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EXPERIMENTAL STUDY OF EFFICIENCY IN SMALL-SCALE RADIOISOTOPE THERMOELECTRIC GENERATORS

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ABSTRACT

Radionuclides can be applied to a wide range of uses, including electrical energy generation. The energy released during their decay process can be utilized for this purpose through various methods, one of which is the nuclear battery. The most widely used method for converting radiation into electricity is through thermoelectric effects, such as the Seebeck effect, employed in Radioisotope Thermoelectric Generators (RTGs), which dominate the market. The radiation emitted by radioisotopes collides with a target material, producing heat that is subsequently converted into electricity. However, RTGs have a relatively low efficiency of around 7%, and this work focuses on exploring methods to enhance that efficiency. The goal is to develop a prototype nuclear battery using an ^{241}Am or ^{242}Cf source, incorporating a vacuum chamber, Seebeck plates, and photovoltaic plates, with the aim of studying how different physical conditions may affect the efficiency of energy conversion.

1. INTRODUCTION

Radionuclides are used in several fields, including medicine, industry, scientific research, and energy production. The radiation emitted during their decay process makes them valuable for applications such as cancer treatment, sterilization, imaging technologies, and power generation. In the context of power generation, the energy released during the decay process can be converted into electrical energy using several methods (see Fig. 1), which are collectively referred to as nuclear batteries.

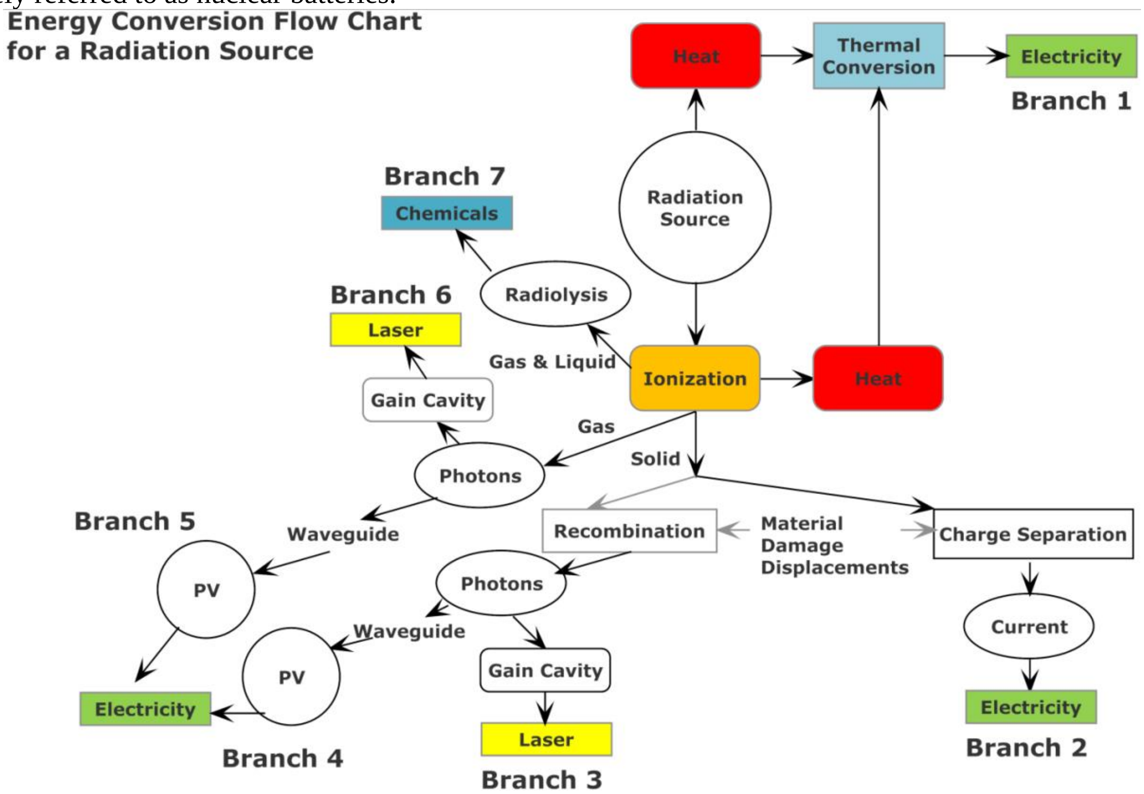

Fig. 1. Techniques for Converting Energy in a Nuclear Battery [1].

