2024; 14 (1): 76–84 Глобальная ядерная безопасность / Global nuclear safety

ЭКСПЛУАТАЦИЯ ОБЪЕКТОВ АТОМНОЙ ОТРАСЛИ
OPERATION OF FACILITIES NUCLEAR INDUSTRY

УДК 621.039.7: 621.311.25
https://doi.org/10.26583/gns-2024-01-10
EDN RRNJCF
Оригинальная статья / Original paper

Исследование комбинированных вариантов размещения выгорающих поглотителей Er и Gd в тепловыделяющих сборках реакторов ВВЭР для оптимизации процесса выгорания

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Аннотация. В водо-водяном реакторе типа ВВЭР избыточную реактивность могут компенсировать материалы с высоким поглощением нейтронов. В статье проведен теоретический и расчетный анализ использования выгорающих поглотителей, размещенных в твэле, для снижения запаса реактивности и увеличения времени перегрузки реакторов типа ВВЭР. Для исследования снижения запаса реактивности расчет выгорания топлива проводился без выгорающего поглотителя и с комбинацией различных выгорающих поглотителей, а именно природного гадолиния (Gd) и эрбия (Er), с использованием упрощенной программы GETERA. В результате расчета установлено, что изменение количества выгорающего поглотителя (Gd, Er) внутри ТВС определяет запас реактивности по выгоранию топлива и повышает эффективность уранового топлива (UO2). Совместное использование Gd и Er приводит к более плавному снижению реактивности реактора за счет меньшего сечения поглощения Er, что позволяет снизить общую массу Gd в твэле и уменьшить эффект блокировки. При расчете использовались концентрации Gd в пределах 1,5% и 3%, а концентрации Er использовались в диапазоне 0,1–0,6%.

Ключевые слова: ВВЭР, выгорающий поглотитель (БА), избыточная реактивность, гадолиний, эрбий, выгорание, ТВС, запас реактивности.

Для цитирования: Рахман А.С.К., Увакин М.А., Хоссен М.М. Исследование комбинированных вариантов размещения выгорающих поглотителей Er и Gd в тепловыделяющих сборках реакторов ВВЭР для оптимизации процесса выгорания.. *Глобальная ядерная безопасность.* 2024;14(1): 76–84. https://doi.org/10.26583/gns-2024-01-10

For citation: Rahman A.S.K., Uvakin M.A., Hossen M.M. Burnable absorber element (Gd and Er) use in the WWER-type reactor to increase the refueling time. *Global nuclear safety.* 2024;14(1):76-84 (In Russ.) https://doi.org/10.26583/gns-2024-01-10

Burnable absorber element (Gd and Er) use in the WWER-type reactor to increase the refueling time

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Abstract. In a WWER-type pressurized water reactor, high-neutron-absorbing materials can compensate for the excess reactivity. Theoretical and computational analyses were conducted in this article to use burnable absorbers placed in a fuel rod to reduce the reactivity margin for extending refueling time for WWER-type reactors. To investigate the reduction of the reactivity margin, the fuel burnup calculation was performed without a burnable absorber and with a combination of a variety of burnable absorbers, namely natural Gadolinium (Gd) and Erbium (Er), applying a simplified GETERA program. The calculation found that the variation of the quantity of the burnable absorber (Gd, Er) inside the fuel assemblies governs the reactivity margin for the fuel burnup and increases the efficiency of Uranium fuel (UO_2). The combined use of Gd and Er leads to a smoother decrease in reactor reactivity due to a smaller Er absorption cross section, which makes it possible to reduce the total mass of Gd in the fuel element and reduce the blocking effect. In the calculation, Gd concentrations employed in the computation at 1.5% and 3%, while Er concentrations were used within the range of 0.1%–0.6%.

Keywords: WWER, burnable absorber (BA), excess reactivity, gadolinium, erbium, burnup, fuel assembly, reactivity margin.

1. Introduction

Presently, WWER-type reactors use partial refueling with extensive campaigns that last 1.5 years, and then it is possible to switch to 2-year campaigns. Ensuring such campaigns necessitates an increase in fuel enrichment, which increases the initial reserve reactivity of the fuel load and therefore needs to compensate the operating system for excess reactivity. This system incorporates a burnable absorber system which is built into the fuel matrix along with a liquid system based on the decomposition of absorber in the coolant. The magnitude and sign of the density coefficient reactivity as well as the volume of low-level liquid radioactive waste at nuclear power plants are adversely affected by the use of a liquid system with a large reactivity margin. Furthermore, liquid radioactive waste management may require further financial outlay. The use of burnable poisons incorporated into the fuel can decrease these negative consequences extensively by increasing the period of the campaign. In WWER-type reactors, strong burnable absorber «gadolinium» is located in the fuel assemblies in the form of oxide (Gd_2O_3), the concentration varies within 5-8% by weight [1-3]. Gadolinium has time to burn up during the first campaign due to the high absorption cross section. This means that it has no impact on the typical unloaded fuel burnup. It is important to note that as the weight of Gadolinium in the fuel increases, the thermal conductivity of the fuel rod decreases, leading to fuel cracking and the release of fission products. Erbium, a less effective neutron absorber and the concentration varies within 0.4-0.7%. The use of Erbium in PWRs has many potential advantages over Gadolinium. The melting point of Er_2O_3 is 2355°C. The Er_2O_3 loading optimization process is similar to Gd_2O_3. Erbium is characterized by a lower total absorption cross section compared to other BAs. The smaller absorption cross section of Erbium provides a relatively soft redistribution of power after its consumption; this generally allows favorable power peaking factor (PPF) to be achieved in Erbium-fueled cores with relatively simple in-assembly and core loading schemes. However, Erbium also results in decreased reactivity per cycle length. So, hybrid BA design of a PWR assembly with a thin layer of Er deposited around Gadolinium-containing fuel pellets has been used to control reactivity by reducing the Gadolinium content and increasing the UO_2 fuel volume.

