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Technical Note

Selection of burnable poison in plate fuel assembly for small modular marine reactors

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ABSTRACT

Small modular reactors have garnered considerable attention in the recent years. Plate fuel elements exhibit a good application prospect in small modular pressurized water reactors for marine applications. Further, improved economic benefits can be achieved by extending the core lifetime of small modular reactors. However, it is necessary to realize a large initial residual reactivity for achieving a relatively long burnup depth finally. Thus, the selection of a suitable burnable poison (BP) is a crucial factor that should be considered in the design of small modular reactors. In this study, some candidate BPs are selected to realize the effective control of reactivity. The results show that $^{231}Pa_2O_3$, $^{240}Pu_2O_3$, $^{167}Er_2O_3$, PACS-J, and PACS-L are ideal candidates of BP, and since the characteristics of BP can increase the final burnup depth of assembly, the economic benefits are gained. Additionally, an optimal combination scheme of BPs is established. Specifically, it is proved that through a reasonable combination of BPs, a low reactivity fluctuation during the lifetime can be achieved, leading to a large final burnup depth.

1. Introduction

Small modular reactors (SMRs) are generally defined as nuclear reactors whose electric power is less than 300 MWe. Such reactors have attracted increasing attention in the recent years. Experts from more than ten IAEA member countries, including the United States, Britain, France, Russia, China and other countries, have established a design scheme of SMRs [1]. Based on their applications, SMRs can be mainly divided into four categories: experimental research reactor, prototype or demonstration reactor, nuclear propulsion power reactor, and commercial power reactor [2–4]. The main driving force for the development of SMRs is to meet the needs of a wide range of users and flexible power generation. The old fossil fuel unit is generally replaced to improve the safety, which also facilitates improved economic benefits [5]. Small nuclear power plant is the ideal main power plant for large marine vessels due to its high power density and small size. The replacement of reactor core in civil marine reactors is time-consuming, expensive, and has extreme requirements for nuclear waste management and radiation protection, which can directly affect the utilization rate of nuclear powered marine reactors. Reducing the number of reactor core replacements during the service of such reactors can substantially improve their economic viability and reduce the amount of nuclear waste. By designing a long-life reactor core, the reactor refueling frequency can be reduced or eliminated, the maintenance cost can be reduced, and the efficacy of the reactor can be improved [6].

The power level and reactor core lifetime are the crucial performance indexes of nuclear reactors. An ideal nuclear power reactor must possess both high power and long core lifetime. Plate fuel has a large heat transfer area, short distance between fuel center and coolant channel, and high heat transfer efficiency [7]. Lower fuel core and surface temperature can be obtained at the same power level and coolant flow rate, or when the fuel core and surface temperature do not exceed the limit, nuclear reactors are allowed to operate at higher power. Further, plate fuel has a compact structure, which is conducive to the miniaturization of reactor core [8,9]. Plate fuel is a commonly used fuel geometry for high flux research reactors and compact nuclear power reactors with high power density [10–13]. Long-life reactors based on plate fuel exhibit immense potential in applications that require both power and lifetime.

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The reactor core lifetime can be enhanced by increasing the loading or conversion ratio of fissile nuclides. In pressurized water reactors (PWRs), it is difficult to achieve ultra-long reactor core lifetime by simply increasing the conversion ratio because the conversion ratio is much less than 1. On the other hand, increasing the reactor lifetime by increasing the loading of fissile nuclides is also faced with the challenge of residual reactivity control. A simple increase in the number of control rods or boric acid concentration cannot allow a smooth release of residual reactivity over the lifetime. The addition of boric acid increases the possibility of leakage at the primary circuit pressure boundary, and excessive addition of boric acid can lead to problems such as positive moderator temperature coefficients. The insertion of control rods can make the power distribution of the reactor more uneven. Burnable poison (BP) has a strong ability to absorb neutrons, and the product formed after neutron absorption can either be a "transparent" nuclide or a nuclide that can continue to absorb neutron, so it has flexible residual reactivity control ability [14]. Therefore, the utilization of BP is an effective method to control the core residual reactivity of long-life PWR.

One of the characteristics of marine reactors is the long life cycle and reduced need for refueling. Therefore, for marine reactors with long-life cycle, a large amount of excess reactivity is needed to compensate for the reactivity loss caused by fuel burnup. This inevitably brings challenges to the reactivity control. Therefore, a detailed study of the utilization of BPs in marine reactors is needed to manage the excess reactivity [5]. For reactivity control in PWR, boric acid is added in light water, and BP is added in the fuel. To avoid the shortcomings caused by the addition of boric acid in nuclear power reactors, BP and control rods are generally used for reactivity control.

Currently, boron, gadolinium, and to some extent, europium [15] and erbium [16] are primarily utilized as the materials for integrated BPs or BP coating in nuclear reactors. In addition to the integrated BP and coating, discrete Pyrex BPs are also widely used in PWRs. However, for higher enrichment, the application of these BPs is limited [17]. It is noteworthy that the above BPs can only act as a neutron absorber to compensate for excessive reactivity [18]. Additionally, the existing studies are based on the analysis of traditional BPs composed of several natural nuclides, and most of them focus on traditional low-enriched fuels and rod-shaped fuel assemblies [17]. There are few studies on the selection and use of conventional BPs for plate fuel assemblies and plate fuel elements. Further, the selection of new BPs based on plate fuel assemblies has not been reported yet.

