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A Comparison of Core Perturbation by Coolant Loss between Sodium and Lead-Bismuth Cooled Reactor

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Abstract

This study performs a comparative analysis of the core perturbation caused by coolant loss between sodium and lead-bismuth eutectic. Considering the Zr-based and the U-based fuel in a 1,000MWth class reactor for TRU incineration, we investigate which coolant shows better performance for negative coolant loss reactivity in each case of fuel type. The calculation results show that in the case of U-based fuel, sodium gives rise to more positive coolant loss reactivity than lead-bismuth. However, when the Zr-based (U-free) fuel is considered, sodium offers negative coolant loss reactivity, whereas lead-bismuth makes the coolant loss reactivity positive. It is recommended to employ sodium coolant for the fertile-free fueled core and lead-bismuth for the core with fertile nuclides.

1. Introduction

Nowadays, lead-bismuth eutectic is regarded as a good liquid metal coolant material due to its several advantageous attributes over sodium. Especially, one of the key points to selection of lead-bismuth is the potential for achieving negative coolant loss reactivity. Many studies on the liquid metal cooled reactor design showed that the negative coolant loss reactivity could be achieved by using lead-bismuth as a coolant [1-3].

However, a question is not cleared but remains to be solved. Is lead-bismuth the best solution for negative coolant loss reactivity in all the cases? Considering any type of fuel and structure materials and/or any dimension of core geometry, lead-bismuth is superior to sodium?

This study performs a comparative analysis of the core perturbation caused by coolant loss between sodium and lead-bismuth eutectic.

2. Methods

2.1 Approaches

Considering the Zr-based and the U-based fuel in a 1,000MWth-class reactor for TRU incineration, we investigate which coolant shows better performance for negative coolant loss reactivity in each case of fuel type.

Firstly, the lead-bismuth cooled core was modeled as the reference core. For the comparative analyses, the lead-bismuth coolant was replaced with the sodium without any alterations of the other design parameters of the reference core. In other words, the boundary conditions for the practical design work were not considered in this study. After all, this work is focused on the comparison of the nuclear characteristic response to coolant loss between the coolant materials, as the preliminary study for the optimal design of liquid metal cooled reactor.

From the obtained results of neutronic calculation, the reaction probability was estimated as the reaction rate of each type reaction over the total reaction rate in the whole core. We investigated how much the reaction probability is changed (increased or decreased) by the coolant loss and how the reactivity is influenced by the change in the reaction probability.

In all the cases considered, it was assumed that the coolant is expelled homogeneously from the active core but the coolant in the other regions is in normal condition, when the core is perturbed by the coolant loss event. The differential reactivity was calculated along the amount of coolant loss in the full range from 0% to 100%.

2.2 Computations

The nuclear data evaluation group at KAERI (Korea Atomic Energy Research Institute) has generated the 80-group cross section data set in the form of MATXS, named KAFAX-F22 [4], for the analyses of a liquid metal cooled reactor. The data of most nuclides in KAFAX-F22 were based on the JEF-2.2. Exceptionally, the data of lead, which is the most important nuclide in this study, was generated from the JENDLE-3.2. The macroscopic cross sections and the fission spectrum for each region in the core were firstly generated using TRANSX code [5] and converted to the ISOTXS format. Secondly, the 80-group transport calculations were performed using DANTSYS [6] with the ISOTXS-formatted data set in order to obtain the region-wise spectrum in the core. In the next step, the 80-group data for each nuclide considered in this study were condensed to the 25-group data with the weighting function of the region-wise spectrum, which were obtained for each region in the previous step. In this step, TRANSX code was employed once again. Finally, all the criticality calculations with these 25-group data were carried out using the diffusion code, DIF3D [7].