The nuclear batteries are particularly useful in environments where conventional power sources are impractical, such as in space missions or remote locations, due to their long-lasting and reliable energy output. In Fig. 1, Branch 1 refers to batteries that use Radioisotope Thermoelectric Generators (RTGs), where the radiation collisions generate thermal energy, which is then converted into electrical energy through thermoelectric effects, such as the Seebeck effect.

Radionuclides can emit various types of radiation, including alpha particles, beta particles, fission fragments, and photons, among others. These radiations lose energy as they interact with the surrounding material, a phenomenon that can be quantified by Linear Energy Transfer (LET). It refers to the amount of energy transferred by radiation to the material it passes through, per unit distance. LET depends on radiation type, its energy and surrounding material. The higher the LET, the shorter the radiation's range. Alpha particles and fission fragments have high LET and short ranges, while photons have low LET and longer ranges.

In the context of a nuclear battery, the transport scale length of radiation (λ_{RadTr}) refers to the distance over which radiation can travel before its energy is significantly absorbed. The transducer transport scale length (L_{Trans}) refers to the effectiveness and operational range of the transducer in converting energy from the radioactive material into electricity. When the value of λ_{RadTr} is close to L_{Trans}, there is an effective coupling between the radiation and the transducer. This means that when the distance over which radiation can travel (λ_{RadTr}) is similar to the effective range over which the transducer can convert this radiation into electrical energy (L_{Trans}), the efficiency of energy conversion is optimized. In other words, the transducer is well-positioned to utilize the available radiation effectively, leading to better performance of the nuclear battery. This coupling is crucial for evaluating the efficiency of nuclear batteries, particularly those with limited dimensions.

Nuclear energy is a stable and reliable source of electricity. Fig.2 illustrates the significant difference in energy density between conventional batteries and nuclear-based ones.

