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Feasibility of Using Burnable Poisons for Reduction of Coolant Void Reactivity in LMR for TRU Transmutation

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A new design concept to reduce coolant void reactivity in sodium cooled core for transuranic element transmutation is proposed. In the new option, some amount of fertile material is removed for reduction of sodium void reactivity. Simultaneously, a burnable absorber material is loaded in replacement of fertile material to compensate for reactivity drop during the fuel depletion. Considering two methods of burnable absorber loading such as the homogeneous and the heterogeneous, the feasibility of the new option using burnable poison are discussed in terms of sodium void reactivity, burnup reactivity, and Doppler effect. In the results, it is found that the homogeneous loading cannot reduce the sodium void reactivity but makes the reactivity more positive. On the other hand, the heterogeneous loading can reduce the sodium void reactivity successfully. It is also noticed that the increment in burnup reactivity swing is negligible when the burnable poison is heterogeneously loaded in the central region of the core. The obtained results lead to the conclusions that if the burnable poison material is loaded appropriately, the sodium void reactivity can be reduced without any significant penalty of increase in burnup reactivity swing.

KEYWORDS: TRU, Transmutation Reactor, Liquid Metal Cooled Core, Coolant Void Reactivity, Burnup Reactivity Swing, Burnable Poisons

1. Introduction

When a transmutation reactor is considered for incineration of transuranic (TRU) elements in the spent fuel from the commercial reactor such as the pressurized water reactor (PWR) and the pressurized heavy water reactor (PHWR), the amount of fertile isotopes (mostly ^{240}Pu) in the TRU fuel is very small. It raises three key issues on reactor core design:

- large reactivity drop with burnup, i. e., burnup reactivity swing,
- small Doppler effect, and
- small delayed neutron fraction.

A solution to these problems is to utilize the fertile material such as ^{238}U and ^{232}Th, mixed with TRU. These fertile materials, however, give rise to another problem of the very positive coolant void reactivity in a liquid metal cooled reactor (LMR) core[1].

In this study, a burnable poison (BP) material is considered as an alternative solution to the problems mentioned above. The advantages and the drawbacks resulting from a massive introduction of BP in a LMR core are investigated. The ultimate goal is to assess the feasibility

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of BP option to reduce the coolant void reactivity without any significant penalty on the other key challenges of fertile material such as burnup reactivity swing, delayed neutron fraction, and Doppler effect.

2. Rationale for BP option

In the conventional fast breeder core, the duty of fertile material is to produce the fissile material as an energy resource. Therefore, the loading amount of fertile isotopes should be sufficiently high. As far as the TRU burner is concerned, the fertile isotope is inevitably loaded in order to solve the problem of safety performance, especially the large burnup reactivity swing. When neutron energy spectrum is hardened due to coolant voiding, the fission cross sections of fertile isotopes increase significantly in the typical fast reactor core and cause the net outcome of very large positive reactivity.

Concerning the primary objective of TRU burner, it is desirable to minimize the loading amount of fertile material, if and only if the safety performance is guaranteed. In order to reduce coolant void reactivity as the key challenging parameter in LMR design, a new design concept is conceived. In the new design option, the approach to reduction in sodium void reactivity is to remove some amount of fertile isotope as the main cause for large positive coolant void reactivity. Against the problem of loss in burnup reactivity compensation caused by removal of fertile material, the additional option of introducing BP material in replacement of fertile material is expected to compensate for reactivity drop due to TRU depletion. In other words, a burnable absorber material can be considered as an alternative means to fulfill its own duty of reactivity compensation without increase in fission cross section upon the coolant voiding event.

3. Approaches

Firstly, a 1400 MWth-class sodium cooled core is modeled as the reference core in which ^{238}U is loaded additionally in the mixture with TRU fuel. In order to investigate the feasibility of the new design concept, some amount of ^{238}U is replaced by a BP material. Considering two methods of BP loading, the homogeneous and the heterogeneous, BP loading effects on the safety performance parameters are analyzed. In order to investigate the sensitivity to the loading amount as well as the loading position of BP material, parametric study is also carried out. Based on the calculation results for all the cases considered, the feasibility is discussed in terms of coolant void reactivity worth, burnup reactivity swing, and Doppler coefficient.

