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Fuel with advanced burnable absorbers design for the BNPP reactor core: Combined gadolinia and erbia

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Abstract
The development of integrated burnable absorbers is undeniable in the world and Bushehr reactor will be no exception to this rule. This work is in line with the change in the fuel type of Bushehr Nuclear Power Plant (BNPP) in the near future. In the proposed core, gadolinia provides the bulk of the hold-down, with no penalty on cycle length, while the erbia is adjusted to obtain the power desired margin. Neutronic parameters include variations of effective multiplication factor versus burnup, reactivity swing, power peaking distribution, critical boron concentration, and, fuel cycle length. The cycle length of the proposed core is 366 days, which is about 74 days longer than the BNPP cycle length. In addition, the results were compared with the Russian proposed core, TVS-2M. The main extra cost is related to the IBA pins numbers which are less in the mentioned core (420 pins) than the TVS-2M core (666 pins).
Keywords: BNPP, Combined IBA, Proposed core, Cycle length, Economical benefits, TVS-2M

Introduction
When the reactor operates for a long time, additional fuel must be included to keep the reactor critical. The positive reactivity caused by excess fuels must be neutralized by the negative reactivity caused by neutron absorbers [1]. It is known that at a certain concentration of the boric acid solution, the MTC is positive and causes instability in the reactor. By using the control rods and burnable absorber (BA), the soluble boron content requirement is reduced, and the MTC is being prevented from becoming positive. Nowadays, replacing of BPRs (burnable poison rod) with IBAs(integrated burnable absorber) due to their favorable effects on reactor safety margins in WWER-1000 reactors is underway. Several studies have been conducted on this issue. The use of gadolinium in reactors is located in France, Japan, Korea, and Belgium [1]. Unfortunately, no comprehensive research has yet been conducted on the concentration, location, and types of the BAs in the BNPP reactor at the core level. Therefore, in this study, a combinational location of two types of IBA pins (mixing gadolinia pins and erbia pins) was evaluated. The results were compared with the TVS-2M core [2]. In the next years, current CrB_2Al BAs will be replaced with gadolinium IBA.

BNPP core description
Bushehr Nuclear Power Plant (BNPP) is a WWER-1000 reactor with a power of 3000 MWth. BNPP core includes 163 fuel assemblies (FA) with a hexagonal arrangement, one-sixth symmetry, and various fuel enrichments [3]. The FAs consist of six types in the first cycle, including FA-16, FA-24, and FA-36 without BA rod; FA-24B20, FA-24B36, and FA-36B36 with 18 BA rods each. The FAs included fuel rods, CrB_2Al BA rods, a central tube (CT), 18 guiding channels, and the system of Neutron and Temperature Measurement Channel (NTMC) [3]. The horizontal cross-section of the BNPP simulated core is shown in Figure 1.

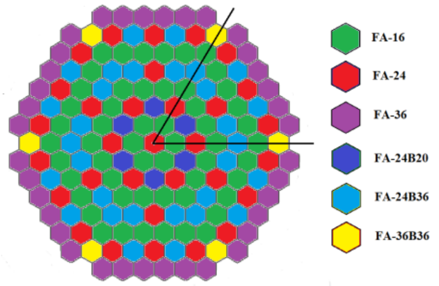

Figure 1. Horizontal cross-section of the BNPP simulated reactor core

In addition, compound of chromium diboride in matrix of aluminium alloy (CrB_2Al) with boron content: (0,020, and 0,036) gr/cm^3 is used as BA [3]. FSAR [3], provides additional information about the BNPP structure.

TVS-2M core description
The development of BA rods and their modifications is undeniable in the world and BNPP will be no exception to this rule. This work coincides with the operational changes and modifications of the Bushehr reactor in the near future. Bushehr reactor core will change from BNPP core (with CrB_2Al BPRs) to TVS-2M core (with Gd_2O_3-UO_2 IBAs). A new fuel, called the TVS-2M, is being used by Russia to upgrade WWER-1000 reactors.

The TVS-2M fuel has been proposed with the aim of reducing power generation costs and increasing cycle length, along with greater inherent safety [11]. The FAs consist of five types in the first cycle, including U13, U22, U39B6, U39A9, U30Y9 FAs with 1.3%, 2.2% 3.89%, 3.9% and 2.89% enrichment respectively [2]. Generally, fuel enrichment is greater in TVS-2M fuel, and the height of the active fuel is 15 cm longer than the BNPP fuel rods. Figure 2. shows the horizontal cross-section of the TVS-2M simulated reactor core.

