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Modeling of the core and analysis of the operation of a nuclear microreactor

Modelado del núcleo y análisis del funcionamiento de un microrreactor Nuclear

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ABSTRACT

This research focuses on a detailed analysis of the operation and modeling of the core of a prototype nuclear microreactor with characteristics similar to Westinghouse's eVinci nuclear microreactor. To achieve this, firstly, the Root_{TM} software is employed to adapt the energy spectrum under which the ^{241}Am-Be source operates. Secondly, the Geant4_{TM} simulation tool is used, where, starting from the configuration of a cylinder embedded in a box, the unit cell is established to obtain a trapezoidal geometry as a geometric component of the hexagonal core of the microreactor. Additionally, the essential parameters of the functions enabling the reproduction of data from a ^{241}Am-Be source are presented in the results, playing a crucial role in initiating nuclear fissions in the uranium dioxide UO_2 fuel rods. Finally, the appropriate dimensions of the various components of the core are established, including the fuel rods, neutron moderators, and control drums located within the microreactor.

Keywords: Nuclear Microreactor, eVinci, Core, Geant4 $_{TM}$, Root $_{TM}$.

RESUMEN

Esta investigación se centra en un análisis detallado del funcionamiento y modelado del núcleo de un prototipo de microreactor nuclear con características similares al microreactor nuclear eVinci de Westinghouse. Para lograrlo, en primer lugar, se utiliza el software Root_{TM} para adaptar el espectro de energía bajo el cual opera la fuente de ^{241}Am-Be. En segundo lugar, se emplea la herramienta de simulación Geant4_{TM}, donde, partiendo de la configuración de un cilindro incrustado en una caja, se establece la celda unidad para obtener una geometría trapezoidal como componente geométrico del núcleo hexagonal del microreactor. Además, en los resultados se presentan los parámetros esenciales de las funciones que posibilitan la reproducción de los datos provenientes de una fuente de ^{241}Am-Be, desempeñando un papel crucial en el inicio de las fisiones nucleares en las barras de combustible de dióxido de uranio UO_2. Por último, se establecen las dimensiones apropiadas de las distintas componentes del núcleo, incluyendo las barras de combustible, los moderadores neutrónicos y los tambores de control localizados en el microreactor.

Palabras Clave: Microreactor Nuclear, eVinci, Núcleo, Geant4 $_{TM}$, Root $_{TM}$.

1 INTRODUCTION

The need to adopt energy sources that minimize the impact on climate change has led to the exploration of innovative technologies in electricity generation [1]. New alternative energies are needed such as wind, solar, and nuclear energy, which significantly reduce greenhouse gas emissions compared to the burning of fossil fuels. According to the International Atomic Energy Agency (IAEA), generating 235,000 kWh of electricity, equivalent to the average electricity consumption of a person for approximately 72.6 years, requires the burning of 87.9 tons of coal, resulting in the emission of 253.281 kg of carbon dioxide CO_2. In contrast, to produce the same amount of electricity using uranium, only 1.1 kg of this fuel is needed, generating approximately 3.064 kg of CO_2 emissions [2].

This means that CO_2 emissions associated with electricity generation using uranium are approximately 83 times lower than when coal is used. However, one of the inherent limitations of renewable energy sources, such as wind and solar, is their intermittent availability. On the other hand, generating electricity from conventional nuclear reactors entails significant costs in terms of investment and maintenance. As a result, nuclear microreactors emerge as a viable alternative to meet the growing energy demand, providing continuous electricity at a lower cost due to their innovative technology. Specifically, microreactors like eVinci of Westinghouse [3] stand out for surpassing the intermittent availability limitations of other renewable energy sources, as they are not reliant on bodies of water or environmental factors. They harness thermal energy from fuel rods through embedded heat pipes, serving a dual purpose by optimizing cooling processes and enhancing system efficiency for electricity generation.

In this context, the purpose of this research is to analyze and describe the operation of a nuclear microreactor prototype through the core modeling in Geant4$_{TM}$, which is an essential part of electricity generation [4]. The use of Geant4$_{TM}$ in this research is based on its outstanding ability to simulate with high precision the interaction of nuclear particles and radiation with matter, which is crucial for understanding the core behavior and, in general, the operation of the microreactor.

