COOLANT LOSS REACTIVITY OF A LEAD-BISMUTH COOLED CORE FOR TRU TRANSMUTATION

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ABSTRACT

This study carried out a systematic evaluation of the core perturbation caused by the coolant loss in a lead-bismuth cooled reactor for TRU incineration, considering the various core design options and the full range of coolant loss amount. The material effects such as neutron moderator, neutron absorber, and fertile nuclide are analyzed. The results obtained in this study warn that Zr as a neutron moderator may diminish the negative reactivity feedback upon the coolant loss considerably and make the reactivity positive. It was also found that B_4C loaded into the fuel rod with TRU can cause the coolant loss reactivity to be positive, whereas the heterogeneous loading of B_4C in the form of assembly block serves to attain the negative reactivity feedback upon the coolant loss. Analyses of the fertile nuclide effect showed that ^{238}U, loaded homogeneously in the core, deteriorates significantly the coolant loss reactivity and give rise to the very large positive reactivity. From the results it is recommended to minimize the amount of Zr loaded with TRU and employ a neutron absorber loaded in the form of assembly block. And, if and only if a fertile nuclide is utilized, another mechanism is necessary to cure the positive coolant loss reactivity

1. INTRODUCTION

Lead-bismuth is getting more attention as a coolant for a fast spectrum core due to its own advantages of the potential for achieving the negative coolant loss reactivity. A number of lead-bismuth cooled core design with negative coolant loss reactivity have been proposed [1, 2]. However, they succeeded to attain the negative reactivity only very small cores, since it was difficult to keep the coolant loss reactivity negative for larger cores. In this connection, the actinide burner design team at MIT (Massachusetts Institute of Technology) proposed the larger core with the streaming fuel assemblies that exhibit the negative reactivity performance upon coolant loss even in case of local non-homogeneous voiding in the central core region [3]. In the streaming fuel assembly, the ends of fuel pins were loaded with stainless steel reflector followed by B_4C absorber pellet enriched with ^{10}B isotope. This strategy, which is similar to that in the small fast reactor proposed by Sekimoto and Su'ud [1], increases the neutron leakage and penalize conversion ratio and so on.

Our previous study investigated the coolant loss reactivity of a lead-bismuth cooled core with the power level of 1,000MWth for TRU (Transuranics) transmutation, assuming that the coolant is expelled by 5% volume uniformly throughout the active core and the reflector on the top and the bottom [4]. The results showed that the uranium-free fuel in the Zr based matrix has the negative coolant density coefficient. However, it becomes positive when the considerable amount of ^{238}U is loaded additionally.

To sum up all the previous studies mentioned above, a question what challenges in core design meet the trade-off between the safety of negative coolant loss reactivity and the neutron economy is not cleared and remains still open. Accordingly, this study intended to carry out a systematic evaluation of the core perturbation caused by the coolant loss, considering the various core design options and the full range of coolant loss amount.

2. METHODS

2.1 APPROACHES

We can consider two categories of core design options: i) material effect, ii) core geometry effect. As the first step, the material effects are analyzed by considering neutron moderator, neutron absorber, and fertile nuclide.

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%.

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, especially focused on the fission reaction.

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 [5], 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 Pb, 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 [6] and converted to the ISOTXS format. Secondly, the 80-group transport calculations were performed using DANTSYS [7] 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 [8].

3. MODEL DESCRIPTIONS

As a reference model, a critical core was constructed based on the design principles of the HYPER (HYbrid Power Extraction Reactor) system which is a lead-bismuth cooled subcritical reactor with the power level of 1,000MWth under development at KAERI for TRU transmutation [9]. The block of B_4C is located above the center of the core for the emergency shutdown as shown in Figure 1. The reflector and the shield assemblies around the active core are filled with lead-bismuth and HT-9, respectively. The homogeneous core was considered and fueled with the chemical form of xTRU+(1-x)Zr uniformly throughout the active core. The weight fraction of TRU to Zr 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. The TRU was assumed to be discharged from the 3.5w/o (weight percent) uranium fueled PWR after 35,000MWD/MTU burnup and cooled for 10 years before loaded into the transmutation core [10].

