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Neutronic analysis of different patterns of ABV reactor core using low enrichment UO_2 fuel

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HIGHLIGHTS

- The criticality calculation of the ABV, a PWR small modular reactor, using low enrichment fuel is investigated.
- The neutronic parameters for the ABV reactor are calculated using low enrichment fuel.
- With 6% enrichment, the length of the reactor cycle and burnup are 2100 days and 31 GWd/T, respectively.

ABSTRACT

Today, small modular reactors have received considerable attention in various countries. The ABV reactor is a PWR small modular reactor that has various applications. This reactor has been used silumin metal fuel with a 16.5% enrichment. In the present work, the efficiency of the conventional UO_2 fuel with enrichment of less than 10% to be used as the main fuel of ABV reactor has been investigated, and four different patterns for the reactor core have been proposed. To perform the calculations, the ABV reactor is modeled using the PARCS neutronic code and the RELAP5 thermohydraulic code. Finally, using computational codes for the proposed patterns of the reactor core, various quantities including reactor cycle length, reactivity, burnup, power distribution, fuel, coolant temperature distribution, and feedback coefficients have been calculated.

KEYWORDS

Small modular reactor
UO_2 fuel
Low enrichment
Neutronic code

HISTORY

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1 Introduction

In recent years, the importance of using nuclear energy has increased due to the limited fossil resources, their rising prices, as well as the presence of environmental pollution. In addition to the leading countries in the nuclear industry, other countries are also seeking to use nuclear energy (Carelli et al., 2010). Today, the importance of using small modular reactors has increased significantly due to the low initial investment, safety, low power level, and small size (Ingersoll and Carelli, 2020). Some of the small modular reactors are ABV (IAEA, 2007; Karimi et al., 2021a,b; Khan et al., 2015), CAREM-25 (Tashakor et al., 2017), SMART (Kim et al., 2014), KLT-40S (Beliavskii et al., 2020), and MASLWR (Modro et al., 2003; Yoon et al., 2017). Reactors with an electric power of less than 300 MW are generally called small reactors. Currently, different types of small modular reactors have been designed in various countries and extensive research is being done in this field (Agency, 2014).

Various applications have been proposed for small modular reactors, such as desalination, nuclear propulsion of vessels, and power supply in remote areas (IAEA, 2007). In this research, for the ABV (IAEA, 2007; Karimi et al., 2021a,b) small modular reactor, the efficiency of low enrichment UO_2 fuels has been investigated and four new patterns for the reactor core have been proposed. The PARCS neutronic code and the RELAP5 thermohydraulic code have been used for the calculations. The PARCS code was developed by U.S. NRC. PARCS is a three-dimensional reactor core simulator that solves the steady-state and time-dependent, multi-group neutron diffusion and SP3 transport equations in orthogonal and non-orthogonal geometries (Downar et al., 2006). These two codes have been coupled together using Parallel Virtual Machine tools to consider the feedback. Finally, using the computational codes, different quantities including cycle length, reactivity, burnup, relative power distribution, temperature distribution, and feedback coefficients have been calculated for the four proposed reactor core patterns.

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2 ABV reactor

The Russian company OKBM has designed the ABV reactor based on various experiences in the field of design, construction, and commissioning of nuclear reactors in this country, as well as considering new technologies. This reactor is of pressurized water reactor type and has an integrated structure with a natural circulation cooling system. The reactor is designed for use as a desalination plant, nuclear propulsion of vessels, and power supply to remote areas. The various components of this reactor, including the core, steam generators, etc., are shown in Fig. 1. Table 1 also provides some general specifications of the reactor.

