NEUTRONIC EVALUATION OF A FUEL BLOCK OF A GT-MHR USING WIMSD5

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ABSTRACT

The goal is to simulate a representative fuel block of a GT-MHR core to analyze the neutronic parameters behavior due the insertion of Pu isotopes and Minor Actinides (MAs) using shuffling scheme. Initially the fuel block was filled with Driver Fuel (DF), and after burned, these fuels are reprocessed and build the Transmutation Fuel (TF). After some cycles, the fuel block was filled with DF and TF fuels. The DF is a mixture of Pu and Np and the TF is a mix of Pu and MAs. The shuffled scheme was evaluated after each cycle. It was verified that neutronic parameters and isotopic composition reach equilibrium and remain within safety limits when this scheme is used. In addition, there were burnup of MAs. The WIMS code was used in the simulations and the following neutronic parameters were evaluated: infinitive multiplication factor, spectrum hardening and reactivity temperature coefficients.

1. INTRODUCTION

The gas turbine modular helium reactor GT-MHR is one of fourth generation reactors studied in the world. It is a graphite-moderated helium-cooled reactor designed in the United States during the 1990s by General Atomics; a few years ago, MINATOM, FRAMATOME, and Fuji Electric joined the project with the aim of building the first prototype before 2010 [2, 4, 5, 6, 9, 11, 12, 13]. One of its benefits is the utilization of the fuel in the form of actinide oxide confined into TRISO (TRistructural-ISOtropic) particles that is used to achieve a high burnup and a high degree of passive safety. TRISO fuel can be fabricated using plutonium and other TRU elements. The GT-MHR has a very high potential as a TRU transmuter from the physics point of view. The moderation by graphite in a GT-MHR produces valuable opportunities for thermal and epithermal neutrons to interact with fissionable and nonfissionable materials, respectively. In particular, graphite allows for the effective use of the resonance absorption of all the TRUs, including $^{241}$Am and $^{240}$Pu, to provide negative temperature feedback and reactivity control and at the same time counteract the reactivity loss by depletion of $^{239}$Pu, the major fissile nuclide in an LWR TRU vector. Of course, accumulation of some actinides such as $^{238}$Pu, $^{242}$Pu, $^{243}$Am, and $^{244}$Cm is unavoidable because of the graphite moderation [3]. In addition, there is possibility to use a special refueled based to shuffling scheme that displaces the fuel pins after each cycle. Several studies [3, 6, 8, 9, 10, 13] have shown that the
permutation of the fuel pins (shuffle scheme), contribute to an optimization of the GT-MHR fuel burnup. The core is filled with two types of fuel: Driver Fuel (DF) and Transmutation Fuel (TF). The DF supplies the neutrons to maintain the fission chain reaction, whereas the TF emphasizes neutron capture to induce a burn transmutation and provide reactivity control by a negative feedback [13]. In this way, the aim of this work is to simulate a representative fuel block of a GT-MHR core to evaluate two types of recharge. In these analyses, the neutronic characteristics and the fuel composition were compared. Two configurations were studied, one with shuffling scheme and another without, where the fuel block was filled with DF and TF and burnt up in one-step. The WIMS (Winfrith Improved Multi-group Scheme) code was used in the simulations [1].

2. METODOLOGY

2.1. Some core characteristics of the studied reactor

The GT-MHR core studied has a cylindrical geometry with 400 cm radius and 10 m high, filled by 13 x 13 matrices of hexagonal blocks containing fuel and graphite. The core consists of three concentric rings with 36 hexagons fuel block; each fuel block has 20.8 cm side and 7.93 m height. These hexagonal blocks have 108 channels of cooler with 0.797 cm diameter, 144 pins filled with DF and 72 pins filled with TF both with 0.662 cm radius. The cooler channels, which surround fuel pins, has 0.635 cm radius. Reflectors with 1.035 m high cover the top and bottom of the core. The GT-MHR fuel (TRISO) are particles formed by 5 layers being fuel, porous carbon, silicon carbide and pyrocarbon (with 2 different densities), particles whose Driver Fuel have 300µm diameter and ones whose Transmutation Fuel have 200µm [6, 8, 10, 13]. The Fig. 1 illustrates the core, fuel blocks and TRISO.

