⁷ metal, the oxide (Pm₂O₃), and the fluoride (PmF₃) are 930, 800, and 670 curies/gm, respectively. Pm₂O₃ with specific activities as high as 770 curies/gm has been used in experimental batteries.⁷

Figure 1. Schematic of Betavoltaic Cell

The output from a slab β source can be calculated using the empirical equations of Loevinger¹² for the dose from a point source. The results of the integration of this function over an infinite Pm^{147} source of finite thickness are shown in Figure 2. Curves showing source efficiency, η , and total power output (for various specific activities) as a function of source thickness, $P(\infty, h)$, are given. See Appendix A for details of the calculations resulting in these curves.

These curves indicate lower power output for Pm^{147} sources than reported elsewhere.^{5,6} This is largely due to the lower value of the accepted average energy for Pm^{147} ; however, refinement of earlier calculations by the author⁵ have also resulted in a slightly different efficiency curve.

The fraction of the total Pm^{147} source output power absorbed to a given distance in silicon ($\rho = 2.4 \text{ gm/cm}^3$) for a particular source thickness (6.14 mg/cm^2) is shown in Figure 3. The curve is not highly dependent on source thickness and may, for practical purposes, be considered to be independent of source thickness. This curve may be used to estimate the power lost in the semiconductors due to surface recombination and to penetration beyond the active area (if the diffusion length is short).

Another factor affecting the energy input to the semiconductor is the backscattering which occurs at the source-semiconductor interface. The backscattering is dependent upon the energy of the beta spectrum as well as the atomic number of the target. The data of Nader, et al.¹³ indicate that one would expect 20 percent of the Pm^{147} betas impinging on a silicon target to be backscattered.

Source Preparation

The preparation of a thin (approximately 5 to 10 mg/cm^2) Pm^{147} source of high specific activity and high purity can be troublesome. The Pm^{147} must not be contaminated with other radionuclides. High energy β emitters or alpha emitters can cause radiation damage problems in the semiconductor, and γ emitters can cause handling problems due to high external radiation.

Procedures for preparing high specific activity Pm_2O_3 sources are given by Barnes, et al.⁷ and Orr, et al.¹⁴ Work on vapor deposition of NdF_3 on silicon¹⁵ looks promising as a method of preparing well-controlled thin PmF_3 sources. No attempts, to my knowledge, have been made to prepare Pm^{147} sources in the metallic form. However, Kircher and Barnes¹⁶ have prepared a small quantity of Nd metal which they found to be reasonably malleable. From this brief experience with Nd, they have indicated that they see no particular problems in preparing thin uniform sources of Pm^{147} metal.

Each of these possible forms of a Pm^{147} source presents certain advantages and disadvantages to be weighed before a choice is made for a betavoltaic battery application. The metal would give the highest source specific activity. It is believed Pm^{147} metal could be prepared with a specific activity of 850 curies/gm or greater. It is believed that the metal sources could be readily prepared and handled in a controlled (inert) atmosphere. However, since Pm oxidizes quite readily, all source preparation and battery fabrication would have to be carried out in an inert atmosphere. If a completed battery containing the Pm metal source were to be accidentally broken open, it could present a serious health hazard because of the rapid oxidation of the source and probable spreading of the oxide upon exposure of the source to the atmosphere.

Figure 2. Output from One Side of Pm^{147} Slab Source

Figure 3. Fraction of Pm^{147} β Power Absorbed to Given Distance in Silicon

High specific activities (approximately 750 curies/gm) have been obtained in preparing Pm_2O_3 β sources.^{6,7} These sources, however, are difficult to make uniform and tend to flake badly. Complete source and battery fabrication would probably have to be carried out in a dry box to control possible radioactive contamination. Again, a serious health hazard would probably be presented if a completed battery containing the Pm_2O_3 source were to be broken open.

It is believed that, by use of methods similar to those used recently¹⁵ in the vapor deposition of NdF_3 , PmF_3 sources of good specific activity (>600 curies/gm) can be deposited directly either on silicon solar cells or on a flash coating of a metal such as Al. Such a source should be sufficiently stable to allow battery assembly outside of dry box areas. As the source would be deposited directly on the solar cell, battery assembly would probably be simplified. Although PmF_3 is probably to some degree soluble in water, it should present considerably less health hazard (than Pm or Pm_2O_3) if a completed battery were to be broken open.

