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Recommended strategy and limitations of burnable absorbers used in VVER fuel assemblies

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Abstract There is an obvious effort to increase the burn up of used fuel assemblies in order to improve fuel utilization. A more effective operation can be realized by extending the fuel cycles or by increasing the number of reloadings. This change is nevertheless connected with increasing the uranium enrichment even above 5% of ^{235}U. Burnable absorbers are widely used to compensate for the positive reactivity of fresh fuel. With proper optimization, burnable absorbers decrease the reactivity excess at the beginning of the cycle, and they can help with stabilization of power distribution. This paper describes properties of several materials that can be used as burnable absorbers. The change in concentration or position of the pin with a burnable absorber in a fuel assembly was analyzed by the HELIOS transport lattice code. The multiplication factor and power peaking factor dependence on fuel burn up were used to evaluate the neutronic properties of burnable absorbers. The following four different materials are discussed in this paper: Gd_2O_3, IFBA, Er_2O_3, and Dy_2O_3. Gadolinium had the greatest influence on fuel characteristics. The number of pins with a burnable absorber was limited in the VVER-440 fuel assembly to six. In the VVER-1000 fuel assembly, 36 pins with a burnable absorber can be used as the assembly is larger. The erbium depletion rate was comparable with uranium burn up. Dysprosium had the largest parasitic absorption after depletion.

Keywords Burnable absorber · Gadolinium · IFBA · Erbium · Dysprosium · Power peaking · VVER fuel · HELIOS code

1 Introduction

The structure of reactor operation has undergone several modifications since the first nuclear power plant (NPP) was built. Reactor operation efficiency was increased by better fuel utilization. The number of fuel assembly reloadings was increased to up to five, and also the length of cycles was raised. Although reactors that operate in 12-month long cycles are still common, there are also reactors that are operate in 18- or 24-month long cycles. Even very long fuel cycles of up to 48 months are considered for light-water reactor (LWR) reactors [1]. There is a long tradition of fuel cycle and reactor operation improvements in the Czech Republic. New studies of fuel cycles focused on extension are still running (for example, [2, 3]).

The main goal of fuel cycle optimization is to increase fuel utilization and keep the number of fresh fuel assemblies as low as possible. Several limitations are applied to fuel batches surveyed by the optimization process. The most important limitation is the limitation of the core power peaking factor FdH. (FdH is the maximal ratio of pin power to average pin power in the core.) The moderation condition of the triangular lattice used in VVER reactors is worse than that of the square lattice used in pressurized

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water reactor (PWR) reactors. There is higher difference in the moderation condition in VVER reactors in the middle part of the assembly and at the periphery. Periphery fuel pins are achieving higher power owing to their better moderation. The enrichment profile of a fuel assembly helps to maintain the FdH limit during reactor operation.

Extension of the fuel cycle is linked to increasing fuel enrichment. The initial fuel assemblies had maximum enrichments of approximately 3.6% of ^{235}U. Now, the enrichment is very close to 5% of ^{235}U, and the fuel burn up can be as high as 45,000–55,000 MWd/tU. Based on [4], it is necessary to raise the fuel enrichment level to up to 5.5% of ^{235}U to achieve a burn up of 70,000 MWd/tU in 12-month long cycles, 5.9% of ^{235}U for 18-month long cycles, and 6.3% of ^{235}U for 24-month long cycles. A burn up level of 80,000 MWd/tU can be reached with an enrichment of 6.2, 6.5, or 7.0% of ^{235}U for 12-, 18-, and 24-month long cycles, respectively.

Increasing the fuel enrichment means a higher reactivity has to be compensate for at the beginning of the cycle. Control rods and boric acid dissolved in a moderator might not be sufficient for reactivity compensation, especially with an enrichment above 5% of ^{235}U. The concentration of boric acid is limited by the moderator reactivity temperature coefficient (MTC). The MTC coefficient has to be negative during the operation of the reactor. Even during the start up period, the MTC value and the rate of its changes are limited. A high boric acid concentration in the moderator leads to an unacceptable positive MTC, i.e., the concentration of boric acid should be below 9 g/kg. (This corresponds to the recommended value of 1500 ppm [5].) In summary, alternative methods for excess reactivity compensation, e.g., in form of burnable absorbers, are necessary.

Burnable absorbers were used in a discrete form (rods or pellets in guide tubes) at first; however, now, it is usual to use integral burnable absorbers that are mixed together with the fuel or are placed at the fuel pellet surface. The addition of the burnable absorber decreases the reactivity of fresh fuel and allows safe transportation or manipulation of fuels enriched above 4% of ^{235}U. Using burnable absorbers in the reactor core compensates for the positive reactivity at the beginning of cycle, and their presence also positively influences the power distribution in the core. A very important characteristic of the burnable absorber is the kinetics of its depletion (i.e., how fast it is depleting) and the influence of products of depletion on system reactivity. Before a burnable absorber is used, its type, concentration, and total amount need to be determined. Integral burnable absorbers could be placed only in selected fuel pins of a fuel assembly, and the number of these fuel pins has to be evaluated by fuel cycle optimization. The most known burnable absorbers are Gd_2O_3 and the integral fuel burnable absorber(IFBA). Other materials considered to be appropriate for burnable absorbers include erbium, dysprosium, europium, or samarium [5]. Although use of an integral burnable absorber is more common, there are also studies that focus on the use of burnable absorber rods. Burnable absorber rods can be used even in combination with an integral burnable absorber (specially for very long fuel cycles) [6].

Use of burnable absorbers is crucial for effective operation of reactors. It is important to optimize the use of burnable absorbers to compensate for the positive reactivity at the beginning of irradiation, especially for fuels with enrichments close to 5% of ^{235}U or higher and to know the impact of burnable absorber on neutron physical characteristics of the core. The total amount of burnable absorber is influenced by its concentration and also by the number of pins per fuel assembly that contain the burnable absorber. The analysis presented in this paper was performed for gadolinium oxide Gd_2O_3, IFBA, erbium oxide Er_2O_3, and dysprosium oxide Dy_2O_3 burnable absorbers. Based on the presented results, it is possible to evaluate the impact of different burnable absorber concentrations or the number of pins with the burnable absorber on fuel properties. The findings presented in this paper were used to support a VVER-440 fuel assembly proposal [2].

2 Properties of burnable absorbers

2.1 Gadolinium

Gadolinium is used in pressurized water reactors in the form of gadolinium oxide Gd_2O_3. Burnable absorbers containing Gd_2O_3 are used also in Czech NPP Dukovany (VVER-440 V-213) and Temelin (VVER-1000 V-320).

The most important isotopes for neutron absorption are ^{155}Gd and ^{157}Gd, with absorption cross sections of 60,737 b and 252,912 b at 0.0253 eV, respectively [7], see Table 1. The products of radiative capture have very low absorption cross sections (approx. 2 b, i.e., very low parasitic absorption).

Gadolinium oxide is used for reactivity compensation during transportation, storage, and at the beginning of fuel irradiation. Gadolinium can be mixed with fuel although the melting temperature and thermal conductivity of the mixture are lower than that for pure UO_2. In order to control the temperature of fuel pins with Gd_2O_3, the enrichment of the pins must be generally lower than that in other fuel pins.

A more profound self-shielding effect can be observed in fuel pins with the gadolinium burnable absorber. Neutrons are absorbed immediately when they enter the fuel region owing to the high absorption cross section of ^{155}Gd

Table 1 Natural composition of considered burnable absorbers and their cross sections at 0.0253 eV (20 °C) [7]

Izotopes	Natural abundance	σ_γ (b)	σ_α (b)
^{152}Gd	0.2	735	0.007
^{153}Gd	–	22,334	0.03
^{154}Gd	2.18	85	0
^{155}Gd	14.8	60,737	0
^{156}Gd	20.47	1.8	0
^{157}Gd	15.65	252,912	0
^{158}Gd	24.84	2.2	0
^{160}Gd	21.86	1.4	0
^{10}B	19.9	0.5	3844
^{11}B	80.1	0.005	0
^{162}Er	0.14	19	0
^{164}Er	1.61	13	0
^{166}Er	33.61	17	0
^{167}Er	22.93	650	0
^{168}Er	26.78	2.7	0
^{170}Er	14.93	8.9	0
^{156}Dy	0.06	33	0
^{158}Dy	0.1	43	0
^{160}Dy	2.34	56	0
^{161}Dy	18.91	600	0
^{162}Dy	25.51	194	0
^{163}Dy	24.9	123	0
^{164}Dy	28.18	2653	0
^{165}Dy	–	3582	0

or ^{157}Gd. Therefore, gadolinium is depleted from the outside to the inside of a fuel pin. Isotopes in the middle of the fuel pellets in fact do not react with thermal neutrons at all as thermal neutrons are captured before reaching the central part of the fuel pins. The self-shielding effect has to be considered during fuel assembly proposition and fuel cycle optimization.