![Figure 1. Core reactor model](image_url)
2.2. Initial composition and reprocessed scheme

The composition of the fuel was based in previous studies [13]. In this work, the LWR spent fuels are reprocessed by uranium and fission product extraction (UREX) where the final products are Pu-Np and Am-Cm [14]. The Table 1 presents the composition to fresh Driver Fuel (DF) and Transmutation Fuel (TF) used in the simulations and the Fig. 2 shows the scheme to obtain the DF and TF.

Table 1. Initial composition of the fresh fuel in weight percentage to DF and TF

<table>
<thead>
<tr>
<th></th>
<th>$^{237}$Np</th>
<th>$^{238}$Pu</th>
<th>$^{239}$Pu</th>
<th>$^{240}$Pu</th>
<th>$^{241}$Pu</th>
<th>$^{242}$Pu</th>
<th>$^{241}$Am</th>
<th>$^{243}$Am</th>
<th>$^{244}$Cm</th>
<th>$^{16}$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>4.587</td>
<td>1.323</td>
<td>50.283</td>
<td>20.290</td>
<td>7.322</td>
<td>4.411</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>11.784</td>
</tr>
</tbody>
</table>

Figure 2. Scheme to obtain DF and TF

2.3. Geometry and refueled scheme

If keeping the same ratio $V_M/V_F$ of active core reactor (108 fuel blocks) it is possible to represent it in a single representative fuel block, maintaining the different fuels and even recharge scheme. This representative fuel block was modeled by a graphite cylinder contains 36 fuel pins (18 DF and 18 TF) distributed in three regions (or rings): inner ring, central ring and outer ring. Each fuel pin has five layers containing in that order: Fuel, Porous Carbon + Pirocarbon, Silicon Carbide, Coolant and Reflector. The Fig. 3 shows the design of representative fuel block for these configurations. An important factor in this reactor is the fuel permutation where after an interval of the time the fuel is displaced in the reactor core. To study the shuffling scheme influence, two cases of burnup scheme were studied: First (C1) without shuffling scheme and second (C2) with shuffling scheme. The case C1 had four cycles of 990 days with a daily burnup of 357.6 MW/THM. In the beginning of the cycle, all the rings of the fuel block were filled with fuel pins. Each ring has 6 DF and 6 TF fuels. The fuel batch remained in the reactor for 990 days. Thus, in the end of 990th day, all the fuel pins were removed of the reactor and fresh fuel pins were inserted. The case C2 had twelve cycles of 330 days with a daily burnup of 357.6 MW/THM where in the end of each 330th day the shuffling scheme was applied. In this configuration, each batch of fuel pins remained in the reactor for 990 days remaining 330 days in each ring. In other words, each batch of fuel pins remained in the reactor for 3 cycles where in the first cycle, this batch was in the inner ring; in the second cycle, it was in the central ring and, in the third cycle, it was in the outer ring. In the first cycle of reactor, only the inner ring was loaded with DF. In the second cycle, the DF was shuffled into the central ring and fresh DF was loaded again in the inner ring. In the
third cycle, the DF from central ring was moved into the outer ring, and the fuels of inner ring took their places; the inner ring was loaded again with fresh DF. After the third cycle, the outer ring fuels were reprocessed to Pu and MAs recovery and mixed with Am and Cm composition from LWR fuel reprocessed to build the Transmutation Fuel (TF). In the beginning of fourth cycle, the inner ring was fueled with TF. In this way, the inner ring had 6 TF pins and 6 DF pins. In the fifth cycle, DF and TF of the inner ring were shuffled into central ring, and inner ring was loaded with fresh TF and DF. This process continued until all rings had TF and DF (6th cycle). Thus, after the 6th cycle, all the rings have TF and DF and the shuffling process continues until last cycle (12th).