3.1 Calculation Methods

In this study, for the analyses of core perturbation upon the sodium voiding, all the core calculations are performed using the diffusion code, DIF3D[2]. And the burnup code, REBUS-3 is employed for considerations of burnup reactivity swing[3]. The flux distributions necessary in the burnup calculation are provided by the nodal diffusion calculation using the same diffusion code, DIF3D. The diffusion calculation is performed with the 9 group IOTXS formatted cross section. The 9 group cross sections are obtained by collapsing the pre-processed MATXS formatted 80 group data, KAFAX-F22[4]. In this step, the utility code, TRANSX, is employed[5]. KAFAX-F22 has been generated by Korea Atomic Energy Research Institute (KAERI) for analyses of fast reactor core. The data of most isotopes are based on the evaluated data of JEF-2.2. The neutron flux spectra as the weighting function for collapsing the 80 group to 9 group data are calculated by the S_N transport cord, DANTSYS[6].

The reactivity coefficients such as sodium void reactivity worth and Doppler coefficient are obtained by two successive criticality calculations for the unperturbed and the perturbed core, respectively. The sodium void worth is calculated by assuming that the 40% volume of coolant material is expelled from all the fuel assemblies uniformly throughout the entire active core. All the core calculations in this study are performed with all control rods out.

3.2 Reference Core Modeling

The reference core modeled in this study is depicted in Figure 1. The geometrical configurations are referred from the precedent study on the sodium cooled TRU burner design[7]. As shown in Figure 1, the reference core is fueled with the uniform enrichment throughout the active core and any core partitioning into several region with the different enrichment are not considered. This core cannot be practical design because the peak linear power would exceed the design limit due to high peaking factor. Nevertheless, it is regarded as relevant to the feasibility study on the BP option in this work since BP loading would impact significantly on the spatial power distribution, especially in the heterogeneous loading.

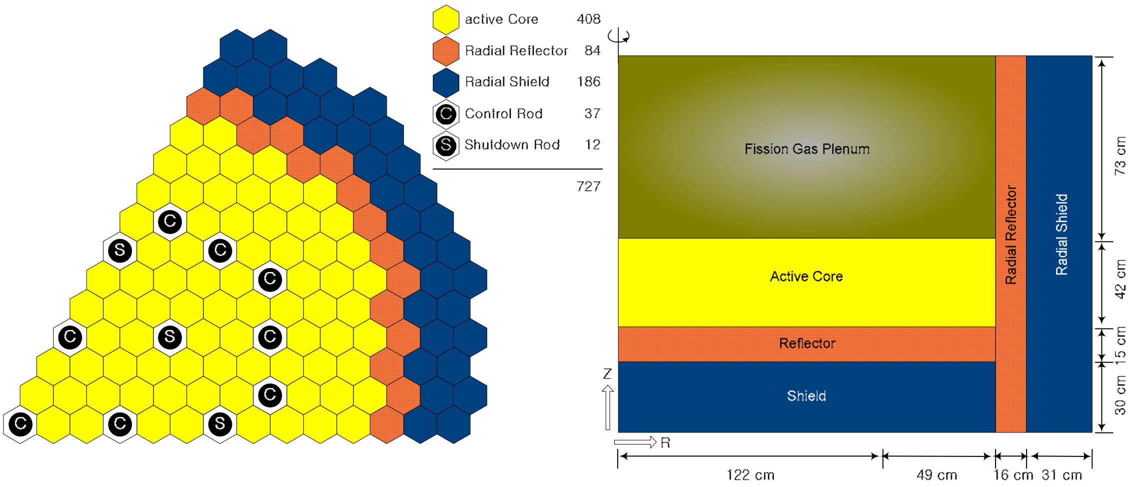


Figure 1 Reference core layout

The geometrical data of the assemblies and fuel pin are based on the Korea Advanced Liquid Metal Cooled Reactor (KALIMER), which is the sodium cooled fast reactor under development by KAERI. As shown in Figure 1, the active core height is very short and the core configuration is a typical ‘pan-cake’ type. A fuel assembly consists of 271 fuel rods and the duct material. HT-9 is utilized as an assembly duct material and the coolant material is liquid sodium. The lattice pitch of fuel pin cell is 8.9 mm and the very tight lattice cell is employed with the pitch-to-diameter (P/D) of 1.2 in order to achieve the hard neutron spectrum.