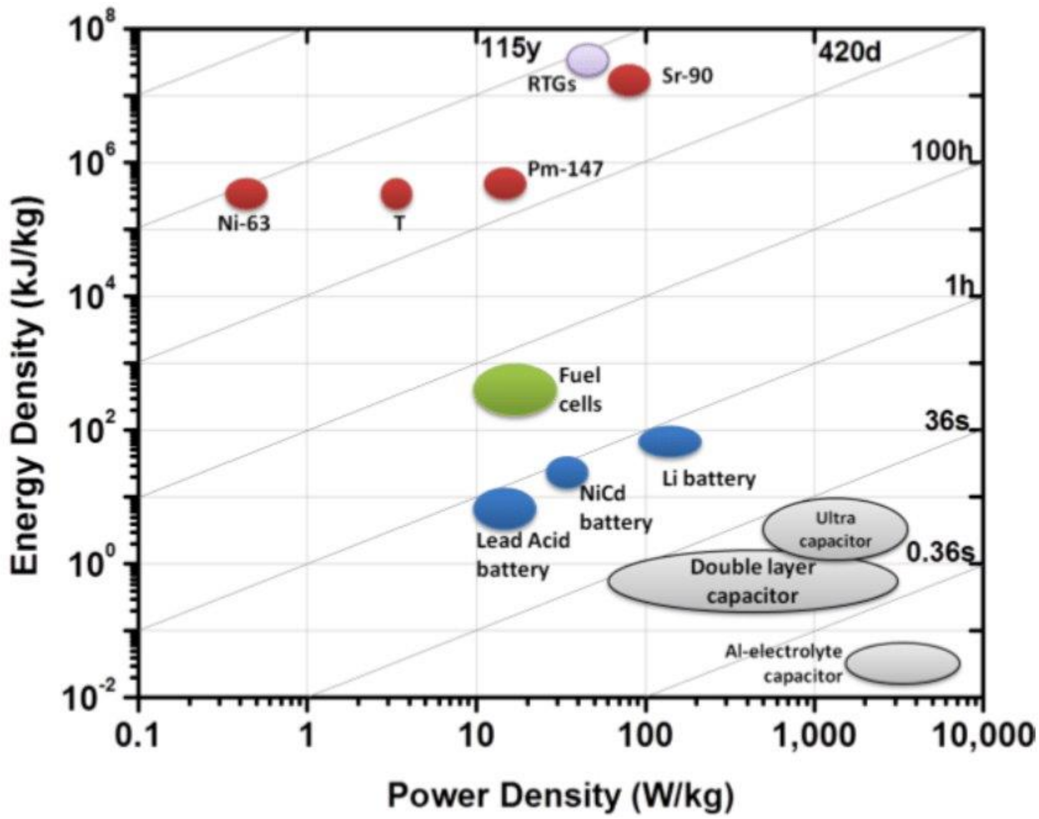

Fig.2 Specific power and energy density of nuclear battery sources and RTGs compared to chemical sources of energy and capacitors [4]

This figure illustrates a difference of 5 to 8 orders of magnitude in energy density between nuclear sources and chemical batteries. This implies that nuclear generators can be produced with significantly less material and can have much longer lifespans, as certain sources can provide energy for centuries. However, they face the challenge of low efficiency in converting this energy, making RTGs quite large and often impractical for most everyday applications. Table 4 presents a comparison of various RTG modules in terms of efficiency, size, and power output.

Tab.1 Comparação entre GPHS-RTG (general purpose heat source-radioisotope thermoelectric generators), MMRTG (multi-mission radioisotope thermoelectric generators), ASRG (advanced Stirling radioisotope power generators), all using Pu^{238} as source. [2]

	GPHS-RTG	MMRTG	ASRG
Electric output,BOM,We	285	125	~150
Heat input, BOM, We	4500	2000	500
RPS system efficiency, BOM, %	6.3	6.3	30
Total system weight, kg	56	44.2	~21
Specific power, We/kg	5.1	2.8	8
Number of GPHS modules	18	8	2
GPHS module weight, kg	25.7	12.9	3.2
Pu-238 weight, kg	7.6	3.5	0.88