There may be other compounds of Pm which would be very stable, insoluble, and give high specific activity; however, little is known at the present time about the rare earth compounds.

Semiconductor

Although the minority carrier diffusion length may be a major consideration in some semiconductors such as GaAs, it is not of significance in consideration of the Pm^{147} -Si betavoltaic battery, because from Figure 3 it is seen that 90 percent of the Pm^{147} source output is absorbed within 50 microns of the surface in Si. GaAs has been ruled out for use in Pm^{147} betavoltaic batteries⁵ because of the short diffusion length and, thus, low efficiency; however, it might be well to keep in mind that with its large energy gap, GaAs would be very attractive if its diffusion length could somehow be increased to perhaps 15-20 microns. With improved semiconductor technology, other large energy gap semiconductors may meet the requirements of betavoltaic batteries.

Extensive and detailed discussions of the theory of p-n junctions as related to betavoltaic batteries are given by Robison and Nelson⁴ and Rappaport, et al.¹ For our purpose here, a discussion is given in terms of the equivalent circuit (Figure 4) of microscopic device parameters. Experimentally, solar cells agree extremely well with the equivalent circuit analysis.

From Figure 4(a) it is seen that the current density (in terms of the surface area of the junction) delivered to the load R_L at voltage V may be written as

$$J = J_g - J_j - \frac{V + JR_s}{R_{sh}} \quad (1)$$

Now J_j may be written as $J_j = J_o (e^{\frac{\lambda V_j}{kT}} - 1)$ where J_o is the reverse saturation current density, V_j is the junction voltage, and $\lambda = q/nkT$. Diffusion theory predicts a value of 1 for n ; however, experimental results with commercial silicon cells give values near 1.5.

(a) General Equivalent Circuit

(b) Practical Betavoltaic Cell Equivalent Circuit

Figure 4. Betavoltaic Cell Equivalent Circuits

For practical betavoltaic cells R_s is small (<10 ohms); therefore, $V + JR_s \approx V$ (this is not true for solar cell operations where the series resistance is significant). For this case (Figure 4(b)) J_g becomes J_{sc} and the current to the load may then be represented by

$$J = J_{sc} - J_o (e^{\lambda V} - 1) - \frac{V}{R_{sh}}. \quad (2)$$

The dependence of the current voltage characteristic on R_{sh} and J_o for fixed λ and J_{sc} is shown in Figures 5 and 6. It should be noted from Equation 2 that the effect of a change in J_{sc} is simply a vertical shift in the current voltage characteristic. Additional current scales (representing various short currents) are given at the right of Figures 5 and 6. It might further be noted that the shape of the current voltage characteristic may be obtained when $J_{sc} = 0$, that is to say the dark diode characteristic of the junction may be used to predict the shape of the current voltage characteristic of the junction in the presence of ionizing radiation.

From Equation 2 and Figures 5 and 6 it is evident that for efficient betavoltaic cell operation, junctions having very low reverse saturation current and high shunt resistance are required. Neither of these requirements is met with present commercially available silicon solar cells (discussed further later). If efficient betavoltaic batteries are to be made, it is felt that significant effort must be put into developing the manufacturing techniques to produce cells for low power operation.

Radiation Damage

As the maximum β energy of Pm^{147} is above the damage threshold for silicon of 145 Kev, cell degradation could result from the Pm^{147} betas penetrating the silicon semiconductor. Flicher, et al.⁶ suggest that radiation damage to n/p cells by the Pm^{147} betas would lead to a 12 percent drop in efficiency during one-half life (2.6 years). Recent work by the author¹⁷ showing a flux rate dependence of electron damage to n/p solar cells indicates that one would expect little if any damage to the silicon during the life of a betavoltaic battery.