In practical TRU burner design, fertile material is considered as the recovered uranium from the spent fuel of commercial reactor. In this study, the recovered uranium is assumed to be 100% ^{238}U because the weight percent (w/o) of ^{235}U is very small. The TRU fuel loaded into the reference core is considered as the fresh TRU extracted from PWR after burnup of 35 GWD/MTH and cooling in 10 years. The metallic fuel is loaded in the chemical form of

x%U+(90-x)%TRU+10%Zr. Here, Zr is loaded in the fuel mixture in order to relieve the fuel swelling in the metallic fuel. The reactor power rating and the cycle length are considered as 1400MWth and 1 year, respectively. The plant capacity factor is assumed to be 85%.

In order to maximize TRU destruction capability, it is intended to minimize breeding of fissile TRU from the fertile material. Therefore, any blanket region is not employed and the weight fraction of fertile material in the active fuel becomes rather small. The fuel composition is estimated as 73.0%U+17.0%TRU+10%Zr. In this viewpoint, the reactivity swing becomes very large inevitably in the TRU burner design. The burnup calculation result shows that the burnup reactivity swing in the reference core is 2.69 %$\Delta\rho$, which is very large in comparison with the conventional breeder reactor. In order to suppress the large excess reactivity, the large number of control element assembly is inserted throughout the active core, as shown in Figure 1.

3.3 Analyses of BP Loading Effect

In this study, boron carbide in the form of B_4C is employed as a BP material. The boron is highly enriched up to 90w/o ^{10}B in order to increase boron burnup and minimize absorber inventory.

3.3.1 Homogeneous Loading

In the homogeneous loading, some numbers of fuel rods are replaced by BP rods in all the fuel assemblies throughout the entire active core. Figure 2 shows the configuration of the fuel assembly in which 30 rods out of the total number of 271 are replaced by BP rods.

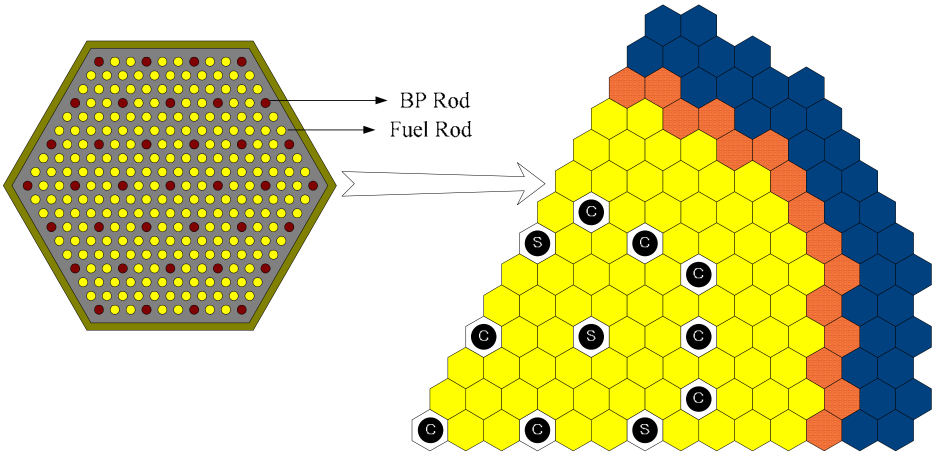


Figure 2 Schematic representation of homogeneous BP loading

For investigation of the effects on the loading amount of BP, the cases study is performed considering the various numbers of BP rods in replacement of fuel rod. For all the cases considered, the concentrations of ^{238}U mixed with TRU in the fuel rod are re-adjusted to maintain the cycle length of 1 year unchanged. Table 1 shows the description of the cases considered for analyses of the homogeneous BP loading. The case is denominated according to the number of BP rods in replacement of fuel rods in a fuel assembly.