2.2 Boron

Boron is used as an absorbing material for the regulation of the fission chain reaction in control rods and control assemblies (B_4C or borated steel), or as a boric acid H_3BO_3 dissolved in the moderator. At the very beginning of nuclear engineering, natural boron was used in the form of borosilicate glass rods as a discrete burnable absorber. Rods were placed into the guide tubes of fuel assemblies. This solution is no longer used as the cladding of rods was usually made from stainless steel and caused additional parasitic absorption of neutrons even after boron depletion. Moreover, use of discrete burnable absorbers worsens the water–uranium ratio owing to displacement of water from the guide tubes. The depleted borosilicate glass was an extra radioactive waste that had to be treated.

Current pressurized water reactors use boron in the form of ZrB_2 that is placed inside the fuel pin claddings. This absorber is known as an integral fuel burnable absorber (IFBA) and is applied in a thin layer on the surface of fuel pellets. In this case, burnable absorber is not mixed with UO_2 and fuel thermomechanical properties are not affected.

The important isotope for neutron absorption is ^{10}B with a cross section of 3844 b for an (n, α) reaction at 0.0253 eV [7] (please see Table 1). The product of the absorption reaction is ^{7}Li, and as it has a very low absorption cross section (approx. 0.05 b, which is similar to zirconium), it does not influence the neutron balance in the reactor. Although depletion from outside to inside the fuel pin is observed even for UO_2, boron does not have the same strong radial depletion as gadolinium isotopes. Boron is typically used in its natural form, but it is possible to increase the ratio of ^{10}B to up to 80% for nuclear fuels with higher enrichments.

2.3 Erbium

Although erbium use in the nuclear industry is not as wide as that for the previous elements, erbium has been used in several PWR reactors [8].

The most important isotope is ^{167}Er with an absorption cross section of 650 b at 0.0253 eV [7] (please see Table 1). Residual absorption by products of radiative capture is higher for erbium than for gadolinium. Depletion of erbium is slower in comparison with those of gadolinium or boron. In fact, the speed of depletion is comparable with that of uranium depletion.

As the cross section of ^{167}Er in the resonance region is comparable with its thermal values in this region, it is impacted by temperature changes due to resonance broadening. For transients that experience an increase in fuel temperature, the effect is similar to that for ^{238}U. According to [8], these erbium properties could be used in advanced fuel concepts. Fuels with matrices that are different from that of ^{238}U lose this temperature feedback. The use of erbium in a fuel matrix could help to stabilize the temperature changes in transients [9].

Erbium oxide can be mixed with UO_2. The thermal properties of such a mixture, such as thermal conductivity and melting temperature, are influenced the same way they are for gadolinium oxide.

2.4 Dysprosium

Dysprosium was used primarily in CANDU reactors as dysprosium oxide Dy_2O_3.

The highest absorption cross section at a thermal energy of 0.0253 eV for ^{164}Dy, which is the most frequent isotope of dysprosium based on its natural abundance value, is 2653 b [7] (please see Table 1). Radiative capture at ^{164}Dy leads to production of ^{165}Dy, which has a low absorption cross section in the thermal region. The second most important isotope is ^{161}Dy, with a thermal absorption cross section of 600 b [7]. Based on the neutron absorptions of lower isotopes that have relatively high natural abundances, there is continuous production of new ^{164}Dy isotopes. Due to this ongoing production, dysprosium has a high parasitic absorption, and it takes a long time to experience full depletion. Dysprosium oxide can be mixed with fuel, which also influences the thermomechanical properties of the fuel.

A list of all considered burnable absorbers, their abundances, and cross sections is provided in Table 1. The energy dependences of the cross sections are shown in Fig. 1.

3 Materials and calculations

3.1 VVER-440 reactors

The full analysis was conducted for a VVER-440 reactor fuel assembly. The VVER-440 reactor is an older Russian pressurized water reactor, with a projected output electric power 440 MW. (Output power of several reactors was increased to up to 510 MW.) These reactors are in operation in Russia, Czech Republic, Hungary, Slovakia, Finland, Ukraine, and Armenia.

Each VVER-440 core contains 349 fuel assemblies, including 37 control assemblies. The control assembly is composed of a fuel part (lower) and an upper absorption part. As the absorption part is lowered into the reactor core, the fuel part is simultaneously ejected below the core. The fuel assembly is composed of 126 fuel pins in a triangular lattice and covered by a shroud. The gadolinium burnable absorber Gd_2O_3 is used.

The average enrichment of a referenced Gd-2M fuel assembly is 4.38 % of ^{235}U. The Gd-2M fuel contains six pins with a burnable absorber with a concentration of 3.35%. Currently, new modifications of the Gd-2M fuel (with altered geometry) are loaded into the core of NPP Dukovany, but these changes are not covered in the presented analysis.

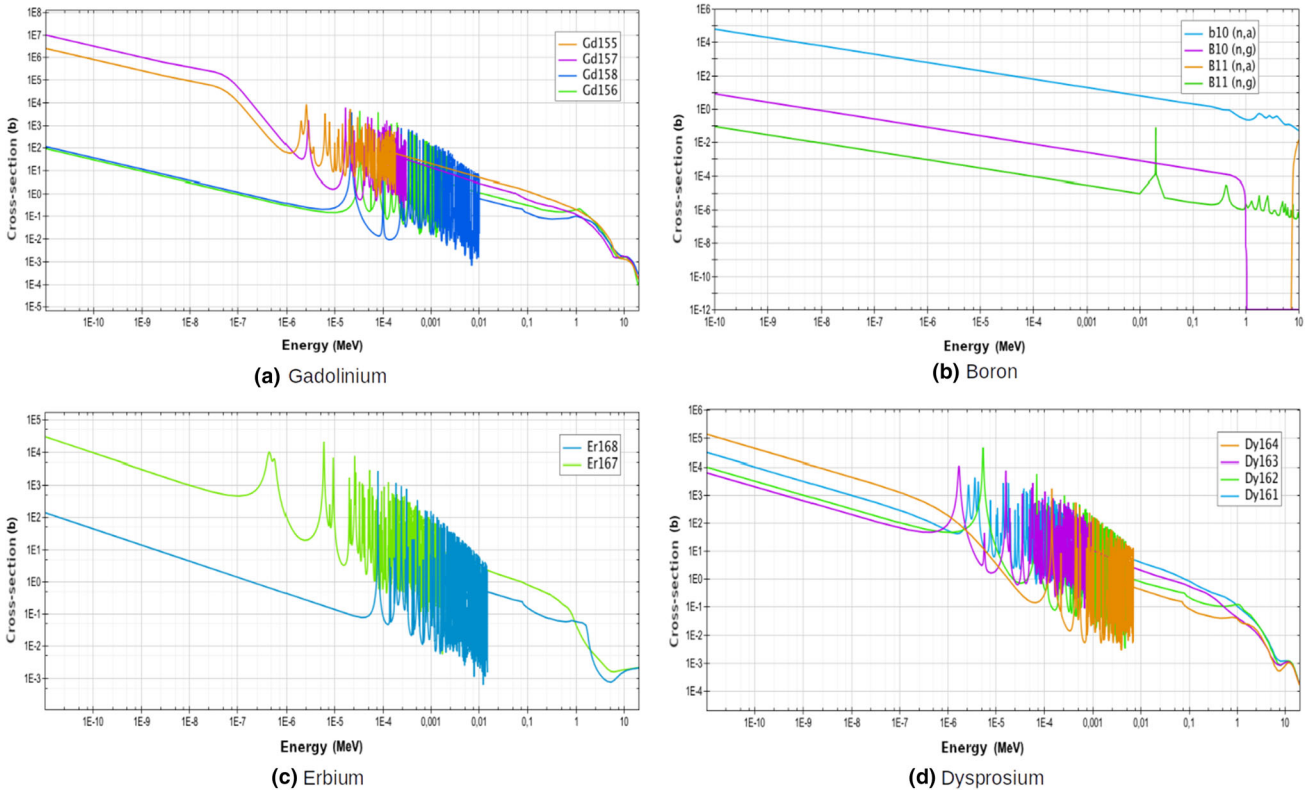

Fig. 1 Energy cross section dependences of the discussed isotopes [7]

3.2 VVER-1000 reactors

The VVER-1000 is a higher power level Russian pressurized reactor. The reactor core is composed of 163 fuel assemblies, each containing 312 fuel pins, 18 guide tubes for regulation, and one central tube for instrumentation. Regulation of the core is provided by 61 absorption clusters that are inserted into the guide tubes of fuel assemblies in defined positions in the core. Gadolinium burnable absorbers in the form of Gd_2O_3 have been used in fuel assemblies since 2010. Before 2010, the fuel supplier was Westinghouse company and fuel assemblies were equipped with IFBA burnable absorbers.