2 METHODOLOGY

To study the operation of a nuclear microreactor, an initial phase of core modeling for a nuclear microreactor prototype was carried out [4] using Geant4$_{TM}$, framework that simulate particle interactions with matter. It is important to note that nuclear microreactors are in a state of development and construction; this research is part of a broader effort in modeling and simulating these prototypes.

The following is a detailed description of the modeling of a microreactor prototype, particularly similar to the design of the eVinci microreactor by Westinghouse[3], see Figure 1. Initially, a cylinder representing a fuel rod was created, with a diameter of 0.01412 m and a height of 1.50 m, composed of uranium dioxide UO_2. Subsequently, this cylinder was placed in a stainless steel box with an opening of 0.01425 m radius designed to accommodate the cylinder, simulating the basic structure where fuel rods and heat pipes are incorporated in the core of the microreactor prototype.

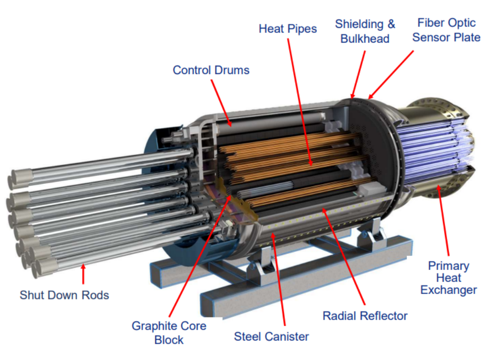

Fig. 1. Internal view of the Westinghouse nuclear microreactor, it is in the construction status and will be available until 2025. [3]

Subsequently, the configuration of the cylinder was replicated within the box at multiple positions to achieve a trapezoidal geometry. Next, a structure encompassing the perimeter of the trapezium was incorporated, simulating the graphite moderator with the goal of thermalizing the neutrons generated as a result of the fission reaction, thereby increasing the probability of interaction with the nuclei. Finally, concerning the geometry, cylinders characterized by a 0.25 m radius and a height of 2.0 m, made of boron carbide B_4C, were included to simulate the control drums. This step was performed to replicate the hexagonal geometry of the nuclear microreactor prototype by repeating the trapezoid, the moderator, and the control cylinders five times.

To initiate the nuclear fission reaction in the uranium dioxide UO_2 fuel rods, a ^{241}Am-Be source was simulated. Since this source emits neutrons in a continuous range of energies, it was necessary to search for approximate functions that described the emitted energy spectrum. Using Root$_{TM}$ software, this spectrum was graphically represented, and an approximate total function was obtained by fitting of seven Gaussian functions, with the purpose of reproducing the spectrum of the ^{241}Am-Be source. It is noteworthy that, being an initial approach to prototype modeling, this work stands as one of the pioneers awaiting validation of experimental results, which are contingent upon the commercialization of nuclear microreactors after 2025.

3 RESULTS

3.1 Operation of a Nuclear Microreactor

At the core of the microreactor, there is a stainless steel monolith consisting of two main channels: the fuel rods and the heat pipes. On one hand, the Americium-Beryllium ^{241}Am-Be source is used to initiate the nuclear fission reaction in the uranium dioxide fuel rods, Equations 1 and 2 describe the process that occurs in a ^{241}Am-Be source.

$$^{241}Am \rightarrow ^{4}He + ^{237}Np \tag{1}$$

In Equation 1, we have an alpha decay reaction of the isotope ^{241}Am, in which the americium nucleus ^{241}Am emits an alpha particle (a helium nucleus) and transforms into a neptunium nucleus ^{237}Np.

$$^{4}He + ^{9}Be \rightarrow ^{12}C + ^{1}n \tag{2}$$

As the alpha particle travels through the surrounding material, which in this case is the beryllium that surrounds the americium in the source, it can interact with beryllium nuclei, leading to the release of additional neutrons due to nuclear reactions described in Equation 2.

When the fission chain reaction is initiated, a significant amount of energy is released in the form of heat, radiation, and additional neutrons. Additionally, a substantial amount of kinetic energy is produced due to collisions between particles in the microreactor core, and this kinetic energy is converted into thermal energy at the system boundaries. To prevent an excessive release of neutrons in these fission reactions, control drums are used, in this case, 90% enriched B_4C, which serves to control the excess neutrons.

On the other hand, the thermal energy released in this process is utilized for various purposes, including electricity generation. The fuel rods are located in the core of the nuclear microreactor alongside the heat pipes, with the monolith acting as a separator. Each heat pipe contains a working fluid, in this case, sodium, in an amount of 100 grams per pipe. For a 4-meter-long pipe, the fuel rods only cover the first 1.5 meters.