Table 1 Case descriptions for homogeneous BP loading effect analyses

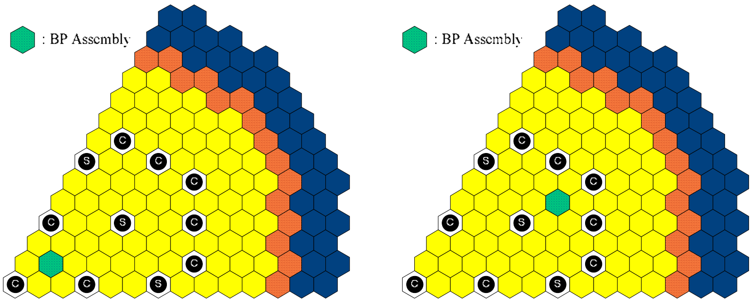
Case	No. of BP Rod per Assembly	Fuel Composition	k_{eff} (BOC)
Reference	0	73.0%U+17.0%TRU+10%Zr	1.02902
HO30	30	57.4%U+32.6%TRU+10%Zr	1.03848
HO60	60	42.7%U+47.3%TRU+10%Zr	1.03917
HO90	90	25.5%U+64.5%TRU+10%Zr	1.03858
HO120	124	90.0%TRU+10%Zr	1.03942

3.3.2 Heterogeneous Loading

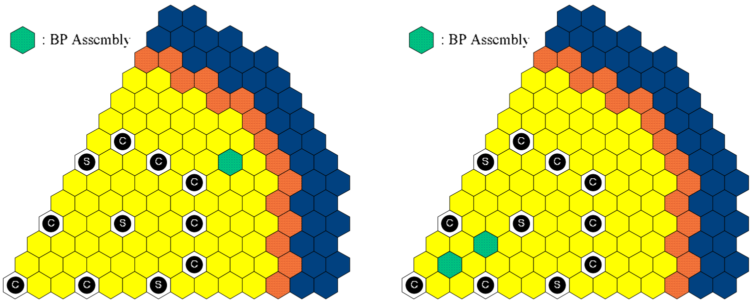
For the analyses of the heterogeneous loading, some numbers of fuel assemblies are removed and replaced by BP assembly, in which all rods are not filled with fuel but BP material. In the heterogeneous loading, the sensitivity to the position as well as the number of BP assembly loading is investigated. The cases considered for the sensitivity analyses are described in Table 2. The case in the heterogeneous loading is denominated according to the location of BP assembly. For example, the case name of HE0302 means that the BP assembly is loaded in the 2nd assembly of 3rd hexagonal ring form the center of the one-sixth symmetry core. In Figure 3, the locations of BP assembly in the heterogeneous loading are described schematically. Especially, in the case of HE3253, two fuel assemblies are replaced by BP assemblies; one is located in the 2nd assembly of 3rd hexagonal ring and the other in the 3rd assembly of the 5th ring from the center of one-sixth symmetry core. Therefore, total numbers of BP assembly loading throughout the entire active core is twelve.

Table 2 Case descriptions for heterogeneous BP loading effect analyses

Case	No. of BP Assembly	Fuel Composition	k_{eff} (BOC)
Reference	0	73.0%U+17.0%TRU+10%Zr	1.02902
HE0302	6	72.0%U+18.0%TRU+10%Zr	1.02908
HE0905	6	72.1%U+17.9%TRU+10%Zr	1.03937
HE1307	6	72.7%U+17.3%TRU+10%Zr	1.03272
HE3253	12	71.3%U+18.7%TRU+10%Zr	1.03134



(a) HE0302 (b) HE0905



(c) HE1307 (d) HE3253

Figure 3 Schematic representation of heterogeneous BP loading

4. Results and Discussions

4.1 Sodium Void Reactivity

The calculation results of sodium void reactivity are given in Table 3. Firstly, it is noticed that the homogeneous BP loading cannot reduce the sodium void reactivity but makes the reactivity more positive despite the weight fraction of fertile isotope is significantly decreased. As the number of BP rod is increased, the sodium void reactivity in the homogenous loading increases toward more positive value. Even in the case of HO120, despite the fertile isotope of ^{238}U is removed completely from the fuel rod, the sodium void reactivity cannot be reduced, contrary to the expectation. On the other hand, the heterogeneous loading can reduce the sodium void reactivity successfully. In all the cases of heterogeneous loading in Table 3, the values of sodium void reactivity are smaller than the values in the reference. It is also noticed that as the location of BP assembly moves toward the central region of the core, the value is reduced much more. Especially, when the number of BP assembly is increased in the HE3253, the sodium void reactivity is reduced significantly.

