Promethium-147 betavoltaic battery model to power micro sensors

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1. Introduction

New energy sources are being developed and improved for various applications. Among them, nuclear batteries are devices that use radioactive decay to generate electricity. The focus of these devices is to provide reliable energy in environments where maintenance is complicated/impossible such as space exploration, oil extraction, and even in a hearth pacemaker. There are many nuclear batteries types: thermoelectric, thermophotoelectric, direct charge, thermionic, mediated by scintillation, direct energy conversion, alphavoltaic, and betavoltaic [1].

In 1953, Paul Rappaport proposed the use of semiconductor materials to convert beta decay energy into electricity. Beta particles emitted by a radioactive source ionize atoms in a semiconductor, creating decompensated charge carriers. In the presence of an electric field of a pn structure, charges flow in one direction, resulting in an electric current. Batteries powered by beta decay became known as betavoltaics. [2].

Radioactive isotopes used in nuclear batteries have a half-life ranging from tens to hundreds of years, resulting in almost constant power. Unfortunately, the power density of betavoltaic cells is significantly lower than that of their galvanic counterparts. Despite this, betavoltaic began to be used in the 1970s in electronic circuits that demand little load [2].

Interest in the use of betavoltaic batteries has grown substantially in recent years due to the prospects for use in microelectromechanical systems (MEMS). New generation MEMS and semiconductor devices require short-term power supplies and long operating times [3]. Often these devices are installed in places where maintenance is difficult or when data is necessary even with a power shortage, such as space operations, seabed exploration, sensors in nuclear reactors, and the removal of oil in the sea at the pre-salt layer [4-6].

Today, several models of betavoltaic microbattery based on different semiconductor materials and different radioactive sources are being investigated. Is very important to study the characteristics and develop prototypes using multiple radioisotopes due to the fact that most isotopes used in this field are difficult to produce, purify, and few contain the necessary properties for its use [7].

Pm^{147} is an ideal candidate for use in nuclear batteries due to its favorable power density (15 μW/cm^2 from Pm_2O_3) and low biological hazard as a result of the emission of very few low-energy gamma photons [8]. Pm^{147} is mainly produced by nuclear activation of highly enriched targets of the parent nucleus Nd^{146} following:

$$Nd^{146}\ [n,\gamma] \rightarrow Nd^{147} \xrightarrow[10.98\ d\ \ \beta^-]{} Pm^{147} \quad (1)$$

Pm^{147} decay is:

$$Pm^{147} \xrightarrow[2.6\ y\ \ \beta^-]{} Sm^{147} \xrightarrow[10^{11}\ y\ \ \alpha]{} Nd^{143} \quad (2)$$

The objective of this work is to create an MCNP® routine to correlate the source thickness with particle number/deposited energy equilibrium. The more radioactive material is added, higher the source thickness will be. The thicker the source is, more beta particles will interact with the source material itself, thus not supplying these electrons to power generation. So, there is a maximum amount (thickness) that can be added due to self-absorption. Knowing this amount will allow posterior power estimates and correct prototype design.

2. Methodology

The radiation quantification was performed by MCNP6® Monte Carlo Code. MCNP6® is a general-purpose, continuous-energy, generalized- geometry, time-dependent, Monte Carlo radiation-transport code designed to track many particle types over broad ranges of energies. The code was developed by Los Alamos National Laboratory, USA. Figures 1 and 2 show the geometries used in the program imput.

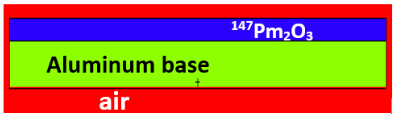

Fig. 1: Imput geometry. Surface area is 10x10 cm, the backing aluminum base has 0.01 cm. Source size varied.

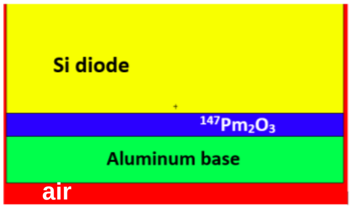

Fig. 2: Imput geometry. Same dimensions of figure 1, but now with a Si diode as the transducer.

Tally f2 (flow of particles through a surface) was used to calculate the number of particles flowing through the source top surface area. Tally f6 was used to calculate the energy deposited in a silicon layer (possible diode transducer). Pm^{147} beta decay spectrum was obtained in ICRP Decdata program. The energy bin function was used so a spectrum can be obtained in the response. The results are independent of source activity (graphs would taller in the y-axis, but have same shape, and same x-axis behavior).

3. Results

3.1 Flow of particles

Figure 3 shows the results the spectrum results for each energy bin (amount of particles that are generated for that specific energy). Figure 4 shows the total results for each thickness.

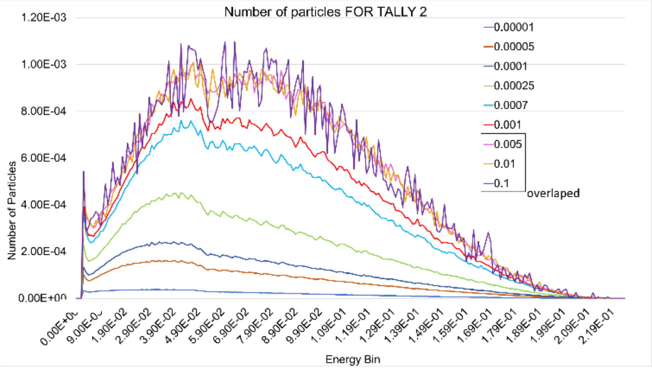

Fig. 3: Number of particles generated for each energy bin. From 0.005 cm, the number of particles overlap.

