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NEUTRONIC ANALYSIS OF A PWR SMR WITH REPROCESSED FUELS

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ABSTRACT

The goal is to initiate studies to evaluate the possibility of inserting reprocessed fuels into Small Modular Reactors (SMRs) based on the Pressurized Water Reactor (PWR) design. In this case, two different reprocessed fuels were evaluated using the GANEX (Extraction of Group Actinides) reprocessing technique; one spiked with thorium, and the other spiked with depleted uranium. The reprocessed fuels substituted the fresh fuels of the equilibrium core, and the core behavior was analyzed. During a fuel cycle, the conversion ratio and the terms of the six-factor formula, responsible for the core's global effective multiplication factor (k_{eff}), have been analyzed, and the three cores, composed with standard fuel (named STANDARD), reprocessed fuel spiked with thorium (named REP-Th) and reprocessed fuel spiked with depleted uranium (named REP-DU), have been compared. This study was carried out using the SERPENT 2.2.1 code with the ENDF/B-VII cross-section library.

1. INTRODUCTION

The NuScale project is a 17x17 small modular reactor (SMR) based on pressurized water reactor (PWR) technology [1]. Although the design project has been discontinued, the NuScale project can still be used to advance SMR studies. In this study, the equilibrium core obtained based on the NuScale FSAR has been obtained using SERPENT 2.2.1 code. After that, considering information and parameters evaluated and developed obtained from the various works in the area of SMR's and reprocessed fuels evaluation carried out by the DEN-UFMG [2-9], two new cores using reprocessed fuels substituting fresh fuels have been designed, one spiked with Th and another spiked with depleted uranium (2%). These reprocessed fuels were obtained using a depleted fuel matrix based on a Brazilian reactor in operation ANGRA I with the GANEX technique, where Pu and MA (minor actinides) are recovered [10], utilizing as a spent fuel matrix, an ANGRA I spent fuel [11,12]. These models were used to evaluate the behavior of conversion ratio (C), that is defined as the ratio between the fissile material created and the fissile material consumed, either by fission or absorption, and the terms of the six-factor formula during burnup when reprocessed fuels are inserted. The evaluated terms of six-factor formula were reproduction factor (η), thermal utilization factor (f), resonance escape probability (p), fast fission factor (ε), for which the product generates k_{inf}, multiplied by the fast non-leakage probability (P_{FNL}) and thermal non-leakage probability (P_{TNL}). These six factors describe the system's inherent capacity for Multiplication directly proportional to the k_{eff} [13]. The reprocessed fuels analyzed in this work are the transuranic fuel spiked with thorium $(TRU\text{-}Th)O_2$ and a transuranic fuel spiked with depleted uranium $(TRU\text{-}DU)O_2$ in your respective models REP-Th and REP-DU, and this study has been carried out using SERPENT 2.2.1 code with ENDF/B-VII cross-section library.

2. METHODOLOGY

2.1 Model development

The core developed has been obtained from [14] that evaluated the better percentage, quantity, and positions of fuel rods with Gd_2O_3 to be inserted in the reactor, analyzing k_{eff}'s by the NuScale FSAR parameters and compared to the other models. The developed core has 37 fuel assemblies 17x17, with assembly pitch = 21.50364 cm and 264 fuel rods with pin pitch = 1.25984 cm, 24 guide tubes, and 1 instrumentation tube. This Standard equilibrium core has 3 types of assemblies, they are: 24 assemblies **Fuel-01** (UO2 with 4.05% of U235), 12 assemblies **Fuel-02** (UO2 with 4.55% of U235 with 16 burnable poison rods (BPR), each containing 6 % of Gd2O3) and 1 assembly **Fuel-03** (UO2 with 2.60% of U235). This percentage and quantity of BPR was a result of comparison between different libraries for different percentages of Gd2O3 and amounts of BPR for the same NuScale model and the value with the lowest fluctuation between libraries was chosen for this model[14]; And 7 subtypes of assemblies: **A-01**- Twice burned - Fuel-01, **A-02** - Twice burned - Fuel-02, **B-01**- Once burned - Fuel-01, **B-02** - Once burned - Fuel-02, **C-01**- Fresh - Fuel-01, **C-02** - Fresh - Fuel-02 and **C-03** - Fresh - Fuel-03. The equilibrium core is represented in Figure 1.1.