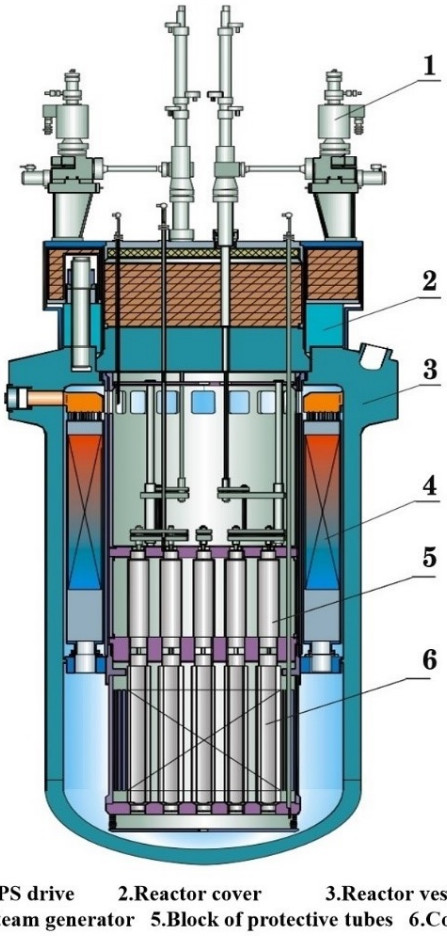

Figure 1: General schematic of ABV reactor (IAEA, 2007).

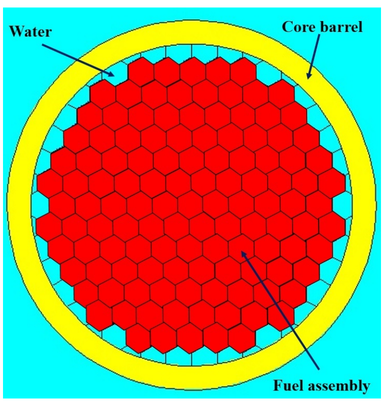

Figure 2: The core structure of ABV reactor core.

3 Method

The ABV Small Modular Reactor is a modern reactor with various capabilities. At the core of this reactor have been used the unconventional metal fuel silumin with a 16.5% enrichment. In this research, the efficiency of conventional UO_2 fuel with enrichment up to 6% has been investigated for use in ABV reactor. This investigation has been performed by modeling the ABV reactor using computational codes. Figures 2 and 3 show the structure of the core and the fuel assembly of the ABV reactor, respectively. In the first step of the modeling, each reactor fuel assembly has modeled using the WIMSD (Carelli et al., 2010) cell calculation code. In this code, the Pij method is used to solve the transport equation and perform calculations. In the next step, a FORTRAN language program has been developed to generate the PMAXS cross-section library. In this program, the WIMSD code is executed for different branches and then the code output is converted to PMAXS format after reviewing and analyzing, and going through several steps. In the next step, to perform core calculations, libraries produced in PMAXS format are provided for the PARCS code.

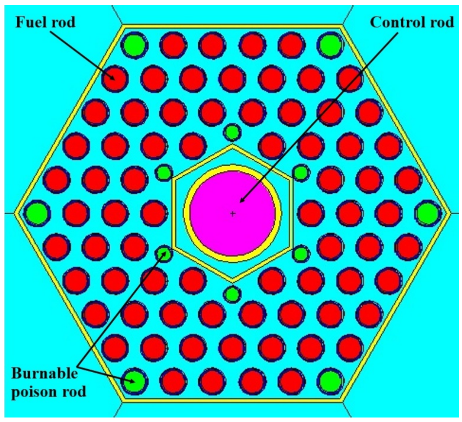

Figure 3: Fuel assembly of ABV reactor core.

Thermohydraulic components of the ABV reactor including lower plenum, core channels, riser, downcomer, etc. are modeled using the code RELAP5 (Ransom et al., 2001). In this code, each reactor fuel assembly is modeled by a pipe and we have a total of 121 pipes (Karimi et al., 2021a,b). To investigate the more accurate of the problem and consider the feedbacks, the RELAP5 thermohydraulic code is coupled with the PARCS neutronic code using the Parallel Virtual Machine tool (Geist et al., 1994).

In the present study, after modeling the reactor core by neutronic and thermohydraulic codes, four patterns for the ABV reactor core have been proposed using low enrichment UO_2 fuel and also using different arrangements. A schematic of these patterns is shown in Fig. 4. In these patterns, UO_2 fuel with 3%, 4%, 5%, and 6% enrichment with different percentages of Gd_2O_3 has been used. In the continuation of this research, some neutronic and thermohydraulic quantities of ABV reactor have been calculated for these four patterns.

Table 1: Characteristics of ABV reactor (IAEA, 2007).

