



**ANÁLISE COMPARATIVA DA UTILIZAÇÃO DE TÓRIO EM PEQUENOS REATORES
MODULARES COM CÓDIGOS DE MONTE CARLO.**
**COMPARATIVE ANALYSIS OF THORIUM UTILIZATION IN SMALL MODULAR
REACTORS THROUGH MONTE CARLO SIMULATIONS.**

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RESUMO

Este estudo tem como objetivo analisar resultados prévios referentes à substituição do veneno queimável Gadolínio (Gd_2O_3), amplamente utilizado em reatores nucleares, pelo elemento Tório (Th). A proposta busca avaliar e validar a viabilidade do emprego de elementos mais abundantes, capazes de prolongar a produção de energia em reatores nucleares do tipo Pequeno Reator Modular (SMR). A demanda por energia nuclear de baixa emissão de poluentes tem impulsionado a pesquisa em tecnologias inovadoras, com os SMRs emergindo como uma solução promissora. Este projeto explora o potencial do Th, que é mais abundante que o Urânio (U) e com grandes reservas no Brasil, como combustível em SMRs. A pesquisa visa contribuir para a eficiência energética, utilizando programas de simulação baseados no Código de Monte Carlo, como o SERPENT, onde são realizados cálculos de células e elementos combustível para entender o comportamento do tório em comparação com o gadolínio. Essa abordagem visa não apenas proporcionar uma compreensão do uso do tório em SMRs, mas também contribuir para avanços significativos em uma matriz energética mais sustentável e segura, com menor produção de resíduos radioativos e melhor controle de reatividade dos reatores.

Palavras-chave: Tório; Energia Nuclear; Pequenos Reatores Modulares; SMR; Veneno queimável.

ABSTRACT

This study aims to analyze previous results regarding the replacement of the burnable poison Gadolinium (Gd_2O_3), widely used in nuclear reactors, by the element Thorium (Th). The proposal seeks to evaluate and validate the feasibility of using more abundant elements, capable of extending energy production in Small Modular Reactor (SMR). The demand for low-emission nuclear power has driven research into innovative technologies, with SMRs emerging as a promising solution. This project explores the potential of Th, which is more abundant than Uranium (U) and with large reserves in Brazil, as a fuel in SMRs. The research aims to contribute to energy efficiency, using simulation programs based on the Monte Carlo Code, such as SERPENT, where calculations of cells and fuel elements are performed to understand the behavior of thorium compared to gadolinium. This approach aims not only to enhance the understanding of thorium utilization in SMRs, but also to contribute to significant advances in a more sustainable and safe energy matrix, with less production of radioactive waste and better control of reactor reactivity.

Keywords: Thorium; Nuclear energy; Small Modular Reactors; SMR; Burnable poison.

1. INTRODUCTION

According to data collected up to 2025 by the World Nuclear Association (WNA), there are 439 nuclear reactors in operation in the world, in 32 countries, with a total installed capacity of 397,561 MWe, which is equivalent to 9% of global electricity production (WNA, 2025).



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Brazil currently operates two nuclear power plants, Angra 1 and 2, which use pressurized water reactors, each of which can generate a power of 640 and 1350 megawatts (MWe), respectively (ELETRONUCLEAR,2024). These facilities demand extensive installation areas, as well as easy access to a large body of water and still require large amounts of financial investment for construction due to the complexity of high-pressure systems.

As nuclear energy is considered a low-emission energy source, according to the International Energy Agency (IEA), such demand has increased in substitution for energy production systems based on fossil fuels, stimulating innovation and research in the sector. Of these innovations in nuclear technology, the most prominent now has been the SMR-type reactor model.

As described by the International Atomic Energy Agency (IAEA), SMRs are advanced reactors with a power generation capacity of up to 300MWe per unit, about one-third the generating capacity of some conventional nuclear reactors. Its characteristics include a smaller physical size compared to conventional ones, easier transportation due to modularity, greater safety due to passive safety systems and flexibility since they can be installed in remote areas that are difficult to access for other electric power generation systems. Furthermore, its advantages are in the shorter construction time and cost, in addition to having a minimized environmental impact since the duration of its fissile fuel can be several years compared to conventional reactors that are around 1 or 2 years.