4. RESULTS AND DISCUSSIONS

4.1 REFERENCE ANALYSES

The reference calculation was performed with all the control assemblies withdrawn. The results show that the reactivity feedback upon coolant loss in the reference core is very sensitive to the amount of coolant loss. At the beginning of the coolant loss event in Figure 2, the reactivity is slightly positive. From the analyses based on the reaction probability it was found that the positive reactivity is caused by increase in the fission reaction probability, in the reverse to the spectrum hardening. However, as the coolant loss is progressed, the positive reactivity decreases and becomes negative when lead-bismuth coolant is expelled over 30% of volume. At this time, the fission reaction probability is decreased, since neutron spectrum is much more hardened in comparison with the beginning of the coolant loss event, as shown in Figure 3.

4.2 NEUTRON MODERATOR EFFECT

In the reference model, a large amount of Zr is loaded, 76.3%, and it softens the neutron energy spectrum considerably. In order to investigate the effect of the neutron moderator, we performed the criticality calculation without Zr in the fuel of the reference model.

The calculation results in Figure 4 shows that the effective neutron multiplication factor decreases on from the starts of the coolant loss event, whereas the value of the reference model in Figure 2 increases at the beginning. The results in Figure 5 reveal that the coolant loss event in the core without Zr hardens the neutron spectrum more than in the reference core. In other words, Zr in the fuel rod of the reference core decreases the magnitude of spectrum hardening when the coolant loss event occurs. Therefore, the increment in leakage probability is decreased. At the same time, the low energy neutrons moderated by Zr near TRU fuel assist to increase the fission reaction probability of the fissile TRU.

4.3 NEUTRON ABSORBER EFFECT

For the analyses of the neutron absorber effects, B_4C was loaded additionally to the fuel in the case of moderator effect analyses without Zr, described in the previous section. The loading amount was determined from the criticality calculations to hold down the effective multiplication factor to around the value of unity. The concentration of ^{10}B was assumed to be 90 w/o. The two types of loading method were considered, the homogeneous and the heterogeneous loading, respectively.

Figures 6 and 7 show the effect of B_4C loaded into fuel rods uniformly throughout the active core, mixed with TRU. On the contrary to the Zr effect, B_4C hardens the unperturbed core spectrum. However, it makes the reactivity positive at the beginning of the coolant loss event, not much different from Zr. When the coolant is expelled from the core loaded with Zr-based fuel, the spectrum softening effect of Zr makes the decrement in capture probability smaller. On the other hand, the capture probability in the core homogeneously loaded with B_4C decreases more, since the microscopic capture cross section of ^{10}B in the fuel rod becomes smaller due to the more hardened spectrum. Therefore, the neurons in the fuel rod are not captured so much in ^{10}B as in the fissionable material. At this time, the degree of spectrum hardening due to the coolant loss is diminished slightly in comparison with the case of moderator effect analyses without Zr and the increment in leakage probability becomes smaller. To summarize the comparison of coolant loss reactivity effect between Zr and B_4C loaded in to the fuel rod, the positive coolant loss reactivity is caused by the increase in the fission cross section of the fissile TRU due to spectrum softening by Zr and the decrease in the capture cross section in ^{10}B in the fuel rod, respectively.

In the case of heterogeneous loading, B_4C is loaded in the form of control assembly block. In Figures 8 and 9, the criticality calculation results are depicted and compared with the results in the case of moderator effect analyses without Zr. These results indicate that the heterogeneous loading of B_4C makes the reactivity feedback much more negative at the early stage of coolant loss, as shown more visibly in Figure 9. When the coolant loss event occurs, the spectrum is more hardened and the neutrons escape from absorption in the fuel and, therefore, the fission probability is decreased significantly. Subsequently, the large amount of neutrons from the fuel is captured by ^{10}B nuclides in the control assembly block without leakage to the outside.

