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Parametric study of the heterogeneous assembly with Thorium applied to NuScale.

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1. Introduction.

Around 80% of energy comes from non-renewable sources. According to estimates [1] there is an estimated growth of global demand and energy about 1.5% each year by 2030, with a 25% reduction in carbon dioxide emissions. Faced with this scenario, nuclear energy will assume an increasingly important role in the global energy matrix, because it is clean and sustainable. Most of the 440 existing second generation nuclear plants are light water PWR type and are already in the decommissioning phase, these are supplied with enriched uranium, overall, the high cost of uranium as a fuel, may make the world's existing plants unfeasible. The high cost of the uranium cycle is about $600/kg, [2] (ESA, 2020) so new alternatives such as thorium are needed, much cheaper.

Thorium can revolutionize the world in many ways, especially when compared to uranium when thorium is irradiated by thermal neutrons by the 233U. The process is completely analogous to U238. It is estimated that uranium reserves still have 70 years of useful life, with thorium this time would extend. Thorium is much more concentrated in the Earth's crust than uranium; thorium reserves are about 3 to 4 times larger than uranium [3](U.S. Geological Survey, 2020). This generates a huge production potential during the mining process. In safer and more efficient comparative terms, it is also advantageous from an energy point of view.

Therefore, the third generation Small Modular Reactors (PRM) will have their relevance in the energy matrix of the countries. The (PRM) are PWR type reactors with capacity from 10MW to 400 MW and have several advantages over conventional reactors, such as shorter construction time, modularity, scalability, location flexibility, diverse applications, mass production savings. [4] (T.Ingersoll, 2021) The PRM chosen for the research was the NuScale [5], due to having a cooling passive system, being safer, smaller dimensioning, thus not exceeding the thermal-hydraulic and neutronic parameters (Vujic, M.Bergamann, Skoda, & Miletic, 2012) [6]. In addition, they have lower linear power density and longer cycle length of 24 months. Second (Black, Aydogan, & Koerner, 2019) [7] The high reflection of modularity translates into a general design economy, about 60% cheaper than conventional PWR reactors. The total result represents a general saving of design, simplification, modularity in 37% of direct costs and 80% of indirect costs.

Thorium nuclear reactors are in a good position to take their position on greenhouse gas emissions. Compared to current reactors results in much less radio toxicity. They are safe fuels and important in the area of nuclear non-proliferation, they can be ideas for the environment. In practice there is a significant reduction in the production of plutonium and other actinides and significantly reduces radio toxicity from long-term waste of thorium-based spent nuclear fuels.

The concept was developed by Radkowsky [8] [9] [10] [11]where the reactor consisted of a Seed region, or fissile material, more to the core, is a Blanket region, with fertile material. The proportions defined for the Seed region is 20% U-235 enriched with the part of Blanket with 90% Tho2 (Kasten, 1998) [12]. The regions are based on the volume ratio of the moderator over the volume ratio in the fuel, for the Seed (Vm/Vf=3.2) and Blanket (Vm/Vf=1.9) region. These studies (Maiorino, D'Auria, & ochbelagh, 2018)

(Stefani, Moreira, Maiorino, & Rossi, 2019) [13] [14] demonstrated the high fuel burning capacity with lower production of radioactive products. This being the case, with an agreement on the non-proliferation of radioactive products and nuclear weapons.

We will address the characteristics of the Nuscale reactor design, simulations of the reactor compared to the original reactor in the SERPENT program developed by (Leppanen, 2013) [15]which have allegedly shown their effectiveness in the calculation of nuclear neuron with Monte Carlo Method (MMC) [16].They have been proven to be an excellent tool for simulations (Sjenitizer & Hoogenboom, 2011) [17], with several applications in industry and Academia, despite being very expensive from a computational point of view. We will use the Lobo Carneiro supercomputer cluster from NACAD-UFRJ. Later we will do a simulation of a reactor with thorium NuScale compared to Uranium NuScale and will benchmark, including with results available in references.

2. Methodology

The study was carried out by the computational model used in SERPENT are Monte Carlo Method (MMC) codes applied to reactor physics and used in several research centers, universities and companies. The code is capable of "burning", that is, it calculates the change in the composition of nuclear fuel and reactor materials, as well as neuronic factors over time as a function of power. SERPENT uses data in ACE format from cross section libraries based on ENDF/B-VII. All results were obtained with a neutron population of 20000, for 2000 active cycles, with 200 inactive cycles, ensuring the reliability of the MMC.

The use of thorium in PWR reactors consists of two design concepts for fuels. The heterogeneous and the homogeneous. The heterogeneous design is much better and more effective for converting 232Th into 233U. This is considered a seed region (fissile) closer to the inner core of the fuel element, and an outer region composed of blanket (fertile), called Seed-Blanket-Unit (SBU). The method approach by Radkowsky Thorium Fuel (RTF) in created by Radkowsky. Finally, the homogeneous element considers a seed fuel element and a blanket one, composing the core. This approach, independent Seed-Blanket called Whole Assembly Seed and Blanket (WASB). Other Seed-Blanket-Unit regions, where each element has fertile or fissile regions, Figure 1 represents the idea.

