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Radioisotope Thermoelectric Generators in Space Exploration

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Abstract:
This research essay will explore the mechanism and performance of radioisotope thermoelectric generators used in spacecrafts, aiming to manifest its validity in the space exploration industry. Data gathered by experts will be utilized to examine its performance, and further compare it with other space power systems. The results indicates that the technology is suitable for powering long-range space missions, and even surpasses new technologies such as advanced Stirling radioisotope generators. Instead of relying on the environment like solar panels, it generates thermal energy using radioactive decay and converts it directly into electricity. Although using thermoelectric effect could lower efficiency, it simplifies the manufacturing process, reducing the cost of its production. This highlights the utility of the technology, and its potential in powering countless more space missions in the future. In the end, the essay will conclude with a summary of main points and the key challenges that lies ahead for radioisotope thermoelectric generators in space exploration.

Keywords: Radioisotope Thermoelectric Generators (RTG); Silicon-Germanium Alloys (SiGe); Seebeck Coefficient; Advanced Stirling Radioisotope Generators (ASRG).

1. Introduction

In the prior century of space exploration, humanity was continuously expanding their exploration of the universe, sending spacecrafts farther into the depth of the cosmos. As missions became longer and distant from sunlight, traditional methods of energy generation are no longer sufficient. Chemical batteries, though highly efficient, its lifetimes are extremely short. Solar energy, while abundant near the sun, it will rapidly diminish as spacecrafts ventures outside of the solar system. Therefore, radioisotope power systems were introduced in 1954, starting with radioisotope thermoelectric generators which was developed by two scientists: Kenneth C. Jordan and John Birden [1].

RTG was developed from the idea of Seebeck effect, where voltage is generated when a temperature gradient is present across a thermoelectric material. It works by converting the heat released from the radioactive decay of radioisotopes into electricity using the thermoelectric effect. For RTGs, the temperature difference exists between the radioactivity and the cold side, which is space [2].

Unlike the heat generation of solar and chemical power systems, the radioactive decay of RTGs creates a consistent power supply, as it does not depend on its environment. Furthermore, Radioactive are also long-lasting and steady as they can span decades and are predictable, making radioisotope power systems superior to other energy sources during that time [3].

In the modern era, radioisotope thermoelectric generators are being incessantly refined as we further advance in science and engineering. Although it was invented decades ago, it still surpasses newer technologies, such advanced Stirling radioisotope generators in terms of reliability and longevity. Therefore, RTGs have powered many imperative space missions, including Voyager 1 and 2, Cassini, Curiosity, and Perseverance [4], enabling us to further unveil the wonders of the universe.

2. Working Principles

2.1 Structure and Components of RTG

Radioisotope thermoelectric generators have a stack of eight general purpose heat source (GPHS) units, as shown in Figure 1, which is where heat is generated using the radioactive decay of plutonium fuel [1].