The enrichment of the fuel assemblies and positions of the pins with the burnable absorber are given by optimization of the fuel cycle. The concentration of gadolinium is 5%, while the number of pins can vary from 6 to 36.

3.3 Calculation code

All calculations presented in this paper were done with the transport lattice code HELIOS v. 2.1 with ENDF/B-VII.0 library. The method of characteristics (MOC) solver for the transport solution was used [7, 10].

The HELIOS code is widely used for calculating group-wise cross sections, diffusion coefficients, discontinuity factors, and other parameters. The calculated data are then transformed into an applied library for the macrocode ANDREA (used also at NPP Temelin). Fuel assembly models and calculation methodology were verified as a part of the HELIOS/ANDREA standardization process request by a Czech regulatory body for all codes used for safety related calculations.

The analysis presented in this paper is at the level of an infinite lattice of a single fuel assembly (2-D calculation). The multiplication factor (k_∞) and power peaking factor (PPF) were used for comparison of individual fuel variants. The PPF gives the maximum ratio of the pin power to the average pin power in the lattice.

The PPF factor calculated by HELIOS is not sufficient for FdH coefficient determination for fuel-batch optimization. Full-core calculations with pin power reconstruction are necessary. However, the PPF gives an estimation of the final power distribution in a fuel assembly.

Optimization of the fuel enrichment profile and fuel batches is necessary to meet the FdH limit. Nevertheless, fuel optimization is not a part of this study. The main goal of this study was to demonstrate the influence of burnable absorbers on fuel assembly parameters. The results for reference fuels are presented to give a better idea of characteristic changes.

This study is limited to an analysis of neutronic properties of fuels with burnable absorbers. The addition of burnable absorbers in oxide form directly to the fuel may lead to changes in the thermomechanical properties of the fuel. This has to be considered in a complex analysis of the fuel cycle [1, 8], and changes in the thermal conductivity are also reflected in the HELIOS/ANDREA fuel temperature model.

3.4 Utilized models and parameters

The HELIOS models used for this analysis respected real fuel geometry, material composition, and operation parameters for NPP Dukovany or Temelin. The utilized burn up steps varied from 500 MW/d at the beginning of depletion to 4000 MW/d for high burn up. (The last calculated value was 60,000 MWd/tU.)

The geometry and material composition of the fuel assembly are identical for all steps of this analysis. Only burnable absorber concentration and positions of pins with the burnable absorber or number of pins with the burnable absorber were changed. The enrichment profile was maintained only in the very first part of the analysis when the burnable absorber concentration was changed.

The position of the pin with the burnable absorber was change within a sixth of the fuel assembly. (Central tube in position 16 was unchanged.) To eliminate other factors, a flat fuel enrichment of 4 % of ^{235}U was applied to all fuel pins with no enrichment profile, and the content of the burnable absorber was set to 3.35% or 3.35 mg/cm for the IFBA. The numbering of the pins in one-sixth of the fuel assembly is shown in Fig. 2.

In the second set of calculations, two pins with a burnable absorber per one-sixth of the fuel assembly were considered. Calculations were done for the non-profiled fuel assembly with 4% of ^{235}U, and the burnable absorber concentration was 2% or 2 mg/cm for the IFBA. All calculations were done only for the 30° segment of the reactor core to decrease a number of possible combination.

The last part of the VVER-440 fuel assembly analysis demonstrates the effect of burnable absorber use in all pins of the fuel assembly. The non-profiled fuel assembly with

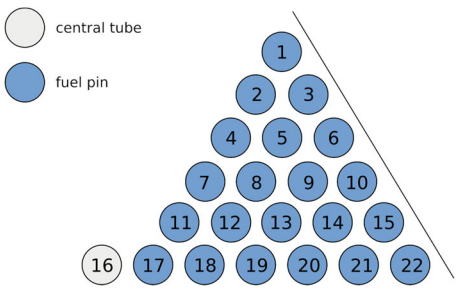

Fig. 2 Numbering of pin positions in one-sixth of the VVER-440 fuel assembly corresponds to the numbering used in HELIOS code

an enrichment 4% of ^{235}U was considered again. The steps for the burnable absorber concentration were 2%, 1%, 0.5%, 0.25%, 0.16%, 0.06%, and 0.03% (for IFBA in mg/cm). The concentration 0.16% corresponds to the mass of the burnable absorber used in the Gd-2M fuel distributed among all pins in the assembly.

A summary of the calculation parameters for VVER-440 assemblies is reviewed in Table 2.

As no further extensive modification of the VVER-440 fuel cycle is expected, the analysis was extended to more recent VVER-1000 reactors. The analysis performed for the VVER-1000 reactors was focused on verifying whether the behavior of the tested parameters would be similar to that found in VVER-440 assemblies. Only the burnable absorbers that can be mixed with UO_2 were used for the VVER-1000 fuel assembly analysis, i.e., gadolinium, boron, and dysprosium.

4 Results

4.1 Concentration of the burnable absorber in the VVER-440 fuel assembly

Burnable absorbers are used in low concentrations and deplete during the first year of operation. The speed of depletion is given by the concentration of the burnable absorber at the beginning. Use of any burnable absorbers causes a decrease in the fresh fuel reactivity. The exact value of the multiplication factor decrease depends on the concentration of the burnable absorber and the number of fuel pins with the burnable absorber.

The burnable absorber concentration changed in the range from 0 to 8 % (weight fraction in fuel mixture) for gadolinium, erbium, and dysprosium. The concentration of IFBA changed from 0 do 8 mg/cm. Owing to different properties of each burnable absorber, different concentrations have to be used in real fuel assemblies. Nevertheless, the purpose of this analysis at this stage is to offer a comparison of the fuel characteristics with various amounts of burnable absorbers without regard to their practical efficiencies.

Table 2 Calculation parameters for VVER-440 fuel assemblies

Tested quantity	Fuel enrichment and tested values range
Concentration	Gd-2M (average enrich. 4.38%) 0–8% (mg/cm)
BA—1 pin	flat 4% of ^{235}U, 3.35% (mg/cm) of BA 60° segment
BA—2 pins	flat 4% of ^{235}U, 2% (mg/cm) of BA 30° segment
BA—all pins	flat 4% of ^{235}U 2, 1, 0.5, 0.25, 0.16, 0.06, 0.03% (mg/cm)

The dependence of the multiplication factor on the burn up for different fuels with different concentrations of burnable absorbers is shown in Fig. 3, while the dependence of PPF factors is shown in Fig. 4. Only few concentrations are presented for better orientation.

Only cases with Gd_2O_3 showed multiplication factor behaviors that were different from that the fuel without a burnable absorber. The fuel with gadolinium exhibits a substantial decrease in reactivity even at the low concentrations (due to high absorption cross section of ^{155}Gd and ^{157}Gd) at the beginning of irradiation. An increase in multiplication factor with the gradually depletion of these isotopes could be observed. This increase is not seen only at very high concentrations where depletion of gadolinium takes a longer time and reactivity of the fuel itself manages to decrease to comparable levels due to fissile material depletion. As mentioned above, there is a strong self-shielding effect in the fuel pins with gadolinium. The self-shielding effect prolongs the influence of the burnable absorber.

