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How does radioisotope thermoelectric generator (RTG) work

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ABSTRACT

Demand for energy has increasing rapidly in the last decade. In 2021 an increase in 5% was observed. Half of this demand was covered by fossil fuels, increasing CO_2 emissions to record levels. With the need for new reliable steady supply sources to be used in places where maintenance is difficult, Radioisotope Thermoelectric Generators (RTG) have been given renewed attention in the past 10 years. RTGs uses radioactive decay to generate electricity. This work presents in a simple manner, the basics of RTG operation, the requirements for construction, and is followed by an example developed at Korea Atomic Energy Research Institute (KAERI). Basic Radiation Physics Concepts, RTG configuration requirements, Thermoelectric effect and materials, and calculations for electric power were presented.

Keywords: **radioisotope thermoelectric generator, RTG, nuclear battery.**

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1. INTRODUCTION

Demand for energy has increasing rapidly in the last decade. Just in 2021 an increase in 5% was observed. Half of this demand was covered by fossil fuels, increasing CO_2 emissions to record levels [1]. Energy is crucial for the advancement of mankind. They allow, for example, real time communication, faster goods transport, medical equipment use and development, scientific research, and heating and cooling systems to work. Demand for energy is different for each category. New sources with reliable steady supply in places where maintenance is difficult are in high demand, such as space exploration. Within this scenario, the Radioisotope Thermoelectric Generators (RTG) meet the criteria for self-sustaining power generation.

RTG's use radioactive decay to generate power. They are a class known as nuclear batteries. Among them there are other types such as thermoelectric, thermophotoelectric, direct charge, thermionic, scintillation-mediated, direct energy conversion, alpha-voltaic, and beta-voltaic. By far, the thermoelectric type (RTG) has received the most attention due to its application in space missions.

The first radioactive electric device was invented in 1913 by the English physicist Henry Moseley. He used a Radium-226 source mounted in the center of a silvery glass sphere and an insulated electrode. Electrons generated by Radium-226 β decay caused a potential difference resulting in the generation of electric current. This current, however, was too low for practical applications. [2; 3].

The first RTG was developed in the US in the late 1950s by the Mound Laboratory, under contract with the United States Atomic Energy Commission (USAEC) [3; 4]. In the early 1970s, the use of RTGs became popular in pacemakers used in patients with heart disease [5; 6]. These devices, produced by the hundreds in the United States and France, used two types of radioisotopes: Plutonium-238 and Promethium-147 [6]. It is estimated that between 1976 and 1990, around 1000 RTGs were used by the Russian government, mainly to power navigational beacons [7].

The first RTG launched into space was SNAP 3B (US Navy, Transit 4A) in 1961, powered by 96 grams of Plutonium-238. This generator has provided about 2.7W of power for over 15 years [8]. Since then, RTGs have been used successfully in space missions, with operating times much longer than those initially conceived [8; 9]. All major space agencies in the world (such as NASA-National Aeronautics and Space Administration, ESA-European Space Agency, Roscosmos-Russian Space

Agency, and Kasi – Korea Astronomy and Space Science Institute) continue to develop new nuclear systems for space exploration. [8].

This work presents the fundamentals of RTG construction followed by a practical example of the device being developed at the Korean Atomic Energy Research Institute.

2. RTG BASIC CONCEPTS

Basic Concepts

When an atomic nucleus has excess energy, that energy can be emitted as radiation. The emitting atom is called a radioactive, radioisotope, or radionuclide. It is identified by the type of atom (atomic symbol Z or atom name) and mass number (A). The nomenclature used can be varied: A-atom name, atom name-A, Z^A, or ^AZ [10]. The emitting atom is also called the parent nucleus and the atom formed after decay is called the daughter nucleus. It is worth remembering that an object that receives radiation only becomes radioactive when subjected to a flow of neutrons from a nuclear reactor or when placed in a particle accelerator. In other words, radioactive sources do not make materials they come in contact turn radioactive (except artificially produced high neutron emission sources in materials with high activation cross section). But materials that have received radiation can undergo chemical and physical changes, resulting in structural modifications. Most of the energy from radioactive decay is dissipated as heat.

When the atom emits radiation (a process called radioactive decay) energy can be emitted in the form of electromagnetic radiation and/or in the form of particles. The unit commonly used is the electron volt ($1{,}06 \times 10^{-19}$ J) [10].