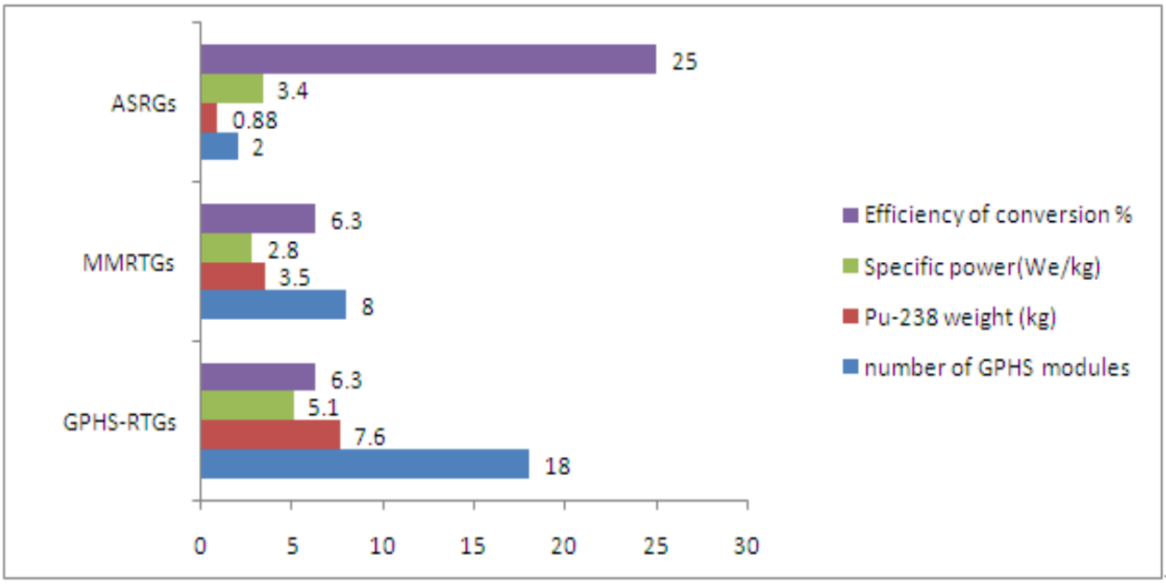

Fig.3 Comparison between GPHS-RTG, MMRTG and ASRG in terms of the number of GPHS modules, weight of used 238Pu, the specific power and efficiency of conversion. Information taken from [2]

Fig.3 complements Table 1 by highlighting that modern radioisotope thermoelectric generators (RTGs), which are predominantly used in space missions due to their high cost-effectiveness, have an efficiency of less than 7%. The promising Advanced Stirling Radioisotope Generator (ASRG) could achieve much higher efficiencies, around 25% to 30%, but this is contingent upon its use of a Stirling engine and is still in the experimental phase. This underscores the need for research aimed at improving the efficiency of these generators, which would facilitate miniaturization and broader everyday applications of this advantageous energy production method. Just as nuclear pacemakers were used in the past, RTGs could also find utility in a wide range of medical and emergency equipment due to their stability and reliability. Furthermore, alongside advancements in the efficiency of these devices, it is essential to focus on developing effective radiation protection measures to enable their widespread use.

Temperature and pressure are factors that can significantly affect the thermal properties of the transducer, impacting its transport scale length and, consequently, its efficiency. In this way, the goal of the present work is to study the efficiency of radioisotope generators as a function of temperature and pressure using vacuum as a transducer.

2. MATERIALS AND METHODS

The experiment involves the development of a prototype designed to simulate a nuclear battery with various features. Fig. 2 and Fig. 3 illustrate this prototype and its main components, which have the following functions:

1. Heat Source as primary energy source. The use of radioactive sources necessitates strict adherence to radioprotection requirements, including proper shielding, monitoring, dose limitations, and emergency preparedness, to ensure the safety of workers and the environment from harmful radiation exposure. Therefore, for safety and to simplify the initial experiments, the present work uses an electric resistance with 50W power at 24 as a heat source, simulating the heat generated by a radioactive source. This methodology enables variation of the electric resistance and allows for studying the model's behavior as a function of heat power without using a radioactive source. The heat can be controlled by a voltage/current controller device.
2. Seebeck plates which converts heat into electrical energy through thermoelectric processes, aids in efficient heat management, and enables power generation. These plates exploit the Seebeck effect, where a temperature difference across two different semiconductors generates a voltage. To enhance heat transfer between the heat source and the semiconductor plate, thermal paste is applied at their interface. Tab. 1 presents the main features of Seebeck plates, and Tab. 2 depicts the relationship of the physical parameters in these plates.
3. Two thermocouples placed at opposite positions of the semiconductor plates for temperature measurement.
4. A vacuum chamber equipped with a vacuum gauge to monitor and control the internal atmosphere. It allows for testing heat transfer behavior at various pressure values (or vacuum levels), simulating the effects of different insulating materials. This component also minimizes heat loss to the environment, thereby enhancing the efficiency of electrical generation.
5. A base as structural support.

