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Research Article

Enhancing the efficiency of the MOX fuel cycle for VVER-1200 using burnable absorbers

Joy Ozoani[1], Yuri Volkov[1]

1 *National Research Nuclear University MEPhI, Moscow, Russia*

Corresponding author: Joy Ozoani (Ozoanijoy@gmail.com)

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Abstract

Margin adoption in a nuclear power plant (NPP) design is a frequent approach to strengthen the design's robustness and provide an efficient way to handle uncertainties. However, the current trend of increasing fuel enrichment, including the use of MOX fuel to achieve a higher burnup, leads to non-uniformity in the energy release (power peaking factor) at the level of the fuel rod lattice, thereby causing a great effect on the reactor margins. One of the ways to reduce the power peaking factor is the use of burnable absorbers (BAs) which helps to minimize the power peaking factor. This work aims at enhancing the efficiency of the MOX fuel cycle for VVER-1200 reactor by replacing the Gadolinium burnable absorber to Erbia burnable absorber.

Keywords

VVER-1200 MOX fuel assembly, Burnable absorbers, Gadolinium, Erbium, Multiplication factor, Power Peaking Factor

Introduction

MOX fuel is a replacement for the low-enriched uranium (LEU) fuel used in light-water reactors, which are the most common type of nuclear reactor (OECD/NEA 2007; MOX fuel 2023). Since the 1950s, there have been significant MOX fuel fabrication activities, and commercial scale operations have been explored since the 1980s. Fabrication conditions become more difficult over time, with tighter standards, more radioactive plutonium to process, higher plutonium contents in MOX fuel to be created, and more stringent waste minimization goals. A considerable number of nuclear power facilities in different countries use MOX fuel assemblies for in-core fuel management. The influence of MOX on neutronic design and safety issues is well understood, and this knowledge provides the basis for the use of higher plutonium concentrations and, as a result, increased discharge burnups. Higher MOX loadings (up to 100%) are being investigated and their feasibility has already been demonstrated (Khoshahval et al. 2016; Abu Sondos et al. 2019a, 2019b, 2019c; Frybortova 2019; Saad et al. 2019).

The main differences between MOX and Uranium fuel include: Decreased worth of mechanical Control and Protection System and boric acid; Non-uniformity in the power distribution within the reactor core; Decreased effective fraction of delayed neutrons, structure and thermo-mechanical fuel properties; Increased radioactivity and heat generation in fresh and spent fuel.

It is a common practice to install a burnable poison at specific points in the core to lessen these management requirements. Therefore, burnable absorbers are employed in PWRs (Pressurized Water Reactors) to reduce the initial concentration of boric acid in the coolant or, in general, to increase the reactivity margin when using the same boric acid concentration and higher fuel

enrichment. They are also employed to reduce the relative power of new fuel assemblies. Fixed burnable absorbers are commonly utilized in the form of boron, gadolinium or erbium compounds that are formed into discrete lattice pins or plates or added to the fuel as additives. Because they can typically be distributed more uniformly than control rods, these poisons cause less disruption to the basic power distribution. Gadolinium is extensively employed as a neutron absorber in the nuclear industry due to the extremely large neutron absorption cross-section of two isotopes, ^{155}Gd and ^{157}Gd. Erbium is considered as one of the weak absorbers because of its low neutron absorption cross-section but there are no such disadvantages when utilizing relatively weak absorbers that can be inserted into all fuel elements or into a large number of them, equating to using a homogeneous absorber throughout the fuel assembly (Iwasaki et al. 2009). Furthermore, minor concentrations of such absorbers in fuel elements do not necessitate lower enrichment and have no effect on the thermal conductivity of the fuel.

In Russia, natural erbium is utilized as an absorber. When fresh fuel enrichment exceeds 5%, the use of erbium eliminates the problem of nuclear safety security in the manufacturing and handling of fresh fuel (Slivin et al. 2016). The dependence of erbium absorption micro-cross-section in this area of energies has a resonance at the energy E = 0.41 eV, which is a property of erbium as a thermal neutron absorber (Frybort et al. 2012). This property causes the spectrum component of the overall coolant temperature reactivity coefficient to have negative values, resulting in a negative overall temperature coefficient even with relatively small amounts of erbium in the fuel elements. When erbium is employed in fuel elements, the thermal conductivity of the fuel does not vary much. However, because erbium isotopes do not have enough time to burn up for the core lifespan, the fuel burn-up is influenced by the amount of erbium in the fuel elements (Fedosov et al. 2018). Erbium is also utilized in combination with Uranium oxide (UO_2). In comparison to Gadolinium, Erbium oxide Er_2O_3 (Erbia) has a lower absorption cross section and hence can be employed at higher concentrations, on the other hand, the absorption cross section of Gadolinium is in the hundreds of barns, only tiny concentrations can be utilized to avoid affecting the neutronic characteristics.