Radioactive activity, A(t), is defined as the number of radioactive decays/second. The official unit is Becquerel (Bq). However, the Curie unit (Ci) is the most used by scientists. The conversion is: 1 Ci = $3{,}70 \times 10^{10}$ Bq [10]. The mathematical law that rules the decay is presented in eq.(1).

$$A(t) = A_{initial} \cdot e^{-\lambda t} \tag{1}$$

where t is time and λ is the decay constant ($time^{-1}$).

The decay constant is calculated from the half-life. Half-life ($T_{1/2}$) is the time it takes for half of the radioactive nuclei in any sample to radioactively decay. After two half-lives, there will be a quarter of the original sample, after three half-lives, one-eighth of the original sample, and so on [10]. The mathematical law that rules for the decay constant is presented in eq.(2).

$$\lambda = \frac{\ln 2}{T_{1/2}} \tag{2}$$

The main advantage of RTGs is that the durability of the device is directly linked to the half-life of the radioisotope used. For example, a battery with an Americium-241 source (being studied as a potential battery source by the ESA [11; 12]) has a half-life of 432.6 years! Imagine a battery with that shelf-life!

While the potential is great, RTGs have 3 main drawbacks:

- low efficiency (typically between 3% and 8%) – (this can be solved by stacking multiple mini battery systems);
- Weight is directly proportional to power. The size of MMRTGs used in space is approximately 45 kg mass, 0.66 m long, 0.63 m diameter [13] – (this can be partially minimized by improving thermal conversion or using energy accumulators);
- High costs and care during manufacturing – (requires a highly specialized and trained team).

Typically, in RTGs, alpha or beta emissions are used. This is because particles have low power to penetrate matter (when compared to gamma-rays and X-rays) depositing their energy in a few millimeters/centimeters of the decay site. In the case of RTGs, the ideal is that the energy is deposited in the thermoelectric material, which will convert heat to electric current. In this case, the material tolerance for radiation must also be calculated (see ref. [14]).

Alpha emission, alpha disintegration, or alpha decay is the method by which an unstable nucleus emits an alpha particle (which is equivalent to the nucleus of a Helium atom - 2 protons and 2 neutrons) to stabilize. Alpha emitters are located in the upper end portion of the radioactive elements table shown in Figure 2 [10]. Beta emission, beta disintegration, or beta decay occurs when an unstable nucleus convert into another by emitting a beta particle. In β^-decay, a neutron is converted into a proton emitting an electron and an antineutrino (neutrino antiparticle). Alpha emitters are located in

the top upper part at the table of radioactive elements while beta emitters are at the bottom of the stable elements row (Figure 2). [10].

