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Evaluation of the Response of Thermogenerators as a Function of Exposure to Irradiation

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1. Introduction

In recent decades, global energy demand has expanded rapidly, registering a growth of 5% between 2010 and 2020, with half of this supply still coming from fossil fuels [1]. To illustrate this scenario, one can observe data centers, which were responsible for 1.5% of global electricity consumption in 2024, with estimates that this value will reach 3% by 2030 (2025), and a forecast that by 2040 there will be a 40% increase in world energy consumption [2]. Several are taking some strategic measures to adapt to this situation, whether by changing energy matrices or by seeking better energy efficiency in their sources.
In the case of Brazil, despite being relatively independent of fossil fuels, the focus is still on hydroelectric power, with a lack of significant investment in other energy sources, leading to a situation with little energy diversity [3], and its efforts to meet the goals of the Paris Agreement are insufficient [4].
Given the urgency to improve energy efficiency in urban and industrial centers through less polluting sources, the process of recovering residual heat from machines and motors is a key approach, and in this context, the use of Thermoelectric Generators (TEGs) emerges. These devices work by reusing residual thermal energy through the Seebeck effect, converting temperature gradients directly into electrical potential, which can be applied to power auxiliary systems and sensors [5].
The electricity generated by TEGs has varied applications, such as energy recovery in vehicles, with estimated savings of 4% for cars and 7% for buses [6], and industrial processes such as dryers and fuel cells [7]. In the case of applying this device in the nuclear sector, particularly in nuclear reactors where heat is abundant, TEGs can convert waste energy to power monitoring systems. This integration enables the use of remote and autonomous sensors, increasing operational safety and reducing installation and maintenance costs [8]. However, in cases of application in environments such as nuclear power plants or outer space, the operation of TEGs may be compromised. This is because these environments have a high level of ionizing radiation, such as gamma rays and neutrons.
Given this scenario, this work is dedicated to the analysis of TEGs subjected to irradiation, aiming to characterize their behavior under radioactive fields. The objective was to quantify the damage caused by different doses of these radiations, aiming to support the development of protection strategies and promote the improvement of the use of these tools in the nuclear sector.

2. Methodology

The study methodology was based on the characterization of electrical parameters, such as voltage and current, of 5 samples of the TEG 127 model, under different thermal regimes and ion radiation, using gamma and neutron sources in the devices. This allowed for the collection of voltage and current measurements under various conditions, including pre-irradiation and post-irradiation regimes, with variable and gradual doses. The aim was to quantitatively analyze the effects that ion radiation can cause on the semiconductor device. All procedures were carried out at the facilities of the Institute for Energy and Nuclear Research (IPEN), where gamma dose irradiation was performed using GammaCell 220 equipment, while neutron irradiation was performed using the IPEN MB-01 and IEA-R1 reactors. In each irradiation experiment, the measurements of the electrical parameters were recorded, thus making it possible to monitor the changes that occurred in the device after irradiation.

