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Optimized BR2 Core Configuration

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ABSTRACT

The objective of the study is to achieve a sustainable BR2 fuel cycle in a long term of reactor operation applying advanced in-core loading strategies. The optimization criteria concern mainly enhancement of nuclear safety by means of reactivity margins and minimization of the operational fuel cycle cost at a given (constant) power level and same or longer cycle length. An important goal is also to maintain the same or to improve the experimental performances. Current developments are focused on optimization of the control rods localization and optimization of the 3-D fuel burn up distribution in the core. The analysis is performed and compared for the reference HEU core and for the fully converted LEU core.

1. Introduction

The objective in this paper is to achieve a sustainable BR2 operational fuel cycle applying different in-core optimization strategies, such as: A. Improvement of reactivity safety margins by optimization of the control rods localization in the core. The control rod effectiveness for a given absorber material depends on the neutron spectrum from one side, and from the other – on the mutual rod distances, which are important for so called shadowing and anti-shadowing effects. B. Minimization of the BR2 fuel cycle costs by fuel economy for the same (or increased) cycle length at a given (constant) reactor power level (MW). This is achieved applying various reloading strategies and methodologies for optimized 3-D fuel burn up distribution, including rotating and flipping upside down fuel assemblies in order to minimize local burn up peaking and achieve more homogenized burn up profile. The analysis is performed for the standard BR2 HEU fuel with burnable absorbers B_4C and Sm_2O_3, mixed in the fuel meat of a fresh fuel element. Comparison with the LEU fuel (UMo, 20% ^{235}U, 7.5 g U_{tot}/cm^3) with cadmium wires (D=0.5 cm) in the aluminum side plates of the fuel element is presented [1].

2. BR2 Core Load Management

2.1 Standard core load configuration

The standard BR2 core configuration for a typical operation cycle is given in Fig. 1. A typical reactor core load configuration contains 6 fresh fuel elements (0% burn up), loaded in channels C in the second fuel channels ring and about 26 to 28 burnt fuel elements with variable mean fuel burn up. Typically low burn fuel elements (10% to 15% burn up) are loaded in the 6 channels A of the central crown, which are closest to the reactor core center. Higher burnt fuel elements (25% to 35%) are usually loaded in channels B and D. The remaining peripheral F,G channels are loaded with highly burnt fuel elements (45 to 50%) and with standard irradiation devices. The mean burn up at discharge of the fuel element is about 50%-60%.

2.2 Reactivity control at the BR2 reactor

The methods used to control the reactivity of BR2 are control rods and burnable poisons. The control rods of BR2 operate from the top of the reactor. Each control rod is mechanically completely independent of the other control rods and each control rod can be inserted in any standard reactor channel. There is, therefore, great flexibility in control rod location and choice of the reactor core configuration.

Six shim-safety control rods, which provide both the coarse normal operational reactivity control (reactivity compensation for burn-up, for Xe-poisoning, for ^{3}He-poisoning) and the safety control (e.g. SCRAM), are loaded in 6 channels C of the standard BR2 core load configuration (see Fig. 1).

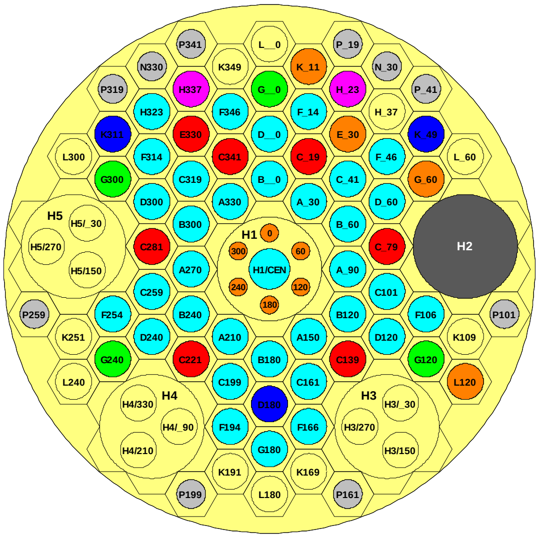

Figure 1. Standard BR2 core load configuration [2]: beryllium (yellow), BR2 fuel elements (light blue), shim-safety rods (red), regulation rod (pink), experimental positions (green, gray and orange), CALLISTO (dark blue).

A special feature of the BR2 reference fuel is the presence of burnable absorbers, boron in the form of B_4C and samarium in the form of Sm_2O_3, homogeneously mixed in the fuel meat of a fresh HEU fuel element. The purpose is to lower the initial reactivity at the beginning of the irradiation of a fresh fuel element, to limit the control rod motion range during operation and to extend the burn-up (GWD/MTU) at discharge of the fuel element (this leads to reduction of the fresh fuel consumption). Another major benefit of the use of burnable absorbers is the constitution of a 'large' inventory of fuel elements with various partial burn-ups. This allows to adapt the local irradiation conditions not only by modifications of the configuration but also by adaptations of the burn-up of the driver fuel in particular channels.