Near the fuel rods, where the thermal energy is higher, sodium undergoes an evaporation process, expanding to the rear end of the pipe. As the heat flows towards the other sud, it moves away from the heat source, and as a result, the temperature decreases. This initiates a condensation process that allows the gas to return to its liquid state, and the heating cycle is restarted thanks to the nuclear reactions occurring in the fuel rods [5].

However, in each cycle carried out by the sodium, energy is transferred to another heat exchanger tube that is supplied with air and operates on a Brayton cycle [6]. Furthermore, using a compressor and harnessing the thermal energy released by the working fluid-containing tube, pressure is increased, and as a result, temperature. This causes the air to expand and drives a turbine, which, in turn, is connected to an electrical generator, resulting in electricity generation.

3.2 Modeling of the Core of a Nuclear Microreactor

The neutrons released by the source emit a continuous energy spectrum, as shown in Figure 2.

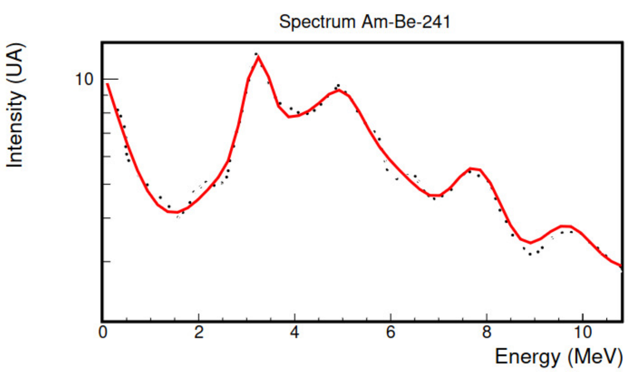

Fig. 2. Emission spectrum of ^{241}Am-Be. ^{241}Am-Be, with fit using Root$_{TM}$.

Figure 2 displays experimental spectrum of a ^{241}Am-Be source arranged in a graph, which has been processed using Root$_{TM}$ software. To properly fit these data, seven independent Gaussian functions have been employed, with each function defined by three specific parameters. The superposition of these seven Gaussian functions generates a total function involving a total of twenty-one parameters, which are listed in Table 1.

The total function is crucial as it describes the energy of the neutrons that initiate the reaction. In this context, it is typical to require thermal neutrons whose energy is on the order of 0.025 electronvolts (eV). To achieve this energy level, the source is thermalized by adding paraffin (C_nH_{2n+2}), which, due to the

Gaussian Funtion	**Mean**	**Sigma**	**Constant**
1	-2.049 ±0.493	1.703 ± 0.846	20.497 ± 8.770
2	2.320 ± 0.058	1.065 ± 0.089	5.065 ± 0.045
3	3.226 ± 0.010	0.338 ± 0.031	11.623 ± 0.226
4	4.809 ± 0.033	1.151 ± 0.056	9.139 ± 0.127
5	6.296 ± 0.059	1.024 ± 0.160	5.286 ± 0.054
6	7.592 ± 0.073	1.180 ± 0.096	5.256 ± 0.083
7	9.730 ± 0.038	1.524 ± 0.088	3.594 ± 0.029
	chi^2	4.81078	
	Edm	0.006803	

Table 1. Parameters of the seven Gaussians that reproduce the data from a ^{241}Am-Be source. Chi^2 funtion: which refers to probability distribution function. Edm stands for Estimated Deviation Measures.

presence of hydrogen in its composition, effectively reduces the energy of the neutrons emitted by the source and increases the probability of initiating a nuclear fission reaction.

Regarding the modeling of the core of a nuclear microreactor with Geant4$_{TM}$, this process occurs in several stages. In the first stage, a unit cell was created, as illustrated in Figure 3. This cell consists of a stainless steel box with dimensions of 0.025 m in width, 0.022 m in height, and 1.50 m in length. Inside it, there is a fuel rod composed of uranium dioxide UO_2 represented in red. Subsequently, this cell was replicated 556 times at different locations, generating a trapezoidal pattern that begins in the row centered at the origin of the x-axis, as observed in Figure 4. It is worth noting that the choice of this initial position was made to simplify the construction of the figure, replicating only a part and then reflecting it along the horizontal axis.