In this paper, the MOX assembly of a VVER-1000 reactor from the benchmark [*Kalugin M., Shkarovsky D., Gehin J. A VVER-1000 LEU and MOX Assembly Computational Benchmark. Specification and Results. - Nuclear Energy Agency Organisation for Economic Co-operation and Development (OECD NEA), 2002.*] was considered, and since the use of MOX fuel increases the micro irregularity of energy release (power peaking factor), an attempt was made to reduce the micro irregularity by replacing gadolinium burnable absorbers with erbium, optimizing the erbium concentration and choosing the location of the burnable absorbers in the fuel assembly.

Materials and methods

While designing fuel cycles for VVER-1200 (Geometry configuration and description are shown in Fig. 2 and Table 1 respectively), the technical and construction decisions realized in actual projects of VVER-1000 and verified in test and commercial operations at Kalinin and Balakovo NPPs were applied. Fuel assembly design for VVER-1200 was based on TVS-2M construction developed by Gidropress (Kalugin et al. 2002).

The MOXGD assembly is shown in Fig. 1 and contains fuel rods with three different plutonium loadings. The central region contains MOX pins with 4.2 wt.% fissile plutonium (consisting of 93 wt.% ^{239}Pu), two rings of fuel rods with 3.0 wt.% fissile plutonium, and an outer ring of fuel rods with 2.0 wt.% fissile plutonium.

Burnup calculations are performed with a power density of 108 MWt/m3 to a burnup of 40 MWd/kgHM with a sufficient number of burnup steps (B = 0, 2, 4, 6, 8, 10, 12, 14, 15, 20, 40 MWd/kgHM).

The simulation of burnup and neutronic calculation of the fuel assembly were performed by the program code

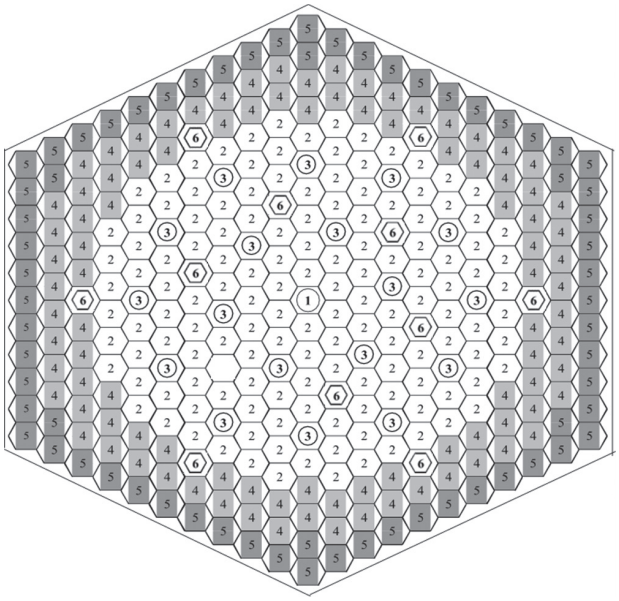

Figure 1. MOXGD assembly configuration. Cell types:1 - Central tube cell; 2 - Fuel cell (with PU3, 4.2 wt.% Pu); 3 - Guide tube cell; 4 - Fuel cell (with PU2, 3.0 wt.% Pu); 5 - Fuel cell (with PU1, 2.0 wt.% Pu); 6 - Fuel cell (with GD1, 3.6 wt.% LEU with 4.0 wt.% Gd_2O_3).

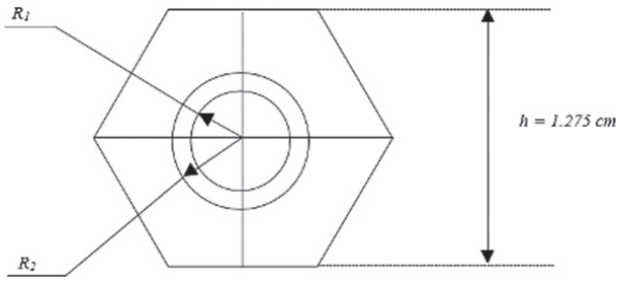

Figure 2. Geometry configuration of VVER-1200 cell.