Characteristics	Value
Rated power-Thermal	45 MW
Rated power-Electric	11 MW
Reactor type	Integral pressurized water reactor on thermal neutrons
Fuel type	Uranium dioxide in silumin matrix
Fuel element type	Fuel pin
Fuel enrichment by U-235	16.5 weight %
Coolant	Water (H_2O)
Number of fuel assemblies	121
Equivalent core diameter	1219 mm
Active core height	1300 mm
Primary coolant circulation	Natural
Primary circuit coolant flow rate	397 t/h
Coolant temperature at core inlet	603 K
Coolant temperature at core outlet	633 K
Primary circuit coolant pressure	15.7 MPa

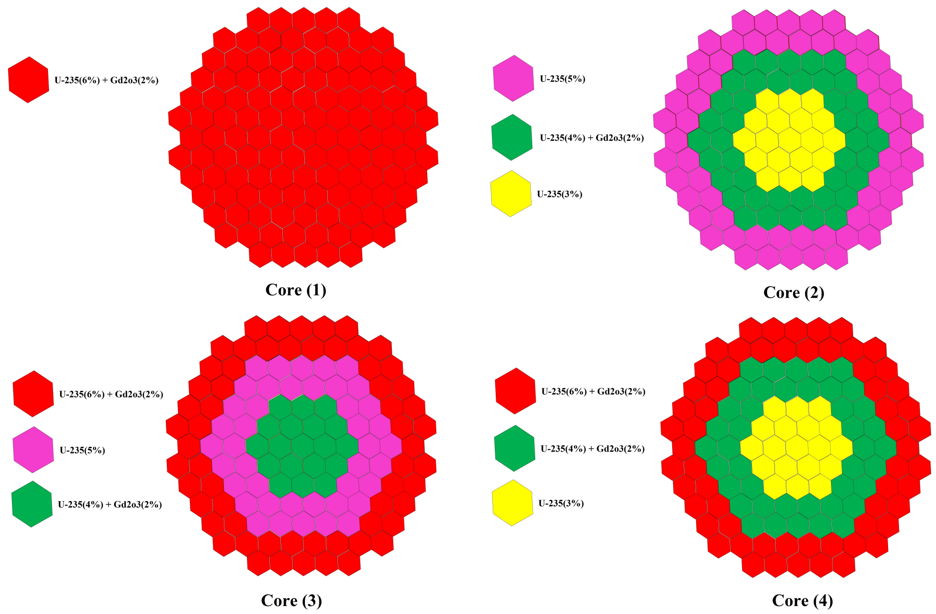

Figure 4: Reactor core configurations.

4 Analysis of the results

After modeling the ABV reactor using the RELAP5 and PARCS computational codes, in the first step, the reactor cycle length has been calculated for the four proposed core patterns. The results of these calculations are shown in Table 2. According to the results, the maximum cycle length is related to the pattern (1) with 2100 days, and the lowest cycle length is related to the pattern (2) with 1260 days. Also, the changes in reactivity versus burnup are shown in Fig. 5. According to this figure, the maximum amount of UO_2 fuel burnup is related to patterns (1), (3), (4), and (2), respectively.

Table 2: Reactor cycle length.

	Core 1	Core 2	Core 3	Core 4
Cycle length (days)	2100	1260	1720	1380

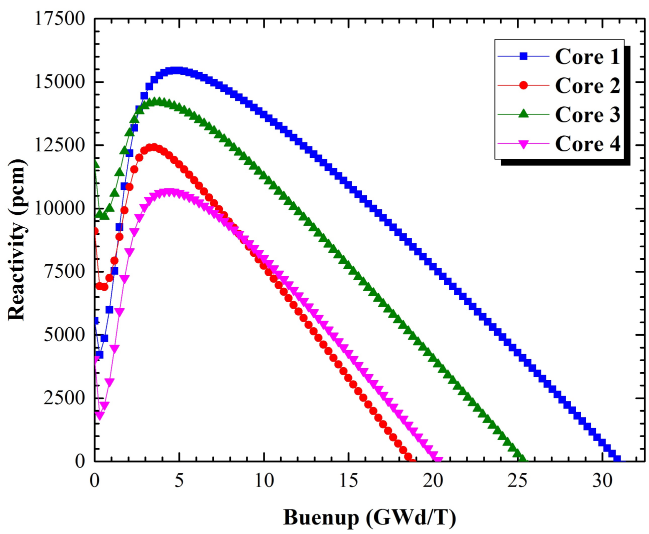

Figure 5: Reactivity versus burnup.

