Determination of the combined effect of boron and gadolinia on the reactivity and safety parameters of (U, Th)O$_2$ fuel

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**Abstract.** This study investigated the combined effect of boron in light water moderator and gadolinia in fuel on the neutronic properties of (U, Th)O$_2$ fuel in Westinghouse small modular reactor. The reactivity control of boron and gadolinia, and the potential of gadolinia in increasing thermal conductivity of its mixed fuel pellet motivated this study. Monte Carlo N-particle code integrated with CINDER90 was used for the calculations. Four fuel assemblies were used: one without boron and gadolinia, one with borated water only while the other two contained borated water plus 16 and 24 gadolinia fuel rods in each of the FAs. The BOC safety parameters was calculated at hot zero power (293.6 K) and hot full power (600 K). The results showed that the moderator temperature coefficient of reactivity was highest in FA without boron and gadolinia and smallest in FA containing boron plus 24 gadolinia fuel rods, while a reverse phenomenon was observed for the fuel temperature coefficient of reactivity. The effective delayed neutron fraction was slightly larger in FA without neutron absorber. The results show that boron and gadolinia decreased significantly the MTC but increased FTC slightly in addition to their initial neutron multiplication suppression role.

1. **Introduction**

During normal reactor operation, starting from the beginning of cycle (BOC) and to the end of cycle (EOC), the state of nuclear reactor as a multiplying medium requires a balanced neutron multiplication [1]. Although, the desire of every reactor operator is to maintain criticality (where the neutron multiplication factor is unity), some level of excess reactivity (supercritical) is needed to maintain normal reactor power over a long period of fuel burn-up [2]. This balanced reactivity is achieved using reactivity control materials. Indeed, mechanical control rod was the only reactivity control measure used in the early stage of nuclear reactor especially in light water designs (PWR and BWR) while innovative soluble boron chemical shim and burnable neutron absorber materials were introduced in the later stage of nuclear technology [3]. Presently, reactivity control mechanism, especially in large light water...
reactors, involves the use of integral fuel burnable absorber (IFBA) in fuel and soluble boron in coolant water for the BOC reactivity control and normal operational flux flattening, respectively.

Today, reliable data and experience have been gained on the use of UO₂ fuel for different nuclear reactor operations, but such cannot be said for thorium fuel that is undergoing series of research and development processes. The Westinghouse small modular reactor (W-SMR) core design with UO₂ reference fuel contains IFBA and pyrex for reactivity control. However, this study group is proposing a W-SMR thorium core utilising IFBA only for BOC reactivity control owing to the large thermal neutron absorption cross section of ²³²Th. It is therefore, pertinent to determine the combined reactivity effect of boron and gadolinia burnable absorber and their potential impact on reactor safety parameter in (U, Th)O₂ as a potential UO₂ fuel alternative in the nearest future. This is very important for SMR and (U, Th)O₂ owing to the role of safety parameters as a reactor design and fuel option deciding factor.

This study was to determine the impact of soluble boron and gadolinia on moderator temperature coefficient of reactivity (MTC), fuel temperature coefficient of reactivity (FTC), delayed neutron fraction and average neutron generation time in (U, Th)O₂ fuel. The W-SMR was used because of its design and passive safety system similarity with AP1000 core and the existing technical know-how on the operation of PWRs. The benchmarked MCNPX integrated with CINDER90 burn-up code was used for the calculations [4].

2. Material and method

Four robust fuel assemblies with boron and gadolinia used in this study are shown in Figure 1. The detailed description of the dimensional values is described in ref. [5]. Table 1 contains (U, Th)O₂ fuel and other material specifications used. The four sets of Fuel Assemblies (FAs) filled with the same (U, Th)O₂ fuel were independently studied: one without boron and gadolinia, one with 3600 ppm concentration of soluble boron in the moderator while the other two contained the same boron concentration in moderator plus 16 and 24 gadolinia fuel rods in each of them. MCNPX 2.7 version with ENDF/B-VII.0 evaluated nuclear data library was used to model the FA geometry as shown in figure 1. As a general-purpose, time-dependent and generalised-geometry simulation code, MCNP uses a continuous energy cross-section library to solve particle (e.g. electron, photon, neutron and coupled system) transport problems.