The IFBA depletes at a lower rate than gadolinium owing to its lower neutron absorption cross section. There is no reactivity increase due to depletion of the absorber. After boron depletion, the multiplication factor behavior is similar to that of a fuel without a burnable absorber, i.e., parasitic absorption is negligible. Unlike for the fuel without a burnable absorber, for high initial IFBA concentrations, the fuel with the IFBA exhibited an increase in the multiplication factor. This is caused by the slower burn up of the fuel pins where IFBA is present at the fuel surface, as it shields the inner part of these fuel pellets and slows down their depletion.

Erbium 167 has the lowest thermal neutron absorption cross section among the compared burnable absorbers. Furthermore, its speed of depletion is the lowest; nevertheless, the character of the multiplication factor burn up dependence is unchanged. The behavior of the multiplication factor is similar to that of the multiplication factor of the fuel without a burnable absorber, and there is no potential reactivity increase due to erbium depletion.

Dysprosium oxide has a large number of different isotopes with high neutron absorption cross sections. A greater number of absorption reactions is necessary for full depletion of this absorber. This effect has an important influence on parasitic residual absorption. The behavior of the multiplication factor is similar to that of the multiplication factor of the fuel without a burnable absorber, and there is no reactivity increase during fuel depletion in the considered concentration range.

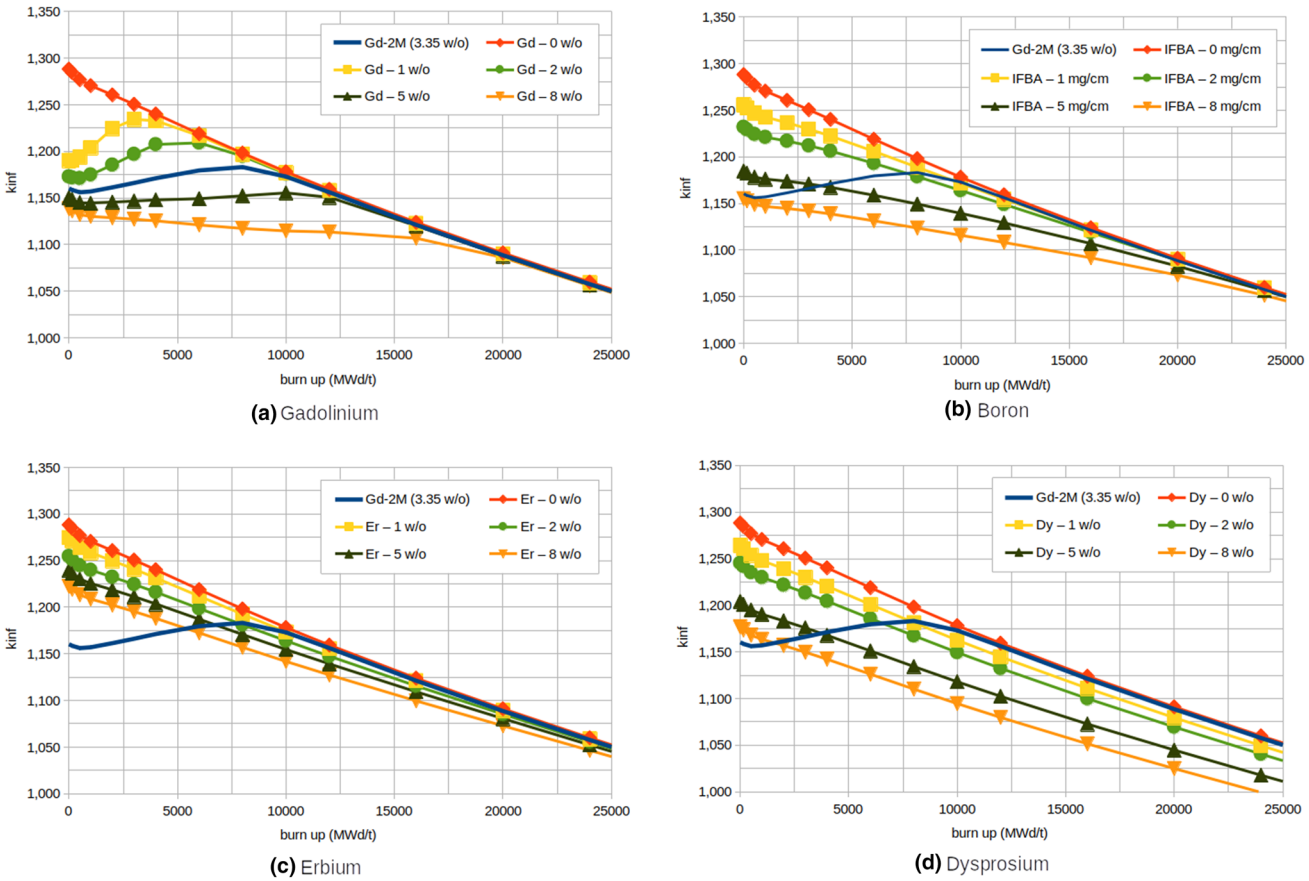

Fig. 3 Impact of burnable absorber concentration on the multiplication factor as a function of burn up in the VVER-440 fuel assembly

The change in the initial reactivity due to burnable absorber presence is summarized in Table 3. It can be seen that gadolinium has a considerable impact on reactivity, and erbium impact is limited. The values of residual parasitic absorption for the two burn up levels are presented in Table 4.

Changes in burnable absorber concentration also influence the PPF. The highest value of the PPF factor is usually observed at the beginning of irradiation. The power in the pins with the burnable absorber is reduced at first. A power shift to the other pins can be also observed. After the burnable absorber is depleted, the power of those pins increases. The differences in the power between pins with and without a burnable absorber lead to a subsequent increase in the PPF factor. With increasing concentration of the burnable absorber, increases in the initial PPF factor can be observed. Gadolinium has the greatest impact on PPF as a result of its high absorption cross section(please see Fig. 4). It is also important to analyze the PPF behavior of the fuel after depletion of gadolinium, i.e., during the time of reactivity increase due to the absence of neutron absorption by the burnable absorber. The duration of gadolinium depletion can be thus determined both from the multiplication factor and the PPF factor burn up dependence.

A similar dependence like in the fuel with gadolinium can be observed also for the fuel with a IFBA. However, even for a maximal concentration of 8 mg/cm, the fuel with IFBA exhibits no significant increase in the initial PPF value in comparison with the fuel without a burnable absorber. PPF curves with different shapes can be observed for IFBA concentrations of 7 and 8 mg/cm. Beyond a burn up level of 30,000 MWd/tU, there is a further increase in PPF that is connected with the strong shielding effect of the IFBA layer. Nevertheless, these values of PPF are still lower than the initial one at all concentrations.

The behavior of the PPF factor for erbium is very similar to that of a fuel without a burnable absorber. The values of PPF are lower, but the shape of the curve remains the same. The fuel with dysprosium oxide also has a small impact on the PPF. A slight change in the behavior could be observed only at the very beginning of irradiation.

4.2 Position of the pins with the burnable absorber

The influence of a burnable absorber depends also on its position in the fuel assembly. The dependence of the