3. Reference Core Modeling

The HYPER (HYbrid Power Extraction Reactor) system was selected as a reference core, which is a 1,000 MWth–class subcritical lead-bismuth cooled reactor under development for TRU (Transuranics) transmutation at KAERI [8]. Based on the design concept of HYPER, a critical core with the power level of 1,000 MWth was modeled. Figure 1 shows the layout of the core. The active core height and the effective core diameters are 1.2m and around 3m, respectively. The thickness of the axial reflector below and above the active core is assumed to be equivalent to the active core height. The reflector and the shield assemblies around the active core are filled with lead-bismuth and HT-9, respectively. The block of B_4C is located above the center of the core for the emergency shutdown as shown in Figure 1. The homogeneous core was considered and fueled with the TRU uniformly throughout the active core. The TRU was assumed to be released from the 3.5w/o (weight percent) uranium fueled PWR after 35,000 MWD/MTU burnup and cooled for 10 years before loaded into the transmutation core. In this study, Zr-based fuel is employed as the reference fuel, consistent with the HYPER design. The TRU nuclides are dispersed in the Zr matrix, and the chemical form is *x*TRU+(1-*x*)Zr. The TRU concentration in the fuel was determined from the criticality calculation to attain the excess reactivity at the beginning of cycle life and keep the cycle length of 365 EFPDs (Effective Full Power Days). At this time, the fuel composition is 23.7%TRU+76.3%Zr. The twelve control elements of B_4C are inserted symmetrically around the center in the form of assembly block in order to suppress the initial excess reactivity and compensate for reactivity drop due to TRU depletion.

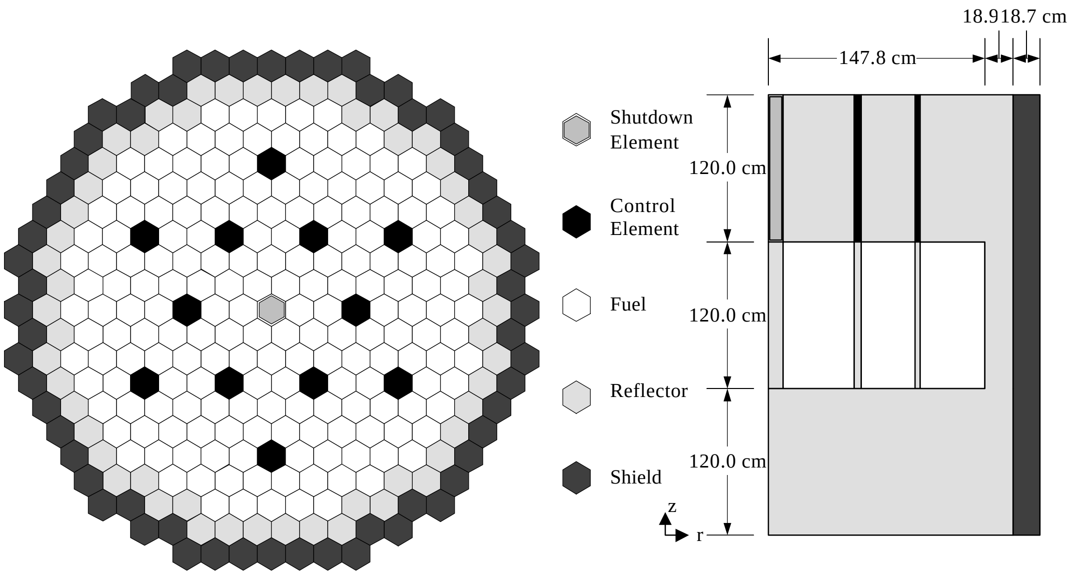


Figure 1. Layout of the reference core

4. Results and Discussions

4.1 Reactivity Calculations

All of the core calculations were performed with all the control assemblies out. Figure 2 and 3 show the calculation results of the multiplication factors with progress in the coolant loss event from the reference core loaded with the U-based fuel and the Zr-based fuel, respectively. In the case of U-based fuel, Zr nuclides as a diluents material were removed out from the fuel rod and ^{238}U nuclides were mixed with TRU and loaded into fuel rods homogeneously throughout the active core.

In Figure 2, the reactivity calculation results in the case of U-based fuel are compared between the sodium and the lead-bismuth cooling. The sodium cooled core shows more rapid increase in the multiplication factor with progress in the coolant loss in comparison with the lead-bismuth cooled core. This is consistent with the current direction to lead-bismuth cooled core design for fast reactor with negative coolant loss reactivity.