2.3 Methodologies for Core Load Management

The core load management of the BR2 reactor is performed using MCNPX 2.7.0 based methodologies [3].

3. Optimization of the Core Load Configuration

In this section we study various in-core load configurations aimed to improve the current BR2 configuration and fuel cycle. The optimization of the control rods localization is considered in the Section 3.1. The purpose is to enhance the reactor safety by increasing the total control rod worth and improving the individual control rod relative effectiveness. The latter is achieved by re-shuffling the fresh and burnt fuel elements in the reactor channels surrounding the control rod position channels, which allow to improve the reactivity equilibrium in the core (see Section 3.2). Section 3.3 deals with optimization of the 3-D fuel burn up distribution in the core, such as: rotating and flipping upside down burnt fuel elements, which allows to increase the reactivity excess at BOC and to minimize the fuel costs. The optimization analysis is performed for the HEU core and after that a comparison of selected safety parameters and variables is performed for the LEU core.

3.1 Optimization of control rod localization

In this Section we compare 2 series of core load configurations. In the first series, the standard core configuration with loaded IPS2 of the CALLISTO loop[1] in the channel D180 is used (see Section 3.1.1), and in the second series – a Be-plug is loaded in the channel D180 (this is described in Section 3.1.2). In the beginning of 2012, the IPS2 which occupied the channel D180, has been removed from the loop. The channel D180 now is currently loaded with safety control rod in highest control rod position or a Be-plug.

Two type control rods core configurations are studied for each of the series: Reference (or standard BR2 CR localization) and new CR localization "CR1":

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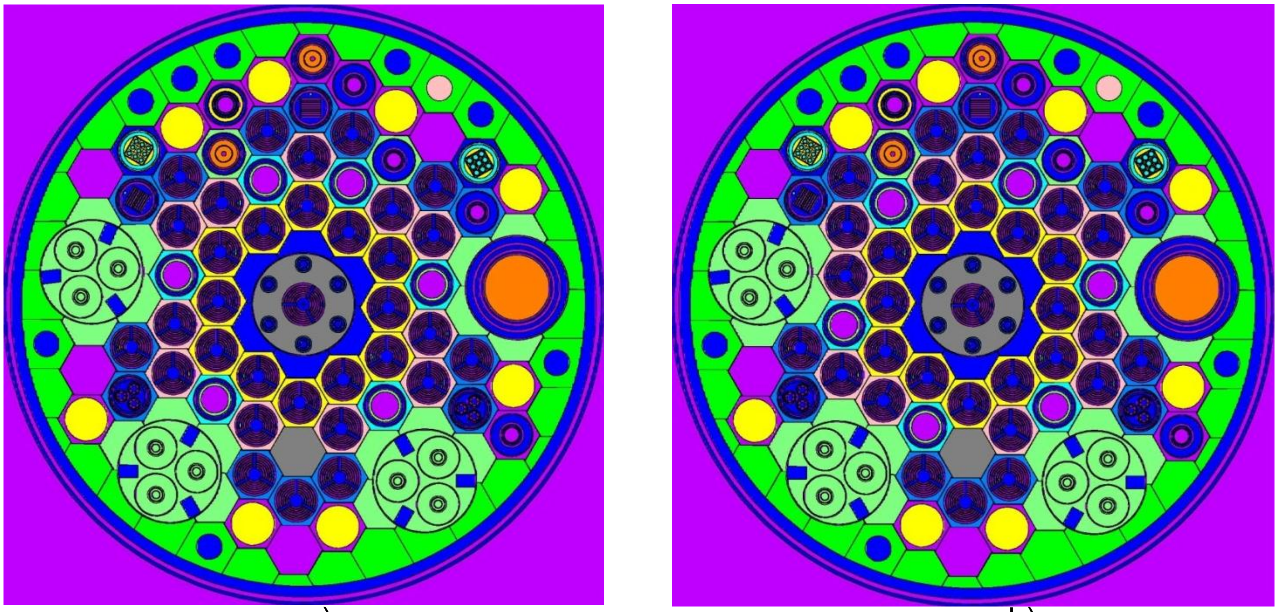
[1] "CALLISTO" is a PWR loop, consisting of 3 experimental rigs, called In-Pile Sections (IPS). It occupies three reactor channels in the BR2 reactor core: K49, D180 and K311. The purpose of the loop is to study the behavior of advanced fuel and structural materials under representative PWR operating conditions (high T° and high pressure). Each IPS is inserted to a thick stainless steel tube, cooled by light water.



a)   b)

Figure 2. MCNPX model of: a) Reference (standard) BR2 CR load configuration; b) New core configuration "CR1" with equidistant control rods location channels.