Radiation damage to silicon caused by an α contaminant in the Pm^{147} can be a serious problem. Pm_2O_3 sources that have been made^{6,7} contained significant amounts of Am^{241} in spite of considerable efforts at purification. Flicher, et al.⁶ suggest that the α emission level from the Pm^{147} source must be less than $2 \times 10^3 \alpha/\text{min}/\text{cm}^2$ for negligible damage. Those Pm_2O_3 sources that have been used in betavoltaic batteries^{6,7} were believed to have only slightly higher levels of α emission than this.

Temperature Dependence

As the betavoltaic battery makes use of a semiconductor device for the energy conversion, the battery output temperature dependence will be determined by the temperature dependence of the semiconductor. The temperature dependence of betavoltaic batteries is discussed in the literature^{2,4} and may well be of concern in many possible applications.

Figure 5. I-V Characteristics, Dependence on R_{sh} and J_o

Figure 6. I-V Characteristics, Dependence on R_{sh} and J_o

The temperature dependence is nearly entirely due to the temperature dependence of the reverse saturation current density. Empirically, it has been found that the dependence can usually be expressed as

$$J_o = A e^{-E_g/BkT}$$

where A and B are constants, E_g the energy gap of the semiconductors, k Boltzmann's constant, and T the absolute temperature. With silicon, this results in a large temperature dependence of the betavoltaic battery output.

Figure 7 gives typical curves from an experimental betavoltaic battery, which show this temperature dependence.

Expected Betavoltaic Battery Performance

The efficiency and performance of betavoltaic batteries are highly dependent on the method of optimization attempted. If one wishes to minimize the amount of isotope used (maximize source efficiency), the power input level to the semiconductor is not maximum. If, however, the semiconductor efficiency is to be maximized, the source output must be maximum; thus, low source efficiency is given. For maximum overall efficiency, there is obviously a trade-off between source and semiconductor efficiency.

If the semiconductor parameters are well controlled (and known), current-voltage characteristics as in Figures 5 and 6 can be predicted, and the overall efficiency can then be maximized if the source power input to the semiconductor can be accurately predicted. Methods that have been used in predicting semiconductor efficiencies^{3, 6} are questionable if commercially available n/p silicon solar cells are used, because R_{sh} is not sufficiently large to be negligible and J_o is normally not greatly different from J_{sc} . Their methods of predicting power input levels from a Pm^{147} source can be taken only as very rough approximations. These methods are questionable, but highly accurate generalized methods of estimating overall efficiencies are not known.

The overall picture becomes even more complex when we consider the possibility of irradiating a thin (approximately 90 microns) semiconductor from both sides. This will greatly increase the input power level to the semiconductor. The effective increase will be less than 100 percent due to surface recombination at the back surface. Probably, a reasonable estimate would be a 70 percent increase in short circuit current over the case of irradiation from only the front side.

The output of a Pm^{147} -Si betavoltaic battery can be estimated by using Figures 2-6. Let us take the case of a 2.0 curie source having a specific activity of 750 curies/gm. From Figure 2 such a source (2.67 mg/cm^2) would have an efficiency (one side) of 0.32 and a power output of 0.24 mw/cm^2 . If we assume that all power absorbed in the first 1.0 micron and beyond 90 microns in the silicon is lost to surface recombination and transmission, respectively, Figure 3 indicates 10 percent power loss.

Figure 7. Betavoltaic Cell Temperature Dependence

Now, if we use a backscatter factor of 20 percent and an average energy expended in generating a hole-electron pair of 3.6 ev, the expected short circuit current density is

$$J_{sc} = (0.90)(0.80) \left(\frac{0.24}{3.6} \right) = 48 \mu\text{amp}/\text{cm}^2$$

The cell output voltage-current characteristic can now be obtained from Figure 4 using the curve with the proper cell parameters.

The above short circuit current is significantly higher than that observed experimentally⁷ (see Appendix B for comparisons). The difference may be in the value used for the average energy to generate a hole-electron pair. Flicher, et al.⁶ give an experimentally determined value of 5 ev which would change the above value of J_{sc} to give good agreement with experimental observations. It is not clear, however, whether the value of 5 ev includes backscatter, surface recombination, or other loss factors.