![Schematic representation of the configuration used in the WIMS code.](image)

**Figure 3.** Schematic representation of the configuration used in the WIMS code.

### 3. RESULTS

#### 3.1. Neutronic Parameters Evaluation

Figures 4, 5, 6 and 7 show the neutronic parameters behavior. Each peak represents a cycle. The C1 configuration has 4 cycles of 990 days so it presents four peaks. As the C2 configuration has 12 cycles of 330 days, it presents twelve peaks. To all cases studied, in the beginning of each cycle occurs an abrupt change in neutronic parameters values. This behavior is due to the insertion of new fuels in the beginning of each new cycle that changes the isotopic composition of the fuel block. Analyzing each individual configuration, the C1 does not show different behavior on the neutronic parameters, between the cycles. Nevertheless, in the C2 configuration, there is a notable variation between the 1st and 6th cycle. There is a gradual reduction in the variations of the neutronic parameters with the number cycles increase. This behavior is due the recharge scheme used in each case. In the shuffling scheme (C2), after the 6th cycle, all the rings have DF and TF. Therefore, to next cycles, there are less variation in the initial composition and consequently less variation in the neutronic parameters. Hence, the shuffling scheme produces a softening in the neutronic parameters.
Fig. 4 shows the behavior of the infinity multiplication factor. To configuration C1 the $k_{\text{inf}}$ variations is approximately 0.45 and to C2 configuration this variation is about 0.1. Thus, the $k_{\text{inf}}$ variation is lesser when the shuffling scheme is used (case C2). This behavior contributes to neutron economy providing an extension of burnup.

Fig. 5 presents the behavior of the fast to total flux versus time. There is a softening neutron spectrum during the burnup to the cases studied. This behavior is probably due the high quantity of the graphite in the fuel block. In the configuration C2, the spectrum to 1st and 2nd cycle is more softening than others cycles. This happens because at 1st and 2nd cycles there is less fuel than the other cycles. Then, the $V_M/V_F$ ratio is bigger than other cycles providing a softening of the spectrum.

Fig. 6 and 7 show the behavior of the reactivity temperature coefficient to fuel ($\alpha_{\text{TF}}$) and moderator ($\alpha_{\text{TM}}$). To analyze the $\alpha_{\text{TF}}$ and $\alpha_{\text{TM}}$ parameter the corresponding temperature was increased to 100K. The $\alpha_{\text{TF}}$ parameter remained negative and decreased during the burnup to all configurations. However, the $\alpha_{\text{TM}}$ parameter increased during the burnup to all configurations becoming positive after the 900th day to the C1 configuration limiting the burnup.

![Figure 4. Infinitive Multiplication Factor versus Days](image)

![Figure 5. Fast Flux/ Total Flux rate versus Days](image)
3.2. Isotopic Composition

Considering the results presented by the configurations C1 and C2, it was evaluated its isotopic composition evolution during the burnup.

Figures 8 to 11 shows the mass variation of the isotopes Pu, Np, Am and Cm in the BOC (B) and EOC (E), to C1 configuration. Due the recharge scheme of this configuration, the three rings have the same initial composition. As the daily burnup value is the same in all rings and cycles, the final composition in the three rings are similar to four cycles. In this way, Figures 8 to 11 present the mass variation to a ring. These figures show a decrease of the total mass of Pu and Np but an increase of Am and Cm to DF and TF. There is a decrease of $^{239}$Pu and $^{237}$Np and an increase to $^{243}$Am, $^{242}$Cm, $^{244}$Cm and $^{238}$Pu. This increase may be contributing to reduce of the reactivity temperature coefficients (see Fig. 6 and 7) due the large thermal absorption cross section of these isotopes.
Figure 8. Driver Fuel composition in the BOC (B) and EOC (E) to C1 configuration