The main objective of this study is to design the BPs of plate assembly. Firstly, the plate fuel assembly is modeled by using DRAGON series program. Secondly, the burnup is calculated for different types of BPs, and their neutronic performance is analyzed. Finally, an optimal combination of BPs with enhanced neutronic performance is selected to achieve improved overall performance. The results may be useful to examine different types of nuclides and elements in the future as well as to analyze the applicability of different types of BP to plate fuel elements.

2. Calculation model and procedures

2.1. Calculation model

The assembly consists of 13 fuel plates, two support plates, and water gaps. Here, UO_2 dispersed in Zr-4 matrix is selected as the fuel, and Zr-4 alloy is used as the material for the cladding, support plates, and matrix.

The designed range of plate fuel thickness is 1.4–4.0 mm [19], and the optimal fuel and moderator ratio under this model is selected for subsequent calculations in this paper. The thicknesses of fuel core, fuel cladding, water gap between two fuel plates, and the support plate are selected as 3, 0.4, 2.3, and 3 mm, respectively (see Fig. 1). A reflection boundary condition is set for the assembly. Dispersion fuel has the advantages of reasonable irradiation stability, excellent thermal conductivity, good corrosion resistance, long service life, and high burnup [20], thus it is widely used in marine reactors. To meet the non-proliferation limit of low enriched uranium, the enrichment degree of uranium cannot exceed 20% [21]. The enrichment degree of UO_2 in this study is 18%. The loading arrangement of BPs is as follows: the BPs are uniformly mixed with the fuel to facilitate dispersion loading, and a symmetrical arrangement of fuel plates containing BPs is considered.

2.2. Calculation procedure

The DRAGON program is used for the transport burnup calculation. DRAGON is a deterministic reactor lattice calculation program developed by Montreal University of Technology, Canada. Many numerical methods can be used to solve 1D/2D/3D neutron transport problems, such as interface flow method, collision probability method, discrete ordinate method, characteristic method, and spherical harmonic function method. The DRAGON program can handle fuel assemblies with different geometric structures (e.g., tube bundles, plates, hexagons) and different reactor types (e.g., light water reactor, heavy water reactor), so it has a strong geometric applicability and flexibility [22]. The feasibility of DRAGON series programs for plate assembly calculation has been verified in the existing literature [23–26], and the complex burnup of BPs (e.g., Gd) can be calculated with a certain accuracy [27,28]. The DRAGON program also considers the energy released by neutron capture in the assembly depletion calculation [29].

2.3. Candidate BPs

The physical properties of candidate BPs are evaluated and compared in terms of the inhibition of initial residual reactivity at early life, reactivity released during the service life, and the final reactivity penalty, and then the BPs suitable for plate assembly are selected. The content of different BPs varies according to their neutron absorption and burnup characteristics. By reducing the loading in the fuel plate, different BPs are added so that the initial value of infinite medium multiplication coefficient (k_{inf}) in the assembly becomes 1.20. Further, by changing the content of BPs in the single board and the number of BP boards in the assembly, the reactivity control requirements are satisfied and a smaller reactivity penalty is finally achieved.

Here, BP materials including non- actinide BPs, actinide BPs, and advanced polymeric BPs are selected as the research object for the analysis.

2.3.1. Non-actinide BPs

The components of non-actinide BP materials are naturally abundant, and the main materials are B_4C, Dy_2O_3, Er_2O_3, Eu_2O_3, Gd_2O_3, and Sm_2O_3.

2.3.2. Actinide BPs [30]

Some actinide nuclides can be converted into fissile nuclides after absorbing neutron. When these nuclides are used as BPs, they can inhibit excessive reactivity by absorbing neutron at the beginning of their lifetime, and they can also use the converted fissile nuclides to prolong the life of the assembly and enhance the reactivity. Finally, it leads to a gentle variation in the residual reactivity. The actinide nuclides selected in this study are ^{231}Pa,

^{241}Am, ^{237}NP, ^{238}Pu, and ^{240}Pu.

2.3.3. PACS: advanced polymeric BP

Polycarboborane-siloxane-ethynyl (PACS) has good corrosion resistance and stability, thus it is an effective BP [31]. Fig. 2 shows the chemical structure of PACS. In this study, two advanced polymeric BPs: PACS-J and PACS-L [32], are selected, and their compositions are shown in Table 1.

3. Candidate BP models

Fig. 3 shows the variation in the k_{inf} of assemblies without BP and with different actinide nuclide BPs as a function of burnup. When the actinide nuclides are used as BPs, the reactivity curve decreases slowly. With the final $k_{inf} = 1.0$, ^{231}Pa and ^{240}Pu [34] extend the life of the assembly due to their own burnup chain relationship. Other actinide BPs exhibit reactivity penalty of different amounts.