1. The Reference CR configuration is shown in Fig. 2a. In this configuration the distances between the control rods are not equal: the control rods S3 and S4 are located farther from each other than the other rods, and the control rods S1 and S2 are located closer than the others. The six CR are loaded in channels C19(S1), C79(S2), C139(S3), C221(S4), C281(S5), C341(S6). The remaining C channels are loaded with fresh fuel elements.
2. The New configuration CR1 is given in Fig. 2b. In this configuration the distances between the different control rods are equal. The six CR are loaded in channels C19(S1), C79(S2), C139(S3), C199(S4), C259(S5), C319(S6). The remaining C channels are loaded with fresh fuel elements.

3.1.1 IPS2 in channel D180

In the first series we consider core configurations in which IPS2 is loaded in the channel D180. IPS2 has big macroscopic absorption cross section due to the presence of large volumes stainless steel constructions and light water. Therefore the location of the control rods S3 and S4 farther from IPS2 in the Reference configuration is reasonable. The reactivity worths in the HEU core for the Reference configuration are compared with the reactivity worths for the New core configuration CR1 in Table I.

From the results presented in Table I, we can conclude that the shutdown margin for the considered HEU configurations is similar and equal to about –5 $. The new core configuration CR1 is +0.27 $ more reactive than the Reference core. The reactivity excess at BOC of the new control rod configuration CR1 is +0.36 $ higher compared to the Reference core, which is due to the higher total control rod worth compared to the Reference core. *The total reactivity gain for the new control rod configuration CR1 is +0.6 $, which is equivalent to saving about 120 grams ^{235}U* by replacing low burnt FE by high burnt FE in the central crown (1 FE 15% by 1 FE 40% ^{235}U burn up; or 2 FE 15% by 2 FE 30% ^{235}U burn up). The reactivity equilibrium is better for the Reference core. The equilibrium of the new core configuration CR1 will be improved in the Section 3.2.

Table I. Comparison of reactivity worths for different control rod configurations for typical BR2 HEU core load with **IPS2 loaded in the channel D180**.

	Reference core (Fig. 2a)	Core – CR1 (Fig. 2b)
Shutdown margin, $\rho_{0,i}=\rho(370\text{ mm})-\rho(0\text{mm})$	–5.00 $	–5.11 $
Critical height at BOC, $Sh_{boc,i}$	545 mm	536 mm
$\Delta\rho_i=\rho(CR_i)-\rho(\text{Reference})$	0	+0.27 $
Reac. exc. at BOC, $\rho_{boc,i}=\rho_i(900\text{mm})-\rho_i(Sh_{boc,i})$	+4.49 $	+4.85 $
Mutual CR worth, $R0_i=\rho_i(900\text{mm})-\rho_i(0\text{mm})$	15.04 $	15.36 $
Worth of S1	1.94 $ (0.155)	2.44 $ (0.196)
Worth of S2	1.85 $ (0.147)	1.81 $ (0.146)
Worth of S3	1.98 $ (0.158)	1.65 $ (0.133)
Worth of S4	2.42 $ (0.193)	1.60 $ (0.129)
Worth of S5	2.36 $ (0.188)	2.50 $ (0.201)
Worth of S6	2.00 $ (0.159)	2.42 $ (0.195)
Sum of six rods, ΣS_i	12.55 $	12.42 $

The sum of the individual control rod worths is about 80% from the mutual total control rods worth due to the anti-shadowing effect. The anti-shadowing effect for the new core configurations is slightly better.

3.1.2 Beryllium plug in channel D180

In the second series core configurations the channel D180 is loaded with beryllium plug which has a positive reactivity effect compared to IPS2. In this case, the reactivity equilibrium in the Reference core significantly worsen: the control rods S3 and S4 located around the channel D180 become very strong due to the presence of Be-plug in D180, and the control rods S1 and S2, located opposite to S3 and S4 become too weak. The reactivity worths for both HEU, Reference configuration and new core configuration CR1, are compared in Table II.

From the results presented in Table II, we conclude that t*he shutdown margin in the new configuration CR1 is improved by –0.63 $ compared to the Reference core.* The new core configuration is –0.28 $ less reactive than the Reference core. The reactivity excess at BOC of the new control rod configuration CR1 is +0.51 $ higher compared to the Reference core. *The total reactivity gain for the new configuration CR1 vs.*

Reference core is about +0.23 $, which is equivalent to saving about 60 grams ^{235}U in the central crown (replacing 1 FE 18% by 1 FE 30% ^{235}U burn up).