For the comparative analyses of core perturbation upon the sodium voiding between the homogeneous and the heterogeneous loading, the adjoint fluxes as a neuron importance function are calculated. As shown in Figure 4, the importance function in the homogeneous loading is steeper than that in the reference. In other word, the fast fission of fertile isotope is much more increased in the homogeneous loading despite the w/o of ^{238}U is decreased, which is the main contributor to the steep slope of importance function.

Table 3 Calculation results sodium void reactivity

Homogeneous Loading Case	Sodium Void Reactivity [pcm]	Heterogeneous Loading Case	Sodium Void Reactivity [pcm]
Reference	657	Reference	657
HO30	983	HE0302	526
HO60	1041	HE0905	542
HO90	1047	HE1307	626
HO120	1048	HE3253	444

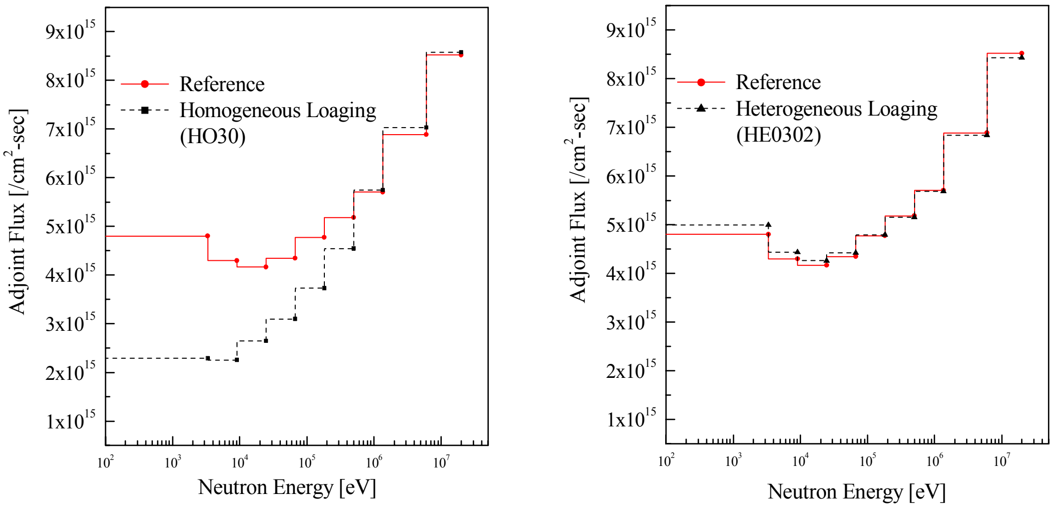


Figure 4 Comparison of neutron importance function with energy

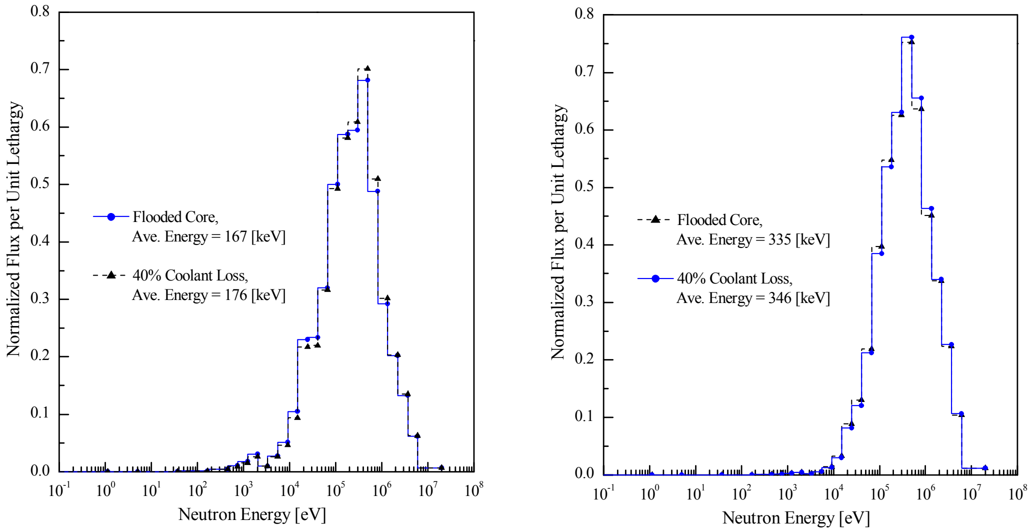
In order to clarify the reason for increase in the sodium void reactivity in the homogeneous loading, the core perturbation is expressed in terms of the reaction probability balance. In Table 4, the calculation results of reaction probability in the homogeneous loading are compared with that in the reference. The reaction probability is estimated as the time rate of each type reaction over the total rate of all type reaction. It is firstly noticed that the increment in leakage probability upon sodium voiding is very much smaller in the homogeneous loading in comparison with the reference. On the other hand, the fission probability is much more increased in the homogeneous loading. The absorption cross sections of both TRU and ^{10}B are significantly greater than that of ^{238}U. Therefore the neutron spectrum in the homogeneous loading becomes harder than that in the reference, as depicted in Figure 5. This spectrum hardening effect accounts for the increase in the sodium void reactivity in spite of the reduction in the w/o of ^{238}U. It can be also noticed that the decrement in capture probability is smaller in comparison with the reference. It is attributed to the fact that the more neutrons are absorbed in the nuclide of ^{10}B when the coolant is expelled from the active core. This effect can be expected to give a contribution to reduction in sodium void reactivity. However, this contribution is cancelled out by the significant increase in fast fission of fertile isotopes. After all, the homogeneous loading of BP makes sodium void reactivity more positive, because the undesirable component of fast fission surpasses the desirable component of parasitic capture.