The relative power distribution diagram for the four core patterns for the BOC, MOC, and EOC states are shown in Fig. 6.

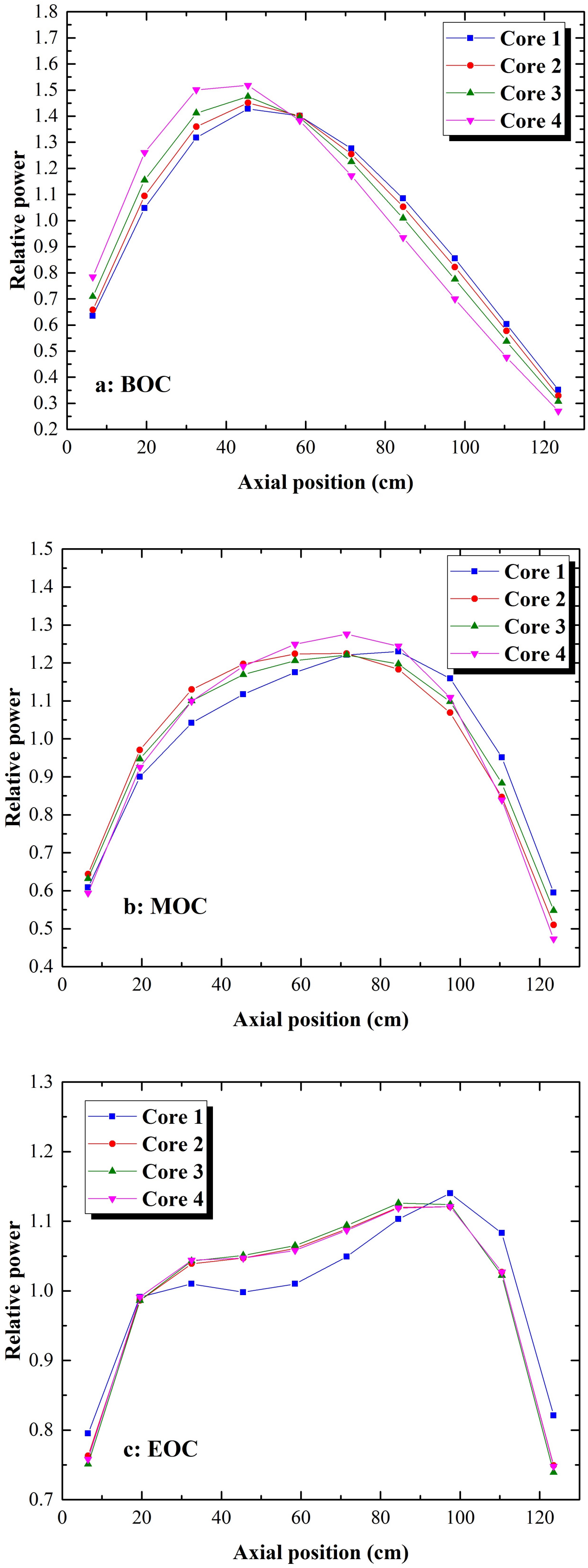

Figure 6: Relative power distribution of reactor cores.

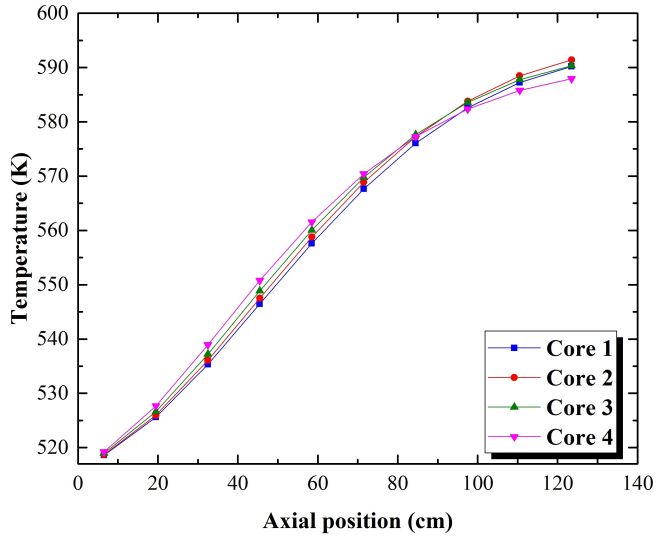

Figure 7: Axial distribution of coolant temperature at BOC.