SCALE 6.2.4 (Wiarda et al. 2015). The Transport Rigor Implemented with Time-dependent Operation for Neutronic depletion (TRITON) control module provides flexible capabilities to reactor designs calculations by providing 2D lattice physics capabilities using the NEWT flexible mesh discrete ordinates code. ENDF/B-VII.1 nuclear data libraries was used. The 2D lattice mesh discrete ordinates code allows calculating the power peaking factor (PPF) as a ratio of maximum of fission reaction rate at the fuel pin to fission reaction rate averaged to all fuel pins.

$$PPF = \frac{[\Sigma_f \cdot \Phi]_{MAX}}{\overline{\Sigma_f \cdot \Phi}}$$

All calculations were performed with zero current boundary conditions and zero axial leakage (infinite lattice of assemblies).

Results and discussions

Any commercial reactor's power peaking factor is an important characteristic. It's the ratio of the assembly's maximum pin power to its average power. It's ideal if the PPF value falls as low as feasible within the recommended range and declines linearly with burnup without any oscillations. The PPF has the recommended limit equals 1.16 for VVER-1000 (Pavlovitchev et al. 1999).

Calculation of reference assembly:

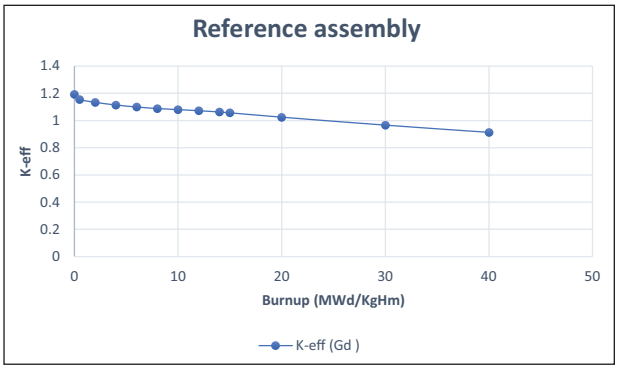

Figure 3. K-eff Vs Burnup for reference assembly (MOXGD fuel assembly).

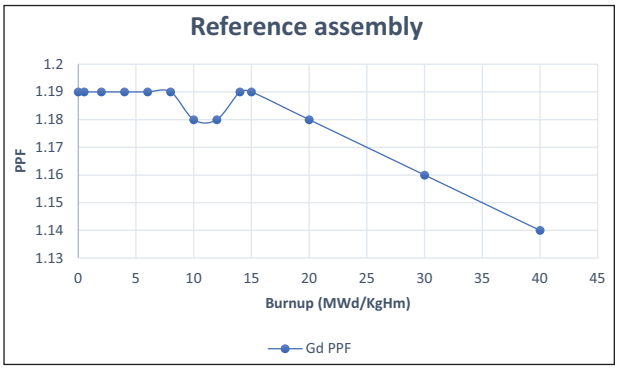

Figure 4. PPF Vs Burnup for reference assembly (MOXGD fuel assembly).

How to reduce the PPF:

a. The same fuel composition as PU3 (Table 2) was taken and named as a new fuel composition PU4 (Table 3);
b. An Er1 fuel composition (Table 3) was created;
c. The same Er isotopic concentration as Er1 was added to PU3 and then, a different Er isotopic concentration was inserted into PU4. See Table 3 for the compositions.

In detail, the experiment started out with 6.6E-4 conc of gadolinium (position 6) as shown in Fig. 8, which gave quite a good K-eff value (Fig. 3) but with high PPF value, then the concentration of Gd was reduced to 1.8E-4 and 2.5E-4 conc of Erbia was added to Position 3 (which contains 4.2 w/o of fissile Pu), this helped reduce the PPF value (Fig. 4) a bit. From observations, the zones with max PPF lies between the zones with Gd and guide tube (position 6 & 3), So these zones were replaced with newly created fuel element containing 4.2 w/o of fissile Pu and 3.5E-4 conc of Erbia (position 7), this helped reduce the PPF even more. In other to determine the best optimum case, the Gd zones (Position 6) were totally replaced with same fuel element composition as position 3 Since it wasn't playing much role in the reduction process and this brought down the PPF to the preferred value while maintaining a good K-eff thereby making Erbia a better burnable absorber.