Fig. 4 shows the variation in the k_{inf} of assembly containing two advanced polymeric BPs as a function of burnup. Because both PACS polymers have high hydrogen content, they can also act as a moderator. Since more fast neutrons can be slowed down to thermal neutrons, the fuel utilization rate is improved, and the final fuel consumption depth of the assembly is increased. In other words, the burnup depth of the assembly containing these two BPs is greater than that of the assembly without BPs. Therefore, when $k_{inf} = 1.0$, the two advanced polymers extend the life of the assembly. Due to their unique characteristics, the reactivity of these polymers shows a small growth trend before 75 GWd/tU, where the reactivity fluctuation of PACS-J and PACS-L increases by nearly 0.1 and 0.15, respectively, and then it decreases drastically.

Fig. 5 shows the variation in the k_{inf} of assembly containing different non-actinide BPs as a function of burnup with natural ratio. During the life cycle of Gd_2O_3, Eu_2O_3, and Sm_2O_3, the reactivity first increases and then decreases, and it is difficult to achieve reactivity control when the initial k_{inf} is high. The nuclides have a small absorption cross section in BPs with different natural ratios, and the nuclides produced by offspring have different absorption cross sections and half-lives. This can lead to reactivity penalty if $k_{inf} = 1.0$. For SMRs, the natural proportion of non-actinide BPs is not the optimal choice for achieving long life. The use of enriched isotopes as BPs reduces the production of burnup chain neutron pronuclei, resulting in the reduction of some daughter nuclei with absorption cross sections and lowering the final reactivity penalty.

Therefore, in this study, the natural proportion of non-actinide BPs (Er_2O_3, Eu_2O_3, Gd_2O_3, and Sm_2O_3) corresponding to enriched isotope oxides ($^{167}Er_2O_3$, $^{151}Eu_2O_3$, $^{157}Gd_2O_3$, and $^{149}Sm_2O_3$) are selected, and all the separate isotopes are enriched at 100%. As shown in Fig. 6, when the enriched isotope oxides are used as BPs, their combustion is faster and the reactivity penalty is smaller. However, the reactivity control of $^{157}Gd_2O_3$, $^{149}Sm_2O_3$, and $^{151}Eu_2O_3$ remains challenging. Fig. 7 shows the reactivity burnup curves of assembly containing $^{157}Gd_2O_3$, $^{149}Sm_2O_3$, and $^{151}Eu_2O_3$ with low initial k_{inf}. The reactivity burnup curve still shows large fluctuations, and the reactivity control is difficult. There is no significant increase in the reactivity of $^{167}Er_2O_3$ assembly during the life cycle. Further, there is no reactivity penalty at end of lifetime, and the burnup is increased.

Fig. 8 shows the variation in the k_{inf} of assembly containing BPs with good neutronic performance as a function of burnup. It is clear that the reactivity of the assembly containing $^{240}Pu_2O_3$, $^{231}Pa_2O_3$, PACS-J, PACS-L, and $^{167}Er_2O_3$ can be controlled throughout the lifetime (no drastic fluctuations). Finally, the burnup depth of the assembly containing BPs exceeds that of the assembly without BPs due to the unique intrinsic characteristics of BPs, which makes them suitable for plate fuel assemblies.

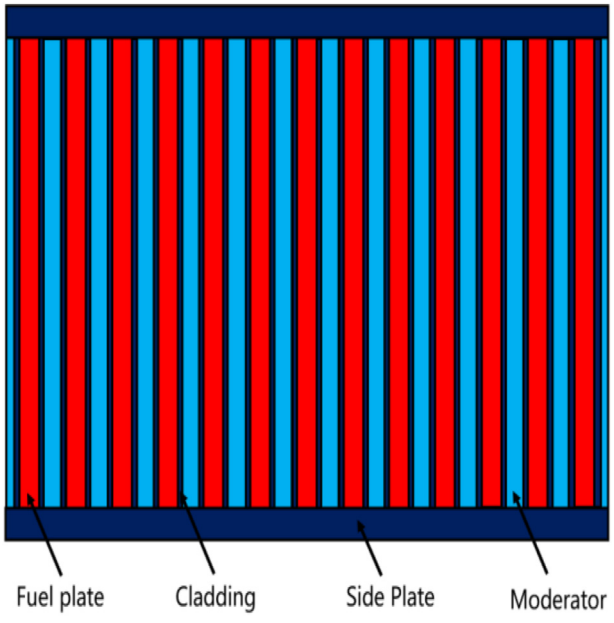

Fig. 1. Schematic of plate fuel assembly.

4. Neutronic features of improved BPs

For quantitative analysis of physical properties of improved BPs, different parameters(multi-objective optimization) are considered, which are listed in Table 2.

$^{240}Pu_2O_3$: ^{240}Pu has a neutron absorption cross-section of 301 barn, and when it is used as a BP, the burnup rate is slow, which allows long-term reactivity control. Specifically, when ^{240}Pu is used as a BP, the mass fraction of BP in a single plate is 0.42%, which reduces the self-shielding effect of the BP and allows it to be consumed almost completely at the end of lifetime. Thus, the fuel assembly life can be extended by 5400 MWd/tU. Fig. 9 shows that the probability of neutron capture by ^{240}Pu to produce the fissile nuclide ^{241}Pu is much greater than the fission probability of ^{240}Pu by interaction with neutrons. Fig. 10 shows that the fission cross section of ^{241}Pu is larger than the capture cross section, which proves that ^{241}Pu is a fissile nuclide. As can be seen in Fig. 11, ^{241}Pu reaches its maximum nucleus inventory (6.08×10^{-5}) at 77,000 MWt/dU and then begins to decrease in supplemental reactivity.