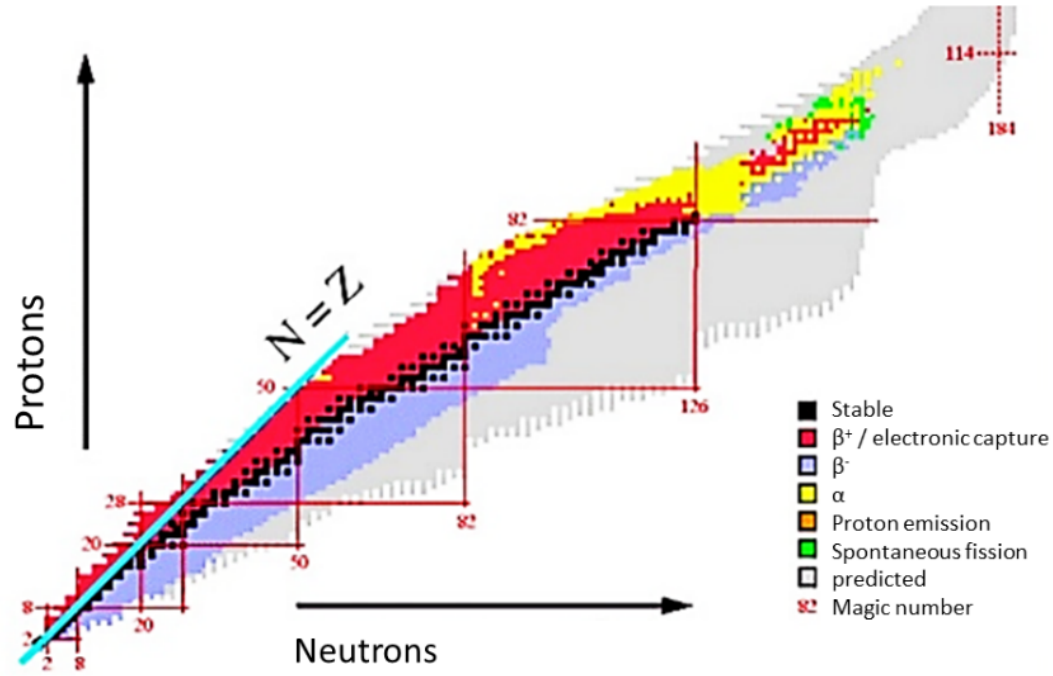

Figure 2: *Radioactive elements table. The black line is where stable isotopes are located. Yellow part is the alpha emitters, and the dark gray part, the beta emitters. Adapted from [15; 16].*

Considering the basic concepts, the basic scheme of an RTG operation can be seen in figure 1.

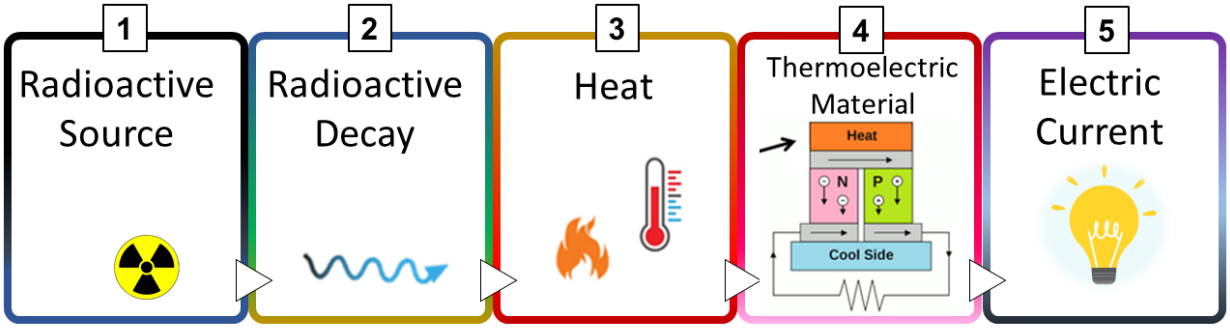

Figure 1: *The step by step of the operation of an RTG. 1) Radioactive Source; 2) Particles and heat emitted in the decay; 3) Use of the released heat; 4) Thermoelectric material; 5) Generation of electric current.*

① *Radioactive Source*

The choice of isotope must consider several conditions that are mainly dictated by the end use of the RTG device. They depend on:

- Achieving a good match in the transducer. That means the emission range should be such that radiation deposit its energy within or as close as possible to the transduce;
- The battery life depends directly on the isotope's half-life, as long as radiation damage in the transducer minimized;
- The energy emitted by radiation, which, together with radioactivity, stipulates effective power;
- The control of the selected isotope supply chain or production. If the isotope is produced naturally as part of the Uranium-238, Uranium-235, or Thorium-232 decay chain, it is easily found, although high amounts can be consumed on purification. If the isotope is a by-product of fission, then it can be recovered by reprocessing spent nuclear fuel. If the isotope needs to be produced in a nuclear reactor or accelerators, high cost enriched targets might be necessary;
- All forms of radiation being emitted by the isotope and its daughter isotope. For example, gamma rays are highly penetrating and therefore require shielding. Shielding may compromise equipment portability [2; 17].

② *Radioactive decay and configurations*

There are many configurations of RTGs, each device having a different combination of fuel (isotope), insulator, contact spacers, and thermoelectric materials. However, the basic geometric arrangement of the main internal components is very similar.

All RTGs are composed of one or several cells that operate to produce the desired voltage and current. Each RTG cell is composed of a capsule of radioactive material coated with a high melting temperature material, one or more thermoelectric elements, thermal insulators, and spacers.

The decay of radioactive material emits particles (alpha or beta) with high kinetic energy. These particles are stopped almost entirely in the radioactive material itself, or in its encapsulation. Most of

the kinetic energy of particles is transformed into heat. This heat generated in the radioactive material capsule is transferred by conduction or convection (depending on the design of the RTG), to the thermoelectric elements and then to the external environment.