Table 1. Description of cell types geometry (Fig. 2)

Cell names	Zones radius (cm)
Fuel cell	$R_1 = 0.386$
	$R_2 = 0.4582$
Central tube cell	$R_1 = 0.48$
	$R_2 = 0.5626$
Guide tube cell	$R_1 = 0.545$
	$R_2 = 0.6323$

Table 2. Material description

Material Name	Comment*	Isotopic content, (atoms/barn cm³)			
Fuel materials					
PU1	MOX fuel with 2.0 wt.% of fissile Pu	^{235}U	4.2672E-5	^{239}Pu	4.2414E-4
	$T_f = 1027K$	^{238}U	2.1025E-2	^{240}Pu	2.7250E-5
		^{16}O	4.3047E-2	^{241}Pu	4.5228E-6
PU2	MOX fuel with 3.0 wt.% of fissile Pu	^{235}U	4.2209E-5	^{239}Pu	6.3621E-4
	$T_f = 1027K$	^{238}U	2.0797E-2	^{240}Pu	4.0875E-
		^{16}O	4.3045E-2	^{241}Pu	6.7842E-6
PU3	MOX fuel with 4.2 wt.% of fissile Pu	^{235}U	4.1652E-5	^{239}Pu	8.9071E-4
	$T_f = 1027K$	^{238}U	2.0522E-2	^{240}Pu	5.7225E-5
		^{16}O	4.3043E-2	^{241}Pu	9.4980E-6
GD1	LEU fuel of 3.6 wt.% of ^{235}U	^{235}U	7.2875E-4	155Gd	1.8541E-4
	containing 4 wt.% o of Gd_2O_3	^{235}U	1.9268E-2	156Gd	2.5602E-4
		^{16}O	4.1854E-2	157Gd	1.9480E-4
	$T_f = 1027K$	^{152}Gd	2.5159E-6	158Gd	3.0715E-4
		^{154}Gd	2.7303E-5	160Gd	2.6706E-4
Non-fuel materials					
CL1	Zirconium alloy	Zr	4.259E-2	Hf	6.597E-6
		Nb	4.225E-4		
MOD1	Moderator, 0.6 g/kg of boron, $T_m = 575K$, $\gamma = 0.7235$ g/cm³	H	4.843E-2	^{10}B	4.794E-6
		^{16}O	2.422E-2	^{11}B	1.942E-5

All concentration needs to be recalculated in wt. % (8.5E-04 – is just sum of nuclear densities of Er isotopes * 10^24 1/cm^3) or as in table below:

Table 3. New material description

PU3	MOX fuel with 4.2 w/o of fissile Pu containing 2.5E-4 of Er2O3	^{235}U	4.1652E-5	^{239}Pu	8.9071E-4
		^{238}U	2.0522E-2	^{240}Pu	5.7225E-5
		^{16}O	4.3043E-2	^{241}Pu	9.4980E-6
		^{166}Er	9.6450E-5	^{168}Er	7.3400E-5
		^{167}Er	6.9850E-5	^{170}Er	1.0300E-5
PU4	MOX fuel with 4.2 w/o of fissile Pu containing 3.5E-04 of Er2O3	^{235}U	4.1652E-5	^{239}Pu	8.9071E-4
		^{238}U	2.0522E-2	^{240}Pu	5.7225E-5
		^{16}O	4.3043E-2	^{241}Pu	9.4980E-6
		^{166}Er	1.3503E-4	^{168}Er	1.0276E-4
		^{167}Er	9.7790E-5	^{170}Er	1.4420E-4
Er1	MOX fuel with 4.2 w/o of fissile Pu containing 2.5E-04 of Er2O3	^{235}U	4.1652E-5	^{239}Pu	8.9071E-4
		^{238}U	2.0522E-2	^{240}Pu	5.7225E-5
		^{16}O	4.3043E-2	^{241}Pu	9.4980E-6
		^{166}Er	9.6450E-5	^{168}Er	7.3400E-5
		^{167}Er	6.9850E-5	^{170}Er	1.0300E-5