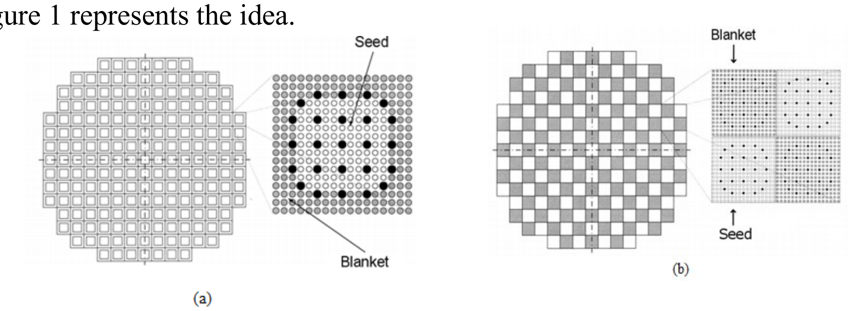

Figure 1-(a) Heterogeneous Loaded Reactor (SBU-RTF), (b) Homogeneous Loaded Reactor (WSAB) [18]

The parametric study with the following proportions of for the seed region (20%wt 235U) at (10%wr 235U) enriched and (20%wt UO2+ 90%ThO2) at (10%wt UO2+90%ThO) for the region of Blanket, a model considering the reactor as a homogeneous reactor mixing water with fissile material, in order to determine the best ratio of the Vseed/Vtotal and Vblanket/Vtotal ratio. Two regions, one with seed (Vm/Vf = 3.2) and with blanket region (Vm/Vf=2.0), according to the literature. Obtain the most effective values for LWR reactors. Criticality of the reactor. Subsequently, to determine the best pitch/diameter ratio for the seed and blanket regions independently, from the volume obtained by the parametric volume study. An approach will be made to examine following the same materials and power density and quantity of number of NuScale rods (17×17). Expect to obtain different diameters and pitch for seed and blanket regions.

The main parameters analyzed in this work (SBU-B) were the K-inf, conversion rate (CR), Beta-effective (Beta-eff), and time generation of prompt neutrons as a function of fuel burning in a total period of

720 days will be compared to the Small reactor Modular Reactor (SMR-NuScale). The K-infinity, as it determines how sustainable the chain reaction in the nucleus will be, (K-inf>=1) indicates that each fission is capable of generating another throughout the study period. The conversion rate (CR) determines the amount of fertile material capable of generating fission is defining by the fissile material over the absorbed, in the higher case >1, it generates more fissile material than it absorbs. The effective-Beta determines the effective delayed neutron fraction reflects the reactor's ability to thermalize and utilize each neutron produced. The generation of ready neutrons, determines the immediate useful life of neutron l, is the average time from the immediate emission of a neutron to its absorption (fission or radioactive capture) or its escape from the system.

3. Results and Discussion

The study determined the best proportion of Blanket Volume 41.53% and Seed Volume 58.47%, totalling 52.856,877 cm³ and seed volume 37.536,123 cm³. The same number of rods from NuScale was selected. To calculate the blanket pitch, total volume divided by the active height 199 cm of the element. When opting for the study with the fixed pitch, varying the diameter of the blanket and seed rod only, as otherwise the dimensional and engineering characteristics of the study would be lost. Despite the higher conversion rate with the increase in the proportion of Blanket Vol/Vt, for a lower proportion of uranium the reaction is not sustainable. Thus, becoming larger than the object of study It is obtained the optimal square area occupied by the total element, being the same total size of the with the number of rods of the Nuscale, thus preserving the characteristics of engineering. The pitch calculation is obtained by dividing the side of the blanket area, by the number of sticks, therefore the 1.2506 cm pitch, for the blanket region. The same reasoning was used to calculate the pitch ratio of the seed region, whose value is 1.245455 cm. Finally, performing an isolated study of each cell, with the concept exposed applied to the fuel rod.The cell with fuel rod with the best seed ratio (Vm/Vf=3.362) and Blanket (Vm/Vf=1.989), as shown configurations of fuel element geometry.

The results are shown in Figure 2, and the respective comparisons between the conversion rate and K-infinity of NuScale and the study model. The Graph 3, represents the comparison of plutonium production in atomic density and uranium burn.The SBU is much smaller than NuScale. The proportion of delayed neutrons is smaller which reflects the reactor's ability to thermalize the neutron. Another important parameter is the reactivity coefficient, as it defines the variation in reactivity with the change in operating temperature. Defined when the reactivity variation divided to temperature variation is from the moderator in pcm, this parameter is called Moderator Temperature Coefficient (MTC), if the temperature is Doppler Temperature Coefficient (DTC) fuel with graphs (a) and (b) in figure 4.

