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

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1. Introduction

About 80% of the energy comes from non-renewable sources. According to an indicator (IEA, 2021) [7] there is an estimated global energy and demand growth of around 1.5% each year until 2030, with a 25% reduction in carbon dioxide deliveries. In this scenario, nuclear energy will assume this increasingly important role in the global energy matrix, as it is clean and sustainable. Most of the existing nuclear plants are of the second generation, are Light Water (LW) type Pressurized Water Reactor (PWR) and are already in the decommissioning phase.

Third-generation Small Modular Reactors (SMR) will have their relevance in the energy matrix of countries. There are several types of SMR type reactors available on the market with different dimensional characteristics, such as AP-1000, SMR-160, mPower, and finally Nuscale. The SMR are PWR-type reactors with a capacity of 10 MW to 300 MW and have several advantages over conventional reactors, such as shorter construction time, modularity, scalability, location flexibility, diverse applications, mass-production economy. (T.Ingersoll, 2021)[22]

The reason chosen for the research was Nuscale, due to its passive cooling system, being safer, smaller in dimension, thus not exceeding the thermal-hydraulic and neutronic parameters (Vujic, M.Bergamann, Skoda, & Miletic, 2012)[24]. Furthermore, they have lower linear power density and a longer cycle length of 24 months. Second (Black, Aydogan, & Koerner, 2019)[2].The high reflection of modularity translates into overall design savings, about 60% cheaper than conventional PWR reactors. The total result represents overall design savings, simplification, modularity at 37% of direct costs and 80% of indirect costs. All 450 reactors existing in the world are supplied with enriched uranium, from a global point of view the high cost of uranium as fuel could make existing plants in the world unfeasible. The high cost of the uranium cycle is about $600/kg, (ESA, 2020)[5] so new alternatives like Thorium, much cheaper, are needed.

Thorium can revolutionize the world in many ways, especially when compared to uranium when thorium is irradiated by thermal neutrons by 233U. The process is completely analogous to U238 and Pu239. It is estimated that uranium reserves still have 70 years of useful life, with thorium this time would be extended. Thorium is much more concentrated in the earth's crust compared to uranium, the thorium reserves are about 3 to 4 times larger than that of uranium (U.S. Geological Survey, 2020)[23] mining. Comparatively safer and more efficient, it is also beneficial from an energy point of view.

Thorium nuclear fuel reactors are in a good position to take their position on greenhouse gas emissions. Compared to current reactors, it results in much less waste. They are safe fuels and important in the matter of non-proliferation of nuclear weapons, they can be ideas for the environment. The often-claimed thorium cycle produces less plutonium and other actinides and significantly reduces the radio toxicity of the long-term waste of thorium-based nuclear fuels is more accurately described as being comparable to that of uranium-based nuclear fuels. In practice, whether this reduction leads to a significant change in the probability of making a safety case for disposal and whether this translates into a reduction in disposal cost.

The Concept was developing by Radkowsky (Radkowsky, The Seed Blanket Concept, 1985)[16] (Kasten, 1998)[8] (Radkowsky & Galperin, The Nonproliferative light water reactor:A new approach to light water reactor core technology, 1998)[17] (Radkowsky & Shayer, The High Gain Light Water Breeder Reactor with a Uranium-Plutonium Cycle, 1988)[18] where the reactor consisted of a region endowed with seed, or fissile material, closer to the nucleus, is a Blanket region, with fertile material. The defined proportions for the seed region is 20% U-235 enriched, with the Blanket part with 90%ThO2 .The regions are based on the moderator volume ratio over the fuel volume ratio, for the region of seed (Vm/Vf=3.2) and blanket (Vm/Vf=1.9). These works (Maiorino, D'Auria, & ochbelagh, 2018)[12] (Stefani, Moreira, Maiorino, & Rossi, 2019)[21] demonstrated the high fuel burning capacity with lower production of radioactive products. Thus agreeing, with agreement on the non-proliferation of radioactive products and nuclear weapons.

We will discuss the design features of the reactor (NuScale Power LLC, 2020)[15], reactor simulations compared to the original reactor in the SERPENT program developed by (Lepp¨anen, 2013)[10] which allegedly have shown its effectiveness in calculating nuclear neutron with Monte Carlo Method (MCM), see being proven as an excellent tool for simulations (Sjenitizer & Hoogenboom, 2011)[20] (Raychaudhuri, 2008)[19], with several applications in industry and academia, despite being very costly from a computational point of view. We will use the supercomputer Lobo Carneiro cluster from NACAD-UFRJ. Later we will make a simulation of a reactor with thorium against NuScale, and we will make the benchmark, including results available in references.