③ *Thermoelectric effect*

Thermoelectric materials, when in contact and in the presence of a temperature gradient, produce an electrical voltage called the Seebeck Voltage (Figure 3). When two metallic conductors, materials 1 and 2 in Figure 3, of different natures are coupled and a temperature gradient is present, electrons tend to migrate from one conductor to the other, generating an electrical potential difference in an effect similar to an electrochemical cell. This effect is known as the Seebeck Effect. The resulting electromotive force is directly proportional to the temperature difference between the hot and cold sides and to the physical properties of the materials [18].

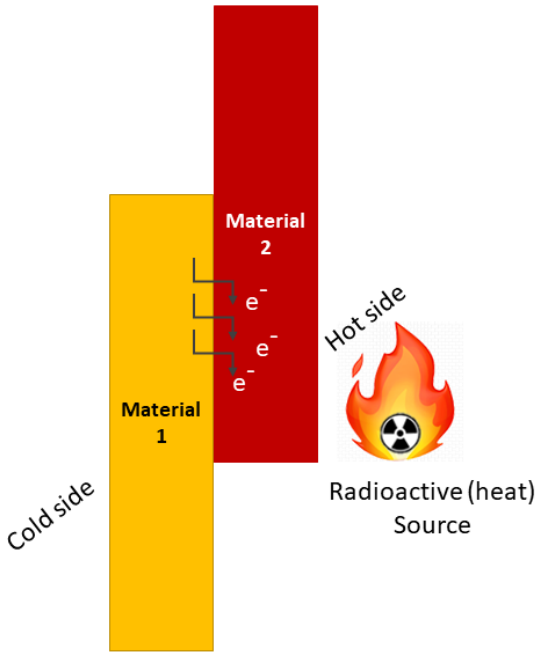

Figure 3: *Seebeck Effect.*

The Seebeck effect is the opposite of the Peltier effect. The first uses heat to generate electrical current, the second uses electrical current to generate heat. The efficiency of thermoelectric

conversion by the Seebeck effect is very low, typically between 3% and 8%, reaching 10% in rare cases [19].

After crossing the thermoelectric elements, the heat is transferred to the outer casing, which often has fins to dissipate unused heat to the external environment through irradiation and/or convection. Thermoelectric elements are usually arranged on the sides of the capsule that contains the radioactive material. One of its sides is in contact with the "hot" source (capsule of radioactive material) and the other side is facing the "cold" side. There must be a temperature difference between the two sides of the thermoelectric elements so that the heat can be transformed into electric current. In principle, the greater the temperature difference between the sides, the greater the efficiency [19].

As the operation depends on the heat flow, the heat generated by the radioactive material must be removed from the device as efficiently as possible. Any amount of heat generated by the radioactive material that does not pass through the thermoelectric elements is wasted energy that contributes to lowering the efficiency of the device. Thus, the design of an RTG must be optimized to ensure that most of the heat generated is used by thermoelectric elements and that the temperature difference between the hot and cold sides is suitable for the material used [19].

Thermal insulation is used to reduce heat loss from sides that are not in direct contact with the thermoelectric elements. In some RTG designs, thermal insulation is also used to increase heat flow to the target area (where thermoelectric materials are placed). Some sides of the material capsule are thermally insulated to concentrate heat and maximize flow [19].

④ *Thermoelectric materials*

There are several combinations of materials that can be used as thermoelectric elements. Each combination of materials has a temperature condition for which the thermoelectric conversion is most efficient.

A good thermoelectric material should have a thermoelectric junction that has [20]:

- high electrical and thermal conductivity to minimize electrical and energy losses;
- high ductility, to be mechanically machined in different thicknesses;
- chemical and thermal stability to withstand high temperatures, possible thermal shocks, and inhibit solid-state reactions;

- minimum electrical resistance in the contact region;
- chemically and physically stable under operating conditions.

The most commonly used thermoelectric materials are bismuth telluride (BiTe), lead telluride (PbTe), antimony, germanium, silver telluride (TAGS), lead-tin telluride (PbSnTe) and silicon germanium (SiGe) [20]. All these materials were used in space missions inside RTGs. Various materials are still being investigated with the aim of producing higher efficiency, low weight power systems with stable performance and long duration (minimizing the influence of radiation damage) [4].

⑤ *Electric power*

Table 1 shows the calculated results of an RTG designed with 5% efficiency to generate 60 electrical Watts (We) of electrical energy. Results are shown for 5 different isotopes (commonly used/considered for RTG).