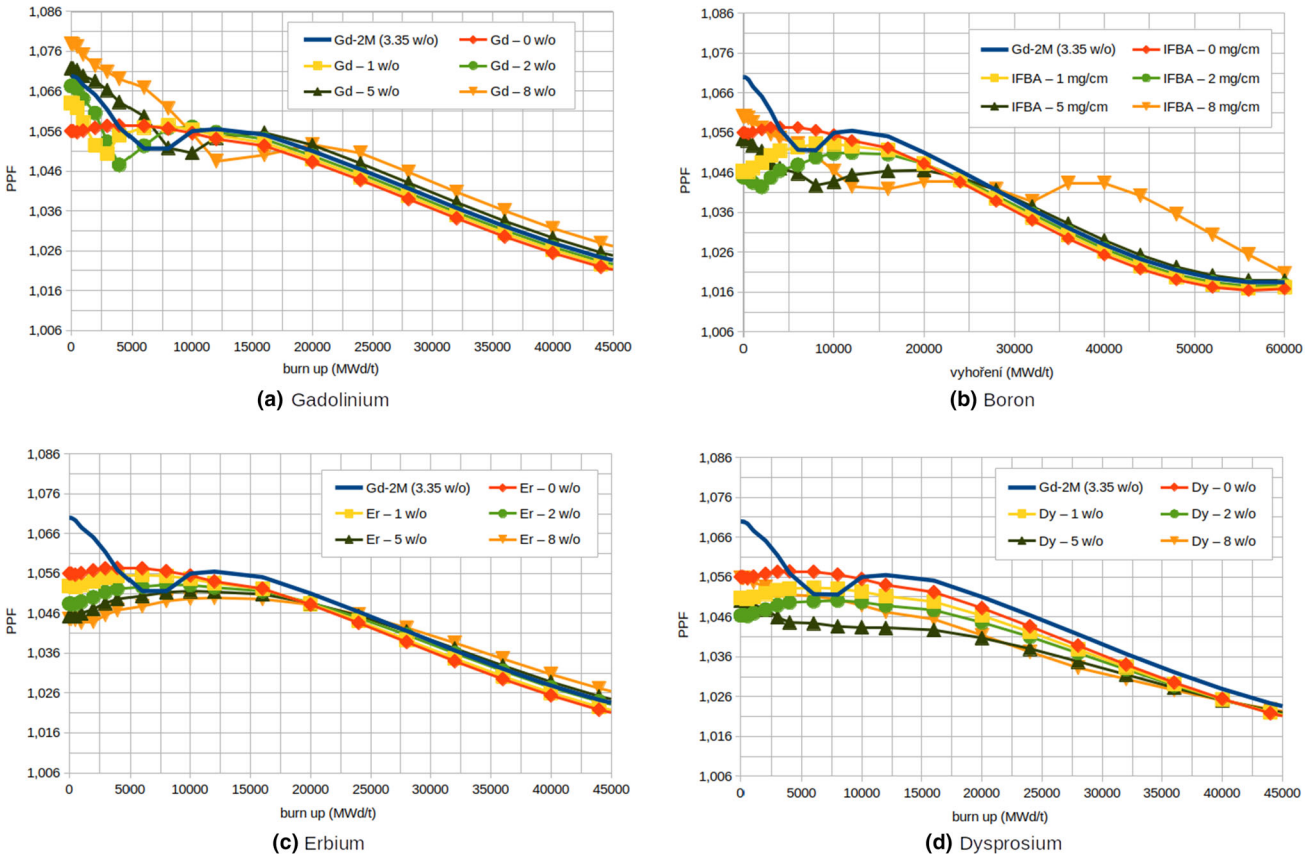

Fig. 4 Impact of the quantities of different types of burnable absorbers in the VVER-440 fuel assembly on PPF as a function of burn up

Table 3 Initial decrease in multiplication factor for different burnable absorbers in the VVER-440 assembly

Burnable absorber	Reactivity drop (pcm)*
Gd-2M—ref. fuel	12,787
Gd_2O_3—8%	14,975
IFBA—8 mg/cm	13,307
Er_2O_3—8%	6596
Dy_2O_3—8%	11,165

* difference between fuels without and with burnable absorber at the beginning of irradiation

Table 4 Residual reactivity bounds on products of absorption or radioactive decay for different burnable absorbers in the VVER-440 fuel assembly

Burnable absorber	44,000 MWd/t (pcm)	60,000 MWd/t (pcm)
Gd-2M—ref. fuel	159	145
Gd_2O_3—8%	286	270
IFBA—8 mg/cm	− 274	− 248
Er_2O_3—8%	479	403
Dy_2O_3—3%	1749	1192
Dy_2O_3—8%	3329	2791

multiplication factor and PPF factor on burn up is shown in Figs. 5 and 6. Only selected representative results are presented. All results were produced with non-profiled fuel assemblies to facilitate the analysis. Results for a profiled Gd-2M assembly design are also plotted for comparison.

Generally, the thermal pin power in the middle part of the fuel assembly is lower than the thermal pin power at the fuel periphery owing to different moderating conditions. The maximum pin power is reached at the periphery as there is a better moderator–uranium ratio. This claim is fully valid for non-profiled fuel assemblies in an infinite lattice. Use of enrichment profiling or burnable absorbers can shift the maximum pin power to the center of the assembly. The worth of the burnable absorber depends on the cross sections and neutron spectra in the respective assembly positions. Owing to power and neutron flux distribution in the assembly, the burnable absorber has a lower impact in the fuel assembly center, and the burnable absorber worth increases while moving toward the periphery.

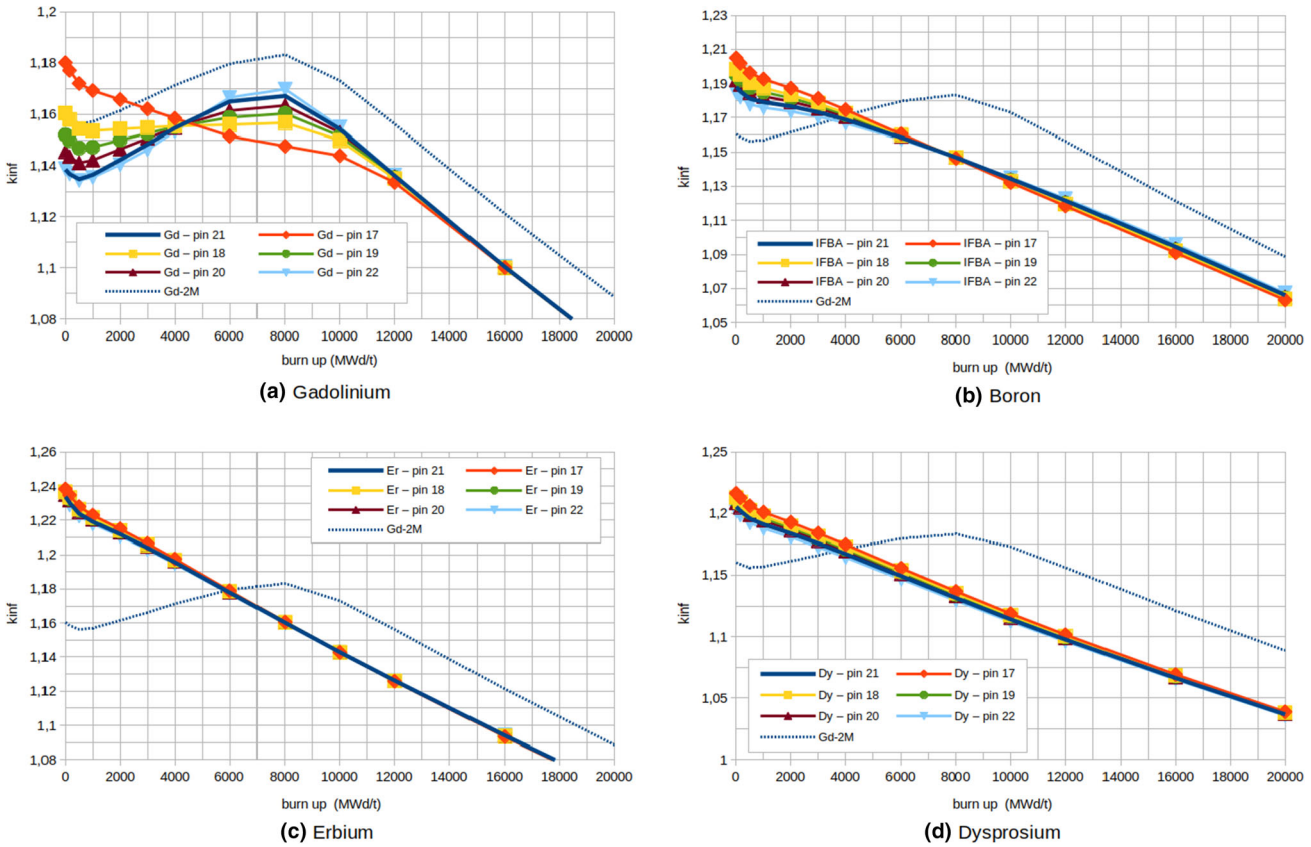

Fig. 5 Influence of change in position of one pin with a burnable absorber in a sixth of VVER-440 fuel assembly on the multiplication factor as a function of burn up

The fuel assembly multiplication factor behaves like a fuel without any burnable absorber when gadolinium is placed in central pins, i.e., position 17 and symmetric. The very high absorption cross section of gadolinium isotopes causes a significant decrease in power in the middle part of assembly. The power is shifted to the periphery, and it leads to faster depletion of peripheral pins.