Table II. Comparison of reactivity worths for different control rod configurations for typical BR2 HEU core load with **Be-plug in the channel D180**.

	Reference core (Fig. 2a)	Core – CR1 (Fig. 2b)
Shutdown margin, $\rho_{0,i}=\rho(370\text{ mm})-\rho(0\text{mm})$	–4.55 $	–5.19 $
Critical height at BOC, $Sh_{boc,i}$	490 mm	499 mm
$\Delta\rho_i=\rho(CR_i)-\rho(\text{Reference})$	0	–0.28 $
Reac. exc. at BOC, $\rho_{boc,i}=\rho_i(900\text{mm})-\rho_i(Sh_{boc,i})$	+5.59 $	+6.1 $
Mutual CR worth, $R0_i=\rho_i(900\text{mm})-\rho_i(0\text{mm})$	13.68 $	15.56 $
Worth of S1 (relative worth in brackets)	1.44 $ (0.124)	1.97 $ (0.160)
Worth of S2 (relative worth in brackets)	1.56 $ (0.134)	1.60 $ (0.130)
Worth of S3 (relative worth in brackets)	2.45 $ (0.211)	2.02 $ (0.164)
Worth of S4 (relative worth in brackets)	2.70 $ (0.233)	2.32 $ (0.188)
Worth of S5 (relative worth in brackets)	1.95 $ (0.168)	2.36 $ (0.192)
Worth of S6 (relative worth in brackets)	1.50 $ (0.129)	2.05 $ (0.166)
Sum of six rods, ΣS_i	11.60 $	12.32 $

On the other hand, the total control rod worth of the new configuration CR1 slightly improves for the case with Be-plug in D180, while the control rod worth of the Reference core significantly worsen compared to the case when IPS2 is loaded in D180. *The total control rod worth in the new configuration CR1 is about 1.8 $ ÷1.9 $ higher than in the Reference CR configuration.*

The reactivity equilibrium for the Reference core worsen compared to the case with IPS2 in D180; the equilibrium in both will be optimized in a further Section 3.2.

The sum of the individual control rod worths is about 85% from the mutual total control rods in the Reference core, and about 79% in CR1 and CR2. *The anti-shadowing effect for the new core configurations is improved by about 6% compared to the Reference core.*

3.2 Optimization of core reactivity equilibrium

In this Section we optimize the relative efficiencies of the individual rods by adapting the irradiation conditions surrounding the control rods in order to achieve equilibrium reactivity distribution in the core. Firstly, the analysis is performed for the HEU in both, Reference CR configuration and new control rods configuration CR1, when a beryllium plug is loaded in the channel D180. After that, the HEU fuel in the optimized cores is replaced by LEU (UMo, 7.5 g U_{tot}/cm^3, 20% ^{235}U, 36 Cd-wires/FE, D_{Cd}=0.5 mm). A comparison between HEU and LEU fuelled cores for each of the configurations can be found in Table III.

The core reactivity equilibrium can be improved by re-shuffling the fuel elements in the surrounding control rod channels: reactive low burnt fuel elements are placed near a weak control rod, and less reactive, high burnt fuel elements are moved near a strong control rod. It was necessary to re-shuffle 6 burnt fuel elements in the Reference core in order to diminish the large reactivity difference between the weakest control rods S1&S2&S6 and the strongest S3&S4. For the new core configuration CR1, only 2 burnt fuel elements had to be re-shuffled in order to diminish the difference between the strongest S4 rod and the weakest S2 rod.

Comparing the results in Table III with those in Table II for a given fuel type (i.e., for the HEU core), we conclude that the safety margins (total control rod, shutdown margin, critical height) are not affected by the re-shuffling of the fuel elements in the considered configurations. The relative control rod effectiveness in the Reference core is improved compared to Table II, however this core is still far from equilibrium: there is still large difference between the strongest S3&S4 rods and the weakest S1&S2&S6. The relative control rod effectiveness in the new configuration CR1 and CR2 is improved compared to Table II. Similar conclusion about the differences between the Reference and new CR1 configurations would be valid also for the LEU core.

Table III. Comparison of reactivity worths for different control rod configurations for typical BR2 load with **Be plug loaded in the channel D180**. Improved equilibrium by re-shuffling fuel elements around the control rods.