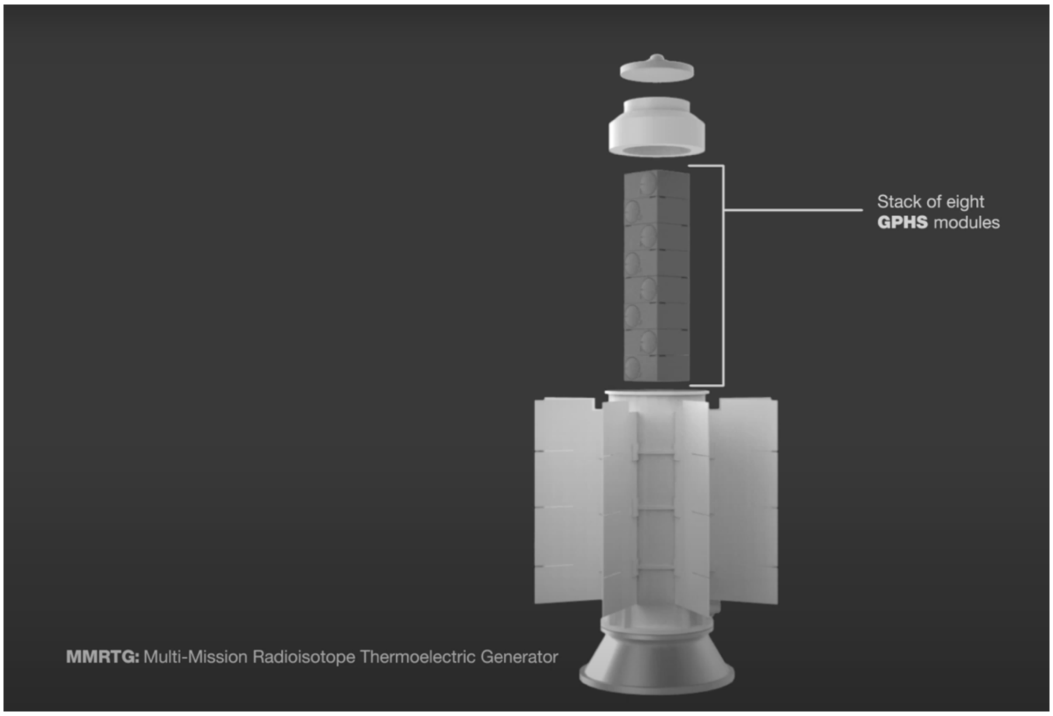

Fig 1. Structure of GPHS units in RTGs [5]

The stack of heat sources are enclosed within a container, on which thermocouples are embedded, as shown in Figure 2. The thermoelectric modules are mainly composed of two kinds of metals or a single semiconductor materials. It connects the GPHS units to a heat sink, creating a temperature gradient across it, generating electricity from the Seebeck effect [1]. On the outside, radiator fins are attached, which acts as a source of heat dissipation [6]. This helps to manage the temperature of the device, avoiding any damage to the internal components. It also creates a perfect heat sink for the thermocouples, contributing to maximizing the temperature difference across the thermoelectric materials.

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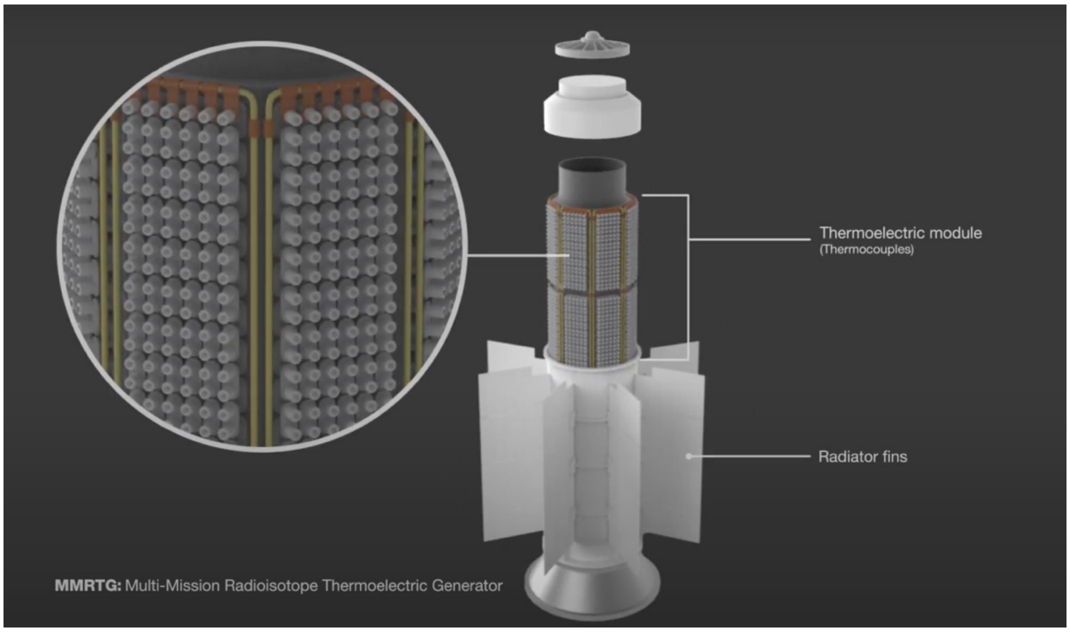

Fig 2. Structure of thermocouples in RTGs [5]

Auxiliary batteries are also connected externally to the device, due to the nature of its radioactivity. The nuclear reaction within RTGs and fissions reactors are slightly different; instead of performing under a controlled chain reaction, it produces thermal energy at a steadily decreasing rate. This prevents any nuclear meltdown or other dangerous phenomena that could potentially affect the operation of the spacecraft. However, the spontaneous radioactivity cannot be terminated to reduce power consumption, inflicting significant waste of energy. To minimize this inefficiency, devices such as rechargeable batteries are utilized to store the energy, saving the energy for future use [4].