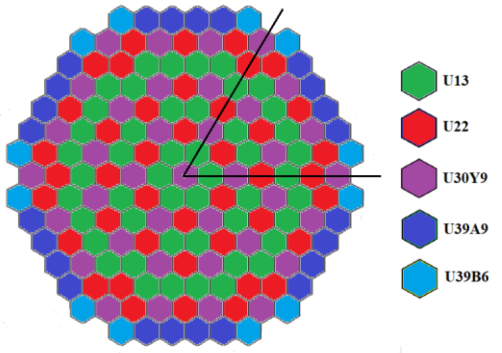

Figure 2.The horizontal cross-section of the TVS-2M simulated reactor core

materials and method

In this research, in the first step, After the complete 3D simulation of the BNPP core, using the Monte Carlo radiation transport code MCNPX [4], the neutronic calculations were thoroughly analyzed. The neutronic parameters that have been studied in this research include variations of effective multiplication factor (K-eff) versus time, reactivity swing, power peaking factor distributions (PPFs), critical boron concentration, and fuel cycle length. The data used for the BNPP are based on FSAR, which was proposed by Moscow Research, Design and Engineering Survey Institute [3]. In the second step, to improve the neutronic parameters and consequently cycle length value, Gd_2O_3-UO_2 IBA pins, were used instead of using BPR pins (current BA, CrB_2Al) and the results were evaluated. In the third step, two types of IBA pins, gadolinium (Gd_2O_3-UO_2) and erbium (Er_2O_3-UO_2) were used together in the BNPP core. So many cases (in terms of BA type, increasing and reducing the number of BA rods and BA arrangments) were examined and the most suitable ones were included in the paper (5 cases). The use of two cylindrical coaxial layers with the same volume of erbium and gadolinium IBA (GdEr pins) as well as gadolinium IBA (Gd pins) is the novelty in this work. In the fourth step, the results were compared with the Russian new fuel, TVS-2M. Finally, the proposed core was evaluated in terms of economic efficiency.

Result of CrB_2Al BPR

In this work, in the first step, the neutronic calculations at the core level were computed using MCNPX code. The BNPP calculated benchmarks specification consists of the K-eff values in Hot Full Power state (HFP), CBC and PPF values at BOC. In Table 1, the relative difference between the calculated values and the values in FSAR [3] is less than 5%, which indicates the accuracy of the calculations. The relative difference is used to compare any value relative to another. In this regard, the relative percentage difference can be used by multiplying the starting value by 100.

Table 1. The main neutronic parameters of the BNPP reactor core

State	K-eff FSAR [3]	K-eff this work	Relative difference ,%	CBC (g/kg) FSAR [3]	CBC (g/kg) this work	Relative difference ,%
HFP	1.18063	1.16777± 0.00013	1.09	6.40	6.70	4.69

Figure 3. presents the behavior of K-eff relative to the time in the BNPP with CrB_2Al. It is noteworthy that the black horizontal dashed line (K-eff = 1) intersects the curve at a certain burnup point called the cycle length. At BOC, there is a drop in the diagrams due to the presence of isotopes Xe-135 and Sm-149 isotopes, which have high neutron thermal absorption cross-sections, and their presence in the reactor has a significant effect on the reactivity changes. Then, due to the fissile material depletion, the diagram goes through a downward trend. The BNPP simulated reactor model is subcritical after about 292.15 days, which corresponds to burnup point, 12.61 GWd/MTU in agreement with the FSAR [3].

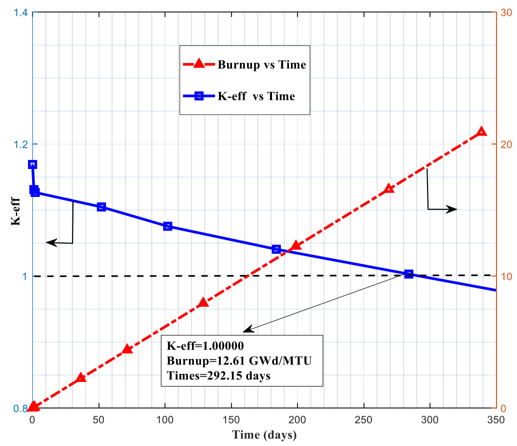

Figure 3. K-eff relative to the time in BNPP core

Minimizing the power peaking factors (PPF) is one of the primary purposes of fuel consumption management. Generally, the power value difference between BA rods and conventional rods increases the PPF values. Increasing the BA concentration increases the PPFs and perturbations in the power distribution [5]. In WWER-

1000 reactors, the moderating conditions in the middle part and at the periphery of FA are different. Periphery fuel rods are reaching higher power due to their better moderation. This difference prevents an ideal uniformity of the power distribution; however, it is almost flat. Figure 4 presents the PPF distributions in the BNPP reactor core at BOC. There are limitations in the PPFs that contribute to the reactor's safety margins. The PPF values remain at all times within the design limit (max=1.35) during BNPP operation. The relative difference between the calculated PPF values and the PPF values in FSAR [3] is less than 5%, which confirms the accuracy of the calculations.