	Reference core (Fig. 2a)	Core – CR1 (Fig. 2b)	
	HEU	HEU	UMo (D_{Cd}=0.4 mm)
Shutdown margin, $\rho_{0,i}=\rho(370\text{ mm})-\rho(0\text{mm})$	–4.59 $	–5.19 $	–4.56 $[2]
Critical height at BOC, $Sh_{boc,i}$	490 mm	499 mm	360 mm
$\Delta\rho_i=\rho(CR_i)–\rho(\text{Reference})$	0	–0.28 $	+4.06 $
Reac. exc. at BOC, $\rho_{boc,i}=\rho_i(900\text{mm})-\rho_i(Sh_{boc,i})$	+5.66 $	+6.1 $	+10.1 $
Mutual CR worth, $R0_i=\rho_i(900\text{mm})-\rho_i(0\text{mm})$	13.81 $	15.57 $	14.56 $
Worth of S1 [$], (relative worth in brackets)	**1.59 (0.136)**	2.20 (0.177)	2.10 (0.178)
Worth of S2 [$], (relative worth in brackets)	1.62 (0.139)	**1.71 (0.138)**	**1.60 (0.136)**
Worth of S3 [$], (relative worth in brackets)	2.40 (0.206)	1.99 (0.160)	1.86 (0.158)
Worth of S4 [$], (relative worth in brackets)	**2.54 (0.218)**	2.16 (0.174)	2.04 (0.173)
Worth of S5 [$], (relative worth in brackets)	1.93 (0.165)	**2.24 (0.180)**	**2.19 (0.186)**
Worth of S6 [$], (relative worth in brackets)	**1.59 (0.136)**	2.13 (0.171)	2.00 (0.170)
Sum of six rods, ΣS_i	11.67 $	12.43 $	11.79 $

3.3 Optimization of 3-D burn up distribution in the core

Highly burnt BR2 fuel elements have asymmetric axial burn up distribution with the maximum burn up just below the mid-plane (see Fig. 3a). From the other side, highly burnt

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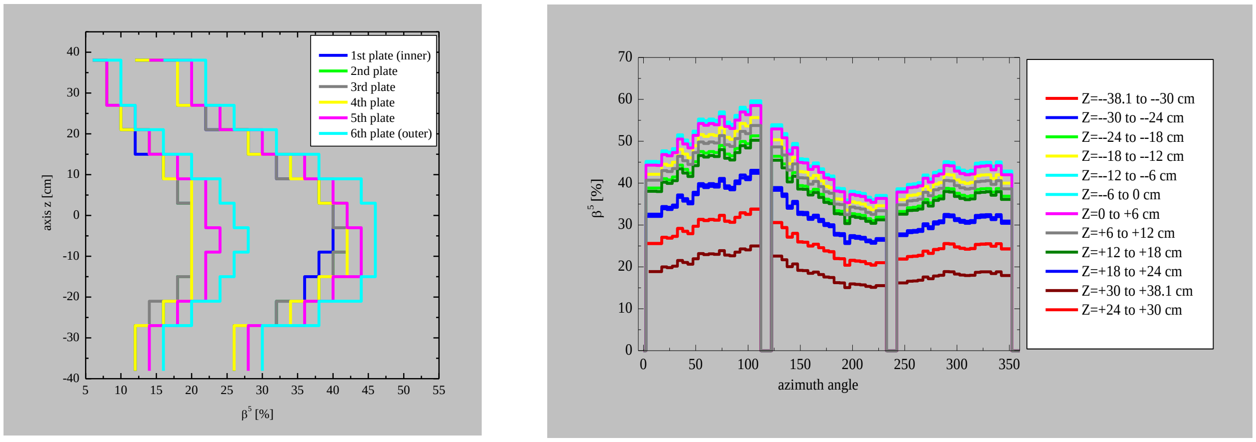
[2] This shutdown margin is calculated for Sh=360 mm.

BR2 fuel elements have strong azimuthal profile with the highest burn up, achieved on the side of the fuel element oriented toward the core centre (see Fig. 3b).



a) b)

Figure 3. a) Axial fuel burn up distribution in the fuel plates of low burnt (left) and in high burnt fuel element (right); b) Azimuth fuel burn up distribution in the fuel plates of a FE.

In this Section we study the effect of 3-D burn up distribution on the core reactivity applying 2 strategies:

- Flipping upside down burnt fuel elements (Section 3.3.1);
- Rotating burnt fuel elements (Section 3.3.2).

The analysis is performed for the equilibrium cores and the results are comparable with those in Table III.

3.3.1 Flipping upside down fuel elements

As it is seen from Fig. 3a, flipping upside down a burnt fuel element will change its axial profile: an axial section with lower burn up will be located below the mid-plane. It is expected that flipping upside down a highly burnt fuel element will make it more reactive, since reactive axial segments will be located around the mid-plane, while flipping a low burnt fuel element probably will not affect strongly the core reactivity due to the higher content of burnable absorbers in the low burnt axial segments. In this section we study several scenarios of flipping upside down burnt fuel elements in different parts of the reactor core. The results are summarized in Table IV.