2. Formulation of the problem

For the partial refueling of the WWER reactor with burnable absorber (BA), a simplified model is used. Firstly, overloads except reconfiguration of fuel assemblies are counted. So, in the active zone repeating forms are built, component of fuel assemblies with several duration of irradiation. It is considered that these shapes for the polycells in the active zone. The multiplying coefficient of this polycell is described as the arithmetic mean of the multiplication values of each specific fuel assembly. It is considered that TVS (FA) consists of individual polycells, in the middle of this poly-cells there is a tweg (UO_2+Gd), and around is the number of fuel rods [4,5]. A full-scale fuel assembly (FA) consists of 331 rods. Among them 285 or 306 fuel rods, 27 or 6 fuels with absorber rods, 18 guide channels and 1 central rod Fig-2. Consequently, the multiplication coefficient for the fuel assemblies and the selected polycells will be the same. Hexagonal structure is considered for the calculation polycells that forming one or two fuel rods. The length of the fuel campaign of a polycell is selected based on the state of the MC (multiplication coefficient) from TVS (FA), that is equal to the critical value, which is accepted from the leakage of neutron values. The purpose of this investigation is to minimize the proportion of excess reactivity, that compensated with the fluid control system, with the varying of fuel rods and the content of absorber (Gadolinium and Erbium). In these circumstances, the amount of low-level radioactive waste (LRW) of WWER-type reactors is significantly reduced.

3. Computational Analysis

The calculations were carried out the program of GETERA is formed for neutron-physical calculation of the cells and poly-cells in the nuclear reactors. This program may be used to solve different kinds of problems: formulation of small-molecule cross sections for accounting large-scale formations, investigation of different characteristics of nuclear reactors in cell and poly-cellular models, calculation of problems such as- burnup of fuels, multiplying coefficient, modeling of various reactor regimes etc. The neutron-physical distribution of neutrons is calculated by the first collisions probability method [6,7].

By using the program GETERA the compensation of the reactivity margin for the fuel with absorber (UO_2+Gd) rod was calculated. For this purpose, the following method was considered.

1. Here, considered WWER reactor fuel assembly with enrichment of fuel ≈ 4.95%.

2. Each fuel (UO_2) rod and Fuel + Gadolinium (UO_2+Gd) rod is divided into four zones, which are shown in figure 1. First zone, which contains fuel. Second zone, contains the shell. The third zone is coolant, and the fourth zone is moderator.

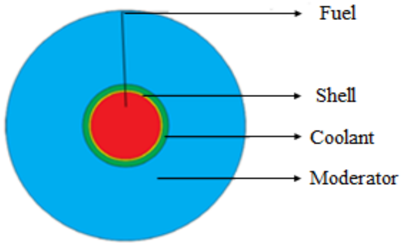

Figure 1. *Pin cell*

3. The distinguished element of periodicity is moved by a ring system component of fuel (Uranium) layers, cladding of fuel rod and coolant layers. GETERA program was implemented in this model.

4. Load changing of Gd in the fuel rod about 1.5-8% (by weight), the dependence $K_{\infty}^{TBC}(t)$.

5. Load changing of Er in the fuel rod about 0.1-0.7% in the triple company.

6. Assuming a threefold partial overload, we find the duration reactor campaign for each dependence according to formula (1):

$$K_{\infty}^{POLY}(t)=\frac{K_{\infty}^{TBC}(t)+K_{\infty}^{TBC}(T+t)K_{\infty}^{TBC}(2T+T)}{3}. \quad (1)$$

End of the fuel campaign $K_{\infty}^{POLY}(t)=K_{\infty}^{CRIT}(t)$ is approximately 1.05 from the above equation. All designations are introduced below:

$K_{\infty}^{POLY}(t)$ – for the polycell multiplication coefficient;

$K_{\infty}^{CRIT}(t)$ – multiplication coefficient for the fuel assemblies;

$K_{\infty}^{CRIT}(t)$ – critical multiplication coefficient;

In the view of computational result analysis two options is considered in here, figure 2 shows the location of large number of fuel rods and a smaller number of absorber rods (306:6) and (285:27).

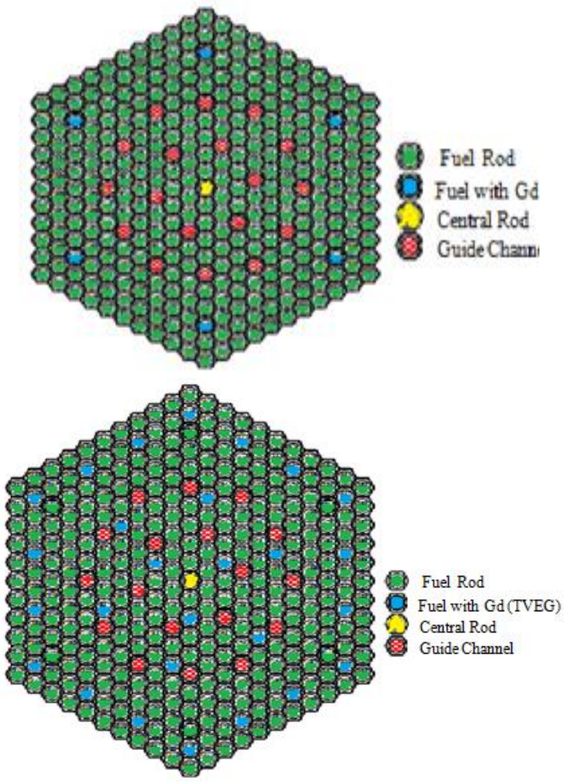

Figure 2. *Arrangement of fuel elements in the fuel assembly's type (306:6) and 285:27*

4. Analysis of the results

Firstly in here calculated the multiplying coefficient $K_{\infty}^{TBC}(t)$ vs time for the fresh fuel (without absorbers) and then calculated multiplying coefficient $K_{\infty}^{TBC}(t)$ vs time for the above two variants 306:6 and 285:27 and shown in the (fig. 3).