4.4 FERTILE NUCLIDE EFFECT

^{238}U nuclides were homogeneously loaded in to the fuel rod without Zr for the fertile nuclide effect analyses. The composition ratio of ^{238}U to TRU was adjusted to keep the effective multiplication factor around the value of unity. From the results shown in Figure 10, it can be noticed that the reactivity coefficient is positive not only at the beginning of the coolant loss event but also the multiplication factor continues to increase with progress in the coolant loss. When ^{238}U nuclides are loaded additionally, the neutron spectrum of the unperturbed core is hardened. Therefore, the resonance capture cross section of the coolant decreases, and the spectrum hardening caused by coolant loss is diminished considerably in comparison with the case of ^{238}U-free fuel, as shown in Figure 5 and 11, respectively. Accordingly, the increment in leakage probability due to coolant loss becomes smaller significantly. Moreover, the fission cross section of ^{238}U is considerably increased.

SUMMARY AND CONCLUSIONS

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

- Zr may diminish the negative reactivity feedback upon the coolant loss considerably and make the reactivity positive.
- The heterogeneous loading of B_4C in the form of assembly block serves to attain the excellent reactivity performance upon the coolant loss.
- However, B_4C loaded into the fuel rod with TRU can cause the coolant loss reactivity to be positive.
- When ^{238}U as a fertile nuclide is loaded homogeneously in the core, they deteriorate significantly the coolant loss reactivity and give rise to the very large positive reactivity.

From these results it is recommended to minimize the amount of Zr loaded with TRU in to the fuel rod and employ a neutron absorber loaded in the form of assembly block. And, if and only if a fertile nuclide is utilized to compensate for the reactivity drop due to TRU depletion during the burnup period, another mechanism is necessary to cure the positive coolant loss reactivity. In this design, the heterogeneous loading of a neutron absorber such as B_4C can be expected to improve the reactivity feedback upon coolant loss as well as assist in reactivity compensation during the burnup period.

ACKNOWLEDGEMENTS

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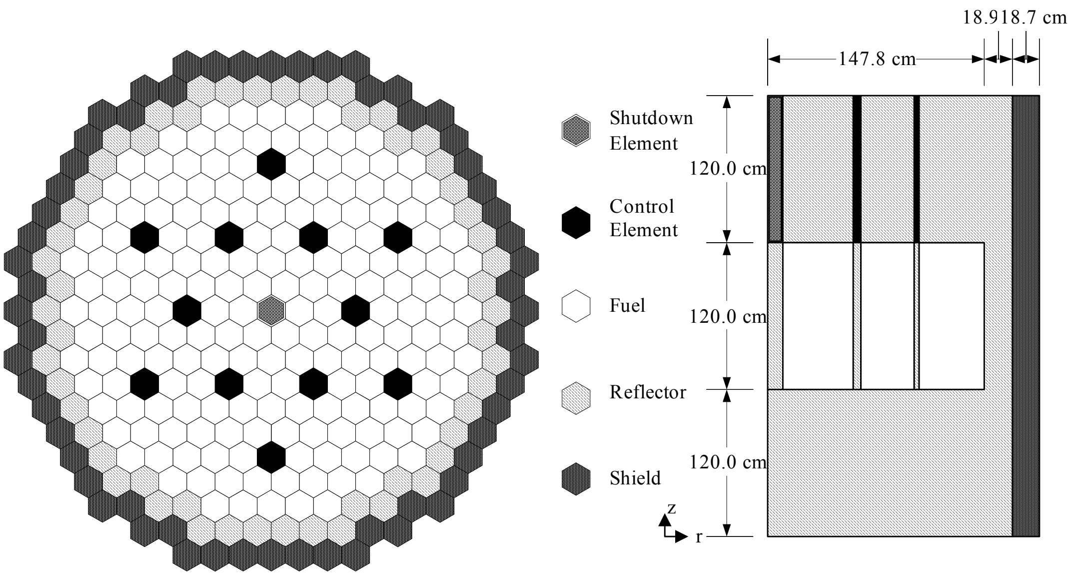

Figure 1. Layout of the Reference Core

