High-power RTG simulation prototype based on skutterudite

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Abstract. In this paper, a simulation prototype of a high-power radioisotope thermoelectric generator (RTG) simulation prototype based on skutterudite is designed. By replacing the isotope heat source with an electrically heated heat source, its output power is 40 W under the condition of 1600 W electric power heating, and the thermoelectric conversion efficiency can reach 2.5%. The simulation prototype contains a total of 8 thermoelectric modules, and each module contains 16 pairs of thermoelectric materials. Its maximum theoretical output power can reach 66 W under the temperature of 550 °C. This research provides a leading guide and reference point for the temperature difference structure of RTGs at the hundred watt level.

Keywords: RTG, skutterudite, thermoelectric.

1. Introduction
With the development of deep space exploration technology and the expansion of deep space exploration activities, the detector's demand for energy is also increasing, especially when working under certain long-term low-light or harsh environmental conditions. Conventional solar cells cannot be used in the case of limited function or battery power supply capacity; there is an urgent need for long-term, highly reliable energy supply. The isotope power source has the characteristics of being unaffected by sunlight, strong environmental adaptability, long life, and high reliability. It is an ideal energy source for deep space exploration tasks.

The United States successfully developed the world's first radioisotope thermoelectric generator (RTG) on January 16, 1959 [1]. They used 46 isotope thermoelectric generator power supplies in 27 space missions from 1961 to November 2011. The output power was from 27 W to 300 W, the mass was from 2 kg to 34 kg, and the highest thermoelectric conversion efficiency reached 6.7%, and the highest mass ratio reaches 52 W/kg and the design life is 5 years [2]. There are still dozens of RTGs operating in space, and the longest working RTG has been in operation for more than 30 years. The Cosmos 84 and Cosmos 90 satellites launched by the Soviet Union in 1965 use isotopic thermoelectric generators as power sources. The isotope $^{210}$Po is used as the heat source, and the electric power is 20 W [3]. In 2013, China's RTG with four u as the radioactive source was mounted on the Chang'e-3 detector [4]. In 2018, Chang'e-4 was equipped with a better-performance RTG with a continuous output power of up to 2 W [5].

In this paper, a simulation prototype of a radioisotope thermoelectric power supply is designed. Under the heating condition of the thermal power of the simulated heat source with the input power of
1600 W, the maximum electric power output of 40 W can be achieved, and the conversion efficiency of about 2.5% is realized, which provides a reference for the development of higher power RTGs.

2. Experiment

2.1. Fabrication

The structure design of the RTG simulation prototype is shown in Figure 1. The heat transfer support structure of regular polyhedron is used, the middle is used to place isotope heat sources, the two ends are used for prototype mechanical interface and thermoelectric interface design, and the sides are used for heat transfer and thermoelectric conversion. The two ends of the thermoelectric module need to be insulated, and the cold end of the thermoelectric module also needs auxiliary heat dissipation measures. The isotope heat source is wrapped in super alloy and is located in the center of the heat transfer support structure in an axial distribution. The graphite collector ring is closely attached to the super alloy surface. The lower end of the heat source is an aluminum alloy base, and the upper end is compressed by a high-temperature resistant stainless steel press block. The hot ends of the thermoelectric modules are evenly distributed on all surfaces of the graphite collector ring, and are electrically insulated by mica sheets. The cold ends are fixed by the spring of the cooling block groove, and the outermost part is sealed and fastened with a cylindrical structural shell, and the internal gaps are uniform. Filled with thermal insulation material, and fins are added to the arc surface of the structural shell for cold end heat dissipation.