2. Metodology

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. The program 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 MCM.

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 [17] and [18], advocate of non-proliferation of nuclear weapons and use of thorium fuel. 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.

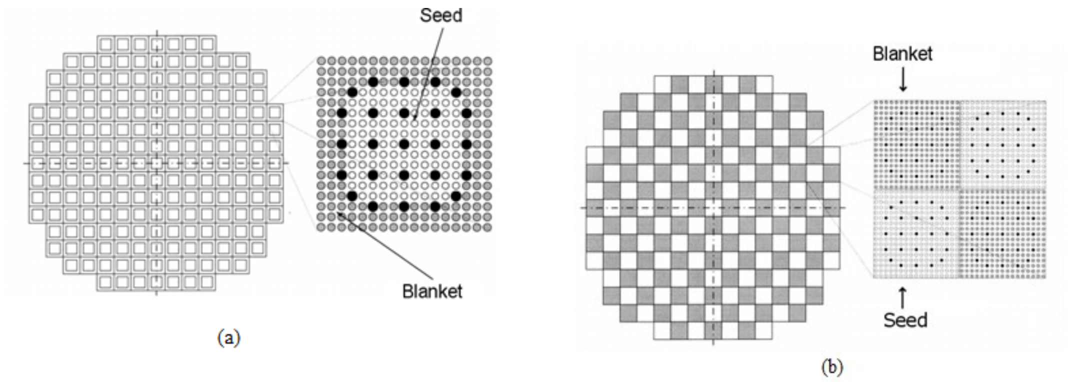


Figure 1-(a) Heterogeneous Loaded Reactor (SBU-RTF), (b) Homogeneous Loaded Reactor (WSAB) (BUSSE, 2000)[3]

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 (A.Galperin & M.Todosow, 2001)[1] 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 pitc h for seed and blanket regions.

The main parameters analyzed in this work 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.

Reference	**K-inf**	**Diference %**	**Observation**	**Moderator**	**Code**
Author	1,02876	*0,0%*	Assembly	H2O	Serpent
(Lindley & G.T.Parks, 2016)[11]	1,18500	*-15,187%*	Assembly	D2O	-
(Keppen, 2020)[9]	1,09500	*-6,439%*	Assembly	H20	SCALE

Table 1 – Computational validation with the author model and other bibliographies

3. Results and Discussion

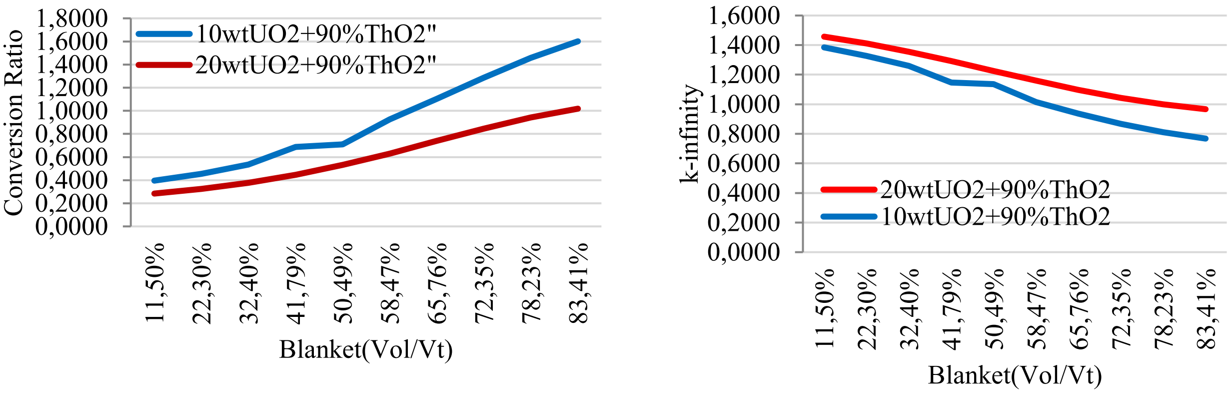
The study determined the best proportion of Blanket Volume 41.53% and Seed Volume 58.47%, totalling 52,856,877 cm^3 and seed volume 37,536.1231 cm^3. The same number of rods from NuScale was selected. To calculate the blanket pitch, it was performed from the total volume divided by the active height

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 characteristics of the study SMR would be lost. Despite the higher conversion rate with the increase in the proportion of Blanket Vol/Vot, for a lower proportion of uranium the reaction is not sustainable. Thus, becoming larger than the object of study. We obtain the optimal square area occupied by the total element, thus the total size of the element obtained was 21.26 cm, by the same number of rods of the SMR-NuScale. 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 by Radkowsky applied to the rod.