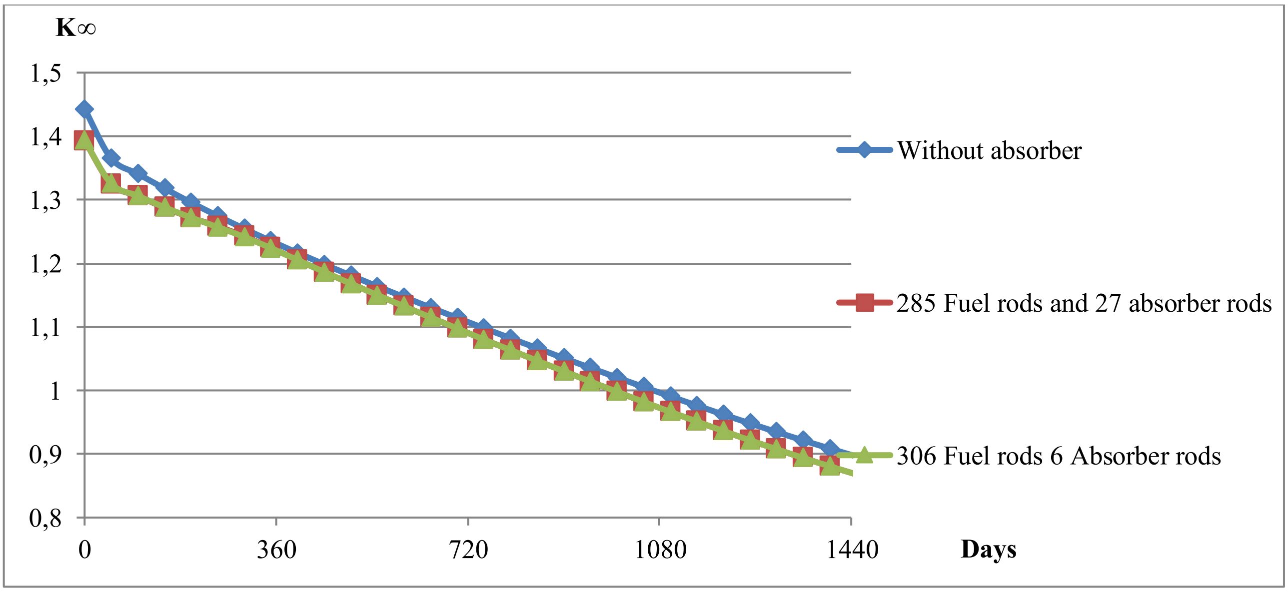

Figure 3. *Multiplication coefficient vs Days of without an absorber and with absorber for the assembly 285:27 and 306:6*

It is seen from Figure 3, the multiplication value of $K_{\infty}^{TBC}(t)$ without absorber is greater than the value of 306:6 and 285:27. In here for the variant 306:6 and 285:27 have 6 and 27 fuel with gadolinium rods respectively. But when more gadolinium rods in the fuel then absorbed more neutrons.

Without burnable absorber the period of a one campaign with a triple refueling was 1.5 years. Consider the case for the fuel assembly 306:6 and the Gadolinium weight content in TVEG (UO_2+Gd) is 3%,4% and 5% respectively. In this condition, each TVEG (UO_2+Gd) can be played as a control rod (strong absorber) and consequently depend on the change of $K_{\infty}^{TBC}(t)$ will be closer to linear (fig. 4). The more Gadolinium in the tweg, the lower initial value and, at the same time, the unloaded fuel burnup is practically does not change. In here especially noted that, the weight load of Gadolinium of 8%, for $K_{\infty}^{TBC}(t)$ which during the first campaign there is fuel and Gadolinium burnup at about the same rate $K_{\infty}^{TBC}(0)=K_{\infty}^{TBC}(T)$.