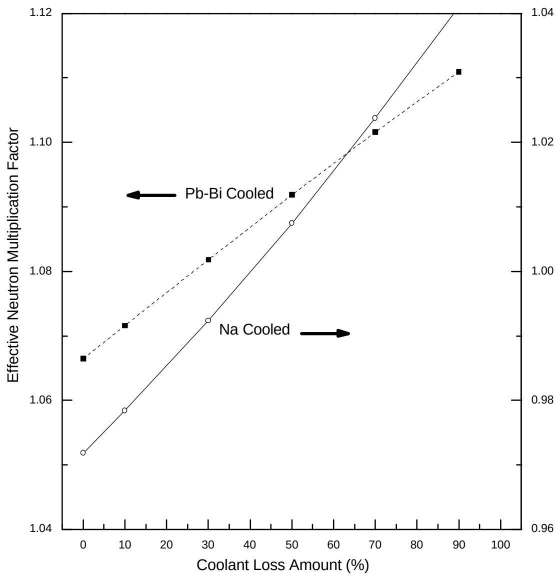


Figure 2. Comparison of multiplication factors in the case of Th-based fuel

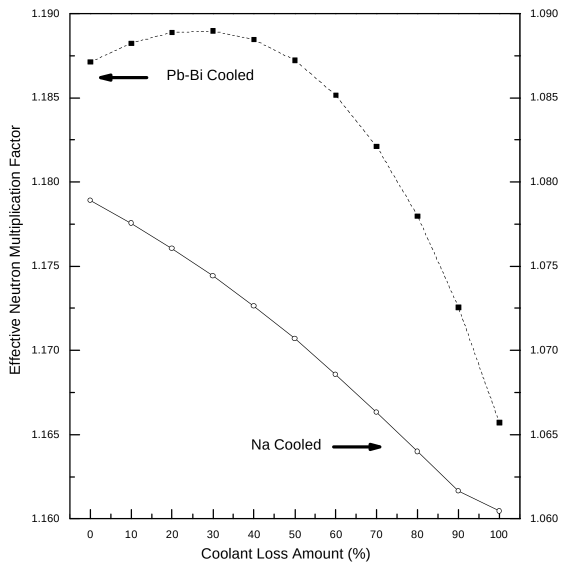


Figure 3. Comparison of multiplication factors in the case of Zr-based fuel

However, the result in Figure 3 shows an interesting finding. Sodium coolant shows the better performance for negative coolant loss reactivity than lead-bismuth eutectic. At the beginning of the coolant loss from the lead-bismuth cooled core, the reactivity is slightly positive. In the case of sodium cooling, the neutron multiplication decreases on from the start of the coolant loss event. This result argues against the statement that lead-bismuth eutectic is superior to sodium considering coolant loss reactivity.

4.2 Comparative Analyses

For the comparative analyses of the core perturbation, the reaction probability of each neutron reaction was estimated quantitatively with progress in coolant loss. The calculation results are listed at Table 1~4.

It can be firstly noticed that difference between the U-based and the Zr-based fuel is characterized by competition of fission reaction with neutron leakage. In the case of Zr-based fuel, the neutron leakage probability is significantly increased, shown at Table 1 and 2. However, the leakage probability in the U-based fuel at Table 3 and 4 does not increase so much in comparison with the Zr-based fuel case but the fission reaction probability is increased significantly. The significant increase in fission probability is attributed to the fact that the fast fission of Th nuclides is increased due to the spectrum hardening. After all, the U-based fuel leads to the positive coolant loss reactivity.

Table 1. Calculation Results of Reaction Probability of Each Reaction in the Lead-Bismuth Cooled Core Loaded with Zr-Based Fuel (unit: %)

Coolant Loss Amount	Leakage	Capture	Fission	(*n*, 2*n*)	k-effective [a]
Flooded Core	8.98	50.52	40.25	0.25	1.18713
10% Loss	9.40 (+0.42)[b]	50.07 (-0.44)	40.28 (+0.03)	0.24 (-0.01)	1.18824 (+0.00111)
30% Loss	10.35 (+0.95)[c]	49.14 (-0.93)	40.28 (+0.00)	0.23 (-0.01)	1.18897 (+0.00073)
50% Loss	11.46 (+1.11)	48.13 (-1.00)	40.20 (-0.09)	0.21 (-0.02)	1.18722 (-0.00176)
70% Loss	12.77 (+1.31)	47.05 (-1.09)	39.99 (-0.20)	0.19 (-0.02)	1.18212 (-0.00510)
90% Loss	14.36 (+1.59)	45.85 (-1.20)	39.63 (-0.36)	0.16 (-0.03)	1.17256 (-0.00956)

[a] Effective neutron multiplication factor
[b] Difference from the value in the flooded core
[c] Difference from the value in the 10% loss

Table 2. Calculation Results of Reaction Probability of Each Reaction in the Sodium Cooled Core Loaded with Zr-Based Fuel (unit: %)