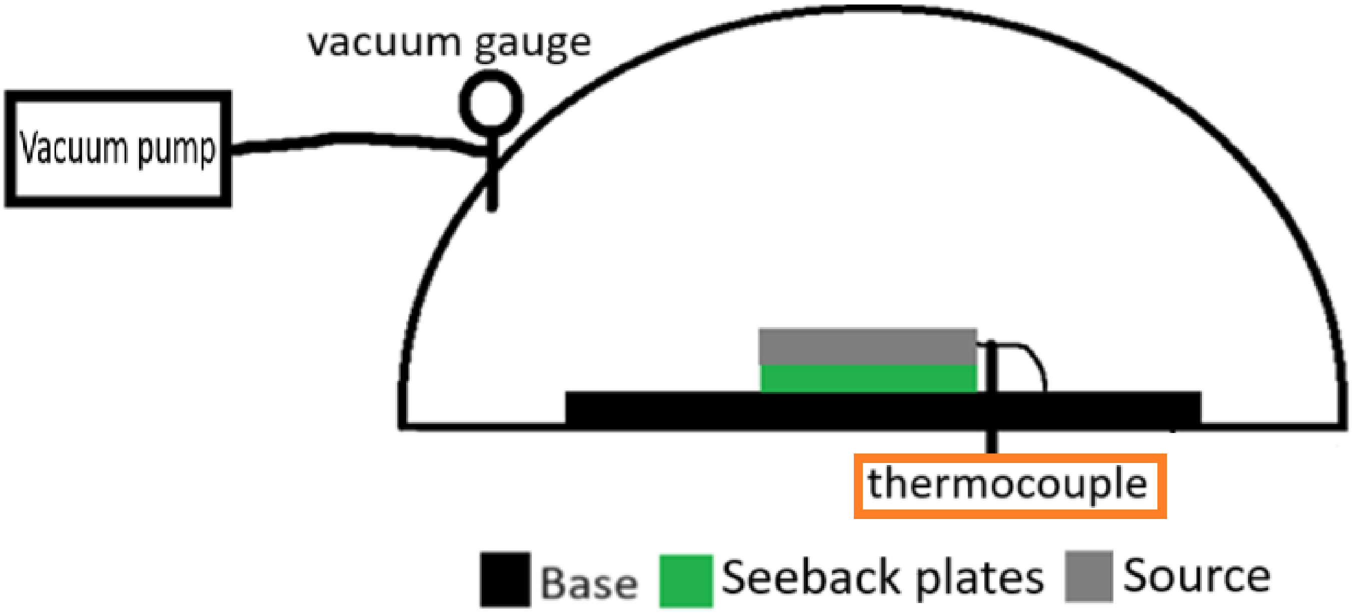

Fig.4. Schematic diagram of the prototype.