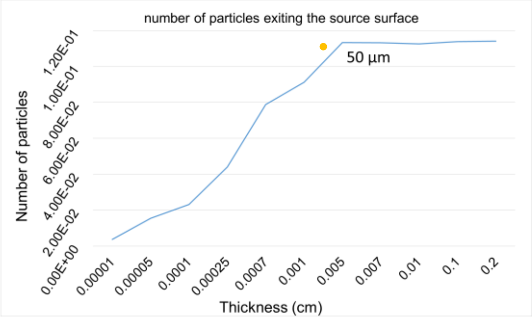

Fig. 4: Total number of particles x source thickness. From 0.005 cm, the total number of particles reached a plato.

3.2 Deposited Energy

Figure 5 shows the results the energy deposited results for each energy bin.

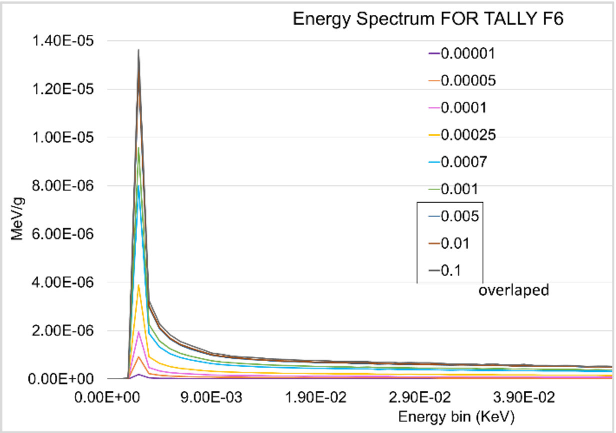

Fig. 5: Energy deposited in silicon for each energy bin. From 0.005 cm, the amount of energy deposited overlap.

Figure 6 shows the total results for each thickness.

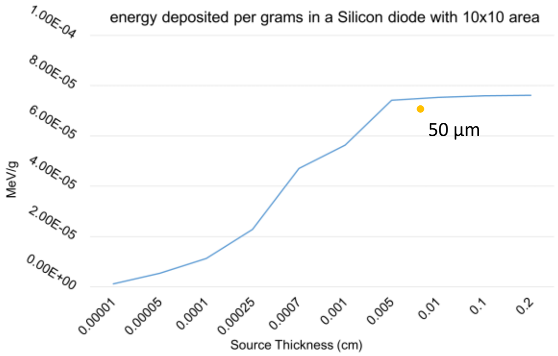

Figure 6: Total amount of deposited energy x source thickness. From 0.005 cm, the total number of particles reached a plato.

4. Discussion

The results clearly show that the 0.005 cm source thickness will provide the most particles with the lesser amount of material and thus deposit more energy in silicon. This effect happens due to the increase of self-absorption. In other words, more material results in more thickness. More thickness increases the probability of the emitted beta particle will interact with the atoms of the source itself never reaching the transducer thus not contributing to power generation (figure 7).

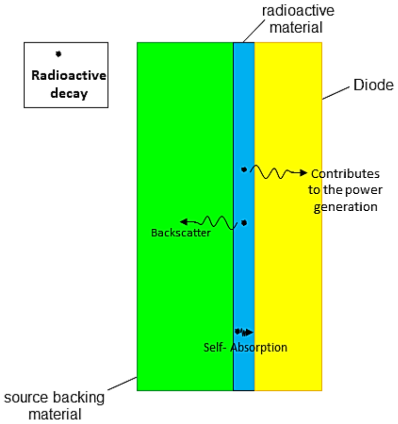

Figure 7: Electrons tracks in the battery model.

5. Conclusion

This work presented study that used MCNP® to model a betavoltaic Pm^{147} battery. The simulations discovered that 0.005 cm source thickness is ideal to generate the largest amount of power with little material as possible. This preliminary test is important because it gives a real estimate of how much material will needed to be used to generate the largest final power output.

REFERENCES

[1] Prelas, M.A., et al., *Nuclear Batteries and Radioisotopes*. 2016, Switzerland: Springer International Publishing.

[2] Prelas, M.A., et al., *A review of nuclear batteries.* Progress in Nuclear Energy, 2014. **75**: p. 117-148.

[3] Bykov, A.S., et al., *Application of Radioactive Isotopes for Beta-Voltaic Generators.* Russian Microelectronics, 2017. **46**(8): p. 527-539.

[4] Oregon State University - College of Engineering. *Radioisotopes Powering Undersea Research*. 2017 [cited 2019 15 May].

[5] Summerer, L. and K. Stephenson, *Nuclear Power Sources: A Key Enabling Technology for Planetary Exploration.* Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2011. **225**(2): p. 129-143.

[6] Bass, J.C. and D.T. Allen. *Milliwatt radioisotope power supply for space applications*. in *Eighteenth International Conference on Thermoelectrics. Proceedings, ICT'99 (Cat. No.99TH8407)*. 1999.

[7] Broderick, K., et al., *Reactor production of promethium-147.* Applied Radiation and Isotopes, 2019. **144**: p. 54-63.

[8] Hinderer, J.H., *Radioisotopic Impurities in Promethium-147 Produced at the ORNL High Flux Isotope Reactor*. 2010, University of Tennessee: https://trace.tennessee.edu/utk_gradthes/717.