Therefore, when ^{240}Pu is used as a BP, ^{240}Pu can achieve long-term control of reactivity and also generate the fissile nuclide ^{241}Pu to supplement reactivity in the middle and late stages of life, allowing an increase of the burnup depth at end of lifetime and improving the fuel utilization.

$^{231}Pa_2O_3$: The neutron absorption cross section of ^{231}Pa is 202 barn, which also enables long-term reactivity control. When ^{231}Pa is used as a BP, the mass fraction of BP in a single plate is 0.73%, which can extend the fuel assembly life by 1500 MWd/tU. This is also because ^{231}Pa has a special burnup chain, where ^{231}Pa is the parent nucleus, and fissionable nuclides ^{232}U and ^{233}U are directly present. The capture and fission cross sections of ^{232}U are shown in Fig. 12. The fission and capture cross sections of ^{232}U are very similar, so ^{232}U can either undergo fission to supplement reactivity or capture neutrons to produce the fissile nuclide ^{233}U. As shown in Fig. 13, ^{232}U reaches its maximum nuclear inventory (1.48×10^{-4}) at 132,000 MWd/tU, which supplements the reactivity and improves the fuel utilization later in the life cycle.

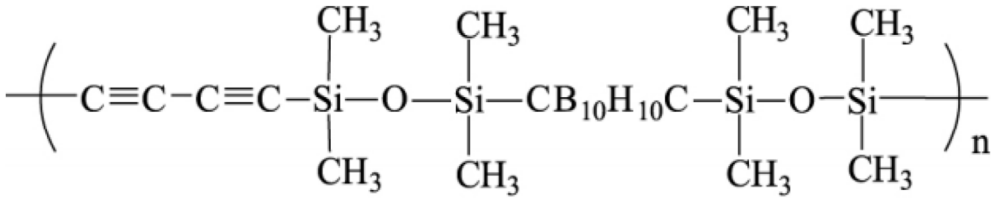

Fig. 2. Chemical structure of PACS.

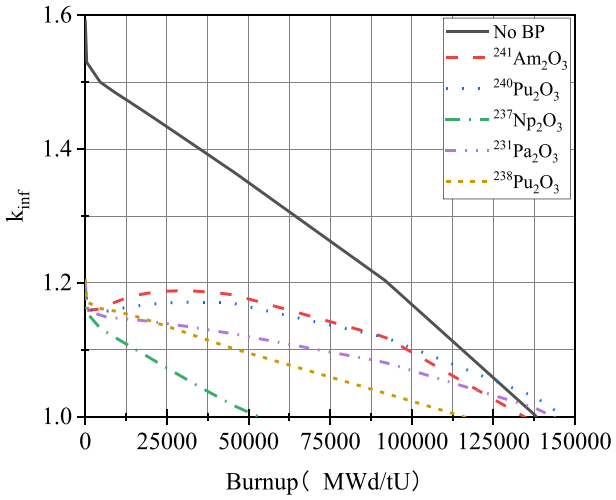

Fig. 3. k_{inf} vs. burnup for assemblies without BP and with different actinide BPs.

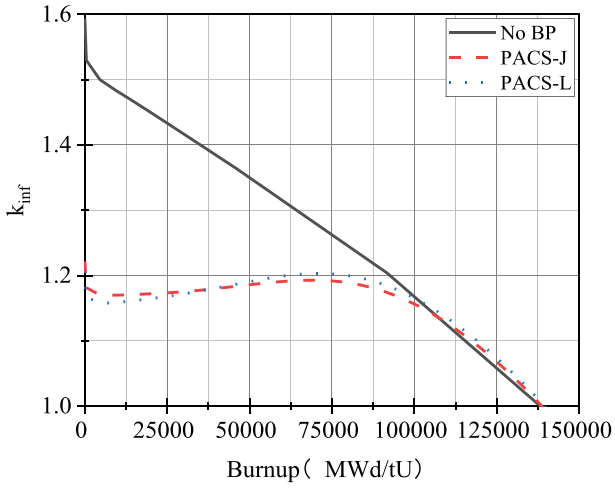

Fig. 4. k_{inf} vs. burnup for assemblies without BP and with different PACS BPs.

Therefore, when ^{231}Pa is used as a BP, it has its own special burnup chain, which makes it possible to extend the burnup at end of lifetime and improve the fuel utilization. The reactivity can be controlled throughout the life cycle.

Next, PACS-J and PACS-L polymers are used as BPs, where ^{10}B is used as the main neutron absorber, whose neutron absorption cross section is 3838 barn. PACS is consumed faster as a single BP, so the content in a single plate is increased (71.4%) to enhance the self-shielding effect of BP. When PACS is used as a single BP, the assembly reactivity still shows an increasing trend at 37,500 MWd/tU, and the reactivity control is still difficult. PACS itself has a high hydrogen content, so it has a moderation effect when used as a BP, which improves the utilization of thermal neutron in the assembly. The assemblies with PACS also have a 400 MWd/tU extension at end of lifetime. Fig. 14 shows the energy spectra of the assembly without BP and with PACS as BP. It can be seen that the thermal neutron energy spectrum is hardened at beginning of lifetime due to the addition of PACS in the assembly. However, the PACS itself has a high hydrogen content, which improves the utilization of thermal neutrons. Fig. 15 shows that the PACS containing assembly produces more fissile nuclides at end of lifetime, which complements the reactivity and extends the burnup.