Increase in the multiplication factor during fuel depletion is observed when the pin with Gd_2O_3 is moved out of the central part. Reactivity increases due to fast gadolinium depletion. This effect is not observed in positions 17, 11, and 18. The highest increase in the multiplication factor is in the periphery positions 1, 3, 6, 10, 15, and 22, and also in position 21. The maximal multiplication factor increase is in positions 1 and 15, where it is approximately 3200 pcm (difference between multiplication factors at a burn up 8000 MWd/tU, time of gadolinium depletion, and 0 MWd/tU).

The fuel reactivity is much less dependent on the position of the pin with IFBA when compared to the gadolinium fuel. The worth of IFBA also increases with distance from the assembly center. The difference in the multiplication factors caused by position changes at the beginning of the depletion reached values as high as 2000 pcm. It was almost 4400 pcm for gadolinium-containing fuels. However, such a large difference was observed only in position 17. By omitting this position, the maximum difference in the initial multiplication factors for the gadolinium fuel would be 2700 pcm.

The pin position change has a negligible effect for the erbium burnable absorber. It can be concluded that reactivity of the fuel assembly is independent of the position of the pin containing Er_2O_3. The difference between the maximum and minimum initial multiplication factors was approximately 600 pcm at the beginning of irradiation, and it decreased with increasing burn up.

Use of Dy_2O_3 in the fuel leads to similar a dependence of the multiplication factor like for IFBA. The difference between the maximum and minimum values of the initial multiplication factors as a function of burnable absorber position is approximately 1500 pcm.

It can appear favorable to place the pin with the gadolinium burnable absorber in the central assembly position as it minimizes the subsequent multiplication factor increase during fuel depletion. This burn up reactivity dependence caused by gadolinium depletion has to be respected during reactor operation. Unfortunately, this strategy would lead to high PPF values in central positions.

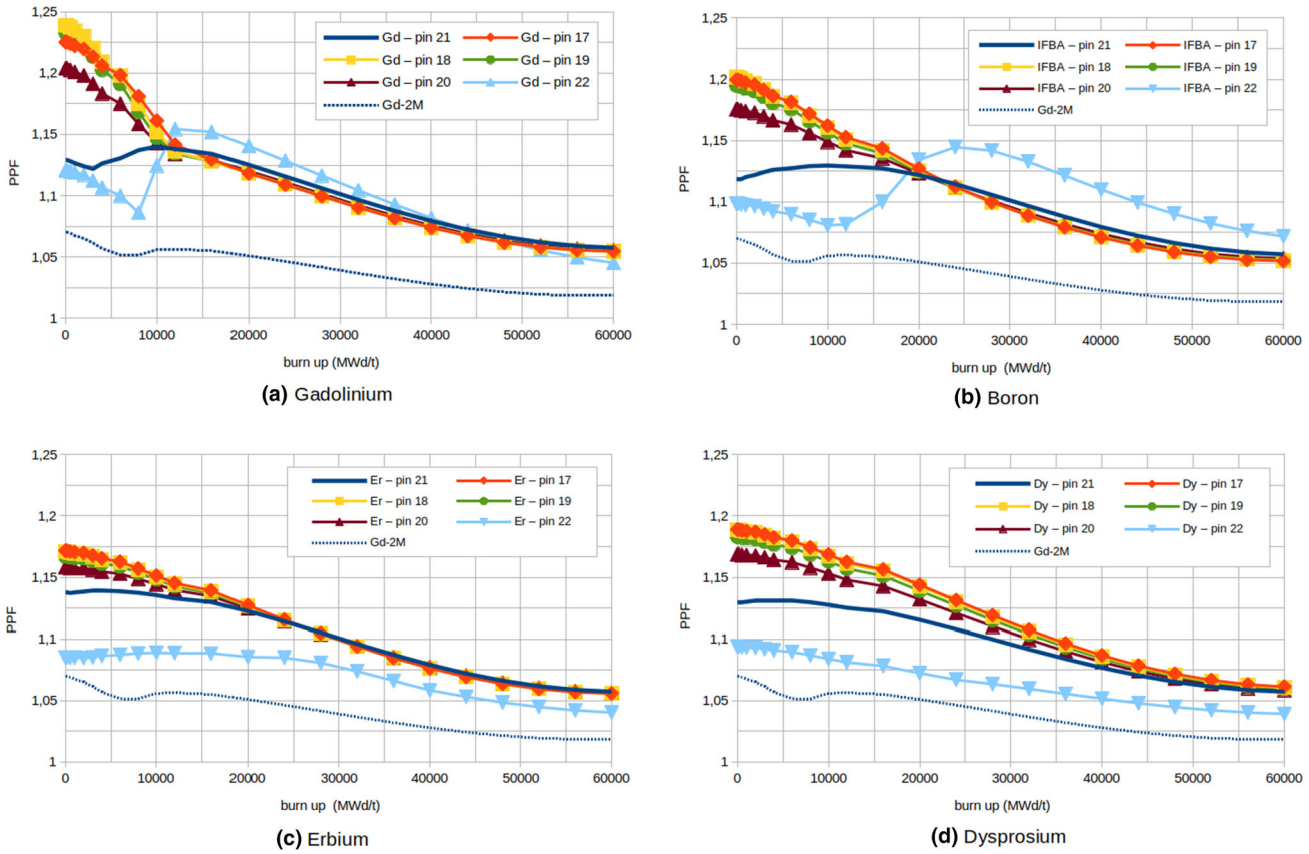

Fig. 6 Influence of change in position of one pin with a burnable absorber in a sixth of the VVER-440 fuel assembly on the PPF factor as a function of burn up

Gadolinium depletes slowly, and the fuel burn up rate is lower. A burnable absorber causes further decrease in power and shifts the power to the assembly periphery. This increased difference between the central and the peripheral power leads to a very high PPF factor value at the beginning of irradiation, especially in positions 17, 11, and 18, where the PPF values are the highest.

Reasonable behavior of the PPF factor during fuel burn up is achievable in positions 21, 15, 10, 6, and 3, i.e., periphery pins with faster gadolinium depletion. Usually the pin with Gd_2O_3 is placed in position 21. Fuel positions 14 and 2 were identified as other reasonable positions for the gadolinium burnable absorber in VVER-440. All PPF values are higher than those of the reference Gd-2M fuel because there is no optimization of the enrichment profile. For comparison purposes, among the non-profiled fuels, it is better to use results for position 21.

A distinct behavior of the PPF factor is observed in position 22. This is the best moderated pin in the assembly and very fast gadolinium depletion; there causes a temporal power increase in these corner pins (and increase in its burn up).

The initial PPF factor is also the highest for the central positions, and it is the lowest at the periphery line for the IFBA cases. Distribution of the PPF factor corresponds to power distribution in the assembly. Boron depletion is faster at the periphery where the thermal power is higher. A behavior similar to that of gadolinium is observed in position 22. Owing to fast boron depletion, the relative power in this pin is observed to increase.

There are only minor differences among the initial PPF values for various pin positions with Er_2O_3. Similarly, like the multiplication factor, the PPF factor remains unaffected by changes in burnable absorber position. A special behavior is again observed for the pin in position 22 owing to reasons stated above.

The same conclusions as for the erbium burnable absorber can be drawn also for the dysprosium burnable absorber. The values of the differences are higher, but they are still lower than the values observed for the fuel with an IFBA.

The VVER-440 fuel assembly is relatively small, and six pins with the burnable absorber are currently sufficient for the initial excess reactivity compensation. Nevertheless, increasing the enrichment beyond 5% of ^{235}U may change the absorber concentration demand. It can be met by increasing the number of pins with the burnable absorber. The behavior of the multiplication factor and PPF factor for

the fuel assembly with 12 pins with the burnable absorber, i.e., two pins with burnable absorber per sixth of the fuel assembly, was analyzed. Results for the multiplication factor dependence on burn up are shown in Fig. 7, and a graph of the PPF factor as a function of burn up is shown in Fig. 8. The reference value corresponds to the flat fuel assembly with an enrichment 4 % of ^{235}U and the respective burnable absorber with a concentration 3.35% or 3.35 mg/cm in position 21. Only several representative values are presented in figures.