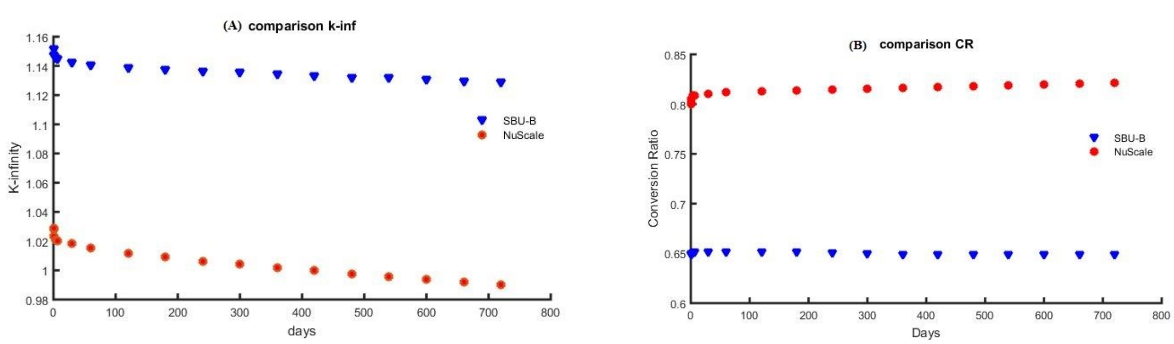

Figure 2- (a) Comparison of NuScale versus SBU-B in relation to K-infinite. (b) Comparison of the NusScale x SBU-B conversion rate.

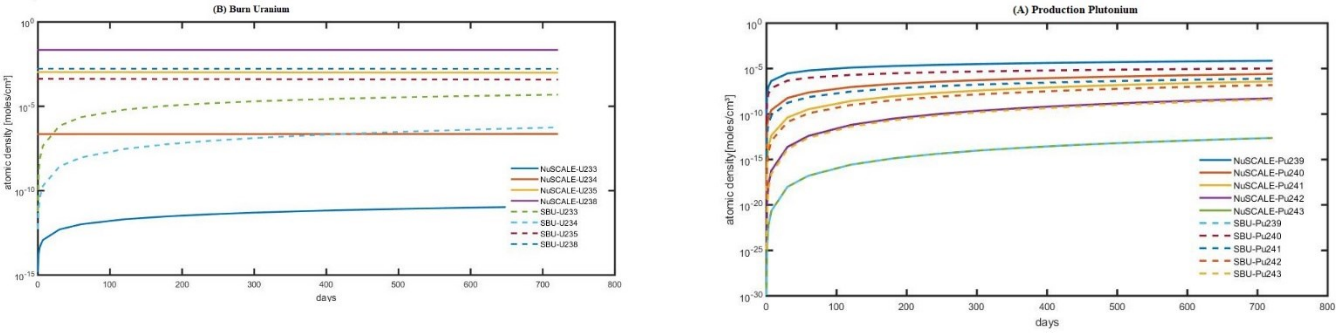

Figure 3- (b) Uranium burn comparison of NuScale x SBU-B and (a) Plutonium production comparison.

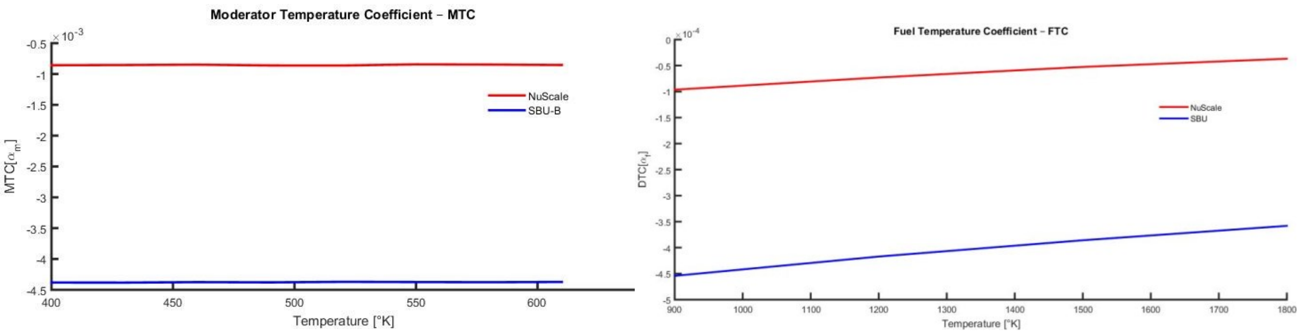

Figure 4-(a) Comparison of reactivity with moderator temperature variation. (b) Comparison of reactivity with fuel temperature variation.

4. Conclusion

In the evaluation of the geometry, a reduction 14-16% of plutonium mainly about 239Pu was obtained .It generated the least amount of fissile plutonium to reduce the generation of long-lived waste (an important sustainability criterion for nuclear energy). It ensured that the kinetic parameters and the reactivity temperature coefficient do not change significantly in order to maintain the current safety and transient behaviour similar; The fuel lifecycle reactor thorium is 24 months or longer as K-infinity is larger and will take more than 720 days to reach subcritical compared to reactor uranium. The SBU is more controllable from a safety point of view. Because the delayed neutron crosses a smaller energy band and is less likely to be lost.

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