Current research involving SMRs using the element ^{232}Th as fuel and burnable poison has been promising, since it is a more abundant element than U in the world and one of the largest Th reserves currently found in Brazil. The ^{232}Th is also responsible for safer reactors since once used as a burnable poison, which are materials that absorb neutrons and can control the reactivity of the reactor by compensating for the excess initial reactivity and maintaining a more stable and safe operation.

2. SMALL MODULAR REACTORS

In the context of the growing mobilization in favor of clean sources of energy generation, research is intensified aimed at solutions that reconcile high efficiency, robustness in terms of safety and high operational reliability. In this scenario, small modular nuclear reactors (SMRs) stand out, whose reduced size compared to conventional reactors makes them well-suited for powering localized grids, serving remote regions, or replacing fossil fuel thermoelectric plants in the process of decommissioning (IAEA, 2020).

Currently, several SMR models are under development around the world, many of which are pending the establishment of regulatory frameworks to enable their commercial implementation. Among its main advantages, in addition to its compact size, is the ability to integrate, in a single module, all the essential systems of a large nuclear power plant. This feature not only optimizes the design, but also significantly raises safety standards, making the technology even more attractive for different energy contexts.

In contrast to SMR designs, conventional nuclear power plants, although widespread, have certain economic disadvantages. The high cost of construction, combined with the long term required for the completion of a project of this size, imposes the need for more robust and far-reaching budget planning. As Kang, Lee, and Lim (2024) point out, the search for economic efficiency, through downscaling, modularization, and standardization, emerges as an innovative alternative, derived from the concept of "economy of scale" historically pursued by conventional nuclear plants. In this context, modular models enable large production, which tends to reduce costs and optimize implementation processes.



3. SERPENT AND MONTE CARLO CODE

SERPENT is a code based on Monte Carlo calculations developed by the VTT Technical Research Centre of Finland, aimed at simulations of nuclear reactor physics. Its main application is in neutron transport calculations, fuel burn (depletion), multi-physics coupled simulations and sensitivity analyses. It is widely used in academic and institutional research for its flexibility in defining geometries, materials, and operating conditions (LEPPÄNEN et al., 2015).

The Monte Carlo Method is based on a set of mathematical techniques applied to the development of calculations in the field of nuclear engineering. This approach involves formulating statistical models for the phenomenon to be represented, thus making it possible to estimate the responses of interest through statistical averages (MAIORINO, 1976).

In addition to enabling the execution of complex calculations in the field of nuclear engineering, the software allows modeling and construction of two-dimensional and three-dimensional cells, enabling detailed graphical analysis of the configuration of these structures. Its architecture allows the segmentation of geometry at multiple levels, through the application of universes, transformations and repetitive patterns, such as square and hexagonal networks, as well as the representation of stochastic geometries, increasing the precision and flexibility of simulations.

3.1. SIMULATIONS

The simulations were carried out to generate data for a comparative analysis, using the same nuclear fuel configuration containing UO₂/Gd₂O₃ or UO₂/ThO₂ arrangements, using the SERPENT program to simulate the isotopic evolution throughout the burning cycle. The objective is to assess the impact of this substitution on fuel geometry in relation to initial and cycle reactivity, burning rate, production of ²³³U isotopes and generation of transuranic waste such as Plutonium 239 (²³⁹Pu).

Simulation Parameters:

- Simplified 2D PWR-type fuel cell geometry
- ²³⁵U Enrichment: 4.6w/o
- Constant temperature: 900 K
- Density of UO₂: 10.28 g/cm³
- Density of UO₂/Gd₂O₃: 10.017 g/cm³
- Density of ThO₂: 10.00 g/cm³
- Burnup period: up to 1750 days

3.2. FUEL CONFIGURATION

The geometric configuration of the rods in the fuel element remains unchanged for both ThO₂ and Gd₂O₃ insertion, as illustrated in Figure 1.