The semiconductor parameters that can be expected are not known. Rappaport, et al.² reported on silicon cells (made approximately 10 years ago) which had parameters of: $J_o \sim 10^{-10} \text{ amp}/\text{cm}^2$, $R_{sh} > 10^6 \text{ ohms}$ and $\lambda \sim 30$. One would then expect that, with the advance of semiconductor technology in recent years, solar cells with parameters this good or better could be made in production. However, from the data of Flicher, et al.⁶ (on their best betavoltaic cell) the parameters are: $J_o \sim 5 \times 10^{-8} \text{ amp}/\text{cm}^2$ and $R_{sh} \sim 5 \times 10^4 \text{ ohms}$. Commercial n/p silicon solar cells purchased for radiation damage studies¹⁷ and cells purchased for fabrication of experimental betavoltaic batteries⁷ showed optimum parameters of: $I_o \sim 10^{-7} \text{ amp}/\text{cm}^2$, $R_{sh} \sim 5 \times 10^4 \text{ ohms}$ with normal parameters of: $I_o \sim 5 \times 10^{-6} \text{ amp}$, $R_{sh} \sim 10^4 \text{ ohms}$. It is believed that these parameters are only an indication of what is acceptable for solar cell operation ($\sim 100 \text{ mw}/\text{cm}^2$ input solar source), not an indication of what could be done if a significant effort were made (series resistance which is a problem in solar application is of little significance at low power). It is believed that, if an effort were made, n/p silicon solar cells could be produced with parameters of: $I_o \sim 10^{-9} \text{ amp}/\text{cm}^2$ and $R_{sh} > 10^5 \text{ ohms}$.

Now, for an indicator of the attainable performance of a near optimum $\text{Pm}^{147}\text{-Si}$ betavoltaic battery, consider the case of a semiconductor 90 microns thick with a 10 curie (750 curies/gm) source on each side. From Figure 3 such a source ($13.33 \text{ mg}/\text{cm}^2$) would have an efficiency of 0.137 and a power output of $0.495 \text{ mw}/\text{cm}^2$. Using the same loss factors and energy per hole-electron pair as before, we have for one side irradiation

$$J_{sc} = 0.90(0.80) \left(\frac{0.495}{36} \right) = 99 \mu\text{amp}/\text{cm}^2.$$

If we assume a 70 percent increase for the source on the back side, $J_{sc} = 170 \mu\text{amp}/\text{cm}^2$. (If the value of 5 ev/hole-electron pair were used, this value is approximately 40 percent high.) Now, from Figure 5, for $J_{sc} = 170 \mu\text{amp}/\text{cm}^2$, $I_o = 10^{-9}$, $R_{sh} = 10^5$, we see the open circuit voltage is approximately 0.40 volt and a maximum power of $\sim 50 \mu\text{w}/\text{cm}^2$ (150 μamp at 0.33 volt). This represents an overall efficiency of 1.4 percent. In the assumed configuration, a number of cells would be stacked in order to utilize both sides of the Pm^{147} sources.

The details of battery assembly have not been extensively investigated. No inherent problems are seen in the assembly of a battery stack, as conceived above, to give an open circuit voltage of approximately 10 volts. Such features as plated thin (a few Å) metal (perhaps Al) contacts covering entire front and back surfaces might make assembly easier.

Battery Life

The preceding discussion has been directed toward the initial battery conditions. Since the power source decays with a half-life of 2.6 years, the battery output will decrease at least this rapidly with time. In fact, one would expect J_{sc} to decrease as the half-life of the isotope, but as V_{oc} decreases with J_{sc} , P_{max} will decrease more rapidly than the isotope. At very low power levels, the current voltage characteristic is linear (Figure 6); therefore, P_{max} decreases as J_{sc}^2 . At the higher power level of the proposed near optimum cell (~50 mw/cm² initial output), a half life of approximately 2 years for decrease of P_{max} seems reasonable.

In the design of a battery for a particular application, one must design for the required current and voltage at the design life, for example 5 years. The initial output required for specified final conditions can be estimated using Figures 5 and 6. For example, suppose one desires an output of 0.22 volt/cell at a current of 20 μ amp/cm² after 5.2 years using semiconductors having $J_o = 10^{-8}$, $R_{sh} = 10^5$ ohms, and $\lambda = 30$. This is met for $J_{sc} = 30 \mu$ amp/cm² at 5.2 years, but J_{sc} has decreased by a factor of four (2 half-lives) in the 5.2 years. This then requires an initial value for J_{sc} of 120 μ amp/cm².