Figure 9. Driver Fuel composition in the BOC (B) and EOC (E) to C1 configuration

Figure 10. Transmutation Fuel composition in the BOC (B) and EOC (E) to C1 configuration
The figures 12 to 23 show the isotopic variations to C2 configuration. These figures presents the mass of Np, Pu, Cm and Am in the beginning (B) and in the end (E) of each cycle to each ring. Can be observed that DF and TF compositions tend to reach an equilibrium state. Analyzing DF, there is a decrease in the total mass of Np and Pu but an increase of Am and Cm in the end of each cycle. However, the total mass of Np and Pu in the end of 12th cycle is greater than it was in the end of 1st cycle; for Am and Cm the total mass decreases. Figures 12 to 17 illustrate this behavior. In the 1st cycle, only DF, in the inner ring, generates the power. In the 2nd cycle, the power is generated by the DF of the inner and central rings and in the 3rd cycle, by the DF of the three rings. Therefore, in 2nd and 3rd cycles, there will be a gradual reduction in the burning of the DF in each ring. In this way, there will be a gradual decrease in the mass variation with the increasing number of cycles.
Figure 13. Driver Fuel composition in the central ring at BOC (B) and EOC (E) to C2 configuration

Figure 14. Driver Fuel composition in the outer ring at BOC (B) and EOC (E) to C2 configuration

Figure 15. Driver Fuel composition in the inner ring at BOC (B) and EOC (E) to C2 configuration
Analyzing TF, there is a decrease in the total mass ofPu, Np, Am and Cm in the end of each cycle. Figs. 18 to 23 show this behavior. The total mass of Am and Cm in the end of 12th cycle is less than the 4th cycle (see Fig. 17). However, the total mass of Pu and Np in the end of 12th cycle is greater than the 4th cycle (see Fig. 14).

Comparing Figs. 12 to 17, the DF displacement of the inner to outer ring generates a decrease in the total mass of Pu and Np and produce an increase in the total mass of Am and Cm. This behavior is due the incineration of Pu and Np and the accumulation of the Am and Cm as the burnup. The increase of these isotopes may be causing a hardening spectrum with the increasing number of cycle, reaching equilibrium after the 6th cycle (see Fig. 5). In addition, with TF displacement, there is a decrease in the total mass of the Pu, Np, Am and Cm (Figs. 18 to 23).

With the objective analyze the global results in the composition to C1 and C2 configuration; the Figs. 24 and 25 presents the initial composition before the burnup (Beginning of Life - BOL) and the final composition after the burnup (End of Life - EOL) to a same bath of DF and TF. To C2 configuration was evaluated the 7th batch. Comparing the DF in BOL and TF in EOL, both the configurations present reduction of $^{239}$Pu and $^{237}$Np and increase of $^{243}$Am,
\(^{238}\text{Pu}\) and \(^{242}\text{Pu}\). The \(^{239}\text{Pu}\) supply the reactivity in the cycle and its reduction decreases the \(k_{\text{inf}}\) values during the burnup (see Fig. 4). In addition, the \(^{238}\text{Pu}\) and \(^{242}\text{Pu}\) are parasitic absorbs and its isotopic increase during the burnup contribute to this behavior. The \(^{237}\text{Np}\) has a large cross section to thermal absorption. The decrease of \(^{237}\text{Np}\) is probably due its thermal absorption that after beta decay transmute in \(^{238}\text{Pu}\). Evaluating the TF, there is a decrease to \(^{241}\text{Am}\) and increase to \(^{242}\text{Cm}\). The \(^{241}\text{Am}\) has a large thermal capture cross section and a large capture resonance integral. Therefore, its decrease is probably its thermal absorption and transmutation in \(^{242}\text{Cm}\).

