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Feasibility of BR2 Fuel Cycle with Different Burnable Absorber Options

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ABSTRACT

The purpose of this study is to demonstrate the capabilities of burnable absorbers used in different composition, quantity and localization in BR2 fuel types. A preliminary feasibility analysis has been performed for HEU (UAlx) and LEU (UMo-dispersed) fuels with various combinations of burnable poisons in form of:

- homogeneously mixture with the fuel meat;
- wires in the Al-side plates.

Reactivity performance, control rod motion, cycle length and fuel burn up (GWD/MTU) prior to discharge are compared in order to assess the fuel utilization. It has been found that the economy of the fuel cycle is significantly improved by using gadolinium poison in a form of homogeneous mixture with the fuel meat. At the same time, the experimental performances for gadolinium are similar as for the standard poisons (boron and samarium) used in the standard BR2 HEU fuel type.

1. Introduction

A series of studies for the feasibility to convert the BR2 reactor from HEU to LEU fuel have been performed during 2008 – 2012 [1-2]. Upfront to the neutronic conversion feasibility evaluations, an optimization of the burnable absorbers in the fuel assemblies for different LEU fuel systems has been performed. In this optimization project, the nature, quantity (or density, if applicable), geometrical form and localization in the fuel assembly of the burnable absorber have been studied. Four different burnable absorbers in form of wires in the aluminum side plates have been analyzed: Er_2O_3, Gd_2O_3, B_4C and Cd. The final choice made for the new burnable absorber was 36 cadmium wires in the Al side-plates of the standard BR2 fuel element. The optimum wire diameter for the U-7Mo LEU (20% ^{235}U) fuel with density 7.5 g U_{tot}/cm^3 is: Ø = 0.5 mm for. The results of these studies have been reported at the RERTR & RRFM conferences [3-5].

New studies are performed with gadolinium absorber in a form of homogeneous mixture with the fuel meat for the standard HEU and for the LEU (UMo) fuel types. The reactivity and experimental performances are compared vs. the standard burnable poisons (B_4C and Sm_2O_3) for the HEU fuel and vs. the cadmium wires for the LEU fuel type.

The neutronics calculations presented in this paper are performed using the MCNPX 2.7.0 code (see Ref. [6]). The calculation methodology is described in details in Ref. [7].

2. Summary of Considered HEU and LEU Fuel System Parameters

Previous studies for feasibility to operate the BR2 reactor with various fuel types using burnable absorber in form of wires in the aluminum side plates (see Fig. 1) have shown that cadmium had the best burn-up characteristics. The other considered absorbers included erbium, gadolinium and boron. The largest core reactivity loss toward EOC was for the erbium poison, while gadolinium and boron had better burn-up characteristics but worse than cadmium. It was also concluded that in fuel types with a given combination of density and enrichment, the principle way to improve the reactivity performance of the BR2 core is by decreasing the wire diameter (see Refs. [1-3]). For smaller wire diameter, the reactivity excess at BOC will be higher, and the reactivity performance during the operation cycle will be improved due to the faster burn up in wires with smaller diameter. Another way to improve the reactivity performance is to remove the inner 6 wires from each Al-side plate, since they contribute to the anti-reactivity of the core and moreover their burn up during irradiation is slower compared to the outer wires.

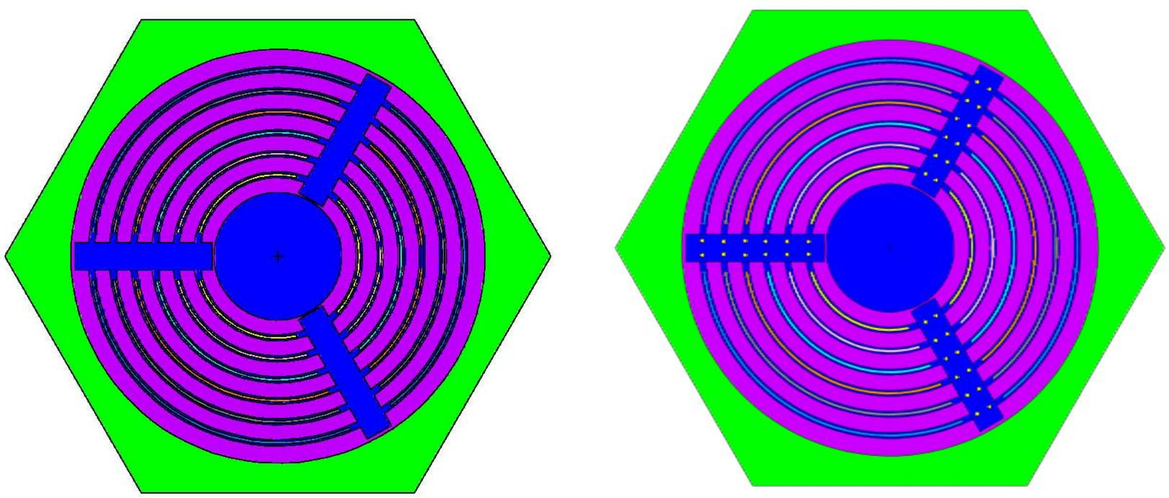

Figure 1. Standard BR2 fuel assembly geometry (left) and with wires in the Al-grooves.

In the present study the performances achieved with fuel types, in which the burnable poisons in form of wires are located outside the fuel meat, are compared to boron & samarium (in form of B_4C & Sm_2O_3) or gadolinium (in form of Gd_2O_3) homogeneously mixed with the fuel meat.

The fuel types used in the preliminary analysis for the feasibility of the BR2 reactor operation are summarized in Table I.

Table I. Considered HEU and LEU fuel system parameters.

	HEU fuel assembly		UMo fuel assembly	
Enrichment [%]	93.0	93.0	19.7	19.7
Density [g U_{tot}/cm^3]	1.3	1.3	7.5	7.5
^{235}U mass [grams]	400	400	482	482
^{238}U mass [grams]	30	30	1978	1978
Cd-wire diameter [mm]	–	–	0.5	–
Number Cd-wires per FE	–	–	36 Al grooves	–
Boron in form of B_4C	3.8 g fuel meat	–	–	–
Sm in form of Sm_2O_3	1.4 g fuel meat	–	–	–
Gd in form of Gd_2O_3	–	2.5-4.0 g fuel meat	–	2.5-4.0 g fuel meat

3. Comparison of the Burn up Rates of Different Burnable Poisons

This section presents analysis of the burn up capabilities of the following burnable poisons:

- cadmium used in a form of wires outside the fuel meat,
- boron & samarium used in forms of homogeneous B_4C & Sm_2O_3 mixtures in the fuel meat,
- gadolinium used in a form of homogenous Gd_2O_3 mixture in the fuel meat.

The major isotopes of interest, which have the highest absorption cross sections, such as ^{10}B, ^{113}Cd, ^{149}Sm, ^{155}Gd and ^{157}Gd, are presented in Fig. 2.

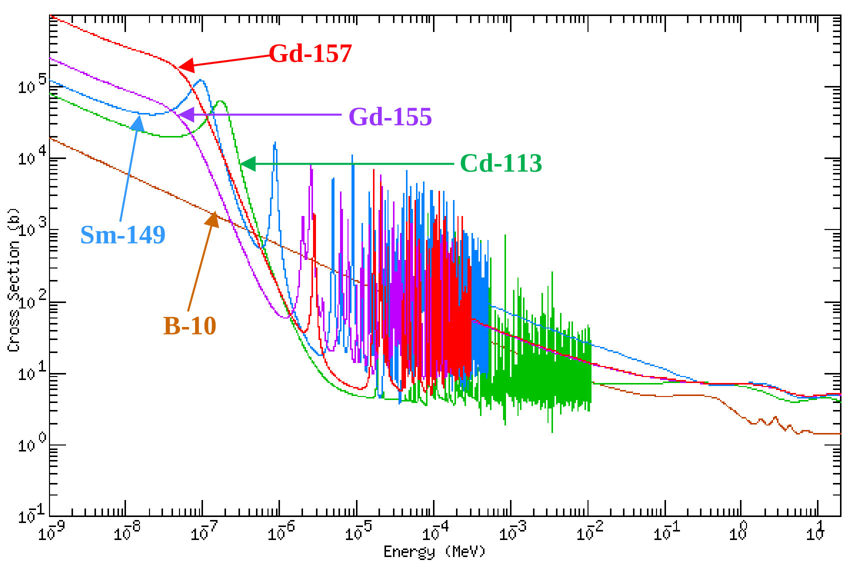

Figure 2. ENDF/B-VII cross sections of major burnable poisons used in the feasibility studies for various BR2 fuel types.

Other important isotopes are ^{151}Sm, which is accumulated during the irradiation and ^{153}Gd, which has also very high thermal cross section, however due to very low natural abundance, its burning is negligible.

The burn up rates of the major burnable isotopes have been calculated by MCNPX 2.7.0 during one operation cycle with duration 30 days. As it is seen from the graphs in Fig. 3, ^{157}Gd acts similarly to ^{149}Sm, burning almost totally in the first 5 days. The burn-up rate of ^{155}Gd, compared to ^{157}Gd is slower, but after 20 days is also totally burnt. The major cadmium isotope, ^{113}Cd and major boron isotope, ^{10}B, are burning almost linearly with time with boron having the slowest burn-up rate.

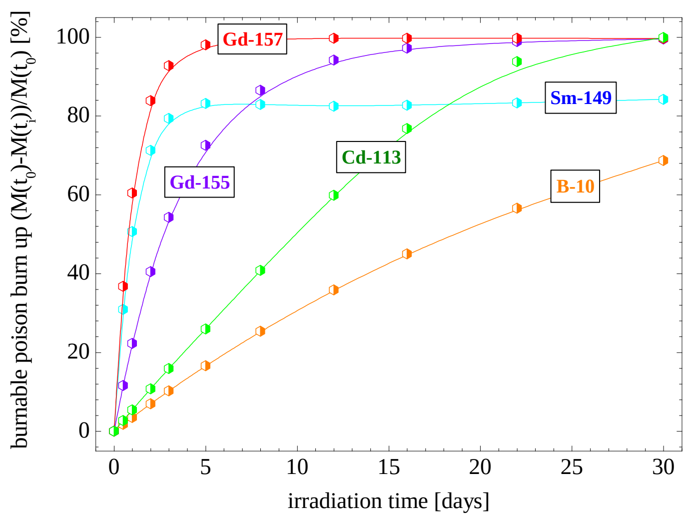

Figure 3. Comparison of burn up rate of different burnable poisons used in the HEU and LEU fuel assembly.

4. Reactivity performances

The reactivity performances, such as reactivity excess at BOC, control rod motion, cycle length and reactivity of a fuel assembly vs. ^{235}U burn-up, are compared in this Section for the HEU and LEU cores using different burnable absorber options.

4.1 Reactivity excess at BOC

The reactivity excess in each core is determined relatively to the reactivity in the HEU representative core for two types of core loadings: a representative load, which contains 33 fuel elements and a modified load, which contains 31 fuel elements (see Table II). The reactivity excess and critical heights calculated at BOC in HEU and LEU cores are presented in Table III.

The HEU fuel types with Gd poison in the meat are very reactive and therefore two different amounts Gd have been considered: 2.5 g/FE and 4.0 g/FE. The initial critical height for both cases is Sh(BOC)> 450 mm, however the control rods during the course of the operating cycle go down. Therefore optimization strategies for feasibility of the HEU fuel type with Gd poison in the fuel meat are considered in the next Section 4.2.

The comparison of the reactivity excess in Table III shows that, the HEU fuel types with standard poisons B & Sm have high critical height for the *modified* load (Sh > 600 mm), while the HEU fuel with Gd poison have critical height around 500 mm for the same load. The UMo cores with Cd-wires and Gd poison 2.5 g/FE have critical height 500 < Sh < 600 mm for the modified load. In the next Section 4.2 we discuss the feasibility for the considered core loadings regarding the cycle length.

Table II. Reactor core loadings used in the calculations.

Reactor fuel channel	^{235}U burn-up [%] Representative load	^{235}Uburn-up [%] *Modified* load	Reactor fuel channel	^{235}Uburn-up [%] Representative load	^{235}U burn-up [%] *Modified* load
A30	16	16	D0	32	32
A90	16	16	D60	***32***	***46***
A150	32	32	D120	***32***	***46***
A210	32	32	D240	***32***	***46***
A270	16	16	D300	***32***	***46***
A330	32	32	F14	46	46
B0	16	16	F46	***46***	***0***
B60	32	32	F106	***46***	***0***
B120	32	32	F166	46	46
B180	16	16	F194	46	46
B240	32	32	F254	***46***	***Be***
B300	32	32	F314	***46***	***0***
C41	***0***	***32***	F346	46	46
C101	***0***	***32***	G180	46	46
C161	0	0	H1/Central	32	32
C199	0	0	**33 FE in Representative Load 31 FE in Modified Load**		
C259	***0***	***Be***			
C319	***0***	***32***			

Table III. Reactivity excess and critical heights at BOC in HEU and LEU cores. The reactivity excess is determined relatively to the representative HEU core.

Representative cores	Cd-wires in Al-grooves	Burnable poisons in the fuel meat	Reactivity excess representative load (33 fuel elements)	Reactivity excess ***modified*** load (31 fuel elements)
HEU-93% ^{235}U, 1.3 g/cm^3	–	3.8 g B/FE 1.4 g Sm/FE	**0.0 $** **(Sh=595 mm)**	–1.28 $ (Sh=658 mm)
	–	2.5 g Gd/FE	+3.53 $ (Sh=465 mm)	+3.39 $ (Sh=472 mm)
	–	4.0 g Gd/FE	+1.38 $ (Sh=551 mm)	+2.00 $ (Sh=519 mm)
UMo-20% ^{235}U, 7.5 g/cm^3	D=0.5 mm	–	+3.57 $ (Sh=466 mm)	+2.45 $ (Sh=503 mm)
	–	2.5 g Gd/FE	+2.12 $ (Sh=514 mm)	+1.18 $ (Sh=548 mm)
	–	4.0 g Gd/FE	+0.16 $ (Sh=588 mm)	+0.35 $ (Sh=580 mm)

4.2 Control rod motion and cycle length

4.2.1 HEU core

The fuel cycles using burnable poisons, homogeneously mixed with the fuel meat, follow somehow similar tendency, which is characterized with a minimum of the control rod position during the course of the operation cycle. However, the minimum of the CR position in fuel types with Gd_2O_3 in the fuel meat is observed earlier in time (about 3-4 days after BOC) due to the faster burn-up of the gadolinium poison compared to boron and samarium. HEU fuel type with 2.5 g/FE Gd poison in the meat is very reactive (low critical control rod position at BOC), characterized with a steep control rod course down during the first operational days. Therefore, in order to respect the safety reactivity margin (> 4.5 $, see Ref. [8]) at the minimum of the CR position, different strategies can be applied specifically for the HEU fuel type, such as:

(i) loading of absorptive experiments (Iridium, stainless steel, etc.) would allow to increase the initial and the minimum control rod critical position by about 100 mm;
(ii) increasing the initial Gd amount in the fresh fuel elements from 2.5 g/FE up to 4.0 g/FE improves the critical height at BOC. However, as it is seen from Fig. 4a, the minimum critical rod position during the cycle is almost not changed (or very little);
(iii) removing from the load fresh and/or burnt fuel elements allows to increase significantly the minimum rod position by about 100 mm (see Fig. 4b).

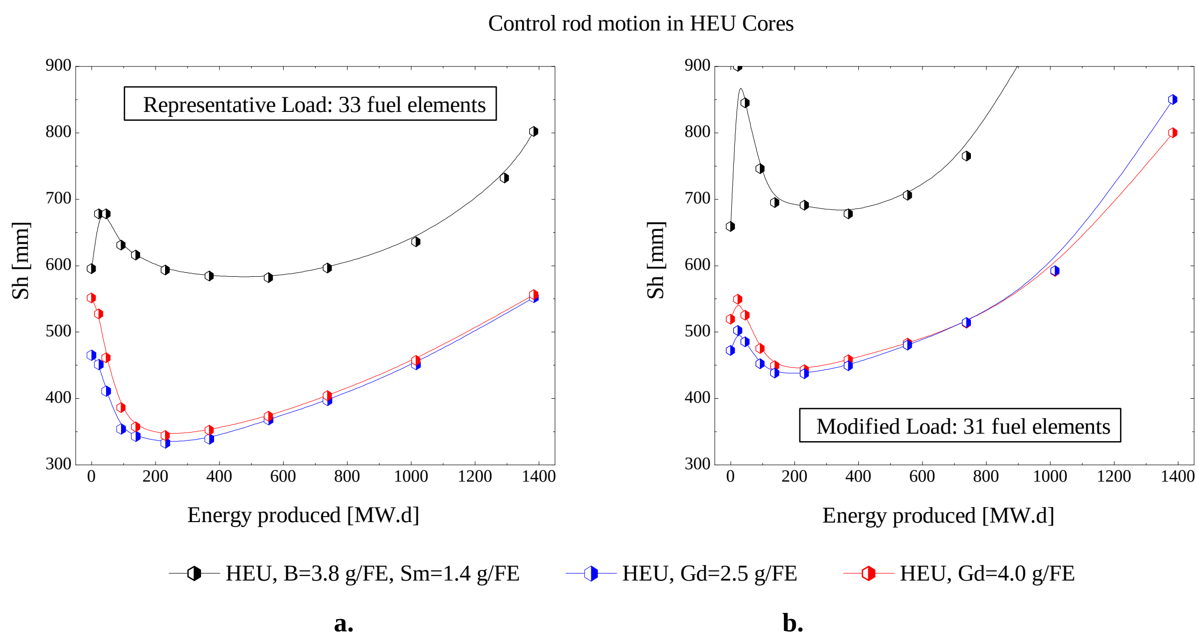

Figure 4. Control rod motion in HEU cores: a. representative load; b. modified load.

The cycle length with Gd in the fuel meat as burnable poison is significantly longer compared to the standard poisons boron and samarium, which is demonstrated for 2 different core loadings in Fig. 4. The economy of the fuel utilization using the gadolinium poison will be discussed in further Section 5.

4.2.2 LEU core

The minimum control rod position for the LEU fuel types with Cd-wires is effective only at the start-up: after the first couple of days, the control rods are almost monotonically withdrawn during the reactor operation. The tendency of the control rod motion with Gd poison in the fuel meat is similar as for the HEU fuel type, however the descending of the rods is less pronounced and in principle the UMo fuel type is feasible for both considered Gd amounts – 2.5 and 4.0 g/FE, as for the representative load (see Fig. 5a), as well as for the modified load (see Fig. 5b). In all cases the cycle length with Gd absorber is significantly longer in comparison with Cd-wires.

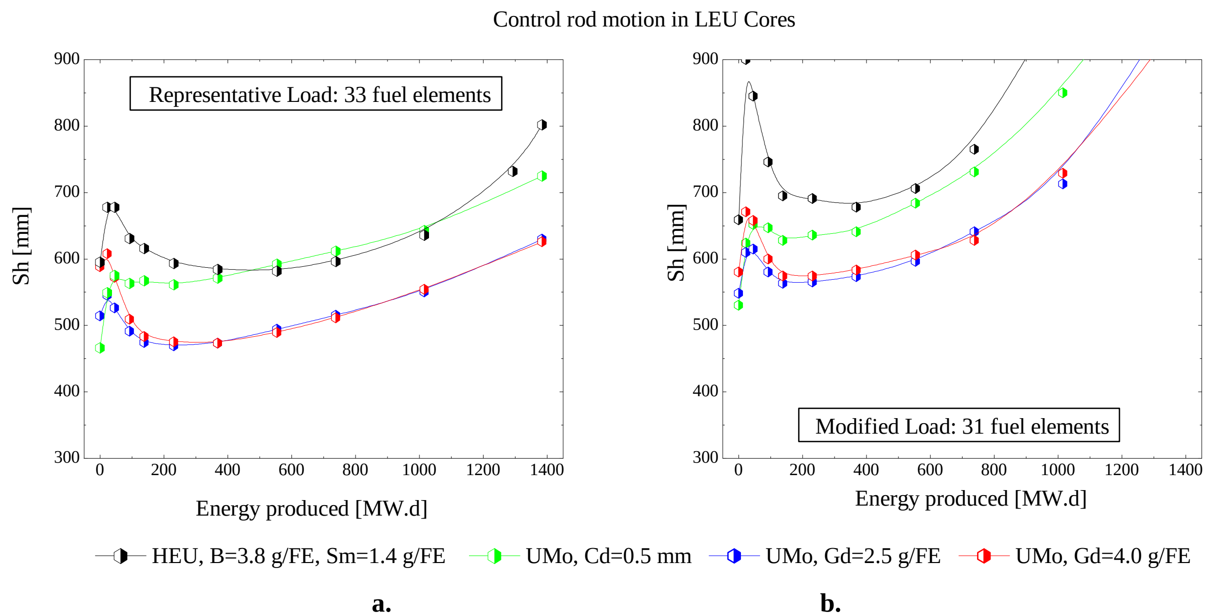

Figure 5. Control rod motion in LEU cores: a. representative load; b. modified load.

4.3 Reactivity of a fuel element vs. ^{235}U burn-up

The performance graph of the reactivity of a fuel element in dollars [$] as function of the mean ^{235}U burn-up [%] has been calculated for the standard HEU fuel and for the LEU fuel type (see Fig. 6). The load of the representative HEU core has been used in the calculations. The methodology for calculation of the reactivity effect is as follows: fuel elements, each with a given mean ^{235}U burn-up [%], are loaded in one and the same channel A270. The reactivity of each fuel element is determined relatively to the reactivity of the fresh [0%] standard HEU fuel element, loaded in the same channel A270 using the following formulae (i=0,…,60% ^{235}U burn up):

$$\Delta\rho(HEU_i) = \rho_{HEU_i}(B^5_{HEU,i}) - \rho_{HEU,standard}(0\%)\ , \quad \Delta\rho(LEU_i) = \rho_{LEU,i}(B^5_{LEU,i}) - \rho_{HEU,standard}(0\%)\ .$$

As it is seen from Fig. 6, the reactivity of the HEU and LEU fuel elements is maximum for the Gd poison and significantly higher for all ^{235}U burn-up values with exception of a fresh fuel element with gadolinium in the fuel meat.

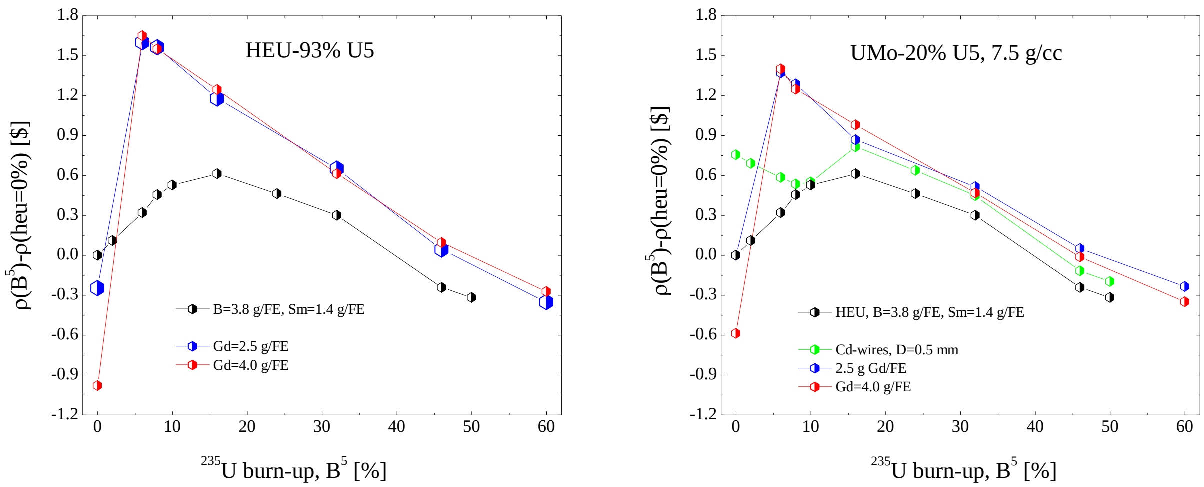

Figure 6. Performance graphs of reactivity of HEU & LEU fuel element vs. ^{235}U burn-up.

5. Fuel Cycle Economy

The results about the reactivity performances shown in the Section 4 demonstrate the economic advantages of the gadolinium poison among the other considered options. We have shown that a fuel cycle for a modified core load with reduced number of fuel elements, is feasible for the HEU and for the LEU fuel types with Gd poison in the fuel meat. At the same time, the HEU fuel cycle with standard poisons B & Sm has significantly shorter cycle length.

Table IV summarizes the main results obtained in the Section 4 for the ***modified*** core load. The data in the table represent the gain in dollars for each considered fuel type relatively to the standard HEU fuel with boron and samarium burnable absorbers.

Table IV. Reactivity gain (in dollars or days) in HEU and LEU cores using different poisons *relatively to the standard HEU core with standard poisons (boron and samarium) for the modified core load*.

Fuel type	HEU-93% (UAlx)		LEU-20% (UMo, 7.5 g/cc)		
Burnable absorber	Gd=2.5 g/FE	Gd=4.0 g/FE	Cd-wires D=0.5 mm	Gd=2.5 g/FE	Gd=4.0 g/FE
Reactivity excess (BOC)	+3.85 $	+2.46 $	+3.73 $	+2.46 $	+1.63 $
Reactivity of fuel element with different ^{235}U burn-up (%)	–0.25 $ (0%) +1.09 $ (8%) +0.55 $ (16%) +0.36 $ (32%) +0.29 $ (50%)	–0.98 $ (0%) +1.08 $ (8%) +0.61 $ (16%) +0.35 $ (32%) +0.30 $ (50%)	+0.75 $ (0%) +0.10 $ (8%) +0.20 $ (16%) +0.16 $ (32%) +0.10 $ (50%)	0.00 $ (0%) +0.85 $ (8%) +0.26 $ (16%) +0.21 $ (32%) +0.29 $ (50%)	–0.60 $ (0%) +0.10 $ (8%) +0.36 $ (16%) +0.20 $ (32%) +0.20 $ (50%)

The gain in reactivity dollars is listed for fuel elements with different mean fuel burn-up. The data in the last row of Table IV show the reactivity difference between HEU fuel element with Gd poison (or LEU fuel element with Cd-wires or with Gd poison in the meat) and a standard HEU fuel element with boron and samarium for different mean ^{235}U burn-up values of the fuel element. As can be seen, except for a fresh fuel element with Gd poison, all other burnt elements with Gd poison have significantly higher reactivity values. Fuels with gadolinium poison in the meat are "more energetic" (see Fig. 7), which would allow to use the uranium more efficiently.

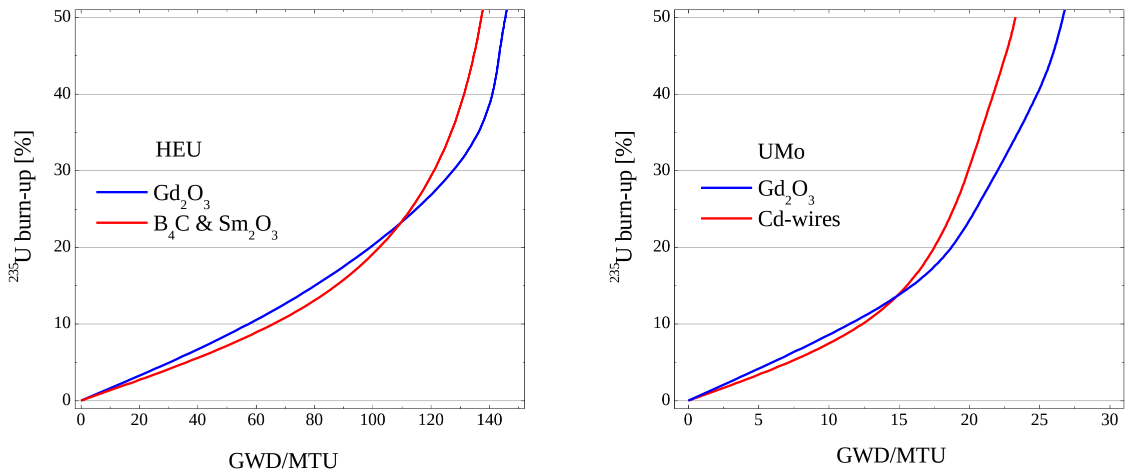

Figure 7. Increasing fuel element burn-up prior discharge by utilization of gadolinium as burnable absorber.

6. Comparison of Experimental Performances

Calculations of thermal, epi-thermal and fast neutron flux distributions in the axial direction have been performed for representative fuel element channels and for typical experimental positions. It has been shown in an internal SCK•CEN report that the experimental performances of the HEU fuel types with Gd poison are similar (or in some instances even better) to the standard HEU fuel type with B & Sm. The experimental performances of the LEU fuel types with Gd poison in the fuel meat have shown about 10% higher fluxes in comparison to the Cd-wires, for which the losses compared to the standard HEU fuel type were in average about 20%.

7. Conclusions

During 2008-2015 a detailed comparative analysis has been performed for the efficiency and absorption capabilities of 3 major candidates as burnable absorber for the new LEU BR2 fuel: Cd, Gd_2O_3, and B_4C. It was shown that the most favorable absorber, used outside of the fuel meat was Cadmium. This was due to the fact that for the minimum wire diameter, which could be fabricated (Ø=0.3-0.4 mm) cadmium had the highest burn up rate. Gadolinium, boron and other considered absorbers are self-shielded for such diameters and therefore they need extremely thin wire diameters (Ø << 0.1 mm) in order to have high burn up rate. Therefore, a preliminary choice of new burnable absorber has been made: 12 or 6 Cd-wires per each one of the three Al-side plates in the fuel element.

Later (current) studies involve analysis of various fuel types (LEU and HEU) with various burnable poisons, homogeneously mixed with the fuel meat: B_4C & Sm_2O_3 as in the standard BR2 fuel, and Gd_2O_3. The presented in this paper studies show that the highest burn up rate has gadolinium due to its 2 major isotopes Gd-155 and Gd-157 which have very high thermal absorption cross sections and deplete very fast with the fuel burn-up.

The analysis of the reactivity performances has shown that the HEU and LEU fuel types with gadolinium in the fuel meat have significantly longer cycle length compared to the standard HEU fuel with standard boron and samarium poisons. The optimum amount of the gadolinium poison for the HEU and UMo fuels is within 2.5-4.0 grams Gd in a fresh fuel element. However, due to the steep control rod course down during the first 3-5 days in the HEU core, it is preferable to use a smaller amount than 4.0 grams Gd in a fresh HEU fuel element.

The reactivity of burnt HEU and LEU fuel element with Gd poison is significantly higher compared to the standard boron and samarium poisons, as well as compared to the cadmium wires.

The experimental performances of HEU fuel type with gadolinium in the fuel meat are comparable to the standard HEU fuel with standard boron and samarium poisons. The neutron flux losses in LEU fuel types with Gd in the meat are about 10% less than for Cd-wires in the Al-side plates.

The preliminary results presented in this paper have shown that fuel types with gadolinium absorber used in a form of homogeneous mixture with the fuel meat have some economic advantages compared to other burnable absorber options.

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