The beginning of cycle (BOC) safety parameters were calculated at 293.6 K hot zero power and 600 K hot full power. For the calculation of MTC and FTC, the temperature cross sections 70c, 71c and TMP card were adequately used on the fuel, moderator and other related materials at the material and cell cards. For the MTC, the light water temperature was lowered from the 600 K to 293.6 K while the fuel temperature remained at hot full power. This was achieved in MCNP by changing the moderator cross section libraries from 71c to 70c and its density from operating density to room density of 99.9 g/cc. For FTC, the moderator remained at its room temperature and density while the fuel temperature was lowered to 293.6 K without change in density since temperature change has a negligible effect on the fuel density. The prompt neutron multiplication factor \(k_{\text{prompt}}\) was calculated by setting TOTNU card to “NO”. In each case, MCNPX performed KCODE calculation to determine the corresponding infinite neutron multiplication factors \(k_{\text{inf}}\), \(k_{\text{ref}}\) and \(k_{\text{prompt}}\). The binding energy effect of hydrogen in light water was accounted for by using thermal treatment \((S(\alpha, \beta))\) capability of MCNPX. The KCODE calculation was performed in each of the four FAs to determine the infinite neutron multiplication factor \(k_{\text{inf}}\) at normal reactor operating conditions. Use was made of 10,000 initial neutrons source, 50 ineffective and 300 effective cycles and 1.0 initial guess of effective criticality with WIMS 69 energy group at 9MWth fuel assembly thermal power. The MTC, FTC and delayed neutron fraction were calculated by using (1), (2), (3) and (4) accordingly. The average neutron generation time was calculated by using (5) which is equal to the prompt neutron lifetime at criticality. The calculation of prompt neutron removal lifetime was done by MCNPX.

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Figure 1. Horizontal cross-sectional view of the modelled fuel assemblies.

Table 1. Composition of fuel and other materials.

| Material/Fuel            | Heavy metal weight percent (w/o) | Density (g/cm$^3$) |
|-------------------------|----------------------------------|--------------------|
| Fuel 1: (U, Th)O$_2$    | $^{235}$U: 13.8, $^{238}$U: 11.2, Th: 75 | 11.5               |
| Fuel 2: (U, Th)O$_2$ + Gd$_2$O$_3$ | $^{235}$U: 13.8, $^{238}$U: 11.2, Th: 66.4 Gd: 8.6 | 11.012             |
| Cladding: Zircaloy-4    | Sn: 1.3 Fe: 0.23 Cr: 0.27 Zr: 98.20 | 6.56               |
| Reflector               | Light water (H$_2$O)              | 0.756              |
| Gap                     | Helium gas (He)                   | 0.00164            |
| Gadolinium isotopes     | $^{152}$Gd: 0.20, $^{154}$Gd: 2.18, $^{155}$Gd: 14.80, $^{156}$Gd: 20.47, $^{157}$Gd: 15.65, $^{158}$Gd: 24.84, $^{160}$Gd: 21.86 | 7.9                |

\[ MTC = \frac{\delta \rho}{\delta T} = \delta \rho \left( \frac{1}{T_{hf} - T_{hp}} \right) \quad (1) \]

\[ \delta \rho = \frac{k_{inf} - k_{hp}}{k_{inf} \times k_{hp}} \quad (2) \]

\[ FTC = \frac{\delta \rho}{\delta T} = \delta \rho \left( \frac{1}{T_{hf} - T_{hp}} \right) \quad (3) \]

\[ \beta_{eff} = \frac{k_{inf} - k_{prompt}}{k_{inf}} \quad (4) \]

\[ \Lambda = \frac{\ell_{prompt}}{k_{inf}} \quad (5) \]

where,

$\delta \rho$ = Change in reactivity due to change in either moderator or fuel temperature,