The rod with the best seed ratio (Vm/Vf=3.362) and Blanket (Vm/Vf=1.989), as shown in figure 3. In figure 4, there are two configurations of fuel element geometry. The results are shown in Figure 5, and the respective comparisons between the conversion rate and K-infinity of NuScale and the study model. Graph 7 represents the comparison of plutonium production in atomic density and uranium burnSBU is much smaller than NuScale. In figure 6, the proportion of delayed neutrons is smaller which reflects the reactor's ability to thermalize the neutrons Another important parameter is the reactivity coefficient, as it defines the variation in reactivity with the change in operating temperature. Defined by the equation (1) and eq. (2), when the temperature variation is from the moderator, this parameter is called Moderator Temperature Coefficient (MTC), if the temperature is Doppler Temperature Coefficient (DTC) fuel with graphs (a) and (b) in figure 8.

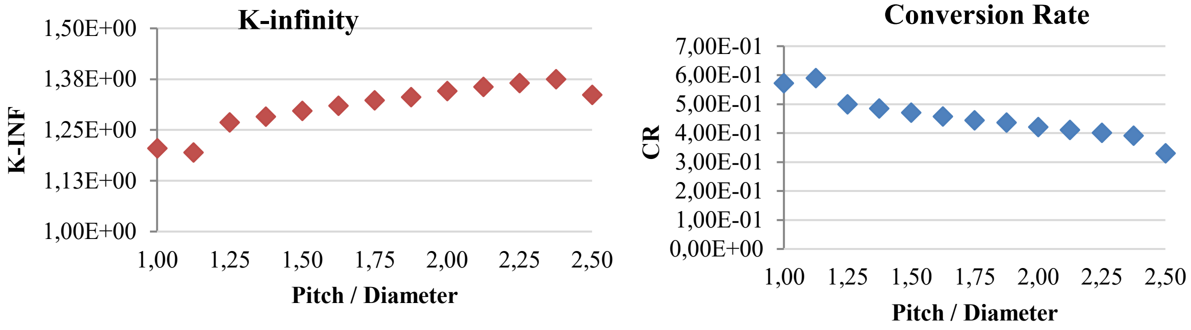
$$\alpha_{fuel} = \frac{d\rho}{dT_f} \tag{1}$$

$$\alpha_{mod} = \frac{d\rho}{dT_M} \tag{2}$$



(a) (b)

Figure 2- (b)Comparison of conversion rate water and fuel mixture and (a) K-infinity for water and fuel mixture.



(a) (b)

Figure 3-(a)K-infinity of the Pitch/Diameter ratio determination. (b)CR of the Pitch/Diameter ratio determination.

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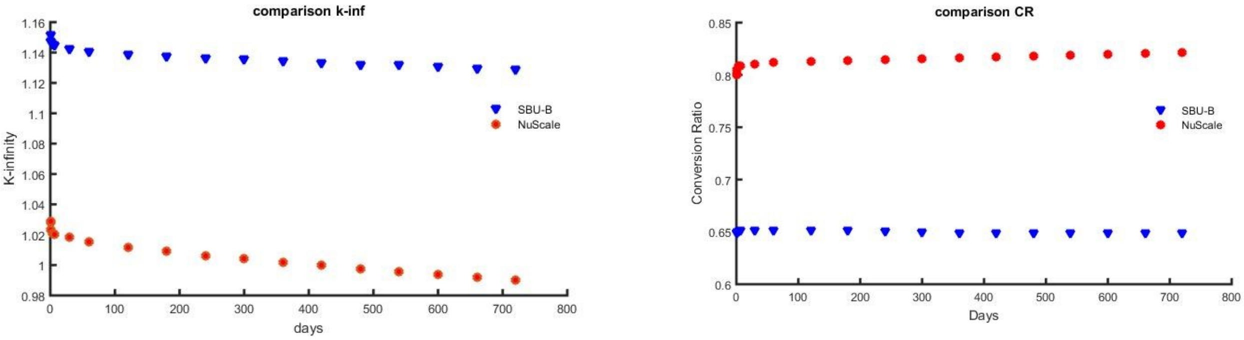
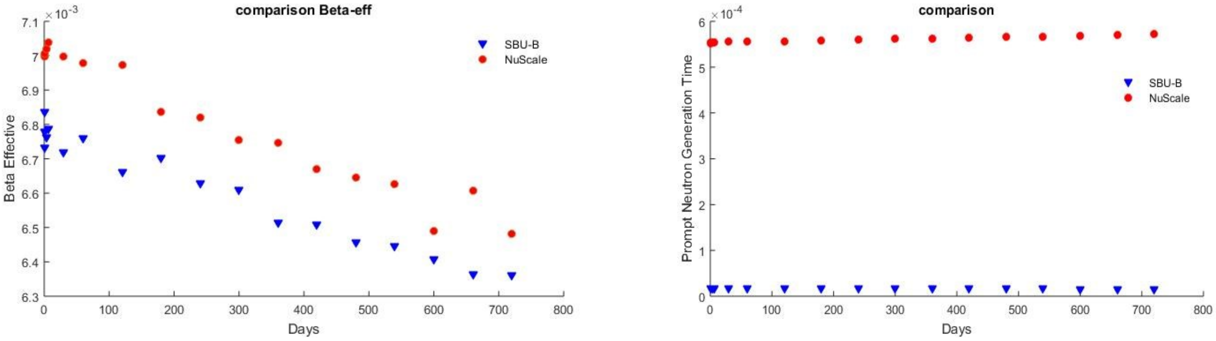
(a) (b)