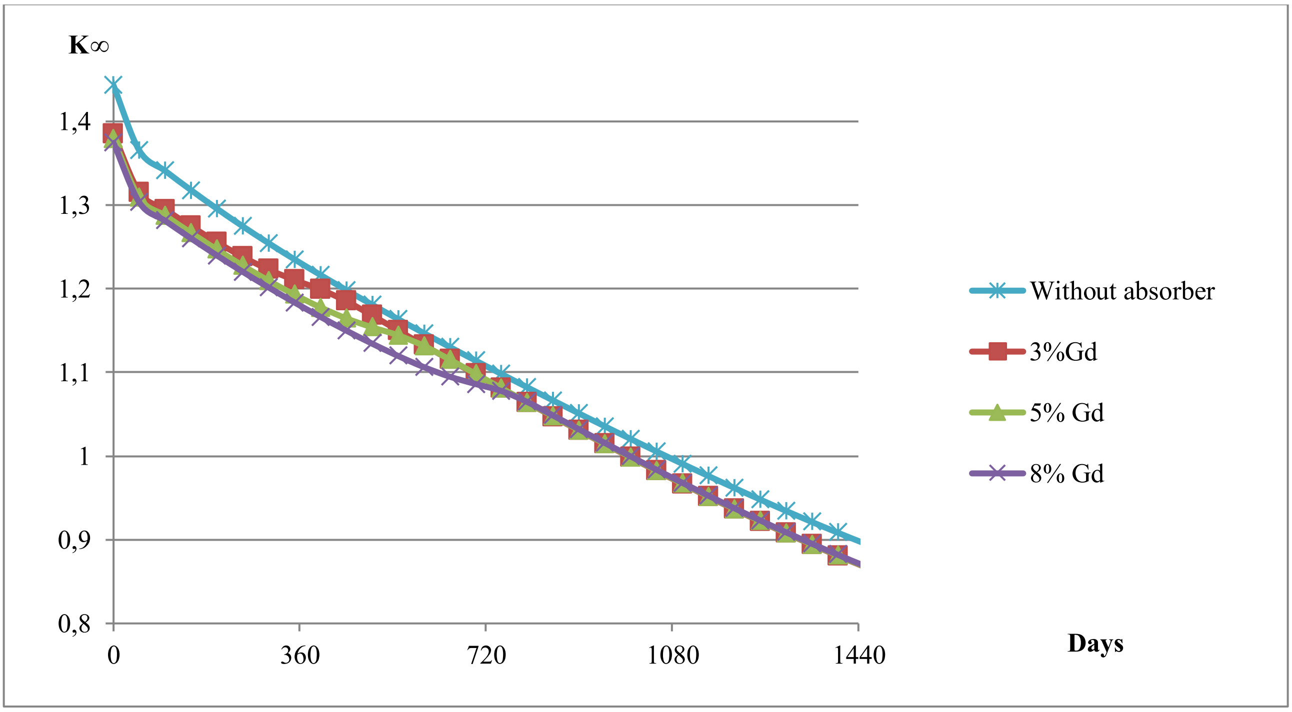

Figure 4. *Multiplication coefficient of FA* $K_{\infty}^{TBC}(t)$ *vs Days in the case of fuel rods: fuel with absorber rods (306:6) for different concentration of Gadolinium*

It is understood that, as a burnable absorber of Gadolinium effect on the fuel burnup. With increasing the concentration of Gadolinium in the fuel campaign, so for the concentration with 8% of Gadolinium campaign was 750 days. For the options 5% and 3%, the campaigns were 550 and 450 days, respectively, then lower the Gadolinium concentration, it is very fast unblocked. At the content of 3% Gadolinium, practically burned out after 450 days, and then the graph $K_{\infty}^{TBC}(t)$ corresponded with the graph of without burnable absorber. The same indicator for 5% and 8% content was 550 days and 750 days, respectively.

For the case when the fuel rod is enclosed by a layer of UO_2 fuel elements (variant 285:27) so, the preliminary value of $K_{\infty}^{TBC}(t)$ decreases significantly, after that the Gd (Gadolinium) is intensively unblocked and then the multiplying coefficient $K_{\infty}^{TBC}(t)$ dependence start to increase in (fig. 5). Figure 6 shows the same dependences for the case when the same content of Erbium (Er) without Gadolinium (Gd) is loaded into each fuel element.

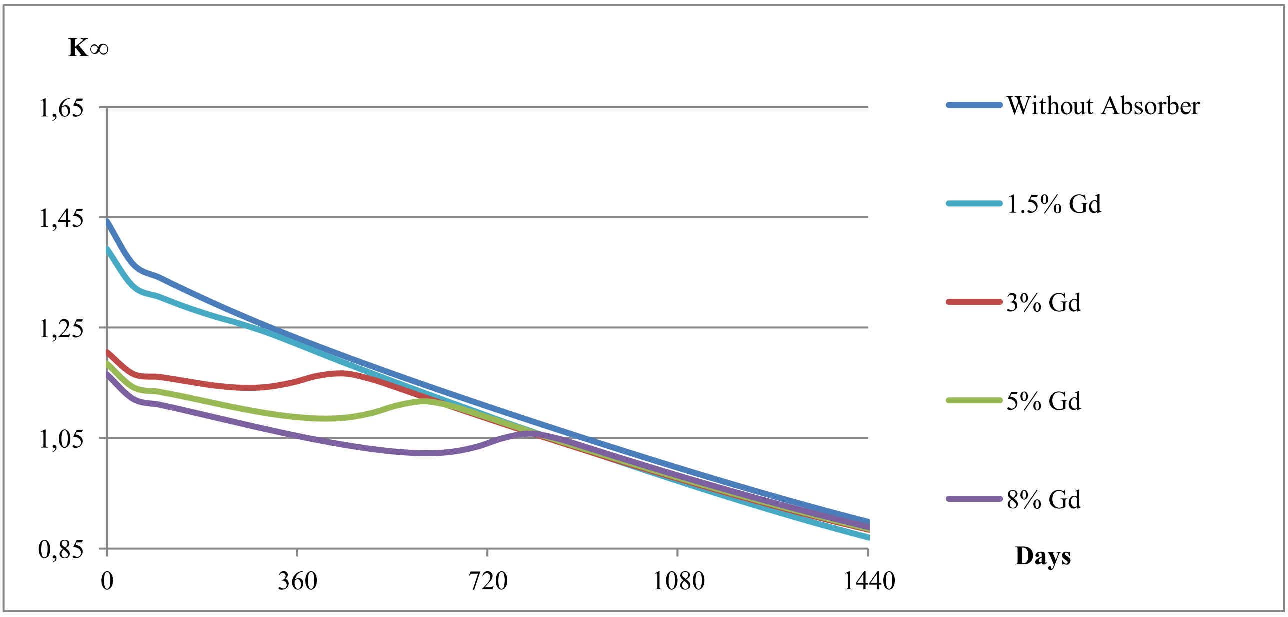

Figure 5. *Multiplication coefficient of FA* $K_{\infty}^{TBC}(t)$ *vs Days in the case of a large number of Gadolinium fuel rods (285:27) for different concentration of Gadolinium*