Table 4 Comparison of reaction probability between the homogeneous BP loading and the reference

Case	Leakage Probability [%]	Capture Probability [%]	Fission Probability [%]	(n,2n) Probability [%]	ν a)
Reference					
Flooded	13.25	51.77	34.75	0.23	2.93917
Voided	13.79	51.00	34.97	0.22	2.94029
Diff. b)	0.54	-0.77	0.22	0.01	0.00112
Homogeneous BP Loading (HO30)					
Flooded	9.34	55.24	35.23	0.19	2.98379
Voided	9.65	54.58	35.58	0.19	2.98504
Diff.	0.31	-0.66	0.35	0.00	0.00125

a) The number of neutron produced per fission reaction

b) Difference = the value in the voided – that in the flooded



(a) Reference

(b) Homogeneous Loading (HO30)

Figure 5 Comparison of neutron flux spectrum between the homogeneous and the reference

On the contrary to the homogeneous loading, the slope of importance function in the heterogeneous loading is depressed in comparison with the reference, as shown in Figure 4. In other words, the spectrum hardening effect is reduced considerably by reduction in w/o of ^{238}U. However, the magnitude of depression is not great enough to account for the significant reduction of sodium void reactivity.

In Table 5, the calculation results of reaction probability balance in the heterogeneous loading are compared with that in the reference. As mentioned above, the increment in fission probability in the homogeneous loading is greater than that in the reference. However, the increment in fission probability in the heterogeneous loading is smaller than that in the reference. In accordance, the increment in leakage probability in the heterogeneous loading is much larger in comparison with the homogeneous loading in Table 4. In other words, the increase in fast fission of fertile isotopes can be suppressed by the removal of ^{238}U as far as the heterogeneous loading is concerned. It is also noticed that the decrement in capture probability in the heterogeneous loading is considerably smaller than that in the reference, since many neutrons are captured parasitically by the locally inserted BP assembly, similarly to the homogeneous loading. It should be noted that this component gives the main contribution to reduction of sodium void reactivity. In other words, the achievement of low sodium void reactivity is primarily owing to the increase in the parasitic capture. In brief, the reduction of sodium void reactivity is achieved by the combination of two mechanisms; the increase in parasitic capture by BP assembly as well as the decrease in fast fission of fertile isotopes.