Conclusion

The work in recent years has shown the feasibility of making useful, low power betavoltaic batteries. The Pm^{147} -silicon battery is the only system which looks attractive at the present time.

Although only experimental batteries have been made to date, it is clear that batteries with currents greater than 50 μ amp/cm² at voltages up to 10 volts can be made. Most batteries made to date have been made using far from optimum materials and techniques.

To make efficient and useful batteries, improved techniques for preparing Pm^{147} sources must be developed. Techniques of manufacturing "solar cells" designed for very low power operation must also be developed. The evidence indicates that considerable progress can readily be made in both these areas.

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APPENDIX A

EFFICIENCY AND POWER OUTPUT OF A Pm^{147} SLAB SOURCE

The output from a slab beta source may be calculated by taking a point source function and integrating over the slab. Such a function, expressed in the dimensionless variable $r = \frac{\mu}{\rho}x$, given by Loevinger¹² is:

$$I = \frac{k}{r^2} \left\{ [c - re^{1-(r/c)}]_1 + [re^{1-r}]_2 \right\}, []_1 \equiv 0, r \geq c \quad (\text{A-1})$$

where

$$c = 3.11 e^{-0.55 E_0} \quad (\text{A-2})$$

and

$$\mu/\rho = \frac{16.0}{(E_0 - 0.036)^{1.40}} \left(2 - \frac{\bar{E}}{\bar{E}^*} \right) \text{ cm}^2/\text{gm of air.} \quad (\text{A-3})$$

μ/ρ is the mass absorption coefficient, E_0 the maximum energy of the beta spectrum in Mev, $\bar{E}$ the average energy per disintegration, $\bar{E}^*$ is the average energy per disintegration for an allowed spectrum of the same energy, and k , a normalizing constant, is evaluated by the requirement that I integrated over all space must equal the average energy per disintegration.

From Figure A-1(a), the dose at P due to a ring of radius y and width dy is $I2\pi y dy \sigma = I2\pi r dr \sigma$ where σ is the surface activity. The dose from an infinitesimally thin, infinite plane source is

$$R(Z) = \int_Z^\infty 2\pi\sigma I(r) r dr = 2\pi k\sigma \left\{ \left[c \left(1 - \ln \frac{Z}{c} - e^{1-(Z/c)} \right) \right]_1 + [e^{1-Z}]_2 \right\}, []_1 \equiv 0, Z \geq c$$

This plane source function may be used to obtain the corresponding function for a slab source. If the specific activity of the source is T (disintegration per unit volume) then the activity of the section dy is $S = Tdy$ (disintegration per L^2) = σ as $dy \rightarrow 0$. The dose at 0 from the thin source at y (referring to Figure A-1(b)) is $R(y)$. The dose at 0 from an infinitely thick slab is

$$\begin{aligned} D(X, \infty) &= \int_X^\infty R(y) dy = \int_X^\infty 2\pi kT \left\{ \left[c \left(1 - \ln \frac{y}{c} - e^{1-(y/c)} \right) \right]_1 + [e^{1-y}]_2 \right\} dy, []_1 \equiv 0, y \geq c; \\ &= 2\pi kT \left\{ \left[c^2 \left(3 - e^{1-\frac{x}{c}} \right) - cx \left(2 - \ln \frac{x}{c} \right) \right]_1 + [e^{1-x}]_2 \right\}, []_1 \equiv 0, X \geq c \end{aligned} \quad (\text{A-4})$$

(a)

(b)

(c)

Figure A-1. Source-Absorber Configurations

For an infinite slab source of thickness h , $D(x, h) = D(x, \infty) - D(x + h, \infty)$. Methods of approximating doses from finite slab sources from calculations similar to this are given by Weinstock, et al.¹⁸