Table 1: Properties for 5 different radioisotopes for an RTG with 60 We at 5% efficiency [21; 22].

Material	$T_{1/2}$ (year)	Emitted particle	Specific power (W_t/g)	Radio isotope mass (kg)	Radioactive Activity (kCi)	Specific Final Power (W_t/g)
$^{238}PuO_2$	87,7	α	0,56	2,142	36,73	0,4936
$^{90}SrTiO_3$	28,8	β^-	0,95	1,263	174,53	0,4597
$^{241}Am_2O_3$	432,6	α	0,11	10,909	37,43	0,1000
$^{3}H_2O$	12,32	β^-	0,36	33,333	32096,64	0,0986
^{63}NiO	101,2	β^-	0,002	600	33708,95	0,0016

* We = Watts electric; Wt = Watts Thermal

The final specific potency was calculated by eq. (3):

$$\bar{P} = \bar{A} \cdot \varepsilon \tag{3}$$

where $\overline{\mathrm{P}}$ is the Specific Final Power (W/g); $\overline{\mathrm{A}}$ is specific activity (decays/g.s); and ε: Average energy released by decay (J).

This equation can be rewritten as a function of the half-life, as shown in eq. (4):

$$\bar{P} = \bar{A} \cdot \varepsilon = N \cdot \lambda \cdot \varepsilon = N \cdot \frac{ln2}{T_{1/2}} \cdot \varepsilon \tag{4}$$

where N is the Number of radioactive atoms per gram of material; $\mathrm{T}_{1/2}$ is Half-life (s); and λ decay constant (s^{-1}). N can be calculated by eq. (5):

$$N = \frac{m}{Mol} \cdot N_0 \tag{5}$$

where m = 1 g; Mol is the molar mass; and N_0 is Avogadro's number. Re-writing eq. (4) in function of N is equal to eq. (6):

$$\overline{\mathrm{P}} = \frac{\mathrm{m}}{Mol} \cdot \mathrm{N}_0 \cdot \frac{ln2}{\mathrm{T}_{1/2}} \cdot \varepsilon \tag{6}$$

3. EXAMPLE OF RTG

The step-by-step of a RTG project is detailed in figure 4.

Our project in Korea Atomic Energy Research Institute (KAERI) is for a Strontium-90 RTG is part of the Korean Space Program. Several models are being developed, from 20 – 200 We. For this project, Strontium-90 was selected due to its long half-life. An international agreement with Rosatom was signed for the supply of the isotope, The necessary space for the device was selected in the Korean Launch vehicle (NURI). Maintenance will be impossible in space, so redundant systems were installed. PbTe was selected due to its radiation resistance. Heat transfer was performed using AN-SYS (Analysis System, a 3D software used in design) and Monte Carlo codes were uses in power, radiation damage, and shielding simulation. Leakage and physical tests were performed in excellence

institutes in Korea. A prototype is already being tested. Figure 5 shows the device geometry and the heat simulation results [23].