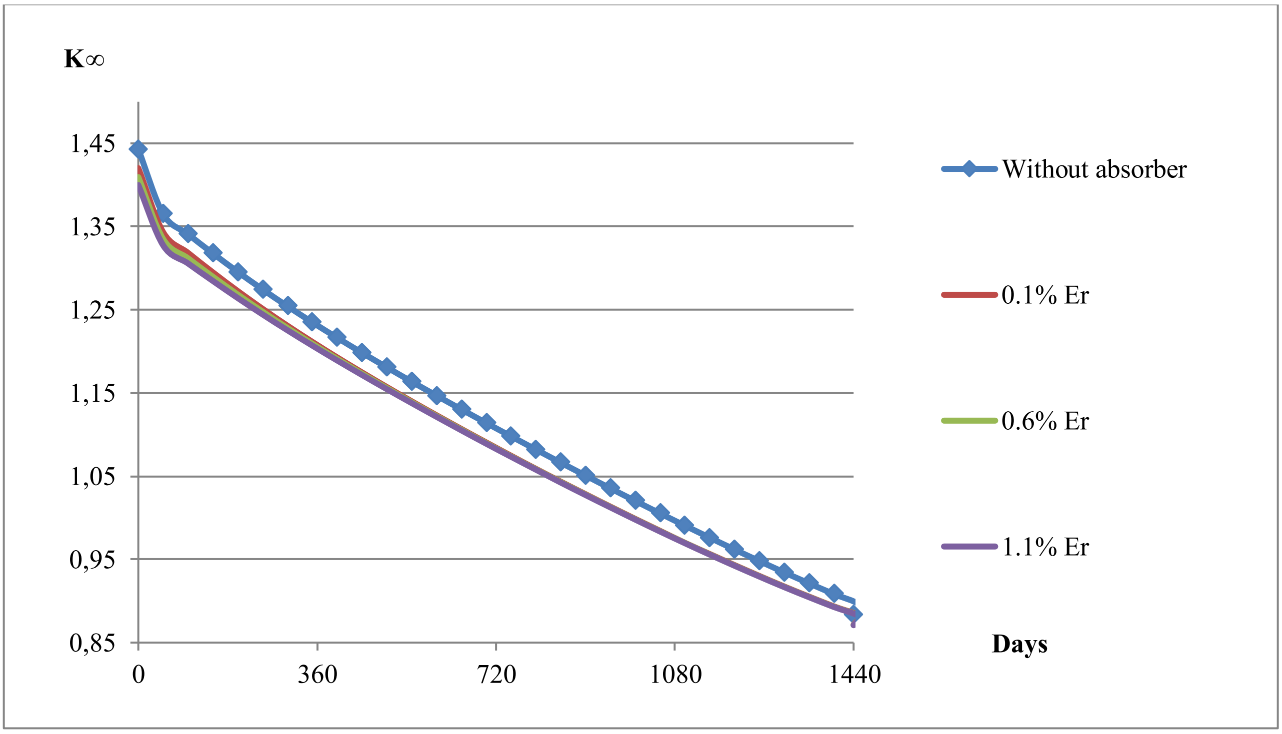

Figure 6. *Multiplication coefficient of FA $K_\infty^{TBC}(t)$ vs Days in the case of different concentration of Erbium*

To calculate the residual margin of reactivity, that is necessary compensating with a liquid system, calculations were made of the change in the value of $K_\infty^{POLY}(t)$ per campaign (fig. 7-9). The depletion was carried out at a constant power of approximately 18.00 MW (average power of one fuel assembly, ($P_{f.a}$=3200/163). For greater accuracy, small burn-up steps were used at the beginning of each cycle to build equilibrium concentrations of most fission product isotopes. Under these conditions, the fuel assembly was worked out over three reactor cycles, each cycle consisting of 480 effective days at full power with 16 MWt.day/kg burnup stages in each cycle.

The following model was developed to describe the effect of partial fuel assembly refueling into the core or burnout of one assembly in the core in three cycles. At first, refueling without rearrangement of fuel assemblies was considered. In this case, a multi-element in the core can be defined as fuel assemblies with different irradiation durations. Second, in the simplest case, the multiplication factor of a polycell is equal to the arithmetic mean of the entire set of fuel assemblies forming the cell.

In this case, the change in the infinite multiplication factor of a polycell with time can be represented by the equation (1):

$$K_\infty^{POLY}(t) = \frac{K_\infty^{f.a}(t) + K_\infty^{f.a}(t+T) + K_\infty^{f.a}(t+2T)}{3} \quad (1)$$

The duration of the life cycle of the nucleus is determined from the condition that at the end of the cycle the average multiplication factor of the poly-cell is equal to the critical value, which provides the value and it is approximately 1.05, as shown in equation (2):

$$K_\infty^{POLY}(t) = \frac{K_\infty^{f.a}(t) + K_\infty^{f.a}(t+T) + K_\infty^{f.a}(t+2T)}{3} = 1.05 \quad (2)$$

For a variant (285:27), when the number of fuel rods is 285, then the dependences are approximately similar as like without an absorber variant (Fig.7). With increasing the burnable absorber Gd in the fuel rods reducing the value of excess reactivity as a result of a decrease in the value of $K_\infty^{POLY}(t)$. This means the maximum excess reactivity margin is at the beginning of the fuel campaign.

In the case of with the large number of fuel rods, depend on $K_\infty^{POLY}(t)$ has a basically several character, such as parabolic dependence. This causes the maximum remaining reactivity margin to shift in time from the start of the campaign. It is a small value, the more absorber (Gd) in the fuel (UO_2) rods, as this also takes place in the case of a fewer number of UO_2 fuel rods. So, increasing of absorber (Gd) in the fuel rods reduces the burnup, for this reason the larger extent fuel (fig. 8).