The total energy (per unit area) dissipated up to a distance x from the infinitely thick slab source is

$$E(x, \infty) = \int_0^x D(x, \infty) dx = 2\pi kT \left\{ \left[3c^2x + c^3 e \left(e^{-\frac{x}{c}} - 1 \right) - \frac{cx^2}{2} \left(2.5 - \ln \frac{x}{c} \right) \right]_1 + \left[e(1 - e^{-x}) \right]_2 \right\}, []_1 = [(c)]_1, X \geq c \quad (A-5)$$

For a slab source of thickness h , the energy absorbed to a distance x may be obtained from (see Figure A-1(c))

$$E(x, h) = E(x, \infty) - [E(x + h, \infty) - E(h, \infty)] \quad (A-6)$$

(The curves of Figure A-1(c) are purely arbitrary.)

The maximum energy (per unit area) attainable from a slab source is

$$E(\infty, \infty) = 2\pi kT \{ 0.0317 c^3 + e \}$$

The source efficiency (one side) is, of course, just

$$\eta = \frac{E(\infty, h)}{\overline{E}Th} \quad (A-7)$$

To evaluate the constant k for the function expressed in the dimensionless units, $\left(r - \frac{\mu}{\rho} x \right)$, the function I must be integrated over all space.

$$E = \int_0^\infty 4\pi k \left\{ \left[c - re^{1-r/c} \right]_1 + \left[re^{1-r} \right]_2 \right\} dr, []_1 0, r \geq c = 4\pi k \left[c^2(3 - e) + e \right]$$

or

$$k = \frac{\overline{E}}{4\pi [c^2(3 - e) + e]} \quad (A-8)$$

The equations for $E(x, h)$ give the energy (Kev) per unit area where k is in units of Kev/disintegration and T is in disintegration per unit volume. The area and volume are in the dimensionless units, $h = \frac{\mu}{\rho} t$, etc.

To convert the equations to give power output in mw/cm^2 , one must remember that a unit volume of source is $\left[\frac{1}{\nu\rho}\right]^3 \text{ cm}^3$ and a unit area of source is $\left[\frac{1}{\nu\rho}\right]^2 \text{ cm}^2$ where $\nu = \mu/\rho$ is the mass absorption coefficient (cm^2/gm) and ρ is the source density (gm/cm^3).

If the specific activity, A , is given in units of curies/gm, then $T = (3.7 \times 10^{10}) A \rho \left[\frac{1}{\nu\rho}\right]^3$ disintegration/sec-(unit volume). The power output of an infinite slab source is then

$$\begin{aligned} P(x, h) &= (\nu\rho)^2 (1.6 \times 10^{-13}) E(x, h) = (\nu\rho)^2 (1.6 \times 10^{-13}) T \left[\frac{E(x, h)}{T} \right] \\ &= (1.6 \times 10^{-13}) (3.7 \times 10^{10}) \frac{(\nu\rho)^2}{\rho^2 \nu^3} A [E(x, h)/T] \\ &= 5.92 \times 10^{-3} \frac{A}{\nu} \left[E(x, h)/T \right] \text{ mw}/\text{cm}^2 \end{aligned} \quad (\text{A-9})$$

If we assume $\bar{E}^* = \bar{E}$ for Pm^{147} and use the values of 223 Kev and 60.54 Kev for E_0 and $\bar{E}$ respectively, Equations A-2, 3, and 8 yield the following constants for Pm^{147} .

$$c = 3.52$$

$$\mu/\rho = \nu = 163 \text{ cm}^2/\text{gm}$$

$$k = 0.766 \text{ Kev}/\text{dis.}$$

Curves of $P(\infty, h)$ calculated from Equations A-5 and 6 are given in Figure 2. A curve of $\frac{P(x, h)}{P(\infty, h)}$ for $h = 6.14 \text{ mg}/\text{cm}^2$ is given in Figure 3 for absorption in silicon ($\rho = 2.4 \text{ gm}/\text{cm}^3$). Figure 2 gives the source efficiency as a function of source thickness.