Therefore when PACS is used as BPs, PACS itself has a moderation effect and improves the thermal neutron utilization. The assembly reactivity of PACS continues to fluctuate, while the effect of helium release on fuel plates needs to be considered when PACS is used as BPs.

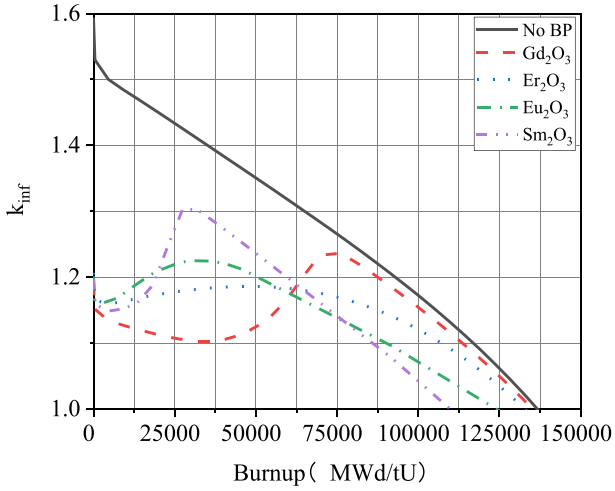

Fig. 5. k_{inf} vs. burnup for assemblies without BP and with different non-actinide BPs.

Table 1
Composition of PACS [33].

BP	Density (g/cm^3)	Composition											
			C	H	B	O	Si		C	H	B	O	Si
PACS-J	1.0	Mass fraction (%)	37	8	24	7	25	Number of atoms per molecule	14	34	10	2	4
PACS-L	0.9		46	7	9	7	30		44	84	10	5	12

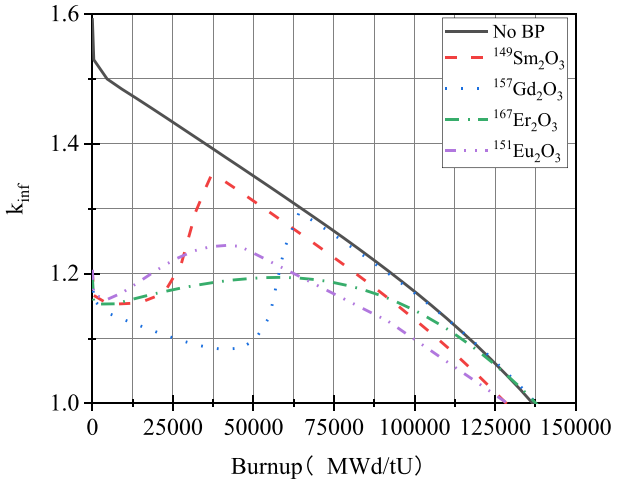

Fig. 6. k_{inf} vs. burnup for assemblies without BP and with different enriched isotope BPs.

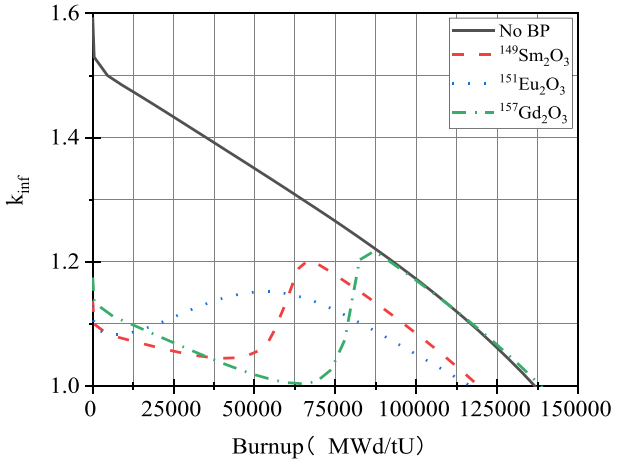

Fig. 7. k_{inf} vs. burnup for assemblies without BP and with BPs of low initial k_{inf}.

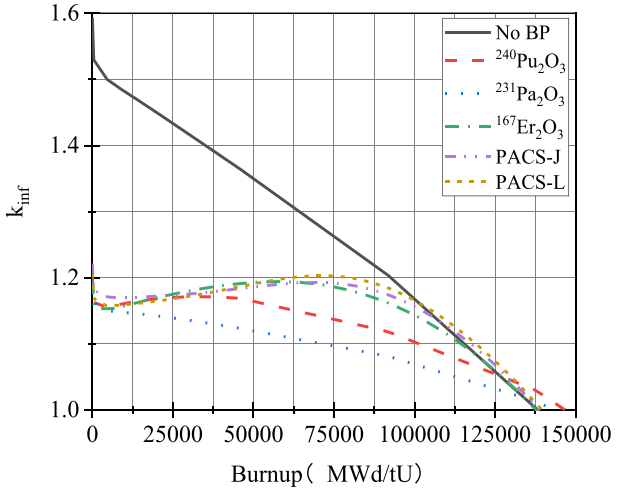

Fig. 8. k_{inf} vs. burnup for assemblies without BP and with BPs having good neutronic performance.