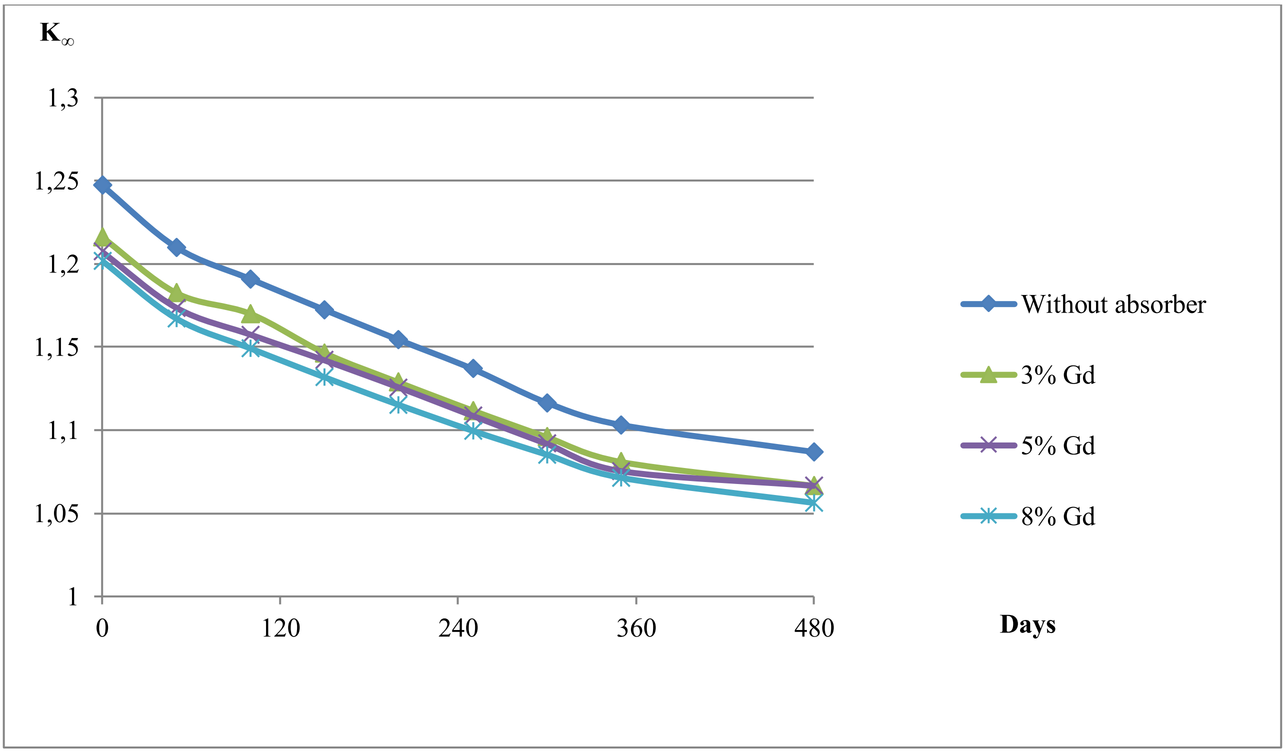

Figure 7. *Multiplication coefficient of poly cells* $K_{\infty}^{POLY}(t)$ *vs Days in the case of fewer absorber (Gd) fuel rods (306:6) in one (480 days) campaign*

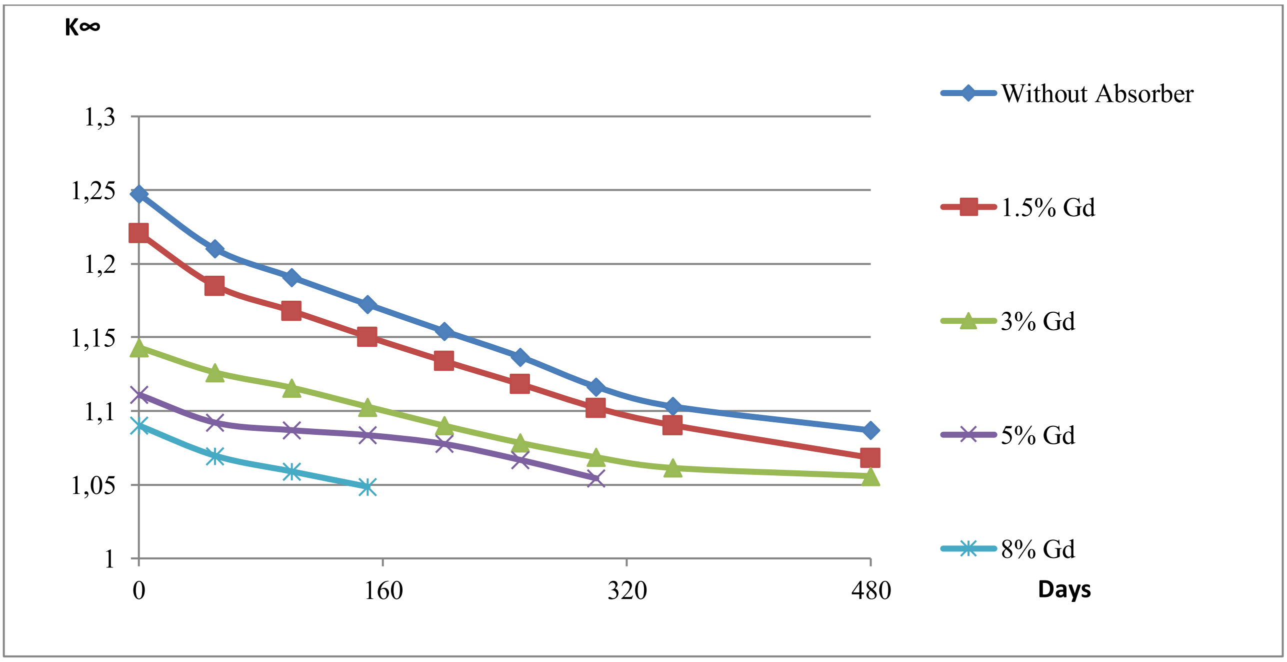

Figure 8. *Multiplication coefficient of poly cells* $K_{\infty}^{POLY}(t)$ *vs Days in case of a large number of absorber (Gd) fuel rods (285:27) in one (480 days) campaign*

When replacing absorber Gadolinium (Gd) with Erbium (Er), it may be placed in all (UO_2) fuel rods, in this case, a uniform loading of fuel assemblies is formed. So, the burnup calculation may be carry out on one elementary cell, or in a layered macro-cell to replace fuel rod on a fuel rod with Erbium. Figure 9 shows graphs of dependence $K_{\infty}^{POLY}(t)$ for various weight contents of Erbium in UO_2 rods. Erbium absorber content in UO_2 fuel rods is varied in the range of 0.1-1.10% by weight. All these investigated results are almost linear character. Because Erbium is a week absorber, so increasing the absorber Erbium content in fuel UO_2 components that quickly reduces the fuel burnup.