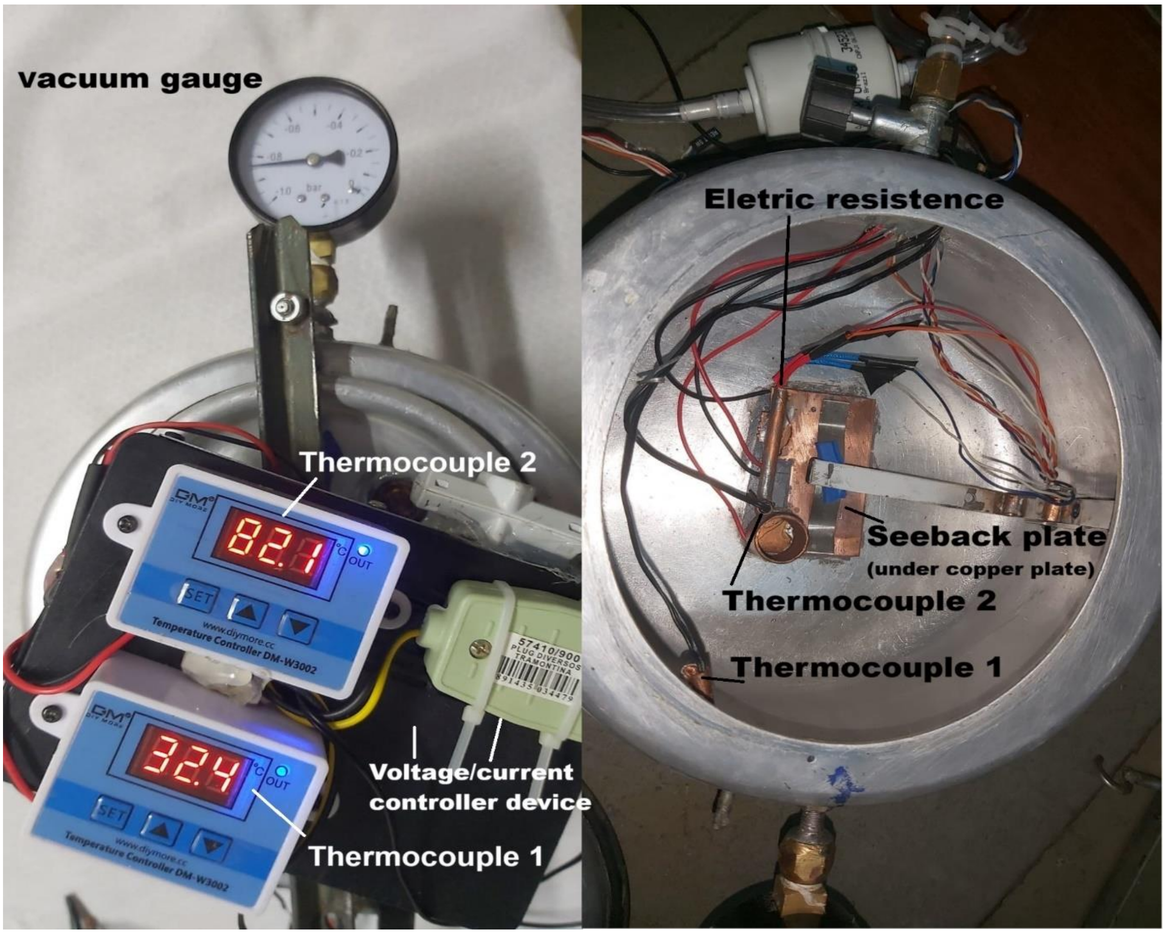

Fig. 5. External and internal assembly of the device.

Tab. 2. Main features of Seebeck plates [6]

Description	Value	Unity
Dimension	40 × 40 × 3.6	mm
Cristal bar dimensions (diameter x length)	30 × 300	mm
Operational environment	-60 – 125	ºC
EMF thermoelectric	> 190	$\mu V^{-1} \cdot ºC^{-1}$
Electric conductivity	850 – 1250	$\Omega^{-1} \cdot cm^{-1}$
Thermal conductivity	15 – 16	$W \cdot ºC^{-1} \cdot cm^{-1}$
Optimized value	$2.5 – 3.0 \times 10^{-3}$	$W \cdot ºC^{-1}$

Tab. 3. Relationship between the physical parameters of Seebeck plates. [6]

Temperature Difference (ºC)	Open-circuit voltage (V)	Electric current (mA)	Seeback coefficient ($V \cdot ºC^{-1}$)
20	0.97	22.5	4.85×10^{-2}
40	1.80	36.8	4.50×10^{-2}
60	2.40	46.9	4.40×10^{-2}
80	3.60	55.8	4.50×10^{-2}
100	4.80	66.9	4.80×10^{-2}

In this work, the vacuum chamber is used to simulate different thermal insulators. Adjusting the internal pressure alters the vacuum conditions, which subsequently impacts the thermoelectric properties, thereby replicating certain parameters of materials unavailable for acquisition. Thus, using this methodology, it is possible to evaluate different projects of nuclear battery for distinct thermal insulators materials. In this sense, the prototype was used to evaluate temperature variation as a function of pressure, ranging from -0.90 bar to -0.25 bar (negative pressure inside the chamber).

In the experiments, the pressure within the vacuum chamber is adjusted, and the electric resistance is activated while the system is allowed to reach thermal equilibrium. The corresponding temperature, voltage, and electric current are then measured. This procedure is repeated for each pressure value ranging from -0.90 bar to -0.25 bar. The experiment was conducted at an ambient temperature of 27.8°C.