![Figure 1. The structure design of this isotope thermoelectric power supply.](image)

2.2. Examination

The schematic diagram of this isotope thermoelectric power test is shown in Figure 2. The test system includes a vacuum auxiliary test system, a refrigeration auxiliary test system, a simulated heating test system, and an isotopic thermoelectric power source. The vacuum-assisted test system is mainly used to maintain the vacuum degree and the emotional atmosphere to prevent the thermoelectric materials from being oxidized. The refrigeration auxiliary test system is used to replace the heat pipe to cool the cold end of the thermoelectric device, further increase the temperature difference and improve the conversion efficiency. The simulation test system is mainly used to simulate the isotope temperature difference power supply.

When inputting the energy test for the isotope temperature difference power supply, first turn on the vacuum auxiliary test system, first vacuum the interior of the isotope temperature difference power supply, and then fill with argon and other emotional gases, so that the thermoelectric module is in an inert gas Atmosphere. Turn on the refrigeration auxiliary test system, and pass the refrigeration liquid to the cooling component of the isotope thermoelectric power supply unit, and take away the heat of the cold end through the liquid cooling cycle, so that the temperature of the cold end of the isotopic thermoelectric power supply is controlled within a reasonable range. Finally, turn on the heating
simulation heat source, turn on the heating switch to display the initial data, adjust the initial heating power to 200 W, and then increase the power of 200 W every 10 minutes. This is to prevent the heating from causing the internal temperature to heat up too quickly, resulting in a large gap between different materials Swelling stress, and damage the prototype. When the heating power reaches 1600 W, when the entire system is stable, adjust the internal resistance of the electronic load to match the internal resistance of the battery, so that the isotope thermoelectric power supply is in the working state of maximum output power.

Figure 2. The schematic diagram of the RTG test.

3. Result and discussion
Figure 3 shows the curve of the output voltage of the radioisotope thermoelectric power supply with power. It can be seen that the output power and the heating power are non-linear. This is because the output power of the thermoelectric device is related to temperature, and the input power is the electric power of the electric heater. It is not the thermal power input to the thermoelectric device. Finally, under the electric power heating condition of the simulated heat source of 1600 W, the radioisotope thermoelectric power supply can achieve a maximum electric power output of 40 W. At this time, its internal resistance is about 2.63 Ω, and the output voltage is about 2.5% conversion efficiency. At this time, the heat source temperature is about 580 °C. According to the heat loss rate of about 78% of the system, the hot end temperature of the thermoelectric device is 450 °C, and the cold end temperature is measured to be 100 °C. At this time, the temperature difference is 350 °C.
Because the wires used cannot withstand higher power heating, in order to obtain the maximum output power of the device in the best working state. RTG conversion module structure was used to geometrically simplify the thermoelectric device structure and establish a heat transfer model, as shown in Figure 4[6].

\[ P = U \cdot I \]  
\[ U = S \cdot (T_{Hs} - T_{Cs}) - Ir \]
Where $T_h$ and $T_c$ correspond to the temperature of the cold and hot ends of the devices, $I$ is the load current and $r$ is the internal resistance, $S$ is Seebeck coefficient of thermoelectric materials. If the hot end temperature is about 550 °C, the performance of the thermoelectric material is optimal and its cold end temperature could be about 150 °C. Under this condition, the theoretical maximum output voltage of the RTG simulation prototype is 12.8 V, and the theoretical maximum output power is 66 W.

4. Conclusions
In this paper, the radioisotope thermoelectric power supply is designed and tested under the conditions of simulated heat source. Under the thermal power heating condition of the simulated heat source with the power of 1600 W, the radioisotope thermoelectric power supply can achieve a maximum electrical power output of 40 W, and the conversion efficiency at this time is about 2.5%. The theoretical maximum output voltage is 12.8 V, and the maximum output power is 66 W. The radioisotope thermoelectric power supply uses simulated thermoelectricity instead of isotope heat sources. It has certain reference and reference significance for the real radioisotope thermoelectric power supply in thermal design and structural design. The follow-up work focuses on radiation protection design and shock absorption design, which can make the thermoelectric power source simulation prototype is closer to the real radioisotope thermoelectric power source, which has the value of aerospace practical application.

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