2.2 Conversion Mechanism

Radioisotope thermoelectric generators produce thermal energy from the radioactive decay of radioisotope fuel, usually plutonium-238. The nucleus of the radioisotope undergoes alpha decay, producing alpha particles and gamma radiation that interacts with the surrounding to release heat [7].

$$ {}^{244}_{94}Pu \rightarrow {}^{232}_{90}Th + {}^{4}_{2}He \tag{1}$$

The heat is absorbed by one end of the thermocouples, which are made of materials such as bismuth telluride, lead telluride, or skutterudites [6]. The charge carriers within the materials moves to the colder side due to the temperature gradient across it (Seebeck effect), creating a voltage difference and electric current [2]. The thermoelectric modules are connected to circuits, which transfers the electric current directly to electronic devices within the spacecraft or to batteries where the energy is stored [4]. The radioactive decay of the fuel is continuous; hence radiator fins attached to RTGs increases the surface for excess heat to be dissipated into space as electromagnetic radiation [1]. This mechanism also helps to maintain the temperature difference across thermocouples, ensuring the incessant production of electricity from Seebeck effect.

In long term, the half-life of plutonium-238 is extremely long, spanning 87.7 years [7]. This ensures a consistent power supply to keep the spacecraft operational throughout its lifetime.

3. Performance Analysis

3.1 Factors Affecting the Efficiency of RTGs

3.1.1 Materials

The material utilized for the thermoelectric modules is a significant factor affecting the Seebeck effect. Each material has their unique Seebeck coefficient, which measures the magnitude of the voltage induced in response to a temperature difference across the material, where $S = \frac{\Delta V}{\Delta T}$ [2]. Each thermocouple has a p-type leg and n-type leg, which have Seebeck coefficients, hence the equation can be modified into:

$$S_p - S_n = \frac{\Delta V}{\Delta T} \tag{2}$$

Furthermore, the thermal property of the material also determines the maximum possible temperature gradient across it. As radioactivity produces energy in the form of radiation, the thermocouples will absorb them, resulting in a rise in temperature. However, the radioactive decay is continuous, and there is a constant heat transfer through couple. Therefore, the maximum stable temperature reached by the material also depends on its thermal conductivity.

In addition to thermal properties, electrical conductivity of the material determines the conversion efficiency from the temperature difference to electrical current. This refers to the resistance of the material, where $R = \frac{V}{I}$.

To ensure high Seebeck coefficient, low thermal conductivity and high electrical conductivity, materials including Silicon-Germanium Alloys (SiGe), Lead Telluride (PbTe), Skutterudites (CoSb3), etc. are used to make the thermocouples in RTGs [6].

3.1.2 Temperature Gradient

The Seebeck effect that occurs within the thermoelectric modules are greatly influenced by the temperature gradient across them. When the difference is higher, more charge carriers will be transferred to the colder region, creating a higher voltage difference which generates a greater current. However, the maximum temperature is restrained by the supply of plutonium fuel and the endurance of the internal components.

Considering that NASA can only produce 1 to 1.5 kilograms of plutonium-238 per year [7], about 3 kilograms of fuel are used for each space mission [6]. To calculate the temperature, the power output needs to be determined first with $P = mp$, where m is the mass of fuel and p is the power per unit mass of plutonium-238 (approximately 0.57 W g-1):

$$P = 1000 \times 0.57 = 1710W \tag{3}$$

There is a total of 572 thermoelectric modules in RTGs [6], and the constant temperature of their hot end is reached once the power absorbed is equal to the power lost. The cold side is connected directly to space, but the radiator fins cannot release heat immediately, resulting in a temperature of around 300 Kelvins [6]. Thus, the equation of thermal conduction can then be used (assuming the modules are made from SiGe [8], cross-section area is 20 mm2, and length is 2.5 cm):

$$P = N\frac{kA\Delta T}{l} \tag{4}$$

Therefore, the temperature difference across each thermocouple in a radioisotope thermoelectric generator is approximately Kelvins.

3.2 Effect of Microgravity on the Performance of RTGs

As radioisotope thermoelectric generators are used in spacecrafts, the condition of microgravity is present. However, unlike some generators, RTGs does not have any mechanical components. It mainly depends on the Seebeck effect for conversion, which does not involve any motion, hence the performance of RTGs is not affected with weak or even no gravity in space.

3.3 Derivation of the General Efficiency of RTGs

The process of energy generation in radioisotope thermoelectric generators commences from the radioactive decay of plutonium-238. The power produced can be derived from the mass and the power per unit mass of the fuel, which is approximately as calculated earlier (1).