Comparing the results for flipped fuel elements vs. not flipped fuel elements, we can conclude the following:

- Flipping highly burnt (30% to 50% ^{235}U burn up) fuel elements in peripheral channels (D,F) we gain +0.4 $ reactivity excess at BOC; the shutdown margin is reduced to –4.5 $.

- Flipping all highly burnt (30% to 50% ^{235}U burn up) fuel elements, we gain +0.9 $ reactivity excess at BOC. However, the shutdown margin is reduced to –3.8 $.
- The gain of flipping only one fuel element located in the central channel H1/C is equivalent to about +(0.15÷0.2) $.
- Flipping low burnt fuel elements (~15% ^{235}U burn up) almost doesn't gain reactivity and moreover the shutdown margin is reduced to –3.9 $.
- For all considered scenarios the total control rod worth does not change compared to the reference case without flipped fuel elements.

Table IV. Comparison of reactivity worths for different axial orientation of the fuel elements in the equilibrium core **CR1 (Be in D180) for HEU fuel**.

	Not flipped FE	Flipped high burnt FE in periphery (D,F)	Flipped all high burnt FE plus H1/C (H1,A,B,D,F)	Flipped all high burnt FE minus H1/C (A,B,D,F)	Flipped all low burnt and high burnt FE (H1,A,B,D,F)
Shutdown margin, ρ_0 [$]	–5.2	–4.5	–3.8	–3.9	–3.9
Critical height at BOC, Sh_{boc} [mm]	499	486	473	477	475
Reactivity excess at BOC [$]	+6.1	+6.5	+7.0	+6.8	+6.9
Mutual total CR worth, R0 [$]	–15.6	–15.5	–15.6	–15.6	–15.5

From all considered scenarios, it seems beneficial flipping upside down only the fuel elements in peripheral channels (D,F,G or H) since in this case the shutdown margin satisfies the limit given in the TS [4]. For this case the gain in reactivity is about +0.4 $, which allows to *save about 60 grams* ^{235}*U* replacing a low burnt (~15%) fuel element by highly burnt fuel element (~32%) in a channel A or B in the central crown.

3.3.2 Rotating fuel elements

The maximum of the azimuth burn up profile in the fuel plates given in Fig. 3b is located always on the side of the fuel element oriented to the reactor core center. If we orient all fuel elements in the central crown with their low burnt side to the core center and high burnt side to the core periphery, then the gain in the reactivity is about +0.2 $ without change of the total control rod worth and shutdown margin. Such strategy will allow saving about 30-40 grams ^{235}U.

4. Optimized Fuel Cycle

In this section we will study the fuel cycle in the equilibrium cores which were presented in Section 3.2 (see Table III). We will compare the reactivity evolution, control rod motion, the cycle length and the safety margin at the minimum of the control rod motion for the Reference core (HEU) and for the new core configuration CR1 (HEU and LEU).

4.1 Reactivity evolution, control rods motion and cycle length

The reactivity evolution and control rod motion during the BR2 operation cycle have been calculated by MCNPX 2.7.0 and compared in Fig. 4 for the following cases:

- HEU core for the Reference CR Configuration as shown in Fig. 2a;
- HEU and LEU cores for the New CR1 Configuration as shown in Fig. 2b.

The comparison of the curves Fig. 4 allows to conclude that the cycle length in the New Core Configuration CR1 <u>for a given fuel type</u> (e.g. for HEU, but the same will be valid for the LEU fuel types) is increased due to the higher control rod worth compared to the Reference CR configuration. The longest cycle length is for the HEU core and for the LEU-UMo core (7.5 g/cm^3, 20% ^{235}U, 36 cadmium wires with D_{Cd}=0.4 mm).