Table 5 Comparison of reaction probability between the heterogeneous BP loading and the reference

Case	Leakage Probability [%]	Capture Probability [%]	Fission Probability [%]	(n,2n) Probability [%]	ν [a]
Reference					
Flooded	13.25	51.77	34.75	0.23	2.93917
Voided	13.79	51.00	34.97	0.22	2.94029
Diff. [b]	0.54	-0.77	0.22	0.01	0.00112
Heterogeneous BP Loading (HE0302)					
Flooded	13.20	51.88	34.70	0.22	2.94338
Voided	13.71	51.21	34.85	0.23	2.94458
Diff.	0.51	-0.67	0.16	0.01	0.00120

a) The number of neutron produced per fission reaction

b) Difference = the value in the voided – that in the flooded

4.2 Burnup Reactivity Swing

The calculation results of burnup reactivity swing are given in Table 6. It is found that the homogeneous BP loading has another drawback of the significant increases in burnup reactivity swing. The burnup reactivity swing increases gradually in proportional to the number of BP rods in replacement of fuel rod.

Table 6 Calculation results of the burnup reactivity swing

Homogeneous Loading Case	Burnup Reactivity Swing [pcm]	Heterogeneous Loading Case	Burnup Reactivity Swing [pcm]
Reference	2.69	Reference	2.69
HO30	3.61	HE0302	2.70
HO60	3.65	HE0905	3.64
HO90	3.62	HE1307	3.67
HO120	3.57	HE3253	2.94

In the heterogeneous loading, the burnup reactivity swing is larger in comparison with the reference. It is attributed to the fact that the absorption cross section of ^{10}B is too small. In other words, the neutron spectrum in the region of BP assembly loading is too hard for BP material to compensate for reactivity drop during the fuel depletion. Moreover, as the location of BP assembly is moved toward the outer boundary region of the active core, the value is increased gradually.

However, the attention should be also directed to the fact that the increment in burnup reactivity swing in the HE0302 is negligible. This result indicates that the sodium void reactivity can be reduced without any considerable penalty of burnup reactivity swing if the BP assembly is inserted in the central region. In addition, it can be expected that the burnup reactivity swing can be reduced much more if the neutron spectrum in the region of BP assembly is rather softened.

4.3 Doppler Effect

The calculation results of Doppler coefficients are given in Table 7. The results show that negative reactivity feedback effect by Doppler broadening is decreased by BP loading regardless of loading method of the homogeneous or the heterogeneous because the considerable amount of ^{238}U as a Doppler absorber is removed. In the homogeneous loading, the Doppler effect is much more decreased than that in the heterogeneous loading because the more amount of ^{238}U is removed. It is an interesting finding that Doppler coefficient is becomes positive when the ^{238}U is removed considerably in both of the HO90 and the HO120. It is attributed to the fact that the Doppler broadening of fission cross section of ^{239}Pu is dominant.

In the heterogeneous loading, the Doppler effect is still smaller than that in the reference. However, the magnitude of Doppler effect reduction is not significant but Doppler coefficient is sufficiently negative because the removal amount of ^{238}U is not large compared to the homogeneous loading.

5. Conclusions

In this study, the feasibility of using BP in LMR core design for TRU transmutation is discussed in terms of sodium void reactivity, burnup reactivity, and Doppler effect. Considering two methods of burnable absorber loading such as the homogeneous and the heterogeneous, the feasibility of the new option using burnable poison are discussed in terms of sodium void reactivity, burnup reactivity, and Doppler effect. In the results, it is found that the homogeneous loading cannot reduce the sodium void reactivity but makes the reactivity more positive. On the other hand, the heterogeneous loading can reduce the sodium void reactivity successfully. It is also noticed that the increment in burnup reactivity swing is negligible when the burnable poison is heterogeneously loaded in the central region of the core.

The obtained results lead to the conclusions that if and only if the BP material is loaded appropriately in replacement of fertile material, the sodium void reactivity can be reduced without any significant penalty of increase in burnup reactivity swing.

The new design concept using BP option has also the inevitable drawback of reduction in Doppler effect. As a further study, dynamic analyses are necessary to investigate the trade-off between the safety performances such as sodium void reactivity and Doppler effect.

Table 7 Calculation results Doppler coefficient

Homogeneous Loading Case	Doppler Coefficient [pcm/K]	Heterogeneous Loading Case	Doppler Coefficient [pcm/K]
Reference	-4.239	Reference	-4.239
HO30	-0.211	HE0302	-3.890
HO60	-0.025	HE0905	-3.690
HO90	0.008	HE1307	-4.090
HO120	0.018	HE3253	-3.640

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