Table 2
Analysis schemes.

BP	$^{240}Pu_2O_3$	$^{231}Pa_2O_3$	PACS-J	PACS-L	$^{167}Er_2O_3$
Neutron absorption cross section (barn) [35]	301	202	3838 (^{10}B)	3838 (^{10}B)	660
Mass fraction (% of BPs in single board)	0.42%	0.73%	25.00%	71.4%	1.40%
Change in the cycle length of assembly with BPs as compared to that without BPs (MWd/tU)	+5400	+1500	+250	+400	+100
Number of fuel plates with BP	13	13	1	1	4

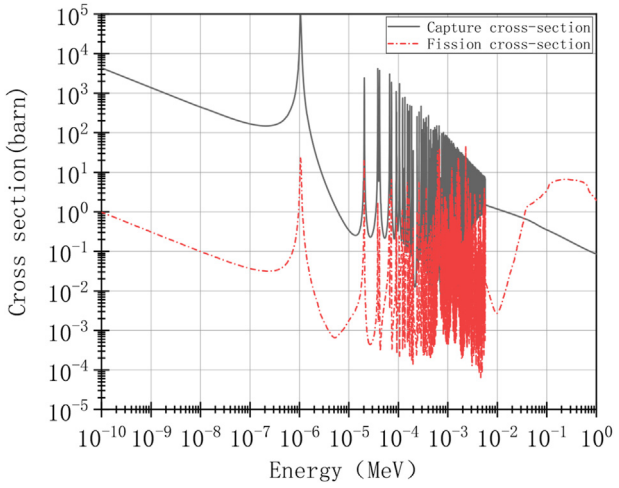

Fig. 9. Capture and fission cross sections of ^{240}Pu.

5. Combination of improved BPs

The selected BPs with improved performance do not cause reactivity penalty, and they increase the final burnup depth due to the burnup chain or their own characteristics. However, compared to the case when single BP is used in the assembly to control the reactivity, the assembly containing BPs ($^{167}Er_2O_3$, PACS-J, and PACS-L) has a larger absorption cross section due to the BPs itself, so the reactivity is released quickly with the combustion of BPs and does not decrease slowly during the lifetime, causing reactivity fluctuation. The assemblies containing Pa and Pu may ultimately lead to residual reactivity because the inherent neutron absorption cross section of BPs is small and the combustion is slow. For 18% fuel enrichment, when only a single BP is used under the larger initial residual reactivity, an effective control of the reactivity cannot be achieved and the requirements of the ideal BPs for marine reactors cannot be satisfied. Therefore, the BPs with larger neutron absorption cross section are properly matched with the BPs with smaller absorption cross section to achieve improved overall performance. The specific matching schemes are shown in Table 3.

Fig. 16 shows the k_{inf} of assembly containing different combinations of ^{167}Er, PACS-J, and PACS-L with BPs having small absorption cross section. By changing the number of BP boards in the assembly, the reactivity burnup curves with smaller reactivity fluctuation and larger burnup depth can be obtained. For BP combination, increasing the number of BP plates with large neutron absorption cross section can inhibit the reactivity initially, but since these BPs burn faster, the reactivity release is faster, thus the reactivity fluctuation is higher, which makes it difficult to control the reactivity. On the other hand, increasing the number of BP

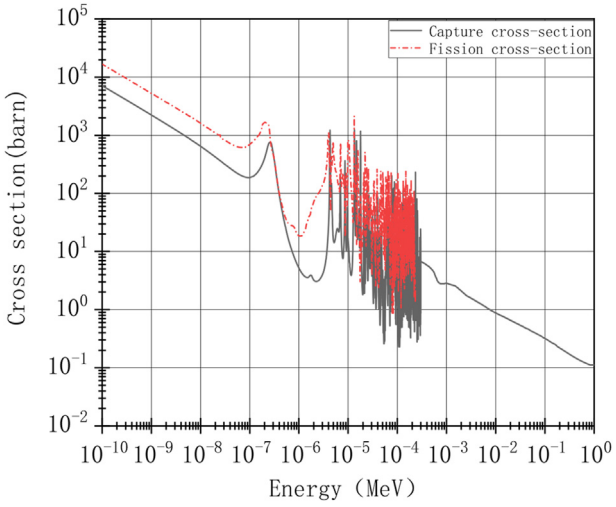

Fig. 10. Capture and fission cross sections of ^{241}Pu.

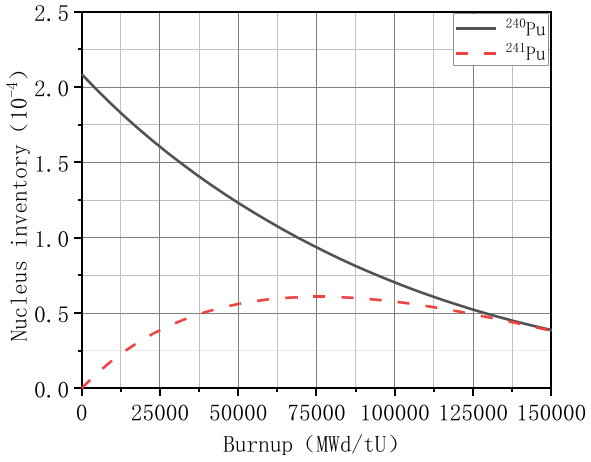

Fig. 11. Variation in the fission product inventory of ^{240}Pu and ^{241}Pu as a function of burnup.