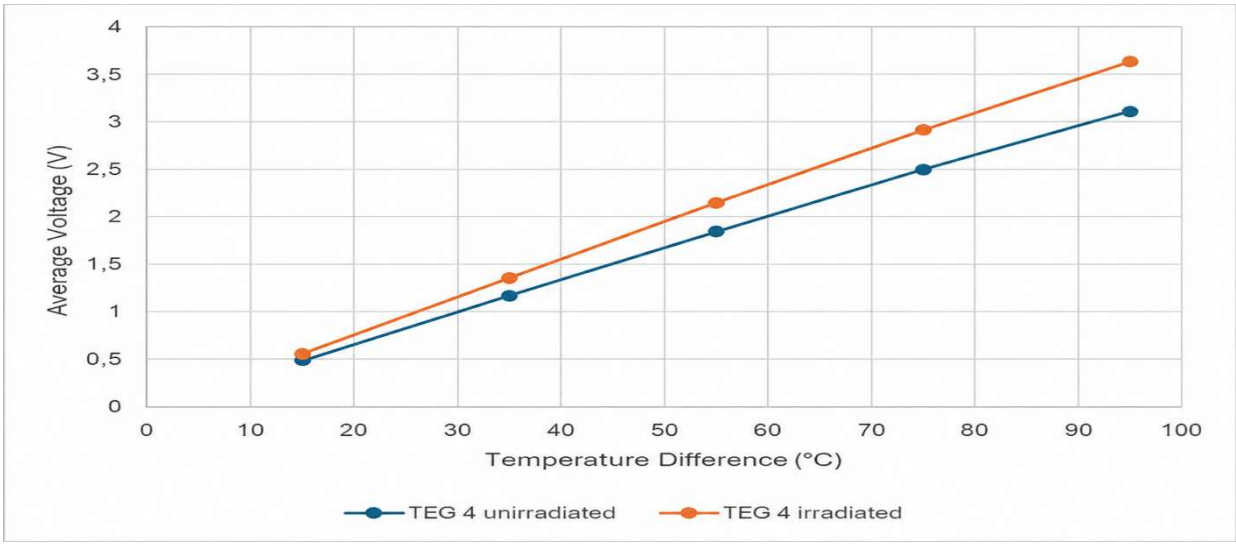


Figure 1: Average Voltage versus Temperature Difference for Irradiated and Unirradiated TEG number

3. Results and Discussion

Regarding the results for one of the TEG devices, the current parameter, across all gamma doses, from 1kGy to 8kGy, did not show a very high change compared to the current values of the same device when it was not irradiated, with a difference of less than 7% in all temperature ranges used in all experiments. In the case of voltage, however, there was an oscillation between the 2kGy dose values and the other doses, since while the difference in voltage of the irradiated device at other doses compared to the non-irradiated voltage values was less than 11.30%, the voltage values for the 2kGy dose were higher than the values obtained before the gamma irradiations, with a difference of 23.10%.

In the case of the results from another TEG device, the values of voltage and current measurements, at all doses, also did not show a very large change when compared to the non-irradiated values, since the voltage differences were not greater than 5.25%, while for the current, the difference was not greater than 5.44%.

Experiments on the influence of neutrons showed that there was a significant change with the TEG devices, where the voltage parameters were increased when compared to the non-irradiated voltage values, with a difference of 15.83% increase in the case of the TEG designated as number 4, while for the TEG designated as number 1, the increase was 30%. This means that neutron irradiation caused an increase in the net Seebeck Coefficient (S) of the device. This is an expected phenomenon in thermoelectric materials exposed to neutrons and occurs due to two main mechanisms. The first is the energy filtering effect, where neutrons (especially fast neutrons) generate atomic displacement defects (APDs), creating clusters of holes and interstitials in the semiconductor lattice.

The second effect is the reduction in carrier concentration. Because neutrons create deep energy levels in the bandgap that act as traps, capturing free electrons or holes and decreasing the total carrier concentration

(n). In degenerate thermoelectric semiconductor physics, the Seebeck coefficient has an inversely proportional relationship with the carrier concentration. Irradiation by fast neutrons destroys μ mobility through scattering centers created when fast neutrons knock bismuth atoms out of their positions, creating islands of amorphous disorder (clusters of defects).

It can be concluded that, at the end of this project, the experiments of the second phase coincided with the expectations stated in the literature, thus having a safety margin of up to 10 kGy of gamma rays, which will not intensely modify or cause the semiconductor to function inappropriately. While in the case of neutron irradiation, with a fluence of up to 1.09×10^{11} n·cm^{-2}, there was a change in the electrical behavior of the semiconductor, leading to an increase in the voltage produced by the device. This is one way to improve the efficiency of semiconductors, in addition to those already existing in the industrial sector, such as modification or replacement of semiconductor materials.

4. Conclusions

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