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ARTICLE

Study on the Sodium Void Reactivity Reduction by Introducing Inner Blanket with Inner Moderator (IBIM) in FBR

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Metal-fueled fast reactors have higher performance than oxide-fueled fast reactors in terms of thermal conductivity and breeding performance. However, the sodium void reactivity (SVR) is more positive than oxide-fueled fast reactors. As a method of reducing SVR in ASTRID, it was examined to introduce Inner Blanket (IB) into the axial center of inner core. IB increases the geometric buckling and enhances neutron leakage by dividing fuel region. In this study, in order to improve the effectiveness of IB, Inner Moderator (IM) is introduced into IB, which is named "Inner Blanket with Inner Moderator (IBIM)". It is expected that IM enhances neutron capture reactions of IB after voiding. This is a new method to further reduce SVR. This paper aims to evaluate the effectiveness of IBIM and clarify the mechanism how IBIM reduces SVR. In conclusion, it was shown that SVR was reduced more in the core with IBIM than in the core without IM, and the mechanism was revealed.

KEYWORDS: sodium-cooled metal-cooled fast reactor, sodium void reactivity, inner blanket (IB), inner moderator (IM), inner blanket with inner moderator (IBIM)

I. Introduction

Fast breeder reactors (FBRs) enable to utilize resources efficiently and reduce high-level radioactive waste. Among FBRs, metal-fueled FBRs have potential to improve safety and economic efficiency because they have higher conversion ratio (CR), burnup and neutron flux. In Japan, however, the technology of metal fuel is immature, while Japan has abundant experience in the use of oxide fuels by developing it for over 50 years.

Generally speaking, one of the issues with metal-fueled reactors is the insertion of more positive sodium void reactivity (SVR) compared to oxide-fueled reactors after coolant voiding. In other words, by reducing SVR, the safety margin of metal-fueled fast reactors can be increased. It is expected to improve social acceptability. In this study, a new method of reducing SVR was proposed.

The magnitude of SVR is determined by the balance between negative reactivity by increased neutron leakage and positive reactivity due to neutron spectral hardening when voiding. This is why it is necessary to enhance neutron leakage when voiding or to suppress neutron spectral hardening in order to reduce SVR. ASTRID[1)] studied in France, which has the flattened and H-shaped core with an axial inner fertile blanket, achieved negative SVR.

This paper focused on this Inner Blanket (IB). IB increases the geometric buckling and enhances neutron leakage by dividing fuel region. This is why introduction of IB reduces SVR.

In this paper, it is proposed to introduce the moderator into IB. This is a new method to further reduce SVR, and it is named "Inner Blanket with Inner Moderator (IBIM)." It is expected that Inner Moderator (IM) enhances neutron capture reactions in IB region when voiding.

This study aims to evaluate the effect of IBIM on SVR and other safety parameters and to clarify the mechanisms of IBIM reducing SVR.

II. Models and Method

First of all, the survey of IBIM specifications using pin-cell model was performed as the preliminary analysis. Next, full core analysis was performed in order to determine optimal IBIM specifications and evaluate core characteristics such as SVR, CR, doppler coefficient, delayed neutron fraction, etc.

1. Pin-cell Model Analysis

In the preliminary analysis, the ASTRID pin-cell model with metal fuel was used. **Table 1** and **Fig. 1** show the pin specifications and the axial layout of the pin, respectively.

Figure 2 shows two different methods to introduce IM: 1) constant IB thickness case and 2) variable IB thickness case. In case 1, a part of IB is replaced with IM while keeping the total IB thickness constant. In case 2, the IB thickness increases with the insertion of the IM.

As for IM material, YH_2 was used.