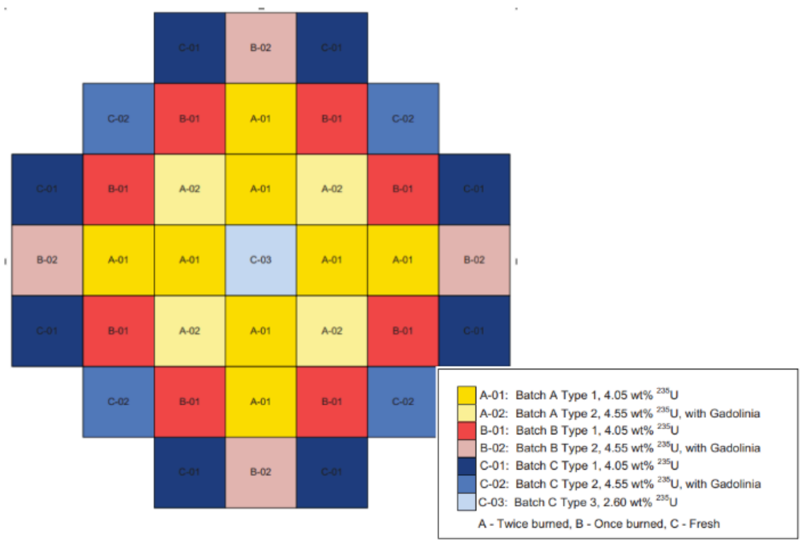

Fig 1.1. Distribution of fuel assemblies in the core on reference equilibrium cycle (Figure taken from NuScale FSAR).

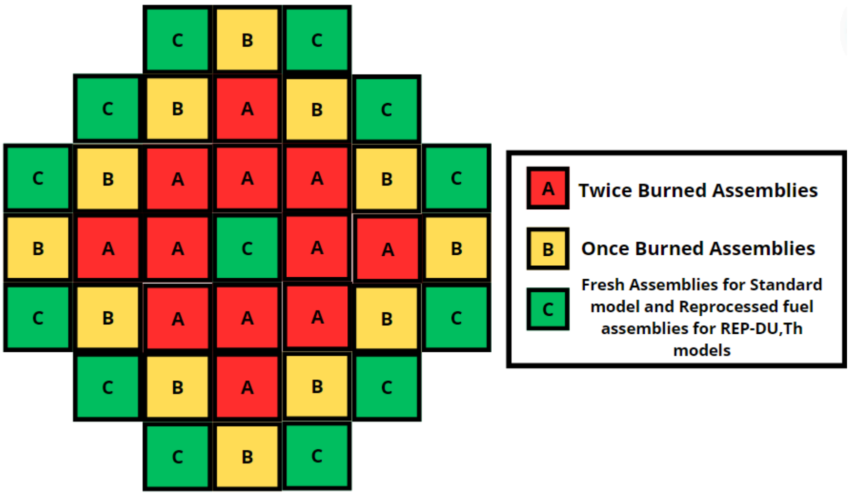

Fig 1.2. The distribution of fuel assemblies in the core on the reference equilibrium cycle is separated, with a core thermal power of 160MW and burnup of 20.67 MWd/kgHM in each cycle, by the number of times burned.

For all cases, a reflective stainless steel (SS304) wall with a thickness of 7,62 cm, a moderator (light water) around the reactor with a 108 cm radius, and a 20 cm moderator column on the top and bottom were added for neutron reflection according to FSAR, were inserted in the model. The following temperatures were used in the simulation using SERPENT 2.2.1 code: water at 600 K, stainless steel at 300 K, fuel at 900 K, helium for the fuel pellet-clad gap at 900 K, and cladding at 600 K [1].