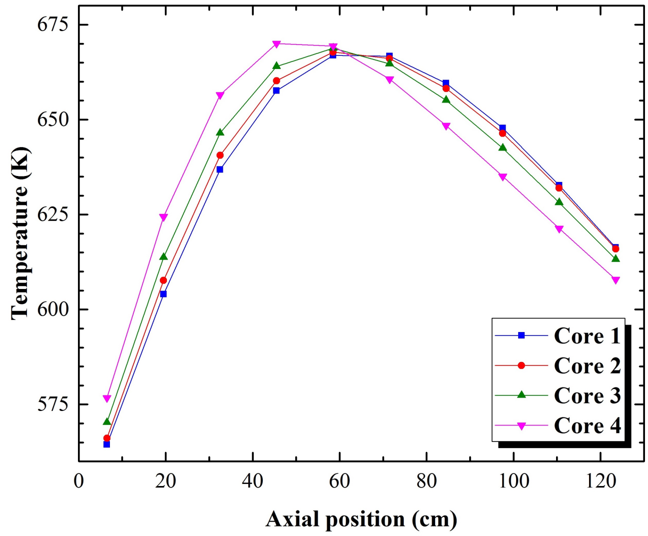

Figure 8: Axial distribution of fuel temperature at BOC.

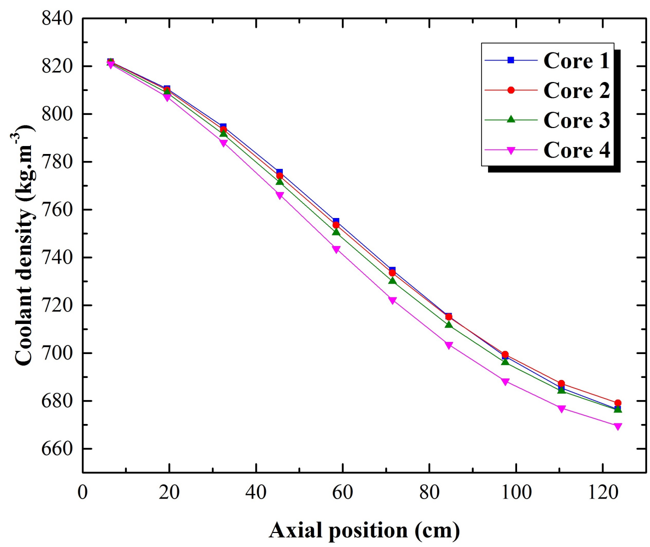

Figure 9: Axial distribution of coolant density at BOC.

The diagrams of axial changes in coolant and fuel temperature at the beginning of the reactor cycle are shown in Figs. 7 and 8, respectively. Also, Fig. 9 shows the trend of coolant density axial changes.

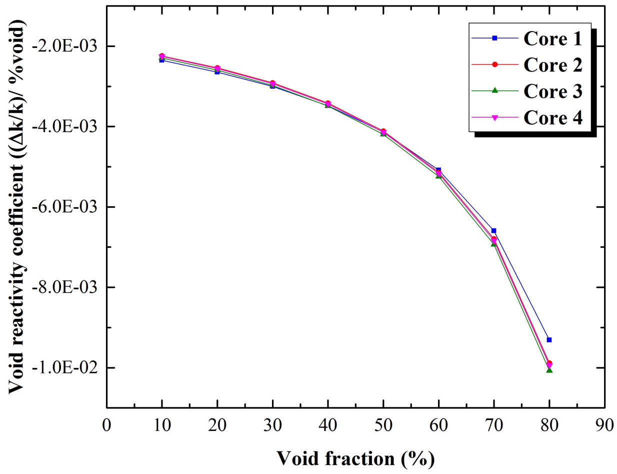

Figure 10: Coolant void feedback coefficient versus void fraction.