Table 1 The pin specifications for analysis.[1)]

Parameter (units)	Value
Output (MWt/MWe)	1200/480
Fuel composition	U-Pu-10Zr
Pu enrichment (wt%)	22.6
Pin OD (mm)	9.7
Cladding thickness (mm)	0.28
Pin pitch (mm)	10.8
Smear density (TD%)	75

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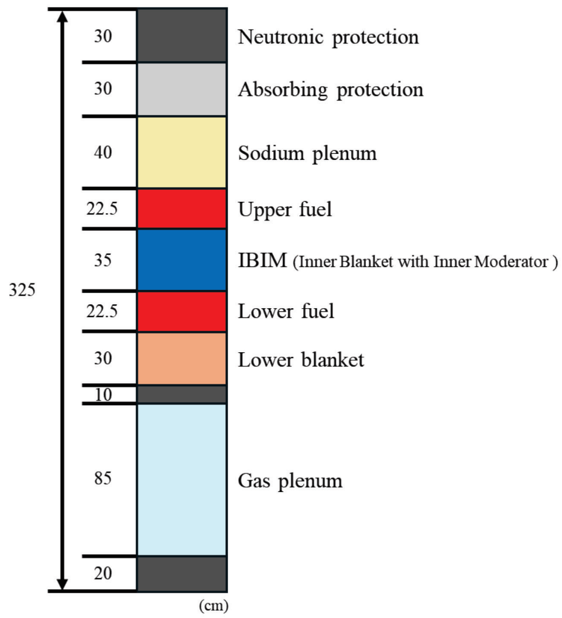

Fig. 1 The axial layout of the ASTRID pin with IBIM[1]

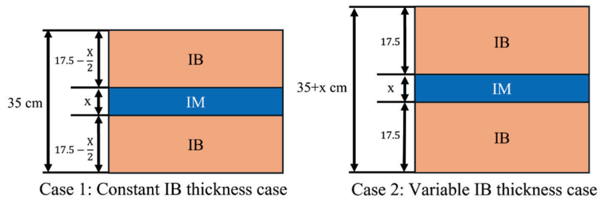

Fig. 2 Methods to load IM

2. Full Core Analysis

(1) Analysis Model

Full core analyses were carried out for a 600 MWe metal-fueled fast reactor studied by the Central Research Institute of Electric Power Industry.[2] **Figure 3** shows the radial and axial layouts of the reference core. It has 108 inner fuel assemblies and 72 outer fuel assemblies, which are surrounded by 114 blanket assemblies. This core has two control systems. The primary control rod system, which has 15 assemblies, is used for adjusting output. The second system, named backup control rod system, has four assemblies and can immediately shut down the reactor. It is used when the first system fails.

Figures 4 and **5** show the layout of the core with IBIM. As shown in them, IBIM with 30 cm thickness was introduced from 2nd to 5th or 6th rows of this reference core. The 1st row is the backup control rod. Introducing IBIM into 7th row was not considered to avoid unacceptable thermal peaks due to higher Pu enrichment of outer core fuels.

Tables 2 and **3** show the core and fuel specifications, respectively. The left arrow in the table indicates the value is the same as that in the left cell. The equilibrium composition at Beginning of Equilibrium Cycle (BOEC) used for the core performance analyses are calculated by averaging the fuel compositions of the beginning of first, second and third cycle obtained by straight burnup calculation of the fresh fuel without refueling.

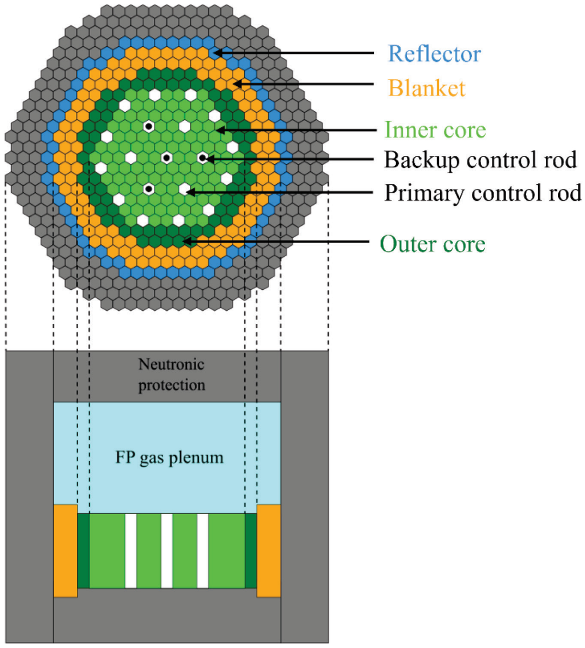

Fig. 3 The layouts of 600 MWe reference FBR[2]