2.2 Obtaining the equilibrium core

To obtain the equilibrium Standard core, the fuel assemblies A-01,02 and B-01,02, assemblies C-01 and C-02 were burned separately for 2 cycles, with a core thermal power of 160MW and burnup of 20.67 MWd/kgHM in each cycle [1], for a total of 41.34 MWd/kgHM, with 200000 neutrons during 1000 histories, discarding the first 300 histories for the convergence, using SERPENT 2.2.1 and ENDF VIIB cross-section library. After obtained the compositions after the respective burnup for each specific assembly, the equilibrium STANDARD core was modeled, inserting the assemblies burned for 1 or 2 cycles into the core in their respective positions as shown in Fig.1.1. The list of isotopes of interest was based on the nuclides considered in the burnup credit criticality analysis for PWR fuels [15] and the xenon and samarium fission products, a poisoning products [13].
For the equilibrium core with reprocessed fuels (REP-DU and REP-Th), the models substitute all the fresh fuels (TYPE C) for reprocessed fuel assemblies. reprocessed fuels were obtained after GANEX reprocessing technique from spent fuel from ANGRA I [11,12]. This reprocessed material has been spiked with fertile material (thorium or depleted uranium) until it obtains the most closely global k_{eff} of the STANDARD model. The k_{eff} difference between the cores models is around 400 pcm. The k_{eff} value was obtained with a percentage of fissile material of 8.24% for REP-DU and 11. 7% for REP-Th at BOC (Begin Of Cycle) [16].

Tab. 1. k_{eff} values obtained for an equilibrium core for different fresh fuels (STANDARD, REP-DU and REP-Th) at BOC.

Core	k_{eff}
STANDARD	1.12665 +/- 14 pcm
REP-DU	1.12674 +/- 16 pcm
REP-Th	1.12645 +/- 16 pcm

2.3 Parameters evaluated

The equilibrium core model (STANDARD), according to FSAR [1], and the core models with reprocessed fuels were evaluated and performed for a 1-cycle burnup for each model. This burnup cycle was 20.67 MWd/kgU, sampling with 200000 neutrons during 300 histories, discarding the first 100 cycles and a heat flux of 160MW for energy normalization. The core takes around 3.2 years to reach the 20.67 MWd/kHM burnup. During this time, the depletion time was divided into 39 steps of 30 days, plus a final step of 15.21 days, to reach the total burnup value. This analysis focuses on the six-factor, using SERPENT 2.2.1 and ENDF VII cross-section library, which makes an estimate when calculating the values of each term according to the specifications of each term [17]. The reproduction factor, **η**, is the ratio between the number of fast neutrons produced by thermal fission and the number of thermal neutrons absorbed in the fuel [13]. The thermal utilization factor, ***f***, describes how effectively the thermal neutrons are absorbed in the fuel [13]. The fast fission factor, **ε**, is the ratio of the total number of fission neutrons (from both fast and thermal fission) to the number of fission neutrons from thermal fissions[13].The resonance escape probability, ***p***, is the fraction of fission neutrons that escape to slow down from fission to thermal energies without being absorbed, defined as the ratio between the number of neutrons reaching thermal energies and the number of fast neutrons decelerating[13]. The neutron can escape while slowing down; as the mean free path of the neutron is relatively large for high energies, this fast neutron leakage has a high probability. However, after slowing down, the neutron can continue to scatter and eventually leak out before absorption. These processes are considered in the effective multiplication factor through the ratio between the number of fast neutrons that do not escape from the reactor core during the slowdown process and the number of fast neutrons produced by fissions at all energies (P_FNL) and the ratio between the number of thermal neutrons that do not escape from the reactor core during the neutron diffusion process and the number of neutrons that reach thermal energies (P_TNL)[13].
For the conversion ratio, the following fissile nuclides, U-233, U-235, Pu-239, and Pu-241, have been considered [17]. For all cases analyzed, the parameters are evaluated during the burnup of each fuel.