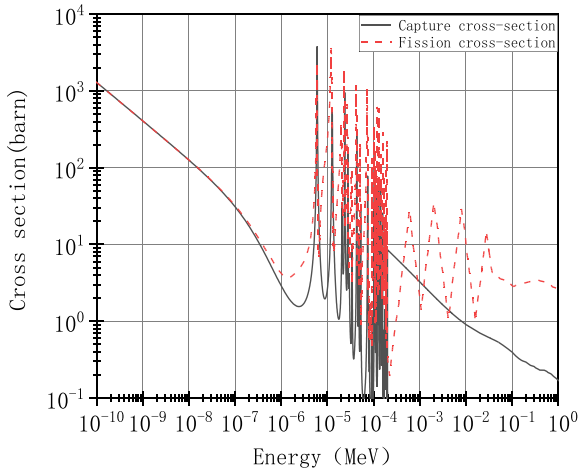

Fig. 12. Capture and fission cross sections of ^{232}U.

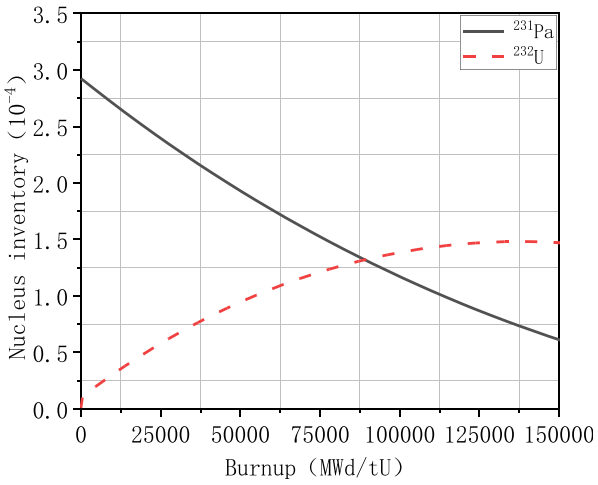

Fig. 13. Variation in the fission product inventory of ^{240}Pu and ^{241}Pu as a function of burnup.

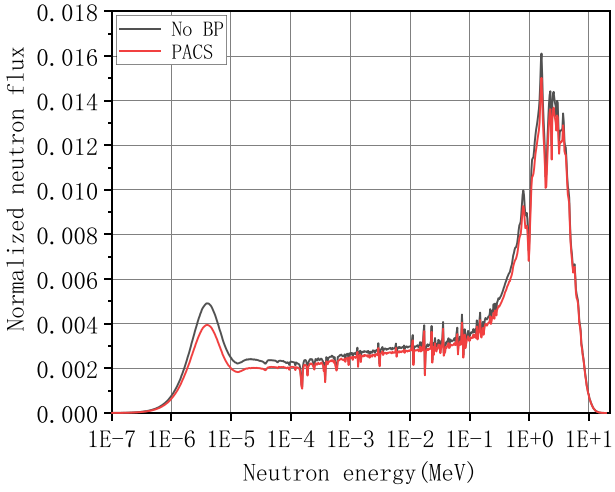

Fig. 14. Neutron spectrum of the assembly with PACS and without BP.

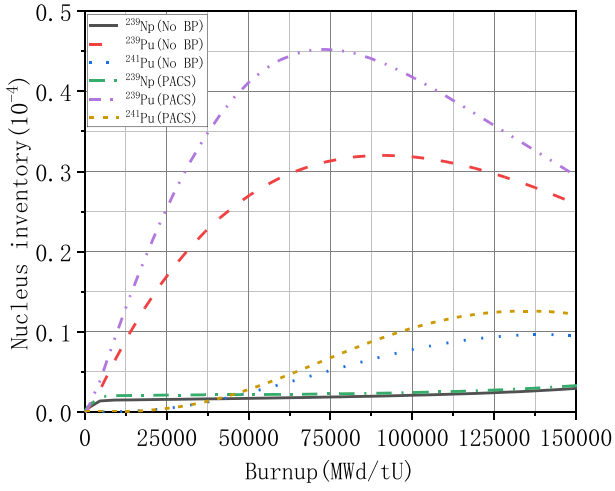

Fig. 15. Variation in the fission product inventory of assemblies without BP and with PACS as BP.

Table 3
Combination schemes of BPs.

BP	PACS-J	PACS-L	^{167}Er
^{231}Pa	PACS-J-^{231}Pa	PACS-L-^{231}Pa	^{167}Er-^{231}Pa
^{240}Pu	PACS-J-^{240}Pu	PACS-L-^{240}Pu	^{167}Er-^{240}Pu

plates with smaller neutron absorption cross section can suppress a part of the initial reactivity, and the burnup of these BPs is slower, thus the reactivity release is slower, and the reactivity fluctuation is smaller. However, such BPs do not burn completely during the lifetime, which leads to a reduction in the burnup depth. Thus, the characteristic features of different BPs should be considered to obtain a reasonable number of two BP plates with different neutron absorption cross sections so that the initial reactivity is small. This can reduce the reactivity fluctuation during the lifetime, and a larger burnup depth can be achieved finally.