Coolant Loss Amount	Leakage	Capture	Fission	(*n*, 2*n*)	k-effective
Flooded Core	8.05	55.12	36.78	0.05	1.07891
10% Loss	8.47 (+0.42)	54.77 (-0.36)	36.71 (-0.07)	0.05 (0.00)	1.07750 (-0.00136)
30% Loss	9.42 (+0.95)	53.97 (-0.80)	36.56 (-0.15)	0.05 (0.00)	1.07442 (-0.00313)
50% Loss	10.53 (+1.11)	53.03 (-0.94)	36.39 (-0.18)	0.05 (0.00)	1.07068 (-0.00374)
70% Loss	11.85 (+1.32)	51.91 (-1.12)	36.18 (-0.20)	0.06 (0.01)	1.06633 (-0.00435)
90% Loss	13.43 (+1.58)	50.54 (-1.36)	35.96 (-0.22)	0.07 (0.01)	1.06046 (-0.00587)

Table 3. Calculation Results of Reaction Probability of Each Reaction in the Lead-Bismuth Cooled Core Loaded with U-Based Fuel (unit: %)

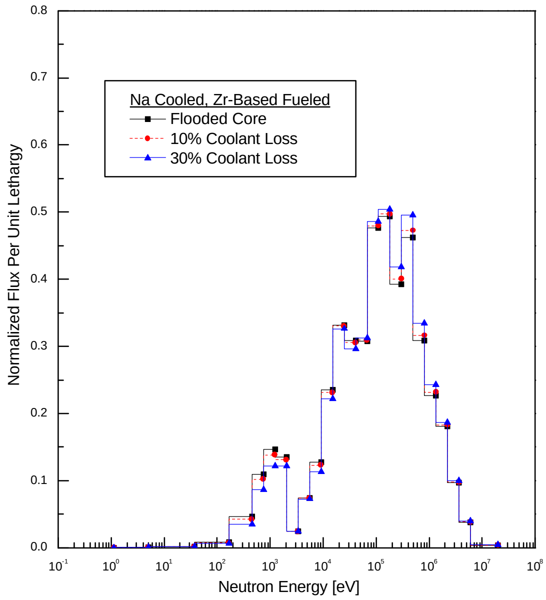
Coolant Loss Amount	Leakage	Capture	Fission	(*n*, 2*n*)	k-effective
Flooded Core	5.68	57.75	36.24	0.33	1.06645
10% Loss	5.91 (+0.23)	57.35 (-0.40)	36.41 (+0.17)	0.33 (0.00)	1.07160 (+0.00516)
30% Loss	6.43 (+0.52)	56.50 (-0.85)	36.74 (+0.33)	0.33 (0.00)	1.08182 (+0.01022)
50% Loss	7.03 (+0.60)	55.58 (-0.92)	37.06 (+0.32)	0.33 (0.00)	1.09185 (+0.01003)
70% Loss	7.74 (+0.71)	54.57 (-1.01)	37.37 (+0.31)	0.32 (-0.01)	1.10159 (+0.00973)
90% Loss	8.59 (+0.85)	53.43 (-1.13)	37.66 (+0.29)	0.32 (-0.01)	1.11094 (+0.00935)

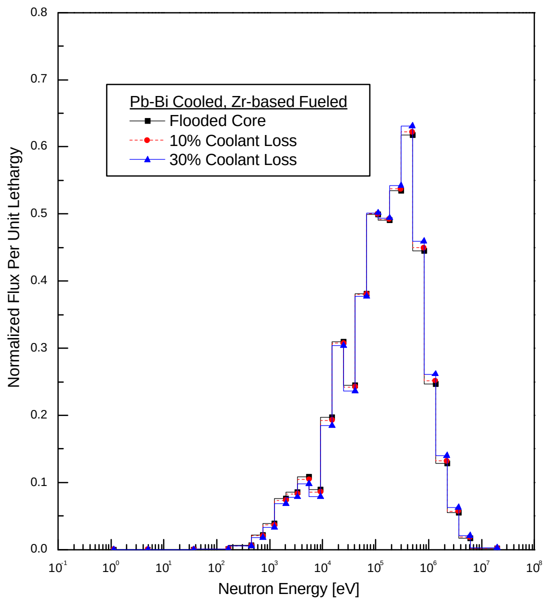
Table 4. Calculation Results of Reaction Probability of Each Reaction in the Sodium Cooled Core Loaded with U-Based Fuel (unit: %)