3. RESULTS AND EVALUATION OF NEUTRONIC BEHAVIOR DURING BURNUP

3.1.The global effective multiplication factor

During burnup, using SERPENT 2.2.1, the k_{eff} value changes, which can result from many factors. Nevertheless, of the six-factor formula, the only one that varied significantly was **η**. The results presented at the beginning of cycle (BOC), for the STANDARD core, a $\mathbf{k_{eff}}$ = (1.12665 +/- 14 pcm) and **η = (**1.64908 +/- 12) pcm and at End Of Cycle (EOC), a $\mathbf{k_{eff}}$ = (0.917373 +/- 19 pcm) and **η = (**1.41219 +/- 17 pcm) . The REP-Th core initializes in BOC with a $\mathbf{k_{eff}}$ = (1.12645 +/- 16 pcm) and **η = (**1.62320 +/- 16 pcm) and ends (EOC) with $\mathbf{k_{eff}}$ = (0.977605 +/- 18 pcm) and **η = (**1.46679 +/- 17 pcm) , and the REP-DU core in BOC with a $\mathbf{k_{eff}}$ = (1.12674 +/- 16 pcm) and **η** = (1.63525 +/- 15 pcm) and ends (EOC) with $\mathbf{k_{eff}}$ = (0.96342 +/- 19 pcm) and **η** = (1.46292 +/- 19 pcm).

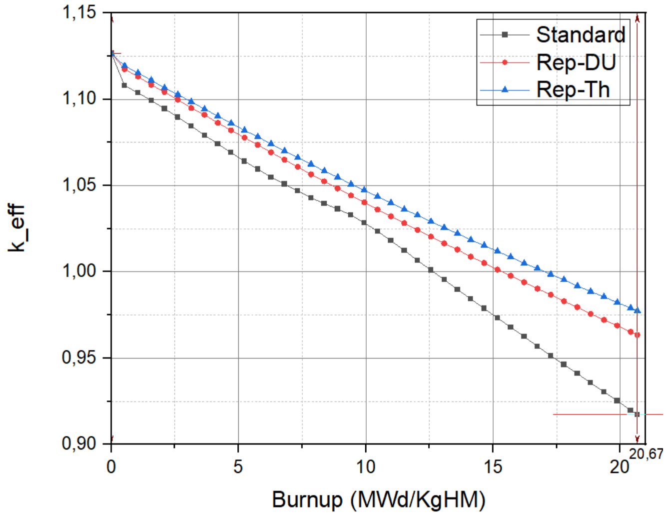

Fig 3.1. Global k_{eff} during burnup.