$\delta T$ = Change in fuel or moderator temperature (K),

$k_{inf}$ = Infinite neutron multiplication factor before any change,

$k_{hp}$ = Infinite neutron multiplication factor before change in moderator temperature and density or in fuel temperature,
\[ \kappa_{inf}^{hfp} = \text{Infinite neutron multiplication factor after change in moderator temperature and density or in fuel temperature,} \]
\[ \beta_{eff} = \text{Effective delayed neutron fraction,} \]
\[ k_{prompt} = \text{Multiplication factor for prompt neutron only,} \]
\[ \Lambda = \text{Average neutron generation time and,} \]
\[ \ell_{prompt} = \text{Prompt neutron lifetime or prompt neutron removal time.} \]

3. Results and discussion

3.1. Beginning of cycle parameters

The beginning of cycle events is paramount to reactor operational safety and efficiency because of how quick events happen within short time scale. In view of this, the initial \( k_{inf} \) and effective delayed neutron fraction were analysed as shown in Figure 2. From Figure 2 (a), the initial \( k_{inf} \) value in FA without any absorber was much higher than others owing to higher fission reactions while that of FA with boron + 24 gadolinium burnable absorber (GdBA) rods was the least because of the larger number of absorber rods. By the design specification of AP1000 for UO\(_2\) fuel with initial \( k_{eff} \) of 1.205 [6] for a fresh core without external control mechanism, the values are within acceptable range for a fuel assembly study. This shows that increasing the GdBA rods above 24 with 3600 ppm boron concentration in such FA arrangement will not be efficient. As shown in figure 2 (b), all the FAs has effective delayed neutron fraction value that are respectively greater than the 0.0065 value for fissile \( ^{235}\text{U} \) but less than 0.0075 designed value for UO\(_2\) fuelled AP1000 reactor. This difference was expected due to smaller delayed neutron fraction value for fissile \( ^{233}\text{U} \) compared to \( ^{239}\text{Pu} \) counterpart from \( ^{238}\text{U} \). Because of the fewer delayed neutron fraction and regardless of the higher thermal neutron absorption cross section of \( ^{232}\text{Th} \), thorium fuelled reactor requires tighter control measures at the BOC.

![Figure 2. The variation of (a) initial \( k_{inf} \) (b) effective delayed neutron fraction.](image)

The moderator and fuel temperature coefficients of reactivity are amongst safety parameters of interest which were calculated using (1) and (3) respectively. For optimised and inherent reactor safety, MTC and FTC of the reactor core are designed to be negative throughout the cycle operation. The MTC and FTC provide a measure of change in core reactivity caused by temperature change in moderator and fuel respectively. A negative MTC represents reduction in reactivity in an event of moderator temperature increase and the reverse is the case for a positive MTC. In this way, a negative MTC reactor core is self-limiting in any sudden moderator temperature increase, and therefore, maintains stability in reactor power.

The variation of MTC and FTC was presented in Figure 3. It shows that MTC was significantly negative in FA without boron and GdBA rod but significantly less negative in FAs with either boron
only or boron plus GdBA absorbers. Since the FAs contained the same fuel and fissile enrichment, difference in MTC was attributed to the presence of boron and GdBA which hardened the thermal neutron spectrum and decrement of fuel load by increasing GdBA fuel rods. On the other hand, the FTC was slightly less negative in FA without boron and GdBA rod while its negativity increased slightly as the number of the GdBA rod increases, therefore, showed a reverse occurrence to MTC. For the fact that FTC is a measure of the number of neutrons absorbed by fertile nuclide in the fuel at fuel temperature change, it therefore, means that boron and GdBA increased thermal neutron absorption in the system. Apart from the increased thermal neutron absorption by neutron absorbers, gadolinia raised the thermal motion of the fuel resulting to larger doppler broadening and therefore, decreases thermal neutron resonance escape probability. This led to the increased negative FTC in FAs with neutron absorber which increased as the number of GdBA rods increases. Generally, the MTC in all the FAs was respectively negative but below the -10 to -60 pcm/K MTC for UO$_2$ fuelled AP1000 reactor core [7]. This was attributed to the type of fuel studied since MTC depends on fast fission factor, fissile and fertile nuclides neutron absorption cross section at various energies, weight percent of fissile material and the reactor initial fuel load. The FTC in all the FAs was significantly above the -2 pcm/K its designed value for AP1000 reactor [8] due to large thermal neutron absorption cross section of $^{232}$Th compared to $^{238}$U and the enhanced neutron absorption by the reactivity control materials.