The initial values of the multiplication factors are lower as more pins with the burnable absorber are in the assembly. However, the behavior of the curves is unchanged. The PPF factor for the gadolinium burnable absorber is higher than that of the burnable absorber in the reference case for all combinations of two pins with the burnable absorber per a sixth of the fuel assembly. Use of two pins with gadolinium (even if the concentration is lower) increases the residual negative reactivity. The rate of depletion is higher when the burnable absorber is shared by two pins. The power increase after gadolinium depletion can lead to PPF factor values that are even higher than the initial one. The PPF factor is lower than 1.2 for most of the pin position combinations.

The PPF factor in the fuel assembly with two IFBA pins is lower than 1.23 for all the considered combinations. Values even lower than in the reference case were observed for several pin combinations. Nevertheless, owing to the short-time power increase after boron depletion, there is also an increase in the power peaking like with gadolinium. Acceptable values of PPF were observed when position 22 was involved.

When two pins share Er_2O_3, the behaviors of the multiplication factor and the PPF factor do not change. All combinations give PPF values below 1.2. There are also some combinations with lower PPF factors than that in the reference case. Furthermore, for dysprosium, there is no change in the curve's character, and PPF factor is always below 1.2.

Use of gadolinium burnable absorbers in all pins leads to subcriticality even for low concentrations of Gd_2O_3. As gadolinium depletes quickly, its multiplication factor is similar to that of a fuel without a burnable absorber after its depletion. The fresh fuel criticality is possible only for the case with 0.03% of Gd_2O_3. Similar conclusions are valid also for the other types of burnable absorbers. For fuel with an IFBA, criticality is possible for 0.5 mg/cm and lower; however, for erbium and dysprosium, it is possible at values 1% of Er_2O_3 and 0.5%, respectively.

Use of Gd_2O_3 in all pins makes the power distribution in the fuel assembly very irregular during the course of depletion, especially for higher concentrations. It is caused by parallel depletion of gadolinium followed by an increase

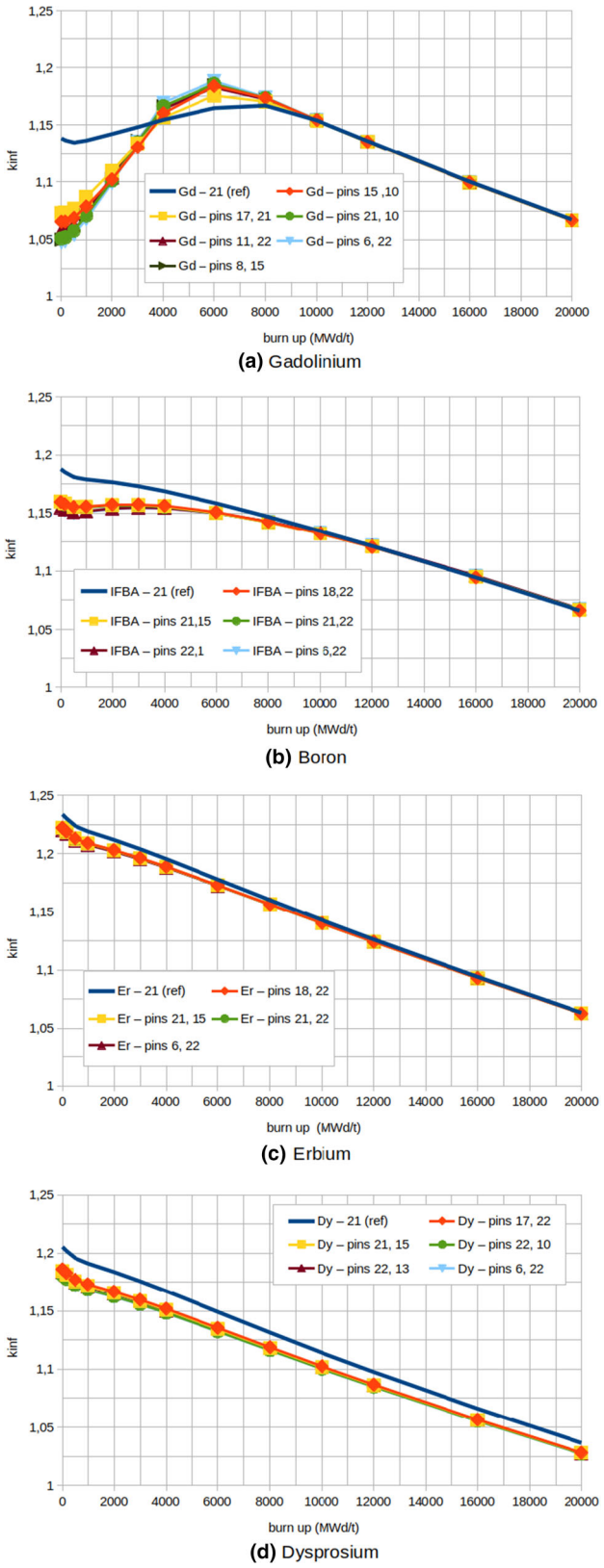

Fig. 7 Influence of change in position of two pins with the burnable absorber per one-sixth of the fuel assembly of the VVER-440 on the multiplication factor as a function of burn up

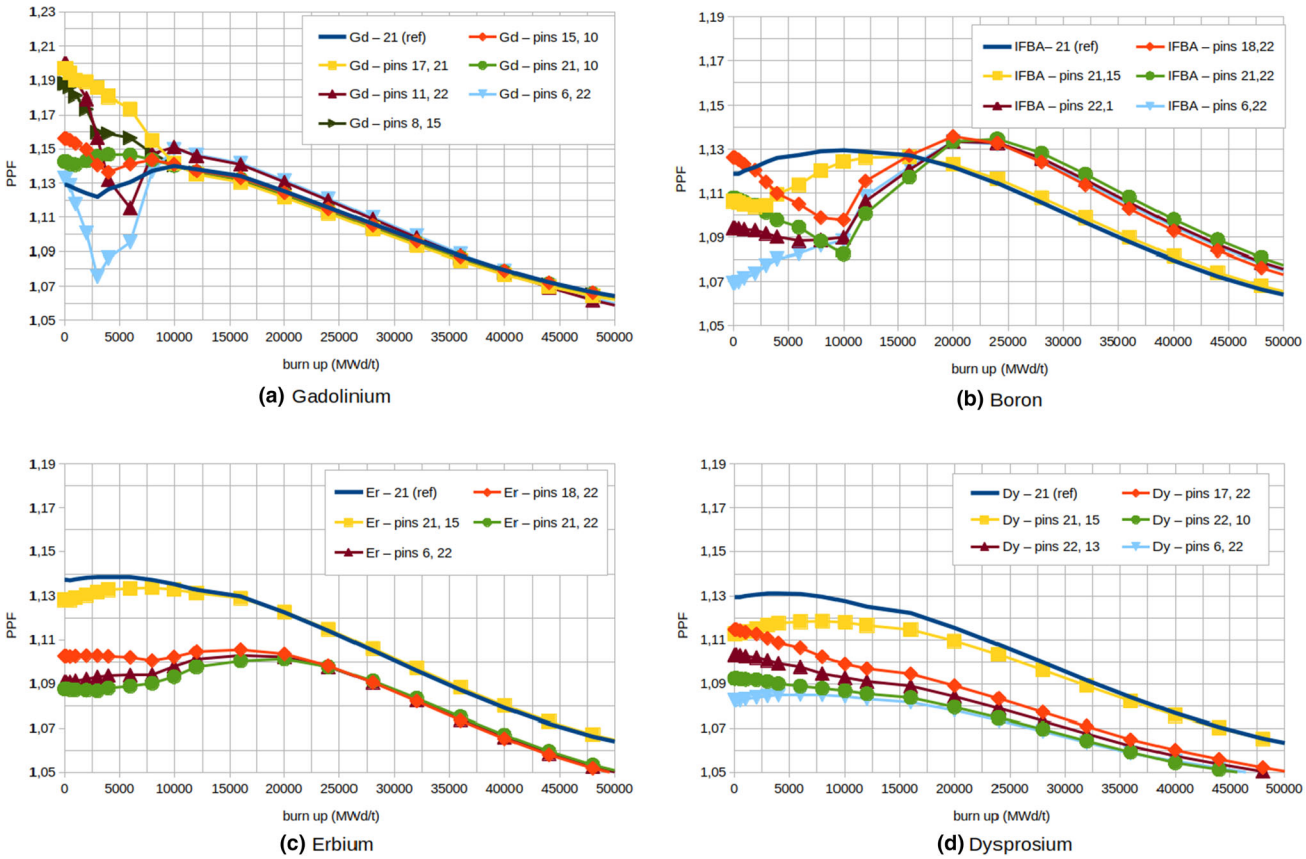

Fig. 8 Influence of change in the position of two pins with the burnable absorber per a sixth of the fuel assembly of a VVER-440 on the PPF factor as a function of burn up

in power after its depletion. Only for very low concentrations, such as 0.03% and 0.06%, is the behavior similar to that of a fuel assembly without a burnable absorber.