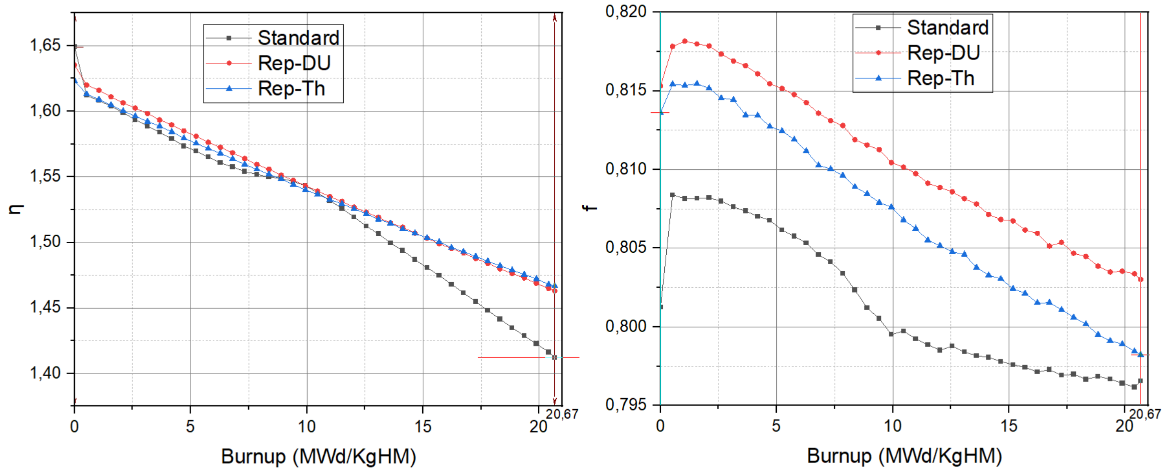

Fig 3.2. Reproduction and Thermal utilization factor for the 3 different models(Standard, REP-DU and REP-Th).

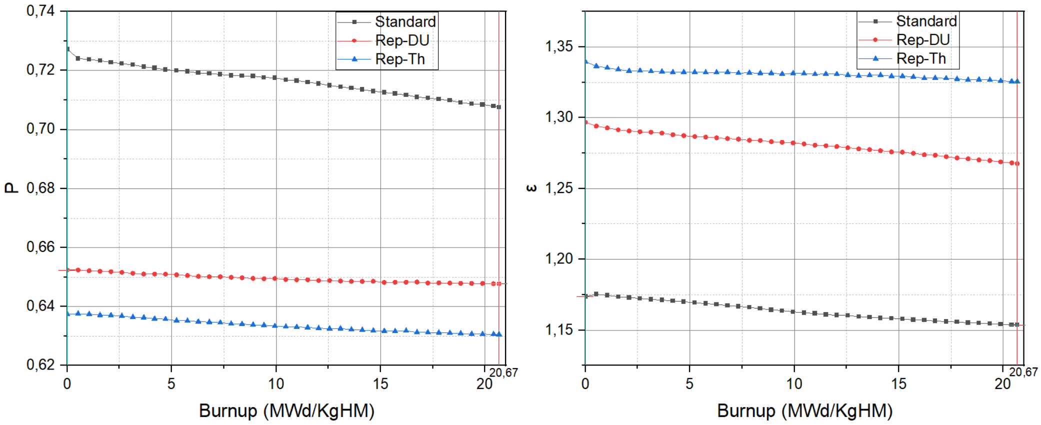

Fig 3.3. Fast fission factor and Resonance escape probability for the 3 different models (Standard, REP-DU and REP-Th).

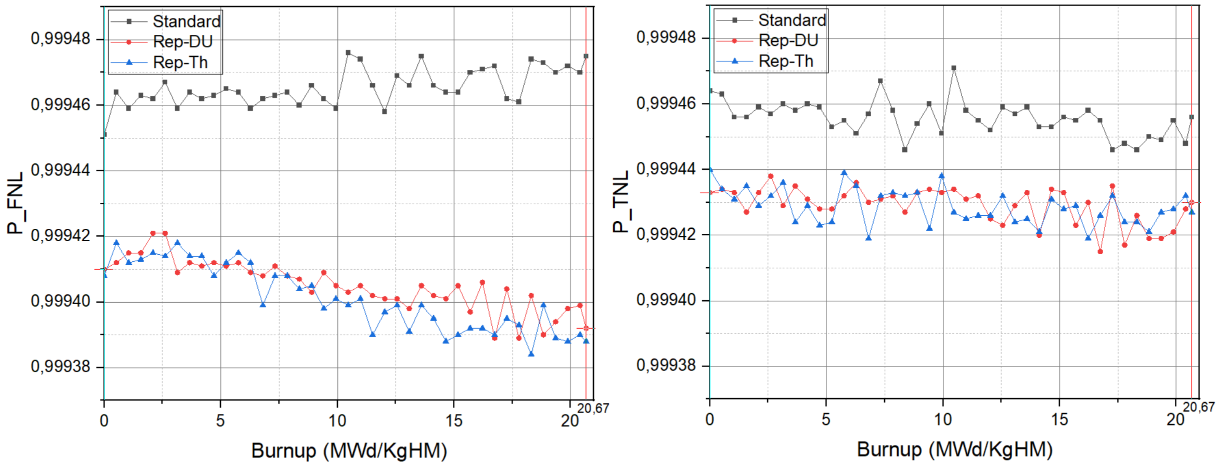

Fig. 3.4: Fast and Thermal Non-leakage for the 3 different models (Standard, REP-DU, and REP-Th).