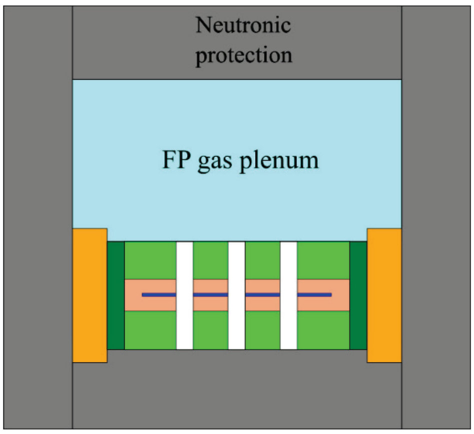

Fig. 4 The arrangement of IBIM

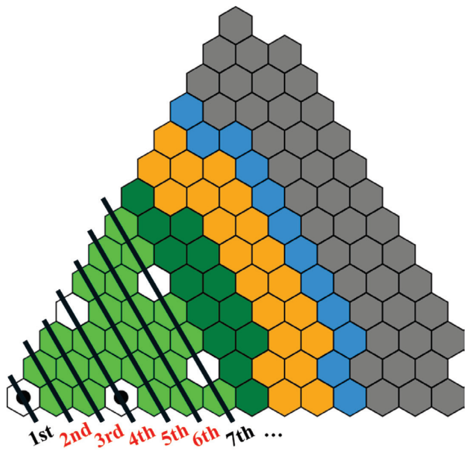

Fig. 5 The 1/6 core cutaway

Table 2 The specifications for reference core[2)]

Parameter (units)	Value
Output	600 MWe（1500 MWt）
Thermal efficiency	40%
Core type	2 regions homogeneous core
Operation cycle length	365 days
Refueling scheme (fuel/blanket)	3/4 batches
Coolant temperature (inlet/outlet)	355/510 °C
Blanket placement	2 radial layers, No axial blanket
Reactor shutdown system	2 systems (primary and backup)
Pu isotopic ratio（239/240/241/242）	58/24/14/4 wt%
Control rod	B_4C
Radial reflector	Stainless steel
Radial neutronic protection	B_4C

Table 3 Dimensions of the reference core[2)]

Parameter (units)	Fuel	Blanket
Pins per assembly	271	127
Smear density (%TD)	75	←
Pin OD (mm)	7.1	11.3
Cladding thickness (mm)	0.5	0.4
Pin pitch (mm)	8.8	12.83
Core height (cm)	100	130
Plenum height (cm)	150	135
Spacer wire diameter (mm)	1.65	1.47
Duct thickness (mm)	4	←
Assembly pitch (cm)	15.97	←
Inter-Assembly Gap (mm)	4	←
Fuel volume fraction (%)	35.8	49.8
Coolant volume fraction(%)	34.4	26.8

(2) Candidate Materials for IM

The selection criteria for IM materials are that they should not dissociate hydrogen under operating temperatures and that they should keep stable shape. ZrH_2 and YH_2 were compared as candidate IM materials meeting these criteria. The hydrogen dissociation temperatures for ZrH_2 and YH_2 are 900°C and 1200°C, respectively, which both meet these criteria.[3)] However, YH_2 tends to be more embrittlement-prone, while ZrH_2 has more shape stability. Therefore, ZrH_2 was selected for IM in the succeeding full core analysis.

3. Method of SVR Calculation

(1) SVR

SVR was calculated by the Eq. (1) assuming all sodium except bond is voided only in the fuel region.

$$\rho\ [\$] = \frac{k' - k}{kk'} \times \frac{1}{\beta_{\mathrm{eff}}}, \qquad (1)$$

where

k: effective multiplication factor before voiding
k': effective multiplication factor after voiding
β_{eff}: effective delayed neutron fraction

(2) Doppler Coefficient

The doppler coefficient was calculated by Eq. (2) assuming the temperature of the nuclides in fuel region increased by 200 K.

$$T\frac{dk/kk'}{dT} = \frac{\Delta k/kk'}{\ln\left(\frac{T+200}{T}\right)}, \qquad (2)$$

where

k: Effective multiplication factor before increasing temperature
k': Effective multiplication factor after increasing temperature
T[K]: Fuel temperature

4. Code

In this analysis, a continuous-energy Monte Carlo code MVP[4)], MVP-BURN which is a burn-up calculation module coupled with MVP code[5)] and JENDL-4.0[6)] nuclear data library were used. **Table 4** shows the analysis conditions for the calculation code. To ensure the accuracy of the analysis, the number of histories, batches and skipped batches were set to reduce error range to 0.05% in the pin cell analysis, and to 0.01% in the full core analysis, respectively. The burnup regions set for MVP-BURN were fuel region, IB region, IBIM region, and radial blanket region.