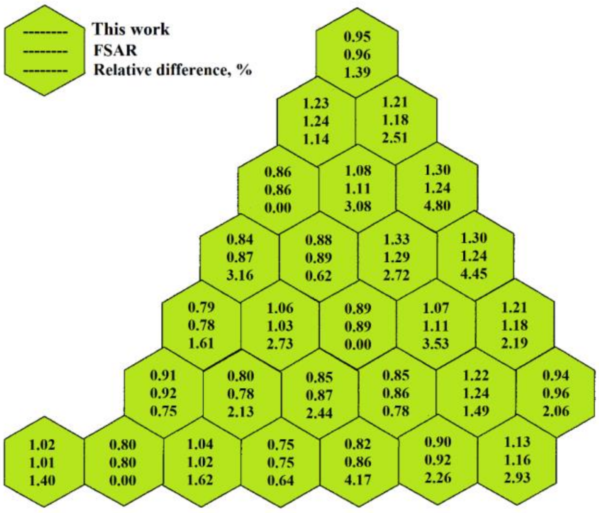

Figure 4. The computed PPFs, related to 1/6 region of the BNPP reactor core at BOC

The new IBA type

The CrB_2Al BPRs in the BNPP core, are located in guiding channels of FA-24B20, FA-24B36 and FA-36B36. Gd_2O_3-UO_2 (gadolinia), Er_2O_3-UO_2 (erbia), were considered to evaluate the effect of the IBAs on the neutronic characteristics of the reactor core and consequently the cycle length value. The intended IBA concentration was used in WWER-1000 operational reactors in different countries (5% concentration). The different IBA type was used instead of using BPR pins (current BA, CrB_2Al) and the results were evaluated. Despite the change in the BA type, the geometry, fuel enrichment, and fuel pins dimensions are the same in the arrangement as the Bushehr reactor core. Figure 5. presents the mentioned IBA type, gadolinium-erbium (GdEr pin, coaxial IBA pin) IBA pin.

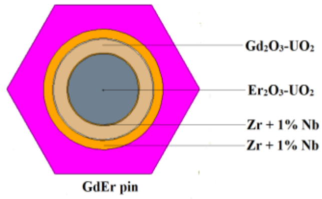

Figure 5. The new IBA type

Result of different IBA

three types of IBA pins, Gd pins, Er pins, and GdEr pins were used in the core to improve the neutronic parameters. So many cases were tested using three IBA types with a different number of IBA pins and different IBA arrangments. The core neutronic parameters of all cases were examined. Five cases with the best neutronic results were selected. In Table 2, five cases with the best neutronic results are listed. According to Table 2, case 5 is the appropriate case and provides better neutronic results. Due to the smaller number of IBA pins used and consequently economical benefits, case 5, which is bolded in Table 2, is selected as the preferred case in terms of greater cycle length value and less reactivity swing value (compared to BNPP reactor core).

Table 2. Five cases with the best neutronic results

Case	K-eff at BOC	Gd pins number	Er pins number.	GdEr pins number	Reactivity swing (ΔK)	Cycle length (days)
BNPP with CrB_2Al BPRs (Base case)	1.16777± 0.00013	-	-	-	0.23	292
BNPP with gadolinium IBA (Gd-based case)	1.14696± 0.00015	18	-	-	0.19	331
Case 1	1.15676± 0.00014	12	6	-	0.21	345
Case 2	1.16288± 0.00012	-	-	18	0.21	353
Case 3	1.14993± 0.00014	12	-	6	0.20	344
Case 4	1.14198± 0.00014	18	-	1(CT)	0.20	346
Case 5	**1.16888± 0.00013**	**9**	**-**	**1(CT)**	**0.21**	**366**

Figure 6. shows the horizontal cross-section of the proposed core.