The energy is then absorbed by one end of the thermocouples, which eventually reaches an equilibrium at the temperature of 1234 Kelvins (2). This creates a temperature gradient of 934 Kelvins across the thermoelectric module, inflicting the Seebeck effect. From the Seebeck coefficient, the voltage difference created can be calculated (assuming SiGe is used):

$$\begin{aligned} S &= \frac{\Delta V}{\Delta T} \\ 0.00025 - 0.00018 &= \frac{V}{934} \\ V &= 0.06461V \end{aligned} \tag{5}$$

To calculate the electrical power output resulted from the Seebeck effect, the equation is required. However, due to the Seebeck effect, the resistance of the thermocouple varies across itself. Therefore, an integration is required to calculate the total resistance across the thermoelectric module:

$$\begin{aligned} R_{total} &= \int_0^L \frac{\rho(T(x))}{A} dx \\ R_{total} &= \frac{1}{20 \times 10^{-6}} \int_0^{2.5\times10^{-2}} \rho(T(x)) dx \end{aligned} \tag{6}$$

In this case, the empirical equation of resistivity can be utilized first to derive the function of resistivity in terms of temperature:

$$\begin{aligned} \rho(T) &= \rho_0 \left(\frac{T}{T_0}\right)^n \\ \rho(T) &= 2\times10^{-5}\left(\frac{T}{900}\right)^2 \\ \rho(T) &= \left(2.469\times10^{-11}\right)T^2 \end{aligned} \tag{7}$$

Assuming the temperature increases linearly across the thermocouples, a function of temperature in terms of length would be:

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$$T(x) = 300 + \left(\frac{934}{2.5\times10^{-2}}\right)x$$
$$T(x) = 37360x + 300 \tag{8}$$

The total resistance can then be calculated using (4) by substituting in (5) and (6):

$$R_{total} = \frac{1}{20\times10^{-6}}\int_{0}^{2.5\times10^{-2}} \rho(T(x))dx$$
$$R_{total} = \frac{1}{20\times10^{-6}}\int_{0}^{2.5\times10^{-2}} \left(2.469\times10^{-11}\right)\left(37360x+300\right)^2 dx \tag{9}$$
$$R_{total} = \left(1.235\times10^{-6}\right)\left[\frac{37360^2x^3}{3} + 11208000x^2 + 90000x + c\right]_0^{2.5\times10^{-2}}$$
$$R_{total} = 0.0204\,\Omega$$

Finally, the total electrical power output would be:

$$P_{output} = 572\times\frac{0.06461^2}{0.0204} = 117\,W \tag{10}$$

The approximate general efficiency of radioisotope thermoelectric generators can then be derived using the fundamental expression of efficiency:

$$\eta = \frac{P_{output}}{P_{input}}$$
$$\eta_{RTG} = \frac{117}{1710} = 6.8\% \tag{11}$$

3.4 Advantages and Disadvantages of RTGs

In general, there are a few notable advantages of radioisotope thermoelectric generators. Firstly, it has a reliable long-term power output, as the half-life of plutonium-238 is over 87 years [7], meaning the radioactive can continue for a long time with minor drops in its activity. Furthermore, RTGs does not have any moving components, which avoids any potential mechanical failure or gradual wear, prolonging its lifetime. Secondly, it produces a consistent supply of energy, because radioactivity does not depend on its environment. Therefore, even though the spacecraft might be far from the solar system, it can still operate as intended. Lastly, as RTGs have a relatively simple structure, it is much easier to manufacture than those with mechanical components, for example. This results in lower cost, contributing to the economy of space exploration.

Nevertheless, RTGs also possesses several limitations. Radioisotopes are extremely rare resources and are difficult to produce [7], hence the supply of fuel would be expensive and relatively slow to prepare. This restrains the amount of plutonium fuel supplied to each radioisotope thermoelectric generator, affecting its lifetime and efficiency. Another drawback is its efficiency [1], which is relatively low compared to other power systems for spacecrafts. This could lead to more waste of energy, which further diminishes its lifetime.

4. Comparison with Other Power Systems in Space

4.1 Solar Power Systems

Solar power systems convert the solar energy from sunlight into electricity using photovoltaic cells, which are mainly composed of silicon. It relies fully on the exposure to sunlight, and has a conversion efficiency of around 25% [9].

An evident drawback of radioisotope thermoelectric generators compared to solar power systems is its efficiency, which is approximately 18% lower. This implies much more energy source is wasted throughout the conversion process, decreasing its potential lifetime. Another weakness is its fuel, while solar power systems rely on sunlight that is almost infinite, RTGs requires radioisotopes which is only supplied at a limited amount. As a result, the maximum lifetime of RTGs would be relatively lower. In term of cost, although RTGs does not possess any mechanical components, they are custom-built and requires the supply of plutonium-238, hence its cost is higher than of solar power systems.