3. RESULTS

Tab.2 presents the values of physical parameters as a function of pressure variation measured inside the vacuum chamber. Clearly, an increase in pressure diminishes the vacuum within the chamber due to the influx of air, which absorbs heat from the hot leg of the Seebeck plates, thereby reducing its temperature. Moreover, the temperature of the cold leg is highest at the lowest pressure value, corresponding to the highest vacuum condition. Under these conditions, heat transfer to the air is minimized, resulting in maximum heat transfer to the cold leg of the Seebeck plates. As expected, this behavior leads to a reduction in temperature variation, which tends to decrease both the voltage and the electric current. The Seebeck effect describes the direct correlation between the temperature difference along a material and the resulting electrical potential difference, which can be described by the equation:

$$V = \alpha_{AB} \cdot \Delta T \qquad \text{Eq (1)}$$

Where α_{AB} is the Seebeck coefficient of p-n junction. This coefficient was calculated for each pressure value evaluated in the experiment showing the coherence of results (see Tab. 3). Also, for a temperature variation of 60°C, the measured voltage and electric current correspond to the values provided by the manufacturer (see Tab. 2).

Tab. 4. Temperature, current and voltage as a function of pressure variation.

Pressure (bar)	**Temperature of Seebeck plates (°C)**			**Electric Current (mA)**	**Voltage (V)**	**Seebeck Coefficient ($V\cdot {}^oC^{-1}$)**
	Hot Leg	**Cold Leg**	**Variation**			
-0.90	105.0	43.4	61.6	45.8	2.434	3.95×10^{-2}
-0.85	106.0	44.4	61.6	46.9	2.513	4.08×10^{-2}
-0.80	105.0	44.8	60.2	43.7	2.389	3.97×10^{-2}
-0.75	105.0	45.0	60.0	43.1	2.379	3.97×10^{-2}
-0.70	106.0	45.2	60.8	44.5	2.412	3.97×10^{-2}
-0.65	105.0	45.3	59.7	41.2	2.422	4.06×10^{-2}
-0.60	104.0	45.4	58.6	40.9	2.391	4.08×10^{-2}
-0.55	103.0	45.4	57.6	41.3	2.377	4.13×10^{-2}
-0.50	100.0	42.5	57.5	39.6	2.364	4.11×10^{-2}
-0.45	100.0	42.4	57.6	40.2	2.386	4.14×10^{-2}
-0.40	101.0	42.3	58.7	38.4	2.362	4.02×10^{-2}
-0.35	102.0	45.2	56.8	35.4	2.345	4.13×10^{-2}
-0.30	98.7	40.7	58.0	35.1	2.370	4.09×10^{-2}
-0.25	98.0	41.7	56.3	39.1	2.352	4.18×10^{-2}

Three multimeters were used to take measurements. Of the three, two provided consistent readings, differing by no more than 0.5 mA, and the average of these values was used. In contrast, the third multimeter recorded the same values but with an order of magnitude ten times greater. For instance, while the other two multimeters indicated approximately 46.5 mA, the third registered 465 mA. When comparing this data to the reference table [6], it may be tempting to assume that the third multimeter's reading is correct. However, studies on the performance of the Seebeck plate SP1848-27145 referenced in [7] and [8] demonstrate that the measurements from the first two multimeters are the most accurate, as shown below:

Tab.5 Single TEG Module Configuration Measurement Instruments [7]

Time (Minute)	Temperature (°C)		ΔT (°C)	Voltage (V)	Current ($V\cdot °C^{-1}$)	Power (VA)	Resistance (Ω)
	Hot Leg	Cold Leg					
5	45	36	12	0.5	0.03	0.01	4.2
10	58	37	21	1.1	0.04	0.03	4.2
15	75	40	35	1.9	0.04	0.04	4.2
20	85	48	37	2.5	0.05	0.05	4.2
25	127	49	78	2.7	0.06	0.05	4.2
30	150	59	91	3.3	0.06	0.06	4.2