Figure 4-(a)SBU-B fuel element configuration compared to (b) NuScale-SMR



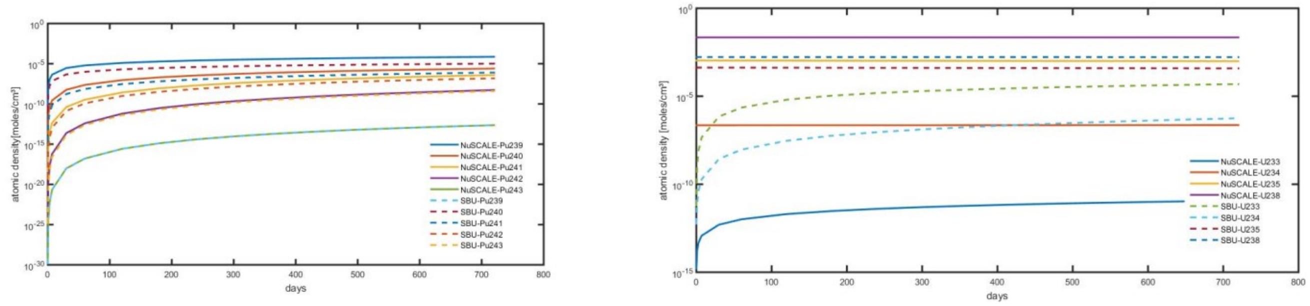
(a) (b)

Figure 5- (a) Comparison relation to K-infinite. (b) Comparison of the conversion rate.



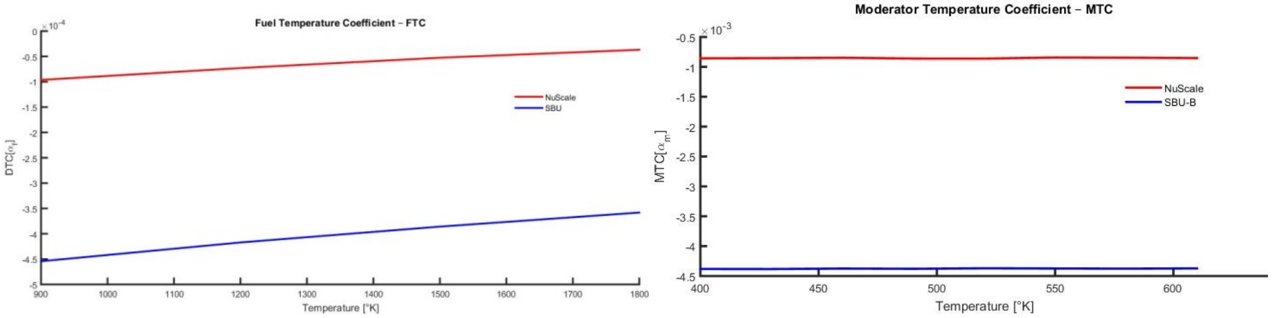
(a) (b)

Figure 6 – (a)Comparison of Beta effective and (b) Comparison prompt neutron generation time.



(a) (b)

Figure 7- (a) Comparison Plutonium production (b)Comparison Uranium burn.



(a) (b)

Figure 8-(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 of 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 is 24 months or longer as K-infinity is larger and will take more than 720 days to reach subcritical compared to NuScale. 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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