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Energy Analysis of Nuclear Batteries Based on Different Radioisotopes

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1. Introduction

Electric energy is essential for powering the various devices used in various human activities, such as cell phones, equipment in hospitals, pacemakers [1] or space exploration [1-10].

In space exploration, if we used conventional electronic batteries, their replacement would be unfeasible, Thus, the use of nuclear batteries has become crucial.

When making a comparison between nuclear and chemical batteries, the amount of energy produced by a nuclear battery is much greater. For example, a Lithium-Ion chemical battery generates 460 J/g and a ^{238}Pu nuclear battery can generate up to $2.19.10^9$ J/g [1].

There is an RTG (Radioisotope thermoelectric generator) model that was used in the Voyager Sonda, which contains ^{238}Pu and is in interstellar space, 17.3 billion km from the Sun. We have an RTG battery in the Curiosity robot on Mars, which can keep it in operation for 14 years [1-10].

One of the main requirements for using radioisotopes as an energy source is that they have a storage energy above 2.10^9 J/g and a long half-life.

The energy source for this type of battery is radioactive alpha decay, and it is possible to calculate the emitted power over its half-life.

Radioisotopes with these characteristics can be produced in nuclear reactors or in particle accelerators [1,11]. Among the radioisotopes that meet these conditions, ^{238}Pu is the most used in the construction of nuclear batteries [1-10]. The ^{238}Pu has a half-life of 87.7 years and a storage power of at least $2.19.10^9$ J/g. However, there are other radioisotopes that have been proposed that also meet these conditions and that can be used for nuclear batteries, such as ^{241}Am and ^{232}U [1]. The ^{241}Am can be produced from the ^{238}U fuel cycle as well as the ^{238}Pu. On the other hand, in the fuel cycle of ^{232}Th as a fertile material, one of the main candidates is ^{232}U, which has similar characteristics to ^{238}Pu.

The mechanism for enabling the conversion of heat into electrical energy is the Seebeck effect [1,9], which consists of a closed electrical circuit built with the junction of thermocouple conductors (different materials), where part of this material comes into contact with the source of heat and another part comes into contact with a cold surface, generating a thermal gradient.

As an example, using ^{238}Pu in a battery in space, there is a heat source with temperatures ranging between 50°C and 125°C and external temperatures in a vacuum of up to -272°C [4].

Some RTG battery models: GPHS (General purpose heat source) RTG-290 watts-^{238}Pu-USA; MMRTG (Multi Mission RTG) – 110 watts-^{238}Pu – USA; RTG-^{210}Po – Russia; RTG-^{241}Am – United Kingdom [1,3,9].

This presentation will perform an energy analysis of the entire system that involves the heat source and thermal energy to the converter for electrical energy. This study aims to analyze the energy production process from different radioactive sources, and to evaluate the conversion processes in the system and its efficiency. The system model will be designed in Matlab/Simulink, in which the energy conversion equations and processes in the system will be described. To simulate the decay heat generated by each of the sources used over time, the nuclear code ORIGEN2.1 [12,13] will be used.

With the use of ORIGEN2.1, it will be possible to evaluate the amount of radionuclides that will undergo the decay process in the sample. It will also allow us to follow the concentrations of these radioisotopes in the sample over time. It is also possible to obtain data on the radioactivity and thermal power generated, data that will be compared and used in this work.

2. Methodology

2.1-Thermocouple-Seebeck Effect

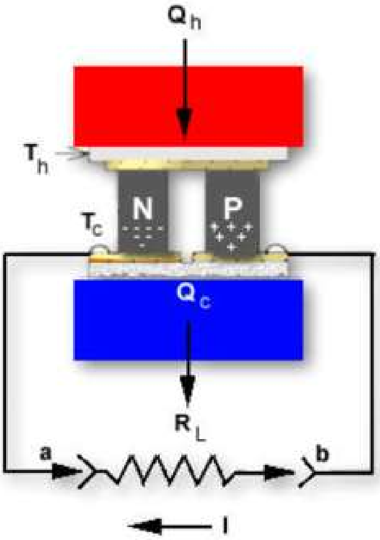

Figure 1 - System overview - reference [13]

The Matlab/Simulink program will be used to describe the equations below:

$$V = S \cdot DT \tag{1}$$

$$I = \frac{S \cdot DT}{(Rc + RL)} = \frac{V}{(Rc + RL)} \tag{2}$$

$$Qh = (S \cdot Th \cdot I) - (0{,}5 \cdot I^2 \cdot Rc) + (Kc \cdot DT) \tag{3}$$

Where:
V - Generator module output voltage
S – Average Seebeck Coefficient in volts/°C
DT – Thermocouple temperature difference, where DT = Th – Tc, where Th is temperature in the hot part and Tc temperature in the cold part.
I - output current in amperes
Rc - internal resistance of the thermocouple set in ohms
RL - load resistance in ohms
Qh – input heat in thermal watts
Kc - thermal conductance of the circuit

2.2-Heat source - Decay of radioactive materials

The formulas and tables below will be demonstrated in the MATLAB/SIMULINK and ORIGEN2.1 computer programs:

Nuclide	Energy od Decay (MeV)	Half-Life (Years)	Type of decay	Power (mW/g)
U-232	5,414	68,9	Alpha	700,088
Pu-238	5,593	87,74	Alpha	555,587
Am-241	5,638	432,2	Alpha	108,573

Table 1: technical information about some radionuclides - reference [1]

$$\mathrm{Qo} = \mathrm{Qh} \tag{4}$$

$$\mathrm{Q(t)} = \mathrm{Qo} \cdot \mathrm{e}^{-\lambda \cdot \mathrm{t}} \tag{5}$$

2.3-Generator Efficiency:

The formulas and tables below will be demonstrated in the MATLAB/SIMULINK program:

$$\mathrm{Eg} = \frac{V \cdot \mathrm{I}}{Qh} \tag{6}$$

3. Expected results

A complete analysis of the entire energy generation chain is expected, from the thermal energy generated by the alpha decay of the chosen radioisotopes to the conversion of this thermal into electrical energy, performed by the Seebeck effect module [1,9] using the program computational MATLAB/SIMULINK.

Also demonstrated that the addition of modules with Seebeck devices increases the electrical power generated and improves the efficiency of the conversion of thermal energy to electrical energy [14]

Also, they demonstrate, through the computer program ORIGEN2.1, the heat generated by the radioactive alpha decay of each analyzed radioisotope, as well as the heat generated by the materials generated in this decay [12,13]

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