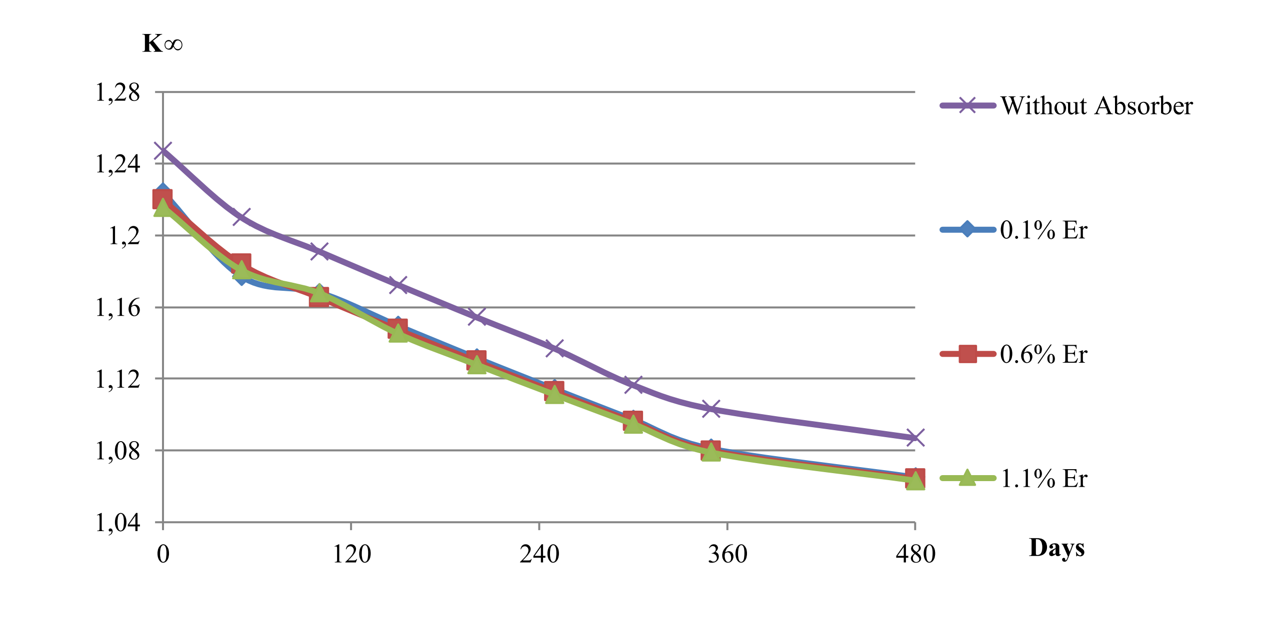

***Figure 9.** Multiplication coefficient of poly cells $K_{\infty}^{POLY}(t)$ vs Days for erbium in one campaign with 3-foldrefueling*

Although all absorber has benefits and drawbacks, and none of them has disproportionate advantage, it is perfectly acceptable to use mixed options, sometime little bit of Erbium in fuel elements is mixed with Gadolinium. In the time of computational analysis, relatively small amount of Gadolinium concentrations were 1.5% and 3%, while the absorber (Er) content difference between 0.1–0.6%. These variable concentrations, in here calculated for the option with the number of fuel rods (285:27) is optimal. The calculation result is shown in figure 10.