Table 4 Analysis conditions for code

	Pin cell	Full core
Code	MVP-3.0	MVP-3.0 MVP-BURN
Data library	JENDL-4.0	←
No. of histories	100,000	←
No. of batches	200	←
No. of skipped batches	50	←
Error range	< 0.01%	←
Boundary condition	Mirror reflector	Black absorber*

*The material that absorbs all neutrons

III. Results

1. Optimization of IM Thickness

Figure 6 shows the effect of IM thickness increase on SVR and CR in the pin cell analysis. The solid lines represent SVR, while the dashed lines indicate CR. The orange and blue lines show the results of Case 1 and Case 2, respectively. IM improved SVR compared to the case of no IM, and the "constant IB thickness case" was more effective in reducing SVR than the "variable IB thickness case". On the other hand, CR is smaller in Case 1 than that of in Case 2 because total IB thickness (i.e. fertile volume) decreases, although it achieves more than unity.

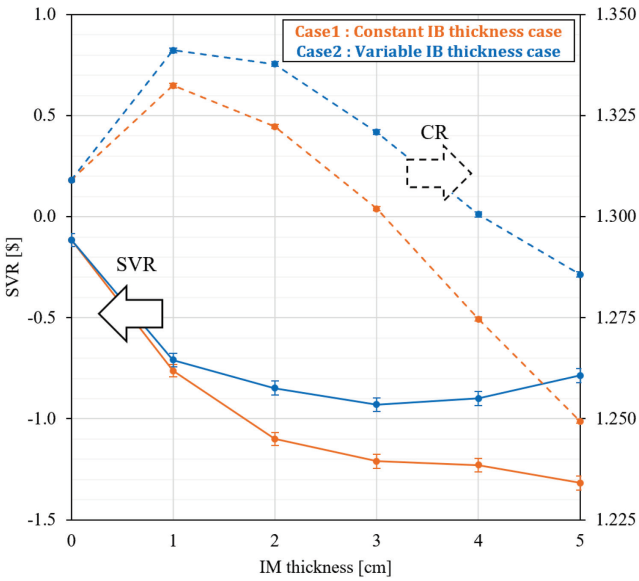

Fig. 6 SVR and CR versus IM thickness on pin cell analysis

Thus, in the full core analysis, the IM was introduced keeping the total thickness of the IB constant. The results of the analysis are shown in **Figure 7**. The solid and dashed lines represent SVR and CR, respectively. The orange lines indicate the results in the case of introducing IBIM in 5 layers, while the blue lines represent the results in the case of introducing IBIM in 6 layers. The SVR values considered with error bars roughly tended to decrease with increasing IM thickness and were reduced more in the case of 6 layers than in the 5 layers case. Based on this result, it was determined that the best method to load IBIM is introducing moderator with 3 cm thickness in the axial center of IB of fuel assemblies from 2nd row to 6th row. With this condition, SVR was reduced to the lowest while achieving CR > 1.

Under these conditions, SVR was reduced by 0.32 $ from the core without IM. **Table 5** shows the core characteristics of the reference core, the core with IB, and the core with IBIM. The introduction of IM increased the power fraction in the IB region from 9% to 11% and decreased the CR and the SVR.