Fig. 17 shows the results obtained by using improved combination of Er, PACS-J, and PACS-L with small absorption cross section. When a small amount of BP with larger neutron absorption cross section is added to the module, the larger initial reactivity can be suppressed. Compared with the case in which a single BP is added to the assembly, adding BP with larger neutron absorption cross section to the assembly with Pa and Pu can suppress the larger initial reactivity, reduce the reactivity fluctuation, and increase the final burnup depth of assembly. When BP with larger neutron absorption cross section is added to the assembly containing Pu, the final burnup depth can be significantly increased. When Er is added to the assemblies containing Pu, greater initial reactivity suppression can be achieved, and a relatively gentle release of reactivity can be achieved during the lifetime. Finally, the BP combustion releases reactivity, and the burnup depth can be up to 149700 MWd/tU. Therefore, for marine reactors, it is better to use Pu and Er in the assembly.

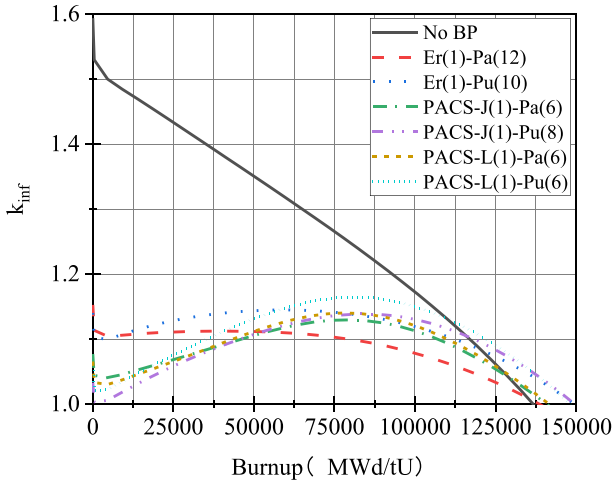

Fig. 17. Variation in the k_{inf} with improved BP assemblies as a function of burnup.

6. Conclusions

To meet the BP requirements of long-life marine reactor, neutronic analysis of different BPs was conducted, and a BP suitable for marine reactor fuel assembly was selected. Further, the burnup properties of non- actinide BP, actinide BP, and advanced polymeric BPs were investigated. The main results of the study are summarized as follows:

(1) ^{231}Pa and ^{240}Pu have small neutron absorption cross sections, so they can achieve a smooth decrease in the reactivity during the lifetime. Meanwhile, due to the presence of fissile nuclides in their burnup chain, they can undergo fission to replenish the reactivity and increase the final burnup depth.

(2) The application of enriched isotope ^{167}Er as a BP causes a slower release of reactivity during the lifetime as compared to that in the case when natural nuclides are applied. Finally, the burnup depth of assembly can be increased because ^{167}Er is completely consumed.

(3) Compared with traditional BPs, PACS-J and PACS-L exhibit better BP characteristics. PACS can be completely consumed during the lifetime, but because it burns faster, the reactivity increases slightly. Finally, the ability of PACS to slow down the neutrons enhances the burnup depth.

(4) To realize long-life operation and meet the overall requirements of BPs for marine reactors, different combinations of BPs can be used.

Overall, in this study, an improved combination of BPs was demonstrated, which not only suppressed the initial residual reactivity but also achieved a larger final burnup depth. It may be noted that the economic feasibility and material properties of the selected BPs were not evaluated in this study. In future, new BPs with better neutronic performance can be investigated to reduce their manufacturing costs and improve their efficacy. Further, the material properties can be examined to improve their cost effectiveness.

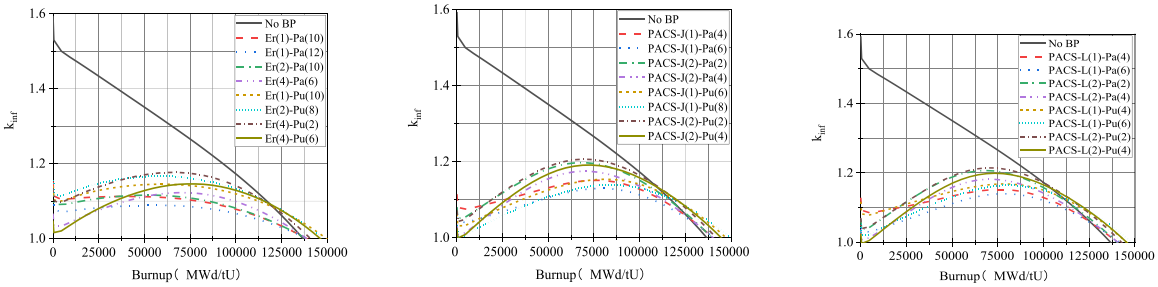

Fig. 16. Variation in the k_{inf} of assembly with different BP combination schemes: (a) Er and Pa/Pu; (b) PACS-J and Pa/Pu; (c) PACS-L and Pa/Pu.

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Declaration of competing interest

The authors declare that they have no conflicts of interest regarding the conduct of this study.

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