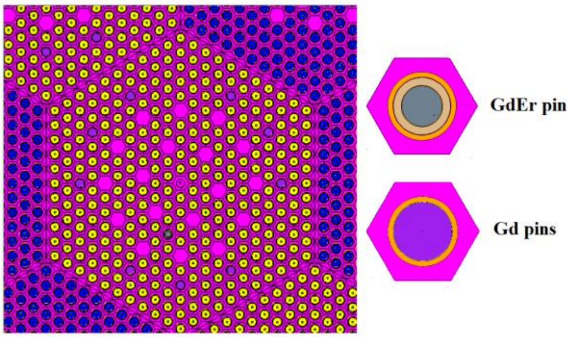

Figure 6. The horizontal cross-section of the simulated proposed core

The K-eff changes versus time in the mentioned case is shown in Figure 7. The cycle length value of the proposed core is about 366 days, which is 74 days longer than the BNPP cycle length.

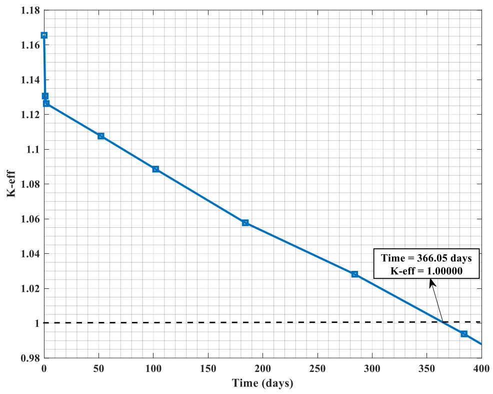

Figure 7. K-eff changes versus time in the proposed core

BNPP, TVS-2M, and the proposed core neutronic comparison

To evaluate the neutronic parameters of the BNPP, TVS-2M, and the proposed core and compare them, it is necessary to assess the K-eff changes of each individual core. Figure 8. presents the K-eff variations relative to time for three different cores. The curves have an almost linear decreasing trend, and there are no increases in reactivity value due to the depletion of IBA pins. At BOC, an initial decrease in the K-eff values is observed, which is higher in the TVS-2M curve than the proposed core due to a large number of Gd pins (666 pins) used compared to proposed core Gd pins (420 pins). The TVS-2M and proposed curves, run parallel to that of the BNPP curve at EOC. According to Figure 8., the proposed curve crosses the K-eff=1-line at 1.35 days later than the TVS-2M core, which corresponds to a 0.34 GW/MTU burnup point difference. MCNPX code calculations show that the burnup value (15.06 GWd/MTU) in the proposed core is the highest compared to other cores, which is in favor of higher fuel consumption and economic efficiency.

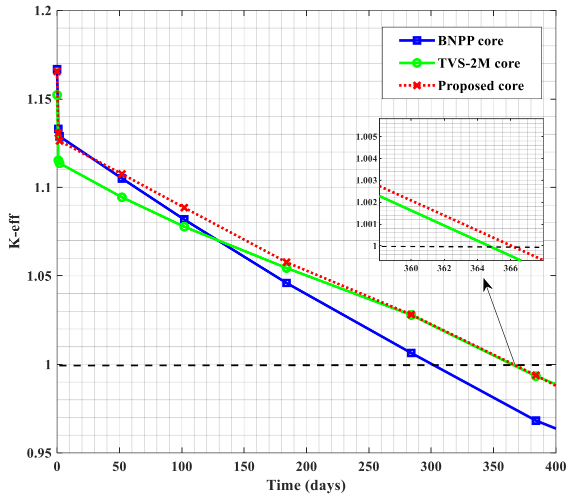

Figure 8. K-eff variations relative to time in three different cores

Table 3 shows, the proposed core is approximately similar to the BNPP core in terms of the initial reactivity reduction. The reactivity swing value in proposed core is reduced compared to the BNPP core and the cycle length value is maximum (about 366 days) compared to the two other cores. The burnup value (15.06 GWd/MTU) in the proposed core is the highest compared to other cores, which is in favor of higher fuel consumption and economic efficiency.

Table 3. Three core neutronic parameters comparison

Core type	K-eff	Reactivity swing	Cycle length (day)	Burnup (GWd/MTU)
BNPP	1.16777± 0.00013	0.227	292.15	12.61
Proposed	1.16888± 0.00013	0.209	366.05	15.06
TVS-2M	1.15383± 0.00013	0.188	364.70	14.72

The power distribution related to three different cores is another important parameter that needs to be evaluated. The PPF values in the proposed core (at BOC and EOC) are less than the PPF criteria value (1.35), which results in a safe margin in the reactor core. There is no FA PPF exceeding the PPF criteria (1.35) in any of the cores at BOC.