![Moderator and Fuel temperature coefficients of reactivity.](image)

**Figure 3.** Moderator and Fuel temperature coefficients of reactivity.

### 3.2. In-cycle burn-up calculations

The performance of the fuel overtime was studied using Burn card of MCNPX and the integrated CINDER90 burn-up code. The variation of neutron multiplication factor with burn-up in all the FAs decreased sharply at BOC due to rapid and increased production of reactor poisons which removed more neutrons from the system. However, it quickly reached equilibrium and maintained a relatively stable and descending slope except for the FA with boron + 24 GdBA rods which experienced reactivity swing between 10 to 30 GWd/tHM. The variation of $k_{in}$ in all the FAs at BOC was discussed in subsection 3.1. The $k_{in}$ of the FAs without absorber and that with boron only had a smooth and linear variation as shown in Figure 4 (a). The $k_{in}$ of the FA with boron + 16 GdBA rods whose value was in agreement with the 1.205 designed $k_{eff}$ of AP1000 for UO$_2$ varied linearly without noticeable positive reactivity swing which is desired for stable reactor power.
Figure 4. Variation of (a) neutron multiplication factor and (b) neutron generation time with burn-up.

The positive reactivity swing in FA with boron + 24 GdBA rods was noticeable but relatively small. The average neutron generation time (Λ) shown in Figure 4 (b) was larger in FA without any neutron absorber and slightly smaller in FAs with boron only between 0 - 20 GWd/tHM but matched and varies smoothly with the values in FAs with boron + GdBA rods when the gadolinia effect was almost zero. This phenomenal occurrence was due to the larger thermal neutron absorption cross section of boron and gadolinium compared to the fuel elements. This results to the reduction of prompt neutron lifetime due to faster removal of thermal neutron in the FAs with boron and GdBA rod leading to the observed shorter average neutron generation time. Therefore, the average neutron generation time increases with burn-up, and inversely proportional to the thermal neutron absorption cross sections of the nuclear fuel materials.

4. Conclusion

This work investigated the combined effect of soluble boron and gadolinia on reactivity and safety parameters with emphasis on their effect on the MTC, FTC, delayed neutron fractions and mean neutron generation time. The MTC in all the FAs was respectively negative showing a larger negativity in FA without boron and gadolinia and smaller negativity in FA with boron + 24 GdBA rods. On the other hand, the FTC was less negative in FA without boron and GdBA rods but most negative in FA with boron + 24 GdBA rods. Although, the MTC in all the FAs was respectively negative, it was below the -10 to -60 pcm/K value for UO₂ fuelled AP1000 reactor core but within acceptable value for a fuel assembly study. The FTC in all the FAs was significantly above the -2 pcm/K designed value for AP1000 reactor. The effective delayed neutron fraction in all the FAs were respectively greater than the 0.0065 value for fissile $^{235}$U but less than 0.0075 designed value for UO₂ fuelled AP1000 reactor. The average neutron generation time increased with burn-up but inversely proportional to the thermal neutron absorption cross sections of the nuclear fuel materials. This shows that boron and gadolinia shortened the prompt neutron lifetime and therefore, decreased neutron generation time except at criticality region where prompt neutron lifetime equals the generation time.

5. References

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