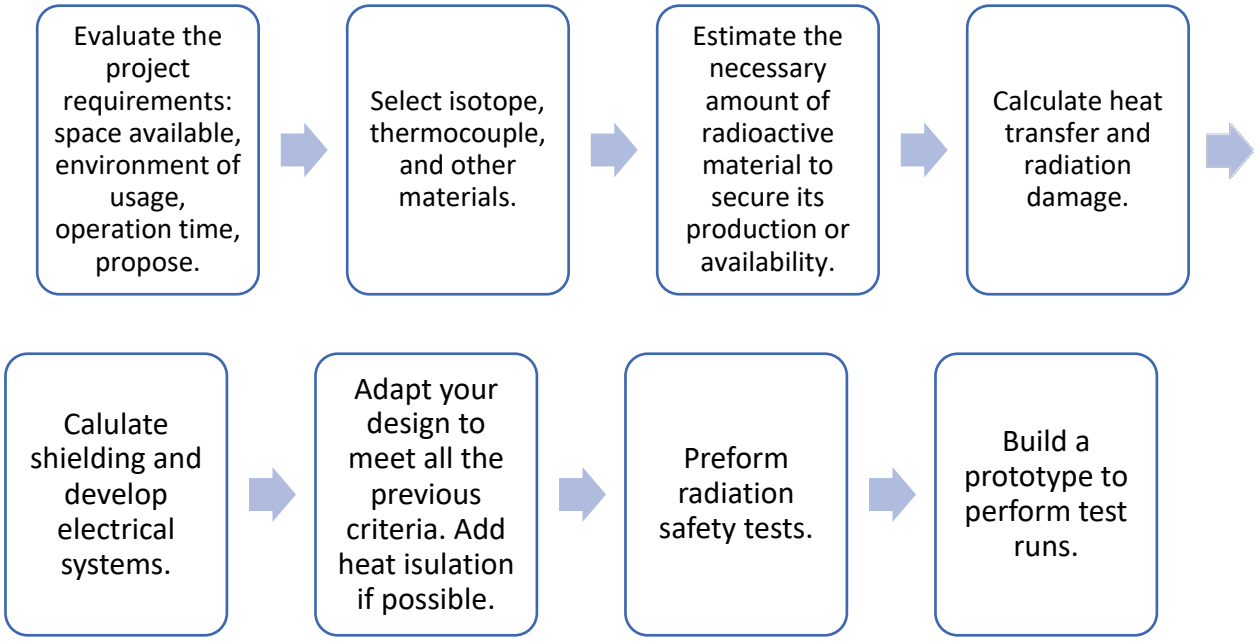

Figure 4: The step-by-step development of a RTG project.

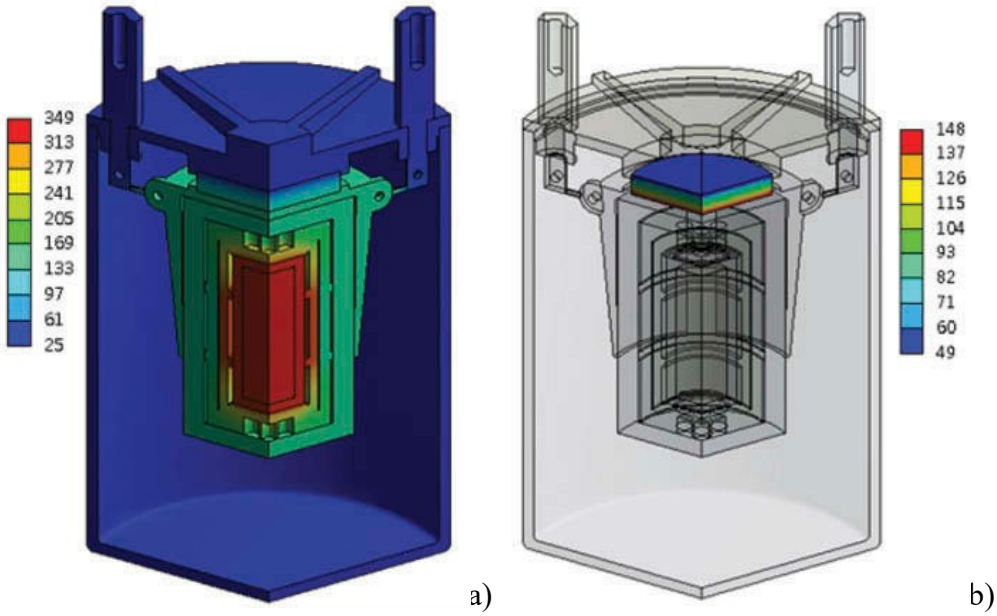

Figure 5: Device geometry and the heat simulation results for KAERI RTG. A) whole device; b) Thermoelectric model heat profile.

Next, a calculation example for the estimation of the necessary amount of radioactive material is shown. Strontium-90 is a pure beta emissor with E_{avr} = 195.8 keV (3.1369x10^{-14} J) and E_{max} = 545.9 keV. Its molar mass is 89.9077 g/mol, half-life is $T_{1/2}$ = 28.79 years. Calculating $\overline{P}$:

$$\overline{P} = \frac{m}{Mol} \cdot N_0 \cdot \frac{ln2}{T_{\frac{1}{2}}} \cdot \varepsilon = \frac{1}{89.91} \cdot 6.023x10^{23} \cdot \frac{ln2}{9.08x10^{8}} \cdot 3.14x10^{-14}$$