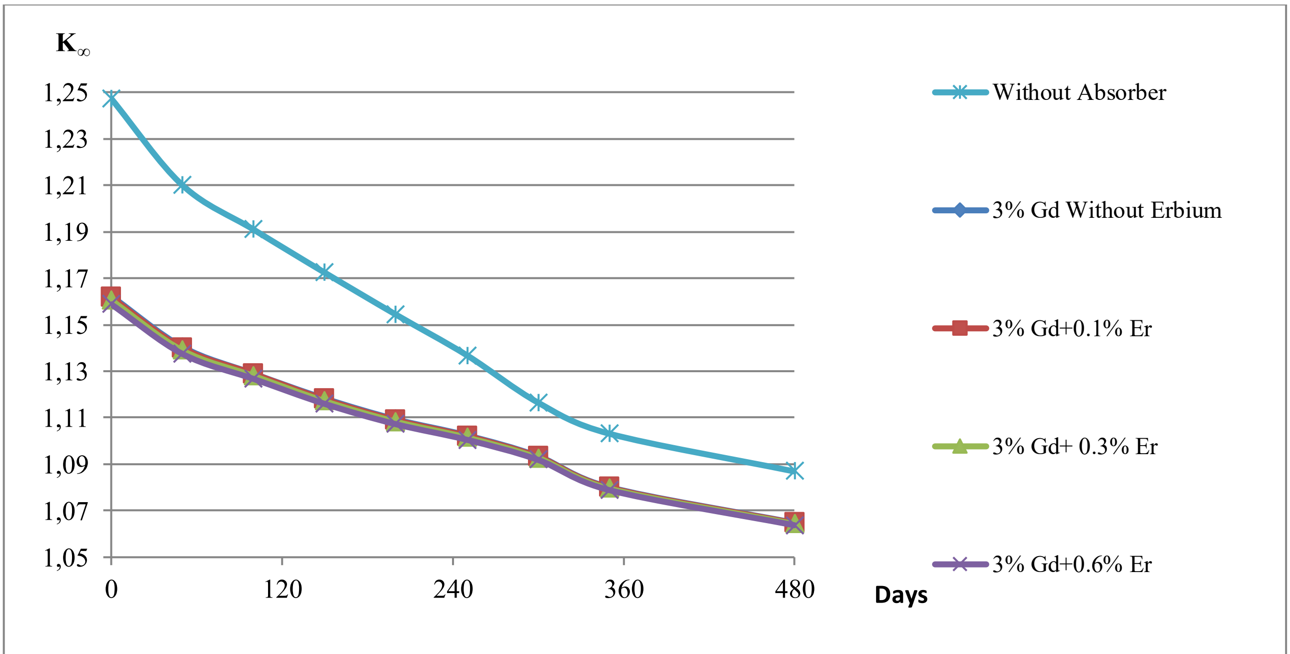

***Figure 10.** Multiplication coefficient of poly cells $K_{\infty}^{POLY}(t)$ vs Days for the two mixed burnable absorbers (Gd+Er) in a campaign at 3-fold refueling*

5. Discussion of the results

In here, reactivity calculated by using formula by the formula (3):

$$p = \frac{\max K_{\infty}^{POLY(t)} - K_{\infty}^{CRIT}}{\max K_{\infty}^{POLY}}\,, \qquad (3)$$

All considered options are illustrated in Table 1 where $\max K_{\infty}^{POLY}(t)$ is the polycell's maximum multiplication factor.

Table 1. *Calculated result of uncompensated reactivity for the all considered options are shown below*

№	Variant	max $K_{\infty}^{POLY}(t)$	K_{∞}^{CRIT}	ρ %
1	Without absorber	1.44	1.05	27%
Variants with fewer TVEG (Fuel+Gd) 306:6				
2	3% Gd	1.380	1,050	24%
3	5% Gd	1.370	1.050	23%
4	8% Gd	1.360	1.050	22%
Variants with a large number of TVEG (Fuel+Gd) 285:27				
5	1.5% Gd	1.390	1.050	24%
6	3.0% Gd	1.235	1.050	14.9%
7	5.0% Gd	1.180	1.050	11%
8	8.0% Gd	1.160	1.050	9%
Erbium Options				
9	0.10% Er	1.420	1.050	26%
10	0.30% Er	1.415	1.050	25.7%
11	0.60% Er	1.409	1.050	25.5%
Variants with a large number of TVEG (Fuel+Gd) 285:27 with mixed absorbers				
12	3.0% Gd+0.10% Er	1.23361	1.050	14.8%
13	3.0% Gd+0.30% Er	1.23094	1.050	14.7%
14	3.0% Gd+0.60% Er	1.22720	1.050	14.4%

Figure 10 clearly shows that at the time of 480 days of burnout, the difference for the option with boron and the option with burnable poisons (BP) in Kef is significantly less than at the beginning. So usage of BP makes it possible to achieve approximately the same energy output with reduced volumes of water exchange. This improves the operational performance of nuclear power plants.

For the fuel enrichment of x=4.95% the reactivity is approximately 27% and it is considered for the triple refueling. The uncompensated reactivity margin, which makes the total reactivity margin for burnup for options with two layers of absorber, that has a weak relationship with the weight content of Gadolinium in the fuel rods.

The uncompensated reactivity margin declines with an increase in the number of absorber rods in fuel assemblies (306:6) to (285:27) and decreases 24% to 14.9% for the 3% of Gadolinium. In the table also shows that,12% of the total reactivity margin uncompensated in the moment of 5% Gadolinium absorber. The lowest value for uncompensated reactivity margin when employing Erbium as a burnable absorber of the overall reactivity at a weight content of 0.6% Erbium in fuel components.

6. Conclusion

From the viewpoint of extending refueling time for WWER-type reactors, theoretical and computational analyses were conducted in this study to use burnable absorbers placed in a fuel rod to reduce the reactivity margin. By applying GETERA program, the calculation was performed without a burnable absorber and with a combination of a variety of burnable absorbers, namely natural Gadolinium and Erbium.

Calculation results showed that varying the amount of the burnable absorber (Gd, Er) inside the fuel assemblies makes it possible to control the reactivity margin for the fuel burnup and increase the efficiency of nuclear fuel (UO_2) usage in the WWER reactors. The combined use of Gadolinium and Erbium reduces the loss in reactor reactivity because of the incomplete combustion of Erbium and the significant reduction of the weight in the content of Gadolinium in the fuel rod, which will not necessitate a decrease in fuel enrichment in twegs (Fuel+Gd). In the computational calculation, Gadolinium concentrations were used as 1.5% and 3%, while the Erbium content was in the range between 0.1%–0.6%.

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ВКЛАД АВТОРОВ:
Рахман А.С.К. – выявление и исследование факторов, требующих дополнительных исследований и принятия компенсирующих мер для решения проблем, написание текста статьи;
Увакин М.А. – концепция и качественная разработка исследования;
Хоссен М.М. – изучение тематического материала, систематизация информации.

AUTHORS' CONTRIBUTION:
Rahman A.S.K. – identification and researching factors requiring further research and the implementation of compensatory measures to address is-sues writing the text of the article;
Uvakin M.A. – conceptualization and qualitative research design;
Hossen M.M. – study of thematic material, systematization of information, results analysis.

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ:
Работа выполнена без внешних источников финансирования.

FUNDING:
The study had no external funding.

ИНФОРМАЦИЯ ОБ АВТОРАХ:
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Поступила в редакцию 22.08.2023
После доработки 19.02.2024
Принята к публикации 22.02.2024

Received 22.08.2023
Revision 19.02.2024
Accepted 22.02.2024