3.2. Conversion ratio

If C > 1, it is often referred to as the reproduction ratio, as in this case, the reactor is creating more fissile material than it is consuming, which, as can be seen in Fig. 3.1, is not the case with these models[18,19]. Something to be expected is that due to the different amounts of fissile material in the compositions of the models analyzed, the Conversion ratio reaches a higher value for the STANDARD model and a lower one for REP-Th, which is also shown in Fig. 3.1.

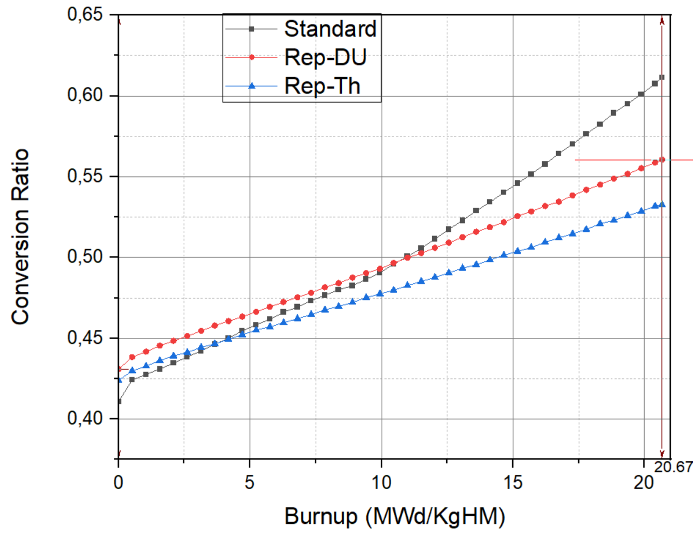

Fig. 3.5. Conversion ratio for the 3 different models(Standard, REP-DU and REP-Th)

4. CONCLUSION

This work analyzed neutronic parameters complementary to other works of this group for the proposed SMR model. It can be seen from the variation of the terms of the six-factor formula that the main impact on the variation of k_{eff} is in the Reproduction Factor, showing that neutron production decreases considerably more for the STANDARD model and remains considerably close for models with reprocessed fuel. By analyzing the other graphs of these terms, greater proximity is observed in the behavior of the models REP-DU e REP-Th. Also, from observing the graphs, such as the conversion ratio, it can be seen that the behavior of the fuels, as expected, has a lower production of fissile atoms per fissile atoms consumed for models with reprocessed fuels since they all have the same design, this is explained by the different composition, as in a reprocessed fuel there is already a greater presence of fissile atoms, which does not happen in the STANDARD model, which is why throughout the burnup this model goes from the model with the lowest conversion ratio to the higher one. It follows the same pattern, showing that the fuels used in this simulation are close to those used in the FSAR of a reactor design, in this case, NuScale reactor.

It shows that using thorium and depleted uranium for spiked reprocessed fuel results in similar fuels. However, using thorium increases the environmental impact of the fuel reprocessing process with the mining and makes the process more expensive. Thus, using depleted uranium to produce reprocessed fuel minimizes the initial impact of mining and minimizes the impact of the final deposition of the fuel. Therefore, using depleted uranium is a more sustainable fuel proposal, as it minimizes the impact on the stages that cause greater environmental degradation in the nuclear energy sector, leaving mining as an option for future generations avoiding the depletion of fundamental resources for nuclear energy.

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