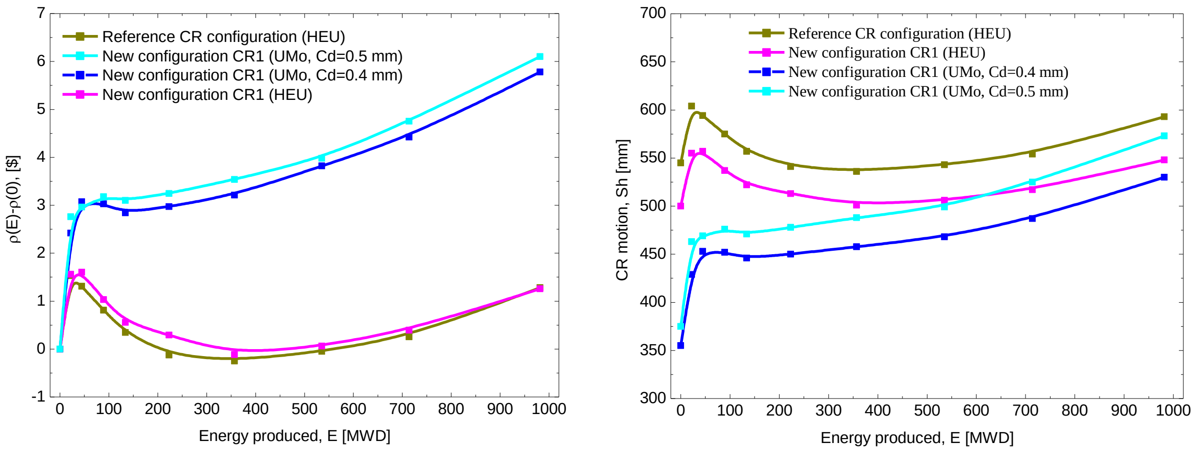


Figure 4. Reactivity evolution and control rod motion during BR2 cycle in HEU core for the Reference CR Configuration and in HEU/LEU cores for the New Configuration CR1.

4.2 Safety margin at the minimum of control rod motion

The safety margin at the minimum of the control rod motion after a scram followed by Xe-Sm transient in the HEU core is improved for the New Configuration CR1 by –0.9 $ (see Table V), which results from the following equations according with the TS [4]:

$$\rho_{\min}[\mathrm{Xe}\,\&\,\mathrm{Sm}] = \mathrm{R0} - \Delta\rho(\mathrm{Sh}_{\min}) - \Delta\rho(\mathrm{Xe}) + \Delta\rho(\mathrm{S7}\,\&\,\mathrm{S8}) - \rho(\Delta\mathrm{T}^\circ)\,, \qquad (1)$$

Where:

$$\mathrm{R0} = \rho(\mathrm{Sh} = 900) - \rho(\mathrm{Sh} = 0)\,, \qquad (2)$$

$$\Delta\rho[\mathrm{Sh}_{\min}] = \rho(\mathrm{Sh} = 900) - \rho(\mathrm{Sh} = \mathrm{Sh}_{\min})\,, \qquad (3)$$

$$\Delta\rho[\mathrm{Xe}] = \rho(^{135}\mathrm{Xe\ at\ Sh}_{\mathrm{min}}) - \rho(^{135}\mathrm{Xe\ at\ equilibrium}) , \tag{4}$$

$$\Delta\rho[\mathrm{S7\,\&\,S8}] = \rho(\mathrm{S7\,\&\,S8, Sh} = 900\ \mathrm{mm}) - \rho(\mathrm{S7\,\&\,S8, Sh} = 0\ \mathrm{mm}) . \tag{5}$$

Each of the terms of Eq. 1 represents a component of the core reactivity balance involved in the evaluation of the shutdown margin. R0 is the total CR reactivity worth presented in Table III. $\Delta\rho(\mathrm{Sh}_{\mathrm{min}})$ is determined from Eq. 3. The label $\mathrm{Sh}_{\mathrm{min}}$ refers to the minimum anti-reactivity available in the core when the critical position is at the minimum of the curve of the CR motion during the operation cycle. $\Delta\rho[\mathrm{Xe}]$ is a measure for the reactivity effect of xenon-135, which is left in the core at the minimum of the CR position after the xenon transient (about 52 hours after the scram). At the minimum CR position, $\mathrm{Sh}_{\mathrm{min}}$, the available anti-reactivity of ^{135}Xe, $\Delta\rho[\mathrm{Xe}]$ in Eq. 4, is determined as the difference between the xenon anti-reactivity at $\mathrm{Sh}_{\mathrm{min}}$ (typically about -1.0\$ to -1.2\$) and the xenon anti-reactivity at equilibrium (about -3.8\$). $\Delta\rho[\mathrm{S7\&S8}]$ takes into account the reactivity worth of the safety rods. Finally, $\rho(\Delta T°)$ is the reactivity insertion due to decrease in temperature as the reactor cools down.

The results presented in Table V allow to conclude that the safety margin at the minimum of the CR motion during an operation BR2 cycle is significantly improved (by –0.9 \$) in the HEU core for the New Configuration CR1 compared to the Reference CR Configuration, which allows to save about 250 grams ^{235}U by replacing 1,5 fresh fuel element by 1,5 45% burnt element in channels D or replacing 2 low burnt fuel elements by high burnt (32%) elements in channels A&B.

Table V. Comparison of safety margins in the Reference and in the New Configuration CR1 at the minimum of CR motion after a scram followed by Xe-Sm transient (for Be-plug loaded in D180).