APPENDIX B

PERFORMANCE OF EXPERIMENTAL BETAVOLTAIC BATTERIES

Although less than a year of life data is available on the experimental betavoltaic batteries made by Battelle Memorial Institute,^{7, 19} some observations can be made. Unfortunately, the early data (approximately the first 3 month's data), except for short circuit current, are of no value for comparative purposes, because the temperature of the batteries was neither controlled nor recorded (the temperature dependence was previously discussed and shown in Figure 7). Comparison of the short circuit current is very difficult, because the early data reported by Barnes, et al.^{7, 19} was taken with a digital voltmeter giving one significant figure below 10 mv and two between 10 and 100 mv. The data given by the battery characteristic curves taken with a transistor curve tracer (erroneously referred to by Barnes, et al.^{7, 19} as dark current characteristic curves) should give good short circuit current data; however, the curve tracer was poorly adjusted, giving a significant separation of the curve near zero volts. Further, these data were not dated.

Starting February 12, 1965, Sandia has been periodically taking data (using a curve tracer) on all cells at 100°F for comparative purposes. Figure B-1 shows changes in the current-voltage characteristics that are typical of the cells of the 24 batteries on which data are being taken. The voltage of the cell shown in Figure B-1 is the highest of any cell in the group, for comparable short circuit currents, but the changes shown are typical.

Two phenomena, neither of which is understood, are shown in Figure B-1.

1. The short circuit current appears to be decreasing less rapidly than would be predicted by the half-life of Pm^{147} . This is not well established at this time due to the limits of the accuracy of the data. In some cells there appeared to be an increase in the short circuit current in the first month or so after battery fabrication; however, again the accuracy of the data is not sufficient to be certain. In any case, the small change in the short circuit current density indicates that little if any radiation damage (resulting in a reduced diffusion length) to the solar cells has occurred.
2. The open circuit voltage is decreasing more rapidly than would be expected from the observed decrease in the short circuit current. This phenomenon is seen to exist essentially on all cells.

Comparison of the observed short circuit currents with the theoretically expected value (previously estimated $48 \mu\text{amp}/\text{cm}^2$ for 2 curies) is difficult, because of the large and unexplained spread in the observed short circuit currents ($11 \mu\text{amp}/\text{cm}^2$ to $38 \mu\text{amp}/\text{cm}^2$ for 2 curies). Table B-I shows the expected efficiencies and ratios of short circuit currents for sources of 2.0, 4.0, and 8.0 curies/ cm^2 made of material having a specific activity of 750 curies/gm.

Figure B-1. Change in Betavoltaic Cell Output Characteristic with Time

TABLE B-I

Betavoltaic Cell Outputs Dependence on Source Activity

Source			Number of Cells Observed	Cell Short Circuit Current		Activity Ratio Taken	Ratio		
Activity (curie/cm ²)	Thickness* (mg/cm ²)	Efficiency**		Experimental	Adjusted†		Theoretical	Observed	Adjusted
2.0	2.67	0.320	42	25	28	4:2	1.54	1.84	1.57
4.0	5.34	0.247	4	46	44	8:4	1.32	1.22	1.30
8.0	10.67	0.167	2	56	57	8:2	2.04	2.24	2.04

*The source thickness was calculated using a specific activity of 750 curies/gm.

**The efficiencies were taken from the curve of Figure 2.

†These are the currents adjusted to give ratios of better agreement with the theoretical ratios (see text).

The average short circuit currents observed (curve tracer data of Barnes¹⁹) for each of the three source strengths as well as their ratios are also shown in Table B-I. If the short circuit current for 2 curies is taken as $28 \mu\text{amp}/\text{cm}^2$ (16 of the 42 cells showed $28 \mu\text{amp}/\text{cm}^2$ or higher), the ratios shown are in good agreement with the predicted ratios (adjustment to 44 and $57 \mu\text{amp}/\text{cm}^2$ for 4 and 8 curies, respectively, are within the accuracy of the data). The absolute values of the short circuit current are about 40 percent lower than expected. This could be, in part, due to much more hydration of the sources than expected. Hydration could also contribute to the large spread in observed short circuit currents. However, it is not believed that hydration will account entirely for either of these.

Data will be accumulated periodically on the 24 batteries (48 cells) until 2 or more years of comparative data are available on the Pm^{147} -silicon betavoltaic batteries.

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