At EOC, The number of FA PPF exceeds the PPF criteria in the TVS-2M core is 5, related to 1/6 region of the TVS-2M reactor core at BOC and EOC. However, there is no FA PPF value outside the PPF criteria value in the proposed core. Therefore, it can be concluded that at BOC, the proposed core has a more uniform distribution than the TVS-2M core.

Economical benefits comparison

The three different core was also evaluated in terms of economic efficiency. Assuming the same fuel manufacturing cost for the CrB_2Al BA and combined IBA fuel, the decrease of the BA pins translates into a saving of several million dollars. The proposed core provided longer cycle operation (saving of about 74 days) if it is used in place of the current BNPP core.

The proposed core will have minimum effect on the fuel fabrication costs. There is no extra cost associated with modifications in the fuel fabrication process, core structure, and also no need for specific licensing. The rise in cost will be only related to the extra cost of the IBA pins numbers which is less in the mentioned core (420 IBA pins) than the TVS-2M core (666 IBA pins). The average BA concentration (5%) is lower than the average BA concentration (5% - 8%) of the TVS-2M reactor, which is less expensive. The active fuel height is the same as the active fuel height in the BNPP core, 353 cm while the active fuel height in the TVS-2M core is 368 cm, which is 15 cm longer. This increases the mass of uranium consumed in the fuel pins if, in the proposed core, this additional cost is eliminated. In addition, the TVS-2M FAs have changed completely, but in the proposed core, there is no change in any of the types of FAs, fuel dimensions, enrichments, and their locations in the core. The structure and dimension of fuel rods, FAs and core is quite similar to the BNPP core.

It can be concluded that the proposed core with the gadolinium and erbium IBAs has a very similar performance to the Bushehr reactor in terms of neutronic computing and reactor operation. This means that the cycle length value can be increased simply by changing the type of BA, the number of BA pins, and their arrangement in the core. But in a core like TVS-2M, with changes in the type of BA, there are many structural changes such as fuel rod Height, fuel enrichment, and FAs types that are not economical.

Conclusions

A comparative study on the performance of different two cores in the Bushehr WWER-1000 nuclear reactor revealed that:

- This paper provides a feasibility study of BA change and increase of cycle length in Iran's only nuclear power reactor without changing the main structure of the Bushehr reactor core and only by changing the number, type, and configuration of BA pins in the core.
- The use of two cylindrical coaxial layers with the same volume of erbium and gadolinium IBA (GdEr pins) as well as gadolinium IBA (Gd pins) is the novelty in this work.
- The proposed core (case 5) was achieved by using nine Gd pins and one GdEr pin (gadolinium+ erbium) in NTMC with a concentration of 5% erbium and gadolinium IBA.
- The PPF values in the proposed core (at BOC and EOC) are less than the PPF criteria value (1.35) in the BNPP reactor, which results in a safe margin in the reactor core.
- It is worth the implementation of the proposed core for about 74 days' increase in the first cycle-length compared to the UTVS core (BNPP reactor core).
- Due to the presence of a large number of gadolinium IBA pins compare to the proposed core, the TVS-2M core consumes less boric acid than the proposed core, however, this number of fuel rods has increased the fuel consumption in various enrichments, which is not cost-effective.

References

[1] *Characteristics and use of urania-gadolinia fuels*, IAEA, Vienna, 1995, IAEA-TECDOC-844.

[2] Y.G., Dragunov, Ryzhov, S.B., Vasil'chenko, I.N. and Kobelev, S.N., 2005. "*Development and adoption of TVS-2M for advanced fuel cycles*", Atomic Energy, 99(6), pp.864-868.

[3] NPP "The Bushehr" Unit 1, *Final Safety Analysis Report (FSAR)*, Revision 0, AEOI, Moscow, 2005.

[4] Denise, B. Pelowitz, LANL, 2008, "*MCNPX User's Manual*", LA-CP-07-1473, Version 2.6.0.

[5] L., Frybortova, 2019. "*Recommended strategy and limitations of burnable absorbers used in VVER fuel assemblies*", Nuclear Science and Techniques, 30(8), p.129.

[6] F., Khoshahval, S.S., Foroutan, A., Zolfaghari, H., Minuchehr, 2016. "Evaluation of burnable absorber rods effect on neutronic performance in a fuel assembly of WWER-1000 reactor", Ann. Nucl. Energy 87, 648–658.