A benefit of RTGs over solar power systems is its consistent supply of electrical power. While solar power systems cannot generate sufficient energy in regions where the sunlight is too weak, the power output of RTGs does not depend on its environment or position. Therefore, it ensures the spacecraft remains operational throughout its lifetime, preventing any prospective accidents in flight. Furthermore, in long-range space missions such as travelling to the outer solar system or beyond, the sunlight is too weak for solar power systems to operate as intended. In this case, RTGs are much more advantageous, as radioactivity persists even in such conditions.

4.2 Chemical Power Systems

Chemical power systems generate electricity using the energy stored in chemical bonds, which can be in the form of batteries or fuel cells. For chemical batteries, the energy stored is converted into electrical energy through redox reaction. While for fuel cells, an oxidizer is combined with the fuel to produce electricity through an electrochemical reaction. Due to the relatively direct conversion, the efficiency of chemical power systems is extremely high, typically around 70% [10].

Similar with solar power systems, a major disadvantage of radioisotope thermoelectric generators compared to chemical power systems is efficiency, which is more than 60% lower. Consequently, apart from just more waste of resource, the unused energy is converted into heat, resulting in extreme temperatures within the device. To prevent any damage to the internal components, devices that manage temperature are required, which increases the cost and weight of the generator. Another identical downside is fuel, as chemical fuels are cheaper and easier to produce. This further increases the overall cost of RTGs relative to chemical power systems, which is harmful to the economy of space exploration.

Nonetheless, RTGs possesses several useful advantages over chemical power systems. While chemical fuel can easily run out, the radioactive decay of plutonium-239 can span decades, resulting in a much longer lifetime. This indicates RTGs have a higher reliability in long-term missions in space. Another upside is the production of heat, which is seemingly inefficient but actually beneficial to the consistent operation of the spacecraft. Satellites are composed of countless devices, including both mechanical and electrical components to achieve its sole purpose. However, some of them may not operate under extremely cold temperature, hence heat supply are often required. In this case, unlike chemical power systems, the side product of RTGs' conversion process can be utilized to provide thermal energy, helping to regulate the internal temperature of spacecrafts.

4.3 Advanced Stirling Radioisotope Generators

Advanced Stirling radioisotope generators is a generator composed of a Stirling engine and a linear alternator, producing electricity using the heat supplied from the radioactive decay of radioisotope fuel. It is a newly proposed technology in the 21st century, attempting to replace radioisotope thermoelectric generators for long-range space missions. Instead of converting thermal energy directly into electricity using thermoelectric modules, it incorporates an intermediate dynamic process to boost the conversion efficiency [11].

In comparison to RTGs, ASRGs has four times higher efficiency, reaching to almost 29% as shown in Table 1. This indicates significantly less consumption of plutonium-238, resulting in both higher power output and less fuel requirement.

Table 1. Performance data of advanced Stirling radioisotope generators [12]

Parameter	Current Best Estimate
Power (at nominal temperatures and fuel loading)	143 W_e (BOM) 127 W_e (EOM)
System Mass	20.24 kg + 1.23 kg if optional spacecraft adapter is used
Overall Dimensions	Less than 76.2 c, length (Z axis) by 45.7 cm height (Y axis) by 39.4 cm width (X axis)
Specific Power	7.0 W_e/kg without spacecraft adapter
System Efficiency	28.6%

However, ASRGs has a shorter lifetime as it contains a mechanical component (the Stirling engine), where gradual mechanical wear would eventually restrain the generator from operating. Furthermore, with a moving component, it also complicates the manufacturing process of ASRGs, resulting in higher costs that could range from 110 million to 260 million USD [12]. Therefore, even though ASRGs possesses higher efficiency, NASA cancelled their plans to replace RTGs in 2013 [11].

5. Conclusion

In conclusion, the integration of radioisotope thermoelectric generators into the space exploration industry is a valid development. Using radioactive decay and the Seebeck, RTGs converts thermal energy directly into electricity, while achieving a steady and consistent power output. Nevertheless, factors including efficiency and fuel limit its potential in generating electrical energy. Despite these drawbacks, RTGs is still superior to other space power systems, such as solar, chemical, and even the new advanced Stirling radioisotope generator. To further develop this technology in the future, the challenges would comprise finding new materials with higher Seebeck coefficient, lower thermal but higher electrical conductivity, and developing methods to produce radioisotope with lower cost and complexity. With these aspects developed and as humanity continue to expand their reach of the observable universe, RTGs will play an indispensable and revolutionizing role in the future of space exploration.

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