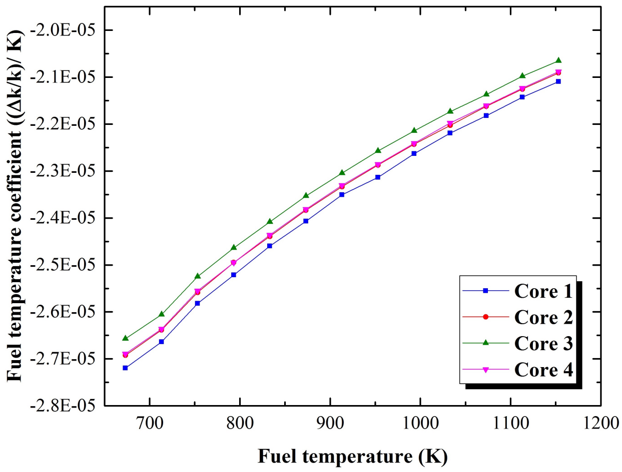

Figure 11: Fuel temperature feedback coefficient versus fuel temperature.

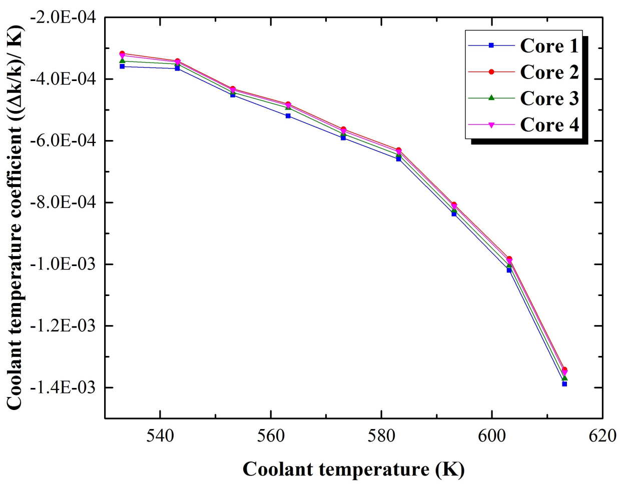

Figure 12: Coolant temperature feedback coefficient versus coolant temperature.

One of the most important issues in the design of nuclear reactors is their safety, and one of the most important issues in examining the safety of a nuclear reactor is the negative feedback coefficients. In this part of the research, feedback coefficients have been calculated for the four proposed patterns. Diagrams of changes in feedback coefficients are shown in Figs. 10, 11, and 12. According to these figures, the values of the feedback coefficients are negative, indicating that the reactor is safe.

The above results show that for ABV reactor the initial uranium enrichment can be selected to be not more than 6% with Gd_2O_3 2%. These enrichments could be obtained with relative ease, and furthermore, the IAEA recommendation on proliferation resistance is regarded. The features of negative reactivity coefficients in the entire operating range, elimination of main circulating pumps (natural circulation) and low power density have caused the ABV reactor to be safe. In the ABV reactor, core power shaping improvement is achieved by distribution of fuel and burnable poisons in the core and compensation of reactivity margin for fuel burnup is effected by gadolinium. The cycle length for pattern (1) is about 2100 days and it is suitable for the purpose of long time cycle length.

5 Conclusion

The ABV reactor is a small modern reactor. This reactor uses silumin metal fuel, which is an unconventional fuel and its production and construction are limited. In this research, the ABV reactor has been modeled using PARCS neutronic code and RELAP5 thermohydraulic code and the efficiency of conventional low enrichment UO_2 fuel for ABV reactor has been investigated. Using UO_2 fuels with 3%, 4%, 5%, and 6% enrichment, four different patterns have been proposed for the ABV reactor core. According to the results, the length of the reactor cycle for patterns 1 to 4 are 2100, 1260, 1720, and 1380 days, respectively. The maximum amount of fuel burnup is related to pattern 1 with a value of 31 $GWd.T^{-1}$. Two patterns 1 and 3 with long time cycle length, are proposed for the ABV reactor core. Cycle length and burnup for the pattern 1 with 6% enrichment are 2100 days and 31 $GWd.T^{-1}$ respectively. These parameters for pattern (3), which is a compound of 4, 5 and 6% enrichment, are 1720 days and 25 $GWd.T^{-1}$ respectively. According to the results, the values of feedback coefficients for the four core patterns are negative. In general, it can be said that using UO_2 fuel, suitable patterns with relatively long cycle length can be suggested for the ABV reactor core.

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