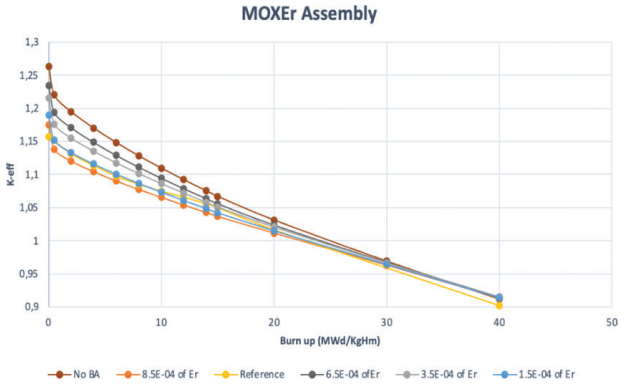

Figure 5. K-eff Vs Burnup for different concentration of Erbia in MOX fuel assembly.

In general, it was discovered that adding Er to the fuel reduces the multiplication factor significantly throughout the burnup period, as illustrated in graphs above (Figs 5 and 6). As a result, the maximum burnup is considerably reduced. The drop is greater at higher concentrations; for example, the proposed variant has a very low burnup with sum total concentration of 8.5E-04.

According to Pavlovitchev et al. 1999, The recommended PPF limit for VVER-1000 is 1.160. The PPF values for

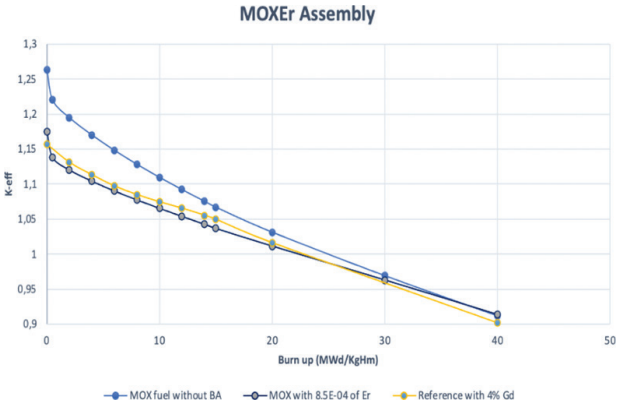

Figure 6. K-eff Vs Burnup for Reference BA (U-Gd), Proposed BA (MOX-Er) and without BA MOX fuel assembly.

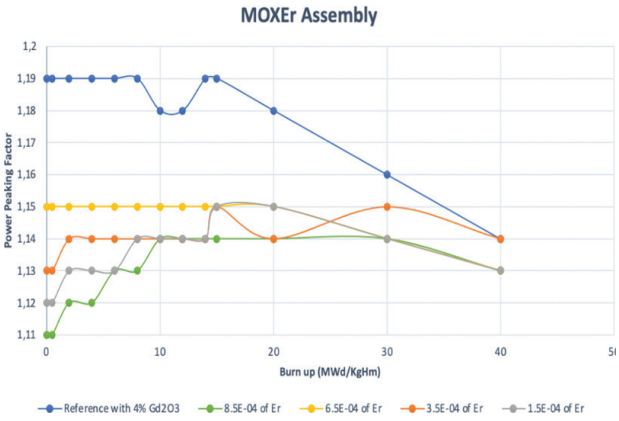

Figure 7. Power Peaking Factor (PPF) vs. Burnup.

MOX-Er BA assembly are below this limit in all burnup steps from 0 to 40 MWd/KgHm (Fig. 7). PPF of the reference MOX-Gd BA assembly on the other hand, is above the limit in the burnup range of 0 to 20 MWd/KgHm and even at 30 MWd/KgHm, it is at its marginal point. The PPF graph of the two assembly designs reveals that the reference MOX assembly with MOX-Gd BA rods is higher with a considerable fluctuation than the MOX assembly with MOX-Er BA rods. And this is because the Gadolinium used as a burnable absorber dwindled and became a minimum, causing this fluctuation which led to a sudden rise in pin power. The pro-