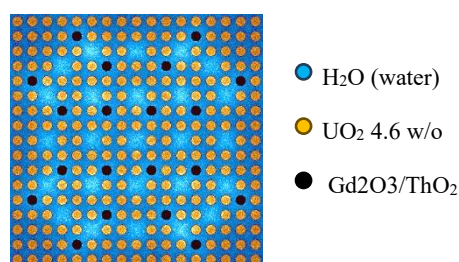


Figure 1 – Fuel element configuration



The incorporation of ^{232}Th into the fuel favors the formation of ^{233}U through neutron capture reactions, allowing its use as an additional fissile material throughout the cycle (IAEA, 2005; MAIORINO et al., 2016). This fertile-fissile conversion represents a relevant energy advantage compared to Gd_2O_3 , whose function is limited to the absorption of neutrons at the beginning of the cycle, without generating useful isotopes after its burning.

4. RESULTS

As demonstrated by Akbari-Jeyhouni et al. (2018), the use of Gd_2O_3 as a burnable poison in a 100 MWe SMR-type reactor causes a marked reduction in initial reactivity, followed by progressive increase as the poison is consumed, requiring strict control of the safety system to avoid reactivity peaks during the cycle. This behavior was confirmed in this study in which the simulation of the burn cycle for a fuel configuration containing $\text{UO}_2/\text{Gd}_2\text{O}_3$ showed a curve with a sharp peak of reactivity around 500 days of operation, followed by a gradual decline until the end of the cycle of approximately 1750 days as seen in Figure 2. This pattern highlights gadolinium's transient absorption behavior, whose progressive burning can generate unwanted variations in reactivity, requiring compensation and control strategies throughout the cycle.

However, the results obtained for the ThO_2/UO_2 mixed fuel show a decreasing and continuous trend of effective reactivity over the burning days, as illustrated in Figure 3. This behavior indicates a more predictable and stable core profile, without the abrupt peaks of reactivity that typically require additional control interventions. The smoothness of the curve

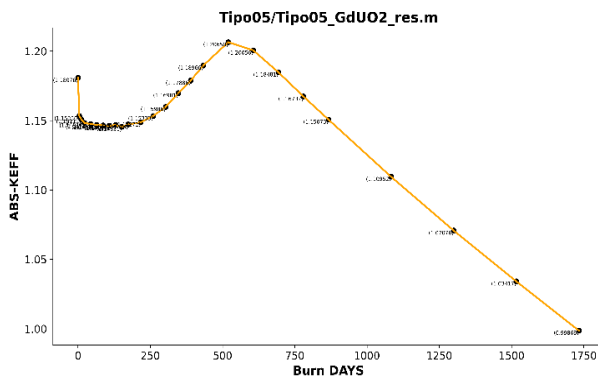


Figure 2 – Burnup $\text{UO}_2/\text{Gd}_2\text{O}_3$

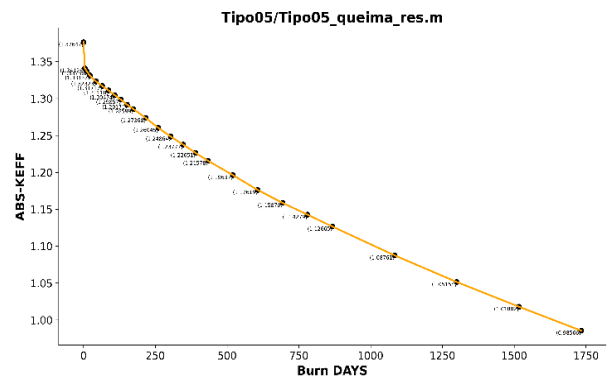


Figure 3 – Burnup ThO_2/UO_2

suggests that thorium, by initially acting as an absorber, facilitates the progressive formation of ^{233}U , as observed in Figure 4, sustaining reactivity efficiently during the cycle. This pattern is in line with previous studies, such as that of Akbari-Jeyhouni et al. (2018), which demonstrated the feasibility of heterogeneous configurations with ThO_2 as a fertile alternative for optimizing cycles in small modular reactors (SMRs).