$$\overline{P} = 0.16\ Wt/g$$

Strontium-90 decays to Yttrium-90, that also decays by beta emission, accompanied by gamma rays and x-rays (at very low probabilities: 10^{-6} to 10^{-3}%). Beta energies are E_{avr} = 933.7 keV and E_{max} = 2280.1 keV. Yttrium-90 decay also contributes for energy generation. Since Strontium-90 (A_1, $T_{1/2}$ = 28.79 years) half-life is much larger than that of Yttrium-90 (A_2, $T_{1/2}$ = 6.67 days) satisfying the conditions for secular equilibrium [24; 25]. The condition is established when:

$$\mathrm{A}_2 = \mathrm{A}_1 \Rightarrow \mathrm{A}_2 = N_1 \cdot \lambda_1 \Rightarrow \mathrm{A}_2 = \left(\frac{\mathrm{m}}{Mol} \cdot \mathrm{N}_0 \cdot \frac{ln2}{\mathrm{T}_{1/2}}\right)_1$$

$$\mathrm{A}_2 = \frac{1}{89.91} \cdot 6.023\mathrm{x}10^{23} \cdot \frac{ln2}{9.08x10^8} \Rightarrow$$

$$\mathrm{A}_2 = 5.11\mathrm{x}10^{12}\,\frac{\mathrm{decay}}{\mathrm{s}} for\ 1g\ of\ Sr^{90}$$

The energy released by Yttrium-90 is:

$$\bar{P}_2 = \overline{\mathrm{A}}_2 \cdot \varepsilon_2 = 5{,}11\mathrm{x}10^{12} \cdot 1{,}49\mathrm{x}10^{-13}$$

$$\bar{P}_2 = 0{,}76\ \mathrm{Wt/g}$$

Final power is then:

$$\overline{\mathrm{P}}_{\mathrm{tot}} = \overline{\mathrm{P}} + \bar{P}_2 = 0{,}16 + 0{,}76$$

$$\overline{\mathrm{P}}_{\mathrm{tot}} = 0{,}92\ \mathrm{Wt/g}$$

Let's assume that this battery would be used to power a 20 We sensor. To establish the mass required for electrical power:

- Total thermoelectric conversion efficiency $\Rightarrow \eta = 5\%$
- Desired electrical energy $\Rightarrow \mathrm{P_{el}} = 20$ W
- Maximum total operating time $\Rightarrow$ T = 27 years
- Decay constant $\Rightarrow \lambda = \frac{ln2}{\mathrm{T}_{1/2}} = 0{,}0241\ \mathrm{years}^{-1}$

Calculating:

$$\mathrm{P_{el}} = \eta \cdot \overline{\mathrm{P}}_{\mathrm{tot}} \cdot M \cdot \mathrm{e}^{-\lambda \cdot T} \Rightarrow M = \frac{\mathrm{P_{el}}}{\eta \cdot \overline{\mathrm{P}}_{\mathrm{tot}}} \cdot \mathrm{e}^{\lambda \cdot T}$$

$$M = \frac{20}{0.05 \cdot 0.92} \cdot \mathrm{e}^{0.0241 \cdot T} \Rightarrow$$

$$M = 432.20 \cdot \mathrm{e}^{0{,}0241 \cdot 27} \Rightarrow 827.94 \text{ g of } Sr^{90}$$

This means that a little less than 1 kg of radioactive material would be needed to supply electrical energy for a 20 W sensor. It's long half-life, thus battery life, make it ideal to be used in environments where maintenance is not possible (such as in space, ocean exploration, etc.).

The research in this area tend to increase in the next year. Besides Korea, ESA is working in their Americium-243 RTG for space exploration and NASA is developing several models including one with a Stirling engine. From new thermoelectric materials to new insulating materials, there are still areas where new discoveries can increase RTG efficiency.

Another relevant fact is that the two main radioisotopes used in the manufacture of RTG (Strontium-90 and Plutonium-238) come from nuclear waste. Both are recovered from the fuel reprocessing process that has already been used in reactors, contributing to the reduction of nuclear liabilities.

4. CONCLUSION

This text presented in a simple and didactic way the basic operation of RTGs, and basic concepts of nuclear physics and thermoelectric conversion. An example Strontium-90 generator was calculated using the concepts presented. Yttrium-90, the daughter isotope of Strontium-90, also contributes to energy generation. In the end, 0.92 Wt/g is reached. To power a 20 We sensor, 827.94 g of radioactive strontium would be needed.

The purpose of decreasing the amount of radioisotope usage is to improve the overall efficiency of the device. This will be the topic that scientists will focus the most attention on in the coming years.

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