	Reference CR conf. (Fig. 2a)	New configuration CR1 (Fig. 2b)		
	HEU	HEU	UMo (D_{Cd}=0.4mm)	UMo (D_{Cd}=0.5mm)
Critical height at $\mathrm{Sh}_{\mathrm{min,I}}$, [mm]	536	500	360	375
$\Delta\rho_{\iota}[\mathrm{Sh}_{\mathrm{min}}]=\rho(900)–\rho(\mathrm{Sh}_{\mathrm{min,i}})$	+4.4\$	+6.0\$	+10.0\$	+9.7\$
Xenon worth $\Delta\rho_{i}[\mathrm{Xe}]$	+2.7\$	+2.7\$	0 [3]	0 [4]
Total CR worth	–13.8\$	–15.6\$	–14.6\$	–14.7\$
Worth of safety rods	–0.5\$	–1.2\$	–1.0\$	–1.0\$
Temperature effect $\Delta\rho_{\iota}[\Delta T°]$	–0.1\$	–0.1\$	–0.1\$	–0.1\$
Safety margin $\rho_{\mathrm{min,i}}[\mathrm{Xe\&Sm}]$	–7.3\$	–8.2\$	–5.7\$	–6.1\$

[3,4] For the UMo cores Shmin=$\mathrm{Sh}_{\mathrm{BOC}}$ and $\Delta\rho_{i}[\mathrm{Xe}]$=0 (see [1]).

The safety margins in all considered LEU cores satisfy the limits given in the TS [4]. It should be noted that the minimum of the CR motion in the UMo cores is at BOC when no xenon-135 is present in the core and therefore $\Delta\rho_i[Xe]=0$ (for more details see Section II.3.4.3 in [1]).

5. Experimental performances

In this section we compare the performances in key experimental positions (such as PRF devices for production of Mo-99) between the Reference CR configuration (HEU core) and the New CR1 configuration (HEU and LEU fueled cores). The fission power deposited in the fuel plates/tubes of the PRF devices is an indication for the amount of the produced Mo-99. Comparing the results for the HEU core given in the Table VI, we conclude that the produced power increases by 19% in the fuel plates of the PRF-device loaded in the channel G0 for the new CR1 configuration, which is due to switching of the CR S6 in the channel C341 with the fresh FE in the channel C319. From the other side, the switch of the CR S5 in the channel C281 with the fresh FE in the channel C259 results in slightly lower (by about –3%) power production in the fuel tubes of the PRF loaded in the channel G240. The latter can be compensated or even improved by loading of an additional FE in the peripheral channel K251. Regarding the PRF performances in the LEU fueled cores, the power production is also increased in the PRF loaded in the channel G0 for the new CR1 configuration, while the power production in the PRF in the channel G240 is reduced significantly for the UMo fuel type.

Table VI. Comparison of total power in the fuel plates/tubes of PRF devices for the two types of CR configurations: Reference CR configuration (Fig. 2a) and New CR1 configuration (Fig. 2b).

	Reference CR Configuration	New CR1 Configuration	
	HEU	HEU	UMo
PRF-plate type (G0)	0.244	0.301 (+19%)	0.267 (+9%)
PRF-tubular type (G240)	0.274	0.265 (–3%)	0.208 (–24%)

6. Conclusions

The study presented in this paper has shown that the BR2 fuel cycle can be significantly improved by various optimization strategies of the current core configuration. Optimized control rod localization by re-arrangement of the anti-shadowing rod effects, allow increasing the control rod worth by about –1.8 $ and improving the shutdown margin by about –0.6 $. At the same time the cycle length in the new core configurations is at least the same or a little higher than in the Reference core configuration. The safety margin at the minimum of the CR motion during an operation BR2 cycle is significantly improved (by –0.9 $) in the new configurations compared to the reference core configuration. The total reactivity gain for the new control rod configurations allows saving of about 350 grams ^{235}U in the central crown replacing low burnt by highly burnt fuel elements (or replacing a fresh fuel element in peripheral channels D by a highly burnt element) at the same cycle length and same energy produced.

The reactivity gain achieved by flipping upside down fuel elements in peripheral channels allows saving of additional 60 grams ^{235}U by replacing low burnt by highly burnt fuel element in the channels of the central crown without jeopardizing the safety limit of 4.5 $ for the shutdown margin.

The analysis performed for the reactivity effect of flipping upside down fuel elements located in the channels around the core center has shown significant gain in reactivity excess at BOC. However, the shutdown margin is reduced below the allowed limit of 4.5 $ according with the TS.

The conclusions have been obtained for the HEU core; however they are valid also for the considered LEU cores.

7. References

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