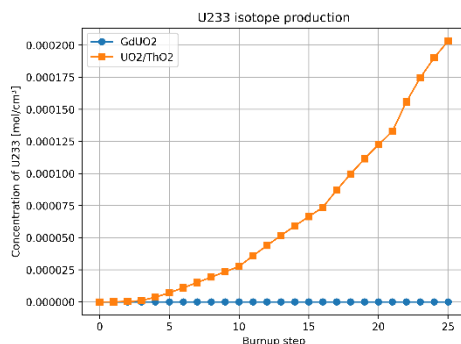


Figure 4 – U^{233} isotope production

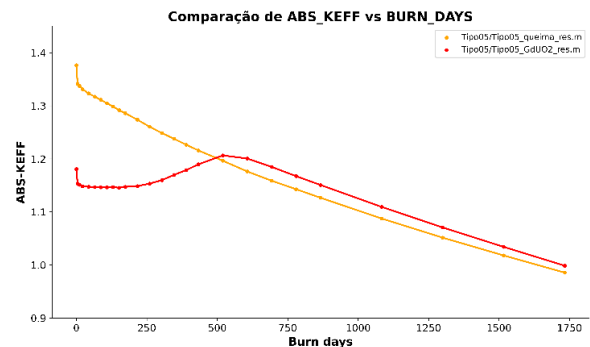


Figure 5 – Comparison of the burn cycle



Although the cycle time is similar to conventional configurations, as in the comparative graph in Figure 5, this approach allows a significant reduction in the use of other burnable poisons, promoting relevant gains in operational safety and neutron efficiency.

In addition, the analysis of the Pu-239 production represented in Figure 6 revealed that the $\text{UO}_2/\text{Gd}_2\text{O}_3$ arrangement presents a higher formation rate of this transuranic isotope, while the UO_2/ThO_2 system demonstrates a more moderate generation.

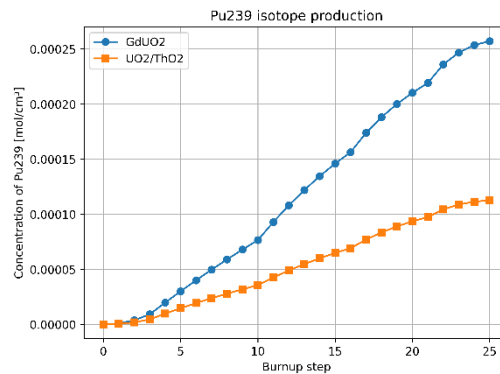


Figure 6 – Pu239 isotope production

This difference in the production of ^{239}Pu has relevant implications from the point of view of nuclear safety and sustainability. The lower generation of ^{239}Pu in fuel with ThO_2 offers a strategic advantage by mitigating proliferation risks, since this isotope can be used in war applications. In addition, it contributes to the reduction of the amount of long-lived radiotoxic waste, which favors the management of tailings and reduces the challenges associated with long-term geological storage. Therefore, the results reinforce the potential of ThO_2 as a promising component for the development of advanced fuels in modular reactors, in line with international guidelines for safety, efficiency and environmental responsibility.

5. CONCLUSIONS

The present investigation showed that the substitution of Gd_2O_3 by ThO_2 as a burnable poison in fuel configurations for SMRs represents a technically viable and potentially advantageous alternative. The simulations carried out with the SERPENT code demonstrated that the use of ThO_2 contributes to a greater stability of reactivity throughout the burning cycle, in addition to favoring the formation of ^{233}U , which implies a more efficient use of nuclear fuel.

Reducing reliance on conventional burnable poisons can result in significant gains in terms of operational safety, simplification of reactive control systems, and optimization of neutronic performance. In addition, the abundance of thorium in the Brazilian territory reinforces the strategic character of this approach, aligning with the guidelines for diversification of the energy matrix and the commitment to more sustainable nuclear technologies.

Based on the simulated results and the reviewed literature, the recommendation to further investigate the use of thorium in SMRs is reinforced, especially considering its potential to reduce the reliance on conventional burnable poisons and improve fuel cycle sustainability.



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