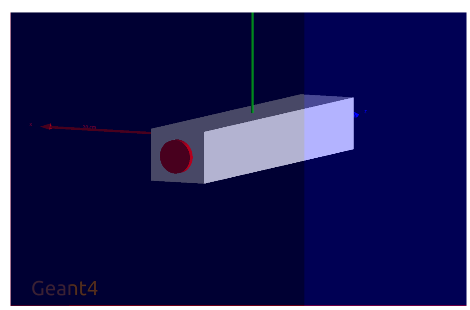

Fig. 3. Unit cell used in the construction of the core of a nuclear microreactor using Geant4$_{TM}$.

In the addition of each of the unit cells, a constant separation of 0.05 m in the horizontal direction and 0.044 m in the vertical direction was maintained between them. Similarly, it is important to note that, using the previously mentioned row as a reference, both the rows located above and below are shifted by 0.025 m with respect to the main row. In other words, all odd-numbered rows are shifted by 0.025 m in relation to even-numbered rows.

Similarly, in the core of the nuclear microreactor, neutron moderators composed of graphite have been integrated, as shown in figure 4, distinguished by their blue color. This incorporation is of fundamental importance, as their main function lies in ensuring the thermalization of the neutrons originating from fission products. This process significantly increases the probability of interaction between neutrons and uranium nuclei, ensuring that nuclear fission reactions remain active over time. These moderators are strategically located around the perimeter of the core, forming a trapezoidal configuration.

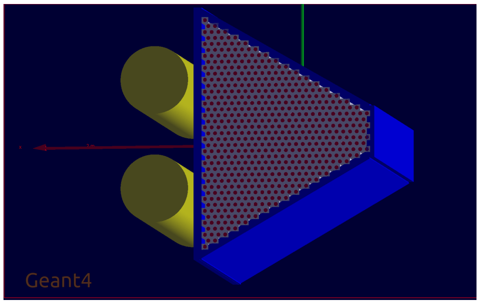

Fig. 4. A section of the nuclear microreactor core modeled with Geant4$_{TM}$.

Similarly, in Figure 4, the addition of the yellow control drums can be observed, which play a critical role in maintaining a controlled fission reaction. Due to their high concentration of boron, atoms that absorb neutrons, allowing the regulation of the chain reaction's speed and preventing the excessive release of energy in the microreactor, as described by Equation 3.

$$^{10}B + {}^{1}n \rightarrow {}^{7}Li + {}^{4}He. \quad (3)$$

Finally, considering that Figure 4 represents only one-sixth of the final composition of the microreactor core, in Figure 5, it is replicated five times more in order to form a complete hexagon representing the core of a nuclear microreactor. The empty inner hexagon is used as a housing for the ^{241}Am-Be source covered with paraffin. This arrangement allows neutrons to be emitted radially from the center of the hexagon.

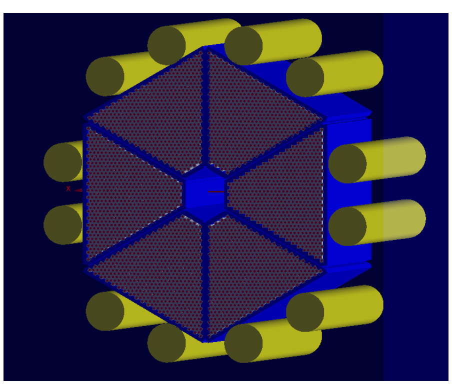

Fig. 5. Modeling of the core of a nuclear microreactor prototype using Geant4$_{TM}$.

This result is the most significant outcome of the research, as it succinctly presents the components of the nuclear microreactor prototype core, displaying dimensions that accurately replicate the symmetry in the cores of these devices, as proposed in nuclear microreactor prototypes.

4 CONCLUSIONS.

This article provides a clear guide on the appropriate dimensions for modeling the core of a nuclear microreactor prototype. This core consists of uranium dioxide UO_2 fuel rods equipped with control drums and neutron moderators to ensure controlled and self-sustaining operation, using simulation with Geant4$_{TM}$. The precise determination of the dimensions of a nuclear microreactor core is of vital importance, as it allows for experimentation with different materials used in the construction of each element to analyze and improve the device's efficiency and overall performance. Having access to the parameters of the Gaussian functions representing the experimental data of a ^{241}Am-Be source is of great relevance. This is because detailed experimental data of such sources are not commonly found in the literature. Having these parameters eliminates the need to search for experimental data, as they allow for a precise approximation in the modeling of the experimental data.

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