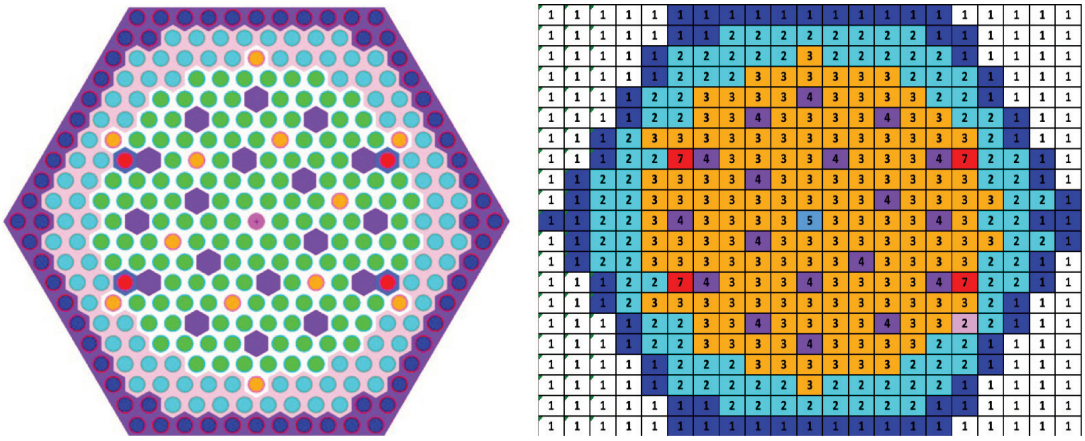

Figure 8. Cartogram of the Profiled MOX fuel assembly with MOX-Er BA rods. Cell types:1- Fuel cell (with PU2); 2- Fuel cell (with PU2); 3 - Fuel cell (with PU3); 4 - Guide tube cell; 5 - Central tube cell; 6 - Fuel cell (with Er1); 7 - Fuel cell (with PU4).

posed MOX-Er BA MOX assembly, on the other hand, has a lower value of PPF than the reference one. This is due to the fact that no gadolinium was used in the MOX-Er BA MOX assembly, and erbium is not a powerful enough absorber to induce a significant change in pin power.

Results:

Table 4. Dependency of power peaking factor on Burnup

Burn up (MWd/ KgHm)	MOX-Gd pinpow	MOX-Er Pinpow (Sum total conc. Of 8.5E-04)	MOX-Er Pinpow (Sum total conc. Of 6.5E-04)	MOX-Er Pinpow (Sum total conc. Of 3.5E-04)	MOX-Er Pinpow (Sum total conc. Of 1.5E-04)
0	1.19	1.11	1.15	1.13	1.12
0.500005	1.19	1.11	1.15	1.13	1.12
2	1.19	1.12	1.15	1.14	1.13
3.99998	1.19	1.12	1.15	1.14	1.13
5.99995	1.19	1.13	1.15	1.14	1.13
7.99993	1.19	1.13	1.15	1.14	1.14
9.99991	1.18	1.14	1.15	1.14	1.14
11.9999	1.18	1.14	1.15	1.14	1.14
13.9999	1.19	1.14	1.15	1.14	1.14
14.9999	1.19	1.14	1.15	1.15	1.15
19.9999	1.18	1.14	1.15	1.14	1.15
29.9999	1.16	1.14	1.14	1.15	1.14
39.9999	1.14	1.13	1.13	1.14	1.13

Conclusions

The MOX-Er BA rods containing Erbium sum total concentration of 8.5E-04 is a better burnable absorber in many ways than the reference assembly with MOX-Gd BA rods containing 4.0% Gd2O3 because the power distribution across the MOX assembly with MOX-Er BA rods is flatter, and the power peaking factor value is smaller than the reference assembly with MOX-Gd BA rods.

Furthermore, the benchmark of NEA OECD has documented the design of MOX fuel assembly to VVER-1000 core (the reference design). The design includes the fuel pins with gadolinium burnable absorber that is the common feature to reduce amount of boric acid in the coolant. In comparison with uranium fuel assembly the MOX assembly increased the power peaking factor (maximum 1.16 in the uranium assembly and maximum 1.19 in the MOX assembly). In this study, the power peaking factor was reduced by replacing gadolinium burnable absorbers with erbium, optimizing the erbium concentration and choosing the location of the burnable absorbers in the fuel assembly. In the reference design the power peaking factor was 1.19 and decline to 1.14 in the end of burnup cycle. Therefore, we proposed the new design of MOX fuel assembly with erbium as burnable absorber, which has the effect of reducing the power peaking factor to 1.11 at the beginning of burnup cycle and slightly increasing to maximum 1.14 during the burnout cycle (Table 4). The further research may include the cross-verification by other depletion codes.

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