Figure 18. Transmutation Fuel composition in the inner ring at BOC (B) and EOC (E) to C2 configuration

Figure 19. Transmutation Fuel composition in the central ring at BOC (B) and EOC (E) to C2 configuration
Figure 20. Transmutation Fuel composition in the outer ring at BOC (B) and EOC (E) to C2 configuration

Figure 21. Transmutation Fuel composition in the inner ring at BOC (B) and EOC (E) to C2 configuration

Figure 22. Transmutation Fuel composition in the central ring at BOC (B) and EOC (E) to C2 configuration
Figure 23. Transmutation Fuel composition in the outer ring at BOC (B) and EOC (E) to C2 configuration

Figure 24. Isotopic weight percentage of one batch in BOL and EOL at BOC (B) and EOC (E) to C1 configuration

Figure 25. Isotopic weight percentage of 7th batch in BOL and EOL at BOC (B) and EOC (E) to C2 configuration
The configuration C1 has bigger isotopic mass variation than configuration C2 between BOL and EOL. Between the two configurations, the case C2 presents less reduction of Pu but shows less increase of $^{243}$Am, $^{242}$Cm and $^{244}$Cm. In this configuration, the average of the reactivity temperature coefficients values is lesser than C1 configuration. Because of the large epithermal absorption resonances in the plutonium isotopes, the moderator and fuel temperature coefficients tend to be more negative. Thus, these behaviors generate less variation in the reactivity temperature coefficients to case C2 as analyzed previously.

Table 2 shows the final comparisons to C1 and C2 configurations to DF and TF. This table presents the behavior of the isotopes during the cycles and the sum of final mass after the burnup. To both configurations, there are a reduction of Pu and Np to DF and TF but an increase of Am and Cm to DF. Between the studied cases, the configuration C1 presents more reduction of Pu and Np (to DF and TF), but more accumulation of Am and Cm (to DF). The discrepancy between the two configurations is in isotopic composition behavior of Am and Cm to TF. The configuration C1 shows an increase and C2 presents a reduction these isotopes. The case C1 presents 24 kg more than C2 in the final composition of Am and Cm. This behavior may be due the shuffling scheme that put the fuel pins in different regions and provides different neutron flux.

| Fuel Type | Isotopes | Configuration C1 | | Configuration C2 | |
|-----------|----------|------------------|-------------------------------|------------------|
|           |          | Behavior in the cycles | Final Mass Sum | Behavior in the cycles | Final Mass Sum |
| DF        | Pu – Np  | Reduction         | 175 kg                  | Reduction         | 225 kg         |
| DF        | Am – Cm  | Increase          | 13 kg                   | Increase          | 9 kg           |
| TF        | Pu – Np  | Reduction         | 115 kg                  | Reduction         | 121 kg         |
| TF        | Am – Cm  | Increase          | 47 kg                   | Reduction         | 23 kg          |

### 4. CONCLUSIONS

Between the studied configurations, the case C2 (with permutation of the fuel pins) generate small changes in the neutronic parameters and causes the reactivity temperature coefficients remain negative during all cycles. In this case was observed that the increase in the number of cycles produce stabilization in the isotopic composition. This stabilization generates less variation of the neutronic parameter evolutions. After the cycles, the configuration C2 presents more quantity of Pu and Np than configuration C1. In the other hand, the concentration of Am and Cm is lesser to configuration C2 (see table 2). This way, the shuffling scheme is more efficient to transmutation of Am and Cm although presents more accumulation of Np and Pu. Nevertheless, a high concentration of the isotopes $^{238}$Pu or $^{240}$Pu is particularly undesirable to potential proliferators because of their very high rates of radiation and decay heat, which complicate handling and manufacturing, and of spontaneous neutron emissions, which can affect the reliability and overall yield of the ultimate device [7]. Therefore, this is an important factor within a nuclear nonproliferation scenario.

Overall, the results indicate that, to obtain an extension of the cycle through the burning of Pu isotopes and MAs, the pin permutations must be used to obtain safe neutronic parameters.
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