Coolant Loss Amount	Leakage	Capture	Fission	(*n*, 2*n*)	k-effective
Flooded Core	5.49	61.21	33.10	0.20	0.97184
10% Loss	5.73 (+0.24)	60.75 (-0.46)	33.32 (+0.21)	0.21 (+0.01)	0.97840 (+0.00656)
30% Loss	6.25 (+0.53)	59.76 (-0.99)	33.77 (+0.45)	0.22 (+0.01)	0.99236 (+0.01396)
50% Loss	6.87 (+0.61)	58.65 (-1.11)	34.25 (+0.49)	0.23 (+0.01)	1.00747 (+0.01511)
70% Loss	7.58 (+0.71)	57.40 (-1.25)	34.78 (+0.52)	0.24 (+0.01)	1.02373 (+0.01626)
90% Loss	8.43 (+0.84)	55.99 (-1.41)	35.33 (+0.55)	0.25 (+0.01)	1.04104 (+0.01731)

On the other hand, the difference in core perturbation between the sodium cooling and the lead-bismuth cooling is mainly governed by competition of fission reaction with not leakage but parasitic capture. In the case of Zr-based fuel at Table 1 and 2, the increment in leakage probability are almost same to each other. Similarly, the U-based fuel cases have no considerable difference between the sodium and the lead-bismuth cooled core, shown at Table 3 and 4.

As well-known, sodium coolant slows down the neutron more than lead-bismuth. And the spectrum is, therefore, more hardened when sodium coolant is expelled in comparison with lead-bismuth coolant, as shown in Figure 4 and 5, respectively. In the result, the increment in fission probability due to fast fission of ^{232}Th in the sodium cooling at Table 4 is much more than in the lead-bismuth cooling at Table 3. At the same time, the capture probability in ^{232}Th nuclide is more decreased in the sodium cooling. At this time, despite the neutron spectrum is hardened much more in the sodium cooling, the increment in leakage probability is not so much greater than in the lead-bismuth cooling. After all, the coolant loss event in the sodium cooled core makes the reactivity more positive than in the lead-bismuth cooled core.





Considering the Zr-based fuel cases at Table 1 and 2, at the early stage of coolant loss event, the core perturbation is propagated in the opposite direction to the U-based fuel. Despite the neutron spectrum is more hardened in the sodium coolant loss event, the fission probability is not increased but decreased much more than in the lead-bismuth cooling, because the fertile nuclides such as ^{232}Th are not contained in the Zr-based fuel. This is attributed to the fact that the capture probability is less decreased in the sodium cooling than in the lead-bismuth cooling, since sodium has smaller resonance capture cross section at the high energy region of neutrons. The capture cross sections of sodium and lead are depicted comparatively in Figure 6, based on the data of JEF-2.2. After all these mechanism, the sodium coolant offers the negative reactivity from the starts of the coolant loss event. Especially, it is noted that the fission probability in the lead-bismuth cooling is increased at the beginning of coolant loss. When the lead-bismuth coolant is expelled in the Zr-based fuel,

Figure 4. Neutron spectrum in the lead-bismuth cooled core (Zr-based

Figure 5. Neutron spectrum in the sodium

the lower energy neutrons moderated by Zr in the fuel rod are absorbed in the fissile TRU nuclides and cause the reactivity to be positive [9].

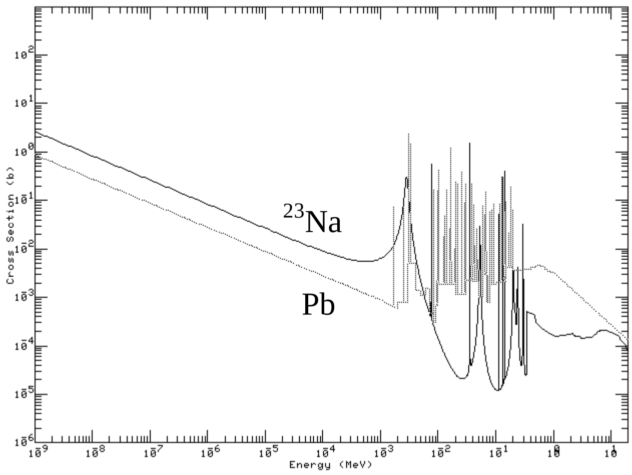


Figure 6. Microscopic capture cross sections of sodium and lead

5. Summary and Conclusions

The results obtained in this study can be summarized as follows:

In the case of U-based fuel, sodium coolant gives rise to more positive coolant loss reactivity than lead-bismuth eutectic. However, when the Zr-based (U-free) fuel is considered, sodium offers negative coolant loss reactivity, whereas lead-bismuth makes the coolant loss reactivity positive.

In conclusion, it is recommended to employ sodium coolant for the fertile-free fueled core and lead-bismuth for the core with fertile nuclides as far as a design challenge to negative coolant loss reactivity is concerned.

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