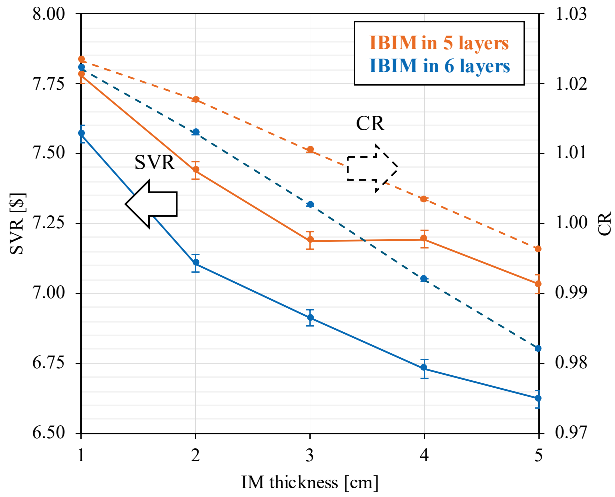

Fig. 7 SVR and CR versus IM thickness on full core analysis

Table 5 The core characteristics of 600MWe FBRs

Parameter (units)	Reference core	Core with IB	**Core with IBIM**
Output (MWt/MWe)	1500/600	←	←
IB thickness (cm)	0	30	←
IM thickness (cm)	0	←	**3**
Pu enrichment (wt%, IC/OC)			
Fresh fuel	15.7/22.4	20.2/26.9	←
Equilibrium fuel	15.1/19.4	17.5/24.2	←
Power fraction in each region (%, IC/IB/OC/RB)			
BOEC	61/0/36/3	35/5/55/5	**34/6/55/5**
EOEC	61/0/35/4	38/9/46/7	**36/11/46/7**
Burnup reactivity (%dk/k)	5.79	6.54	**6.88**
Averaged burnup (MWd/kg, IC/OC)	95/84	64/108	**66/107**
Conversion ratio	1.034	1.026	**1.002**
Effective delayed neutron fraction β_{eff} (10^{-3})	3.71	3.70	**3.74**
Doppler constant (10^{-3} Tdk/dT)	-3.261	-4.143	**-4.943**
Sodium void reactivity($)	+7.38	+7.17	**+6.85**

2. Mechanisms how IBIM Works in Reducing SVR

Figure 8 shows the difference between capture reaction rate before and after voiding in the inner core region. $\Delta R_{capture}$ in the figure is defined as

$$\Delta R_{capture}(E) = R'_{capture}(E) - R_{capture}(E), \quad (3)$$

where the $R_{capture}(E)$ is the capture reaction rate at E eV before voiding and the $R'(E)$ is the one after voiding.

In both cases of no IM and 3 cm IM, the capture reactions after voiding increased in high energy region, and the capture reactions around 3 keV increased like a spike because neutrons were absorbed mainly by Uranium-238 in IB region instead of sodium after voiding. IM also enhances neutron capture reactions in the order of keV (orange striped area). Although, in blue striped area, IM decreases capture reactions, it doesn't affect as in orange area because the capture cross-section decreases with increasing the neutron energy in general. In other words, IBIM moderates neutrons and promotes neutron capture reactions in order of keV. This is the mechanism of IBIM reducing SVR.

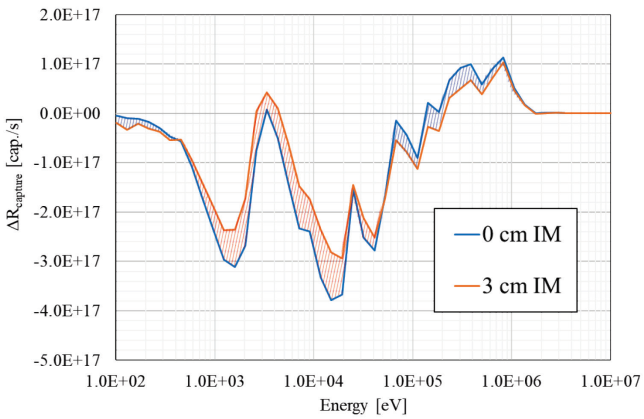

Fig. 8 Comparison of the difference of neutron capture reaction rate $\Delta R_{capture}$ for the full core without and with IM

IV. Conclusion

This paper discussed the method of further reducing Sodium Void Reactivity (SVR) by introducing the moderator into the axial center of Inner Blanket, namely Inner Blanket with Inner Moderator (IBIM).

By introducing IM with 3 cm thickness into IB of fuel assemblies from 2nd row to 6th row, SVR is reduced by about 4.5% compared to the case of no IM.

The mechanism how IBIM reduces SVR was discussed by evaluating the difference between capture reaction rate before and after voiding. It was clarified that moderator introduction in the inner blanket (i.e. installing IBIM in the axial center of the core) works to moderate neutrons and promote neutron capture reactions after voiding in the region of IB in the energy range of keV.

Acknowledgment

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