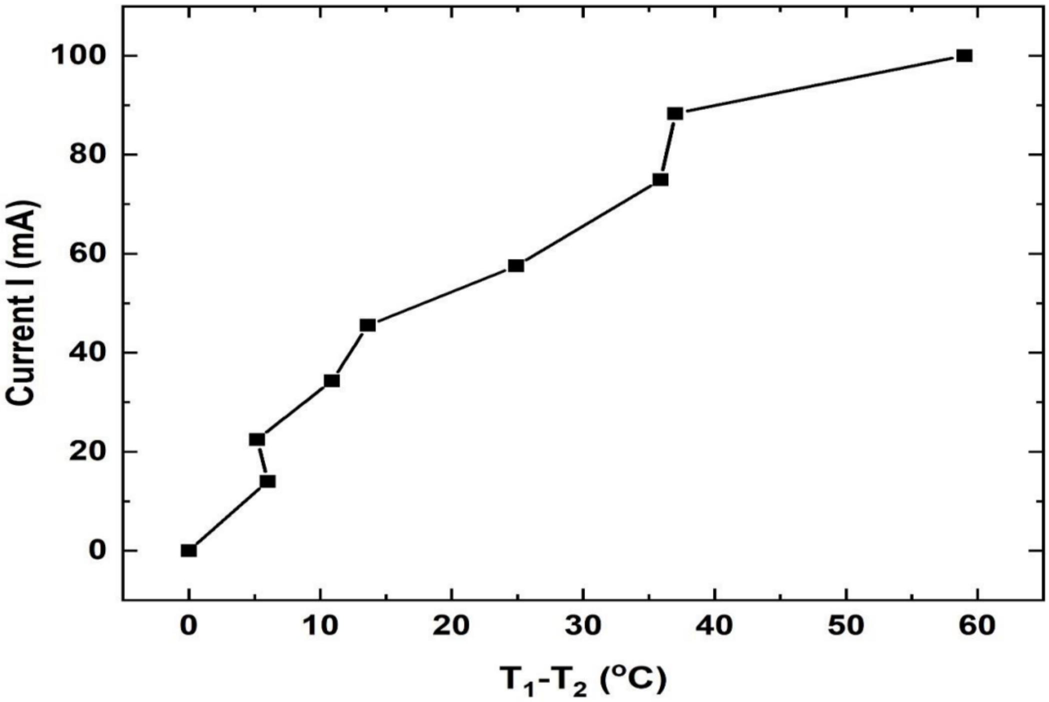

Fig.7 A plot of output current I against temperature difference T_1-T_2. [8]

By examining Figures 4 and 5, we can see that the current value for this model of plate tends to be closer to 50 mA, which aligns with measurements from two of the multimeters but not the third. This discrepancy is likely due to a defect in the scale of the third multimeter. Additionally, considering a possible typographical error on the seller's website, it was decided to adjust the data in Table 2 to correct this inconsistency. This error only happened with the current data; all the multimeters yielded the same values of voltage within the error of 0.05V in approximation.

4. CONCLUSIONS

The experiments with the developed prototype show results consistent with those described in the literature. Decreasing the vacuum condition implicates in the augment in the heat transfer to the air reducing the generated voltage. Thus, as expected, a material with high thermal insulator coefficient may provide a better efficiency to electric energy generation in a nuclear battery.

When comparing the Seebeck coefficient in Tab.3 for ΔT = 60°C with that in Tab.4, we observe a variation ranging from 0.45×10^{-2} $V\cdot°C^{-1}$ at 0.90 bar of negative pressure to 0.22×10^{-2} $V\cdot°C^{-1}$ at ambient pressure. This demonstrates how air influences the thermoelectric properties of the system. By isolating the plate's coefficient from the air's coefficient, this study can be further developed to obtain the similarity relationship between the thermoelectric properties at different vacuum levels and those of the materials we aim to simulate for studying various RTG models.

This paper presents a primary study using the developed prototype, but future works will employ it to a step consisting of checking the maximum temperature that the device will reach as a function of the source element and the vacuum level. This step is based on testing the hypothesis that the maximum temperature that the device can reach depends on the starting level of vacuum that is produced. The less air there is, the less energy will be lost from the source/system to the environment, allowing the battery to reach higher temperatures. Additionally, future research will also include using radioactive sources such as ^{252}Cf (E = 6.2 MeV) and ^{241}Am (E = 59.5 keV) to test a fully functional RTG. ^{252}Cf emits alpha radiation approximately 3% of the time and undergoes spontaneous fission, generating various fission fragments, while ^{241}Am primarily emits alpha particles and photons.

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