In the case of IFBA, the PPF factor is similar to that of a fuel without a burnable absorber for concentrations up to 0.25 %. Further increase in the concentration of the absorber leads to a higher PPF factor owing to irregular boron depletion and the power increase that follows.

The behavior of the PPF factor for erbium is similar to that of a fuel without a burnable absorber and also the values of PPF are low. The PPF factor may further decrease in value if the fuel enrichment profiling is optimized. The PPF is higher than 1.2 for 4% of Er_2O_3 only.

The dysprosium burnable absorber shows a behavior that is similar to that of the IFBA. The curves are comparable to those of a fuel without a burnable absorber for low concentrations of Dy_2O_3. There is a power increase caused by the parallel depletion that occurs with an increase in the dysprosium concentration. A demonstration of the results is shown in Fig. 9.

4.3 Applicability to larger VVER-1000 fuel assemblies

Having completed the study for the VVER-440 fuel assemblies, I studied the kinetics of burnable absorber depletion and its influence on the main fuel assembly characteristics for selected cases with VVER-1000 fuel assemblies. Burnable absorbers based on gadolinium, erbium, and dysprosium used in 6–36 fuel pins per assembly (with a mass fraction of 5%) were analyzed. Furthermore, the effect of burnable absorber concentration change was demonstrated. The initial concentration of the burnable absorber affects the kinetics of depletion, i.e., how long it will take to deplete the burnable absorber.

It was found that the depletion dependence of the multiplication factor and the PPF factor is similar to those of VVER-440 fuel assemblies. Again the multiplication factor exhibits a different behavior for Gd_2O_3. The time of depletion of the burnable absorber depends on the absorber's concentration. The number of pins with the burnable absorber influences mainly the initial reactivity of the fuel assembly (initial drop of multiplication factor).

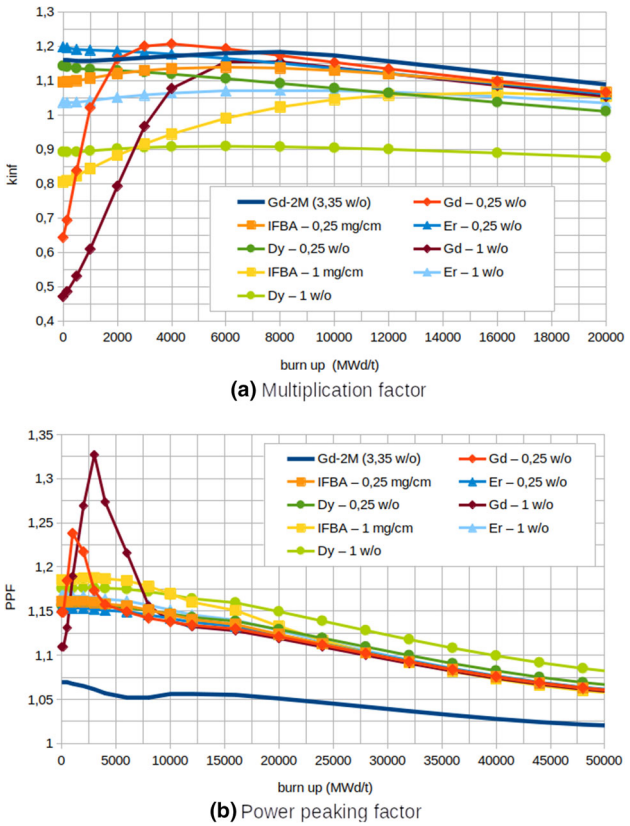

Fig. 9 Influence of the use of a burnable absorber in all pins of the fuel assembly of VVER-440 on the multiplication factor and PPF factor as a function of burn up

The change in PPF shows a behavior that is similar to that of the VVER-440 assembly. The PPF is higher for gadolinium, and this increase is more significant for a higher number of pins with the burnable absorber in the assembly.

5 Discussion and conclusions

Burnable absorbers can decrease fresh fuel assembly reactivity, especially in assemblies with an enrichment close to 5% of ^{235}U or higher. Three types of burnable absorbers that can be mixed with UO_2—Gd_2O_3, Er_2O_3, and Dy_2O_3—were studied in this analysis together with one burnable absorber that is placed at the surface of the fuel pellets—IFBA.

The concentration of the burnable absorber influences the kinetics of its depletion. It is usual for the burnable absorber to be depleted during the first cycle in a nuclear reactor. The actual time of depletion depends on operational parameters and the nuclear properties of the burnable absorber, especially at the absorption cross section (see Table 1), and its concentration. Generally, a higher concentration of the burnable absorber translates into a longer depletion time, but a high absorption cross section increases the speed of depletion. The time during which the burnable absorber has an influence on the fuel assembly characteristics is given by a combination of both. From the presented figures, it is clear that the highest speed of depletion was observed for fuels with gadolinium and IFBA. Erbium depletion was the slowest, and erbium had a long-term effect even at low concentrations. Furthermore, it also has a minimum impact on power distribution in the fuel assembly because the ^{167}Er absorption cross section is comparable with the fission cross section of ^{235}U.

After depletion of the main neutron absorbing nuclides of the burnable absorber, the residual effect of the burnable absorber on fuel assembly reactivity should be as low as possible. The decrease in reactivity due to the products of the absorption reactions is the lowest for IFBA. Moreover, in the case of gadolinium and erbium, the parasitic absorption is acceptable. It is different for dysprosium, however. Natural dysprosium is a mixture of several isotopes, and all of them have high absorption cross sections. There is continuous production of new neutron absorbing isotopes by the dysprosium burnable absorber. The time during which the burnable absorber has an influence is increased, and in the standard fuel cycle, it represents significant parasitic absorption(please see Table 4).

The initial reactivity of the system is given by the total amount of the burnable absorber, and it also depends on number of pins with the burnable absorber. Generally, for VVER reactors, the pin power is the highest at the fuel assembly periphery as a result of better neutron moderation of these pins (considering flat fuel enrichment and no burnable absorber). The distribution of power in the fuel assembly influences the reactivity worth of the burnable absorber. A high neutron flux results in a high reactivity worth of the burnable absorber. The increased number of pins with the burnable absorber means further decreasing of the initial reactivity, but the kinetic of depletion remains unchanged and it is given by the initial concentration. The most significant differences between positions of pins with the burnable absorber are observed for fuels with Gd_2O_3, and minimum differences are in fuels with Er_2O_3—pin position dependence is negligible.

The results reveal that six pins with the burnable absorber in the form of Gd_2O_3 or IFBA are sufficient for the VVER-440 fuel assembly (total 126 pins). On the other hand, it is possible to have 18 pins with burnable absorber in larger fuel assemblies, like in VVER-1000 reactors (total 312 pins), without significant increase in the PPF factor. The safety limit for PPF could be fulfilled even for more pins with the burnable absorber when the VVER-1000 fuel assembly enrichment optimization is performed. The PPF factor does not show any significant changes caused by increased number of pins with erbium or dysprosium.

It can be concluded that gadolinium has to be used in a heterogeneous configuration, i.e., in several pins in suitably chosen positions, and it is useful for 12-month cycles. Erbium and dysprosium can be used in a homogeneous mixture in all pins of fuel assembly. The use of low erbium concentrations, approx. 1%, is appropriate for optimization of 18- or 24-month cycles.

Dysprosium, europium, and samarium are specifically used in the production of burnable absorbers. These absorbers can be included in analyses of very long fuel cycles. A burnable absorber with a relatively low initial concentration has a long-term impact on fuel reactivity.

This study was used to support a proposal for fuel assemblies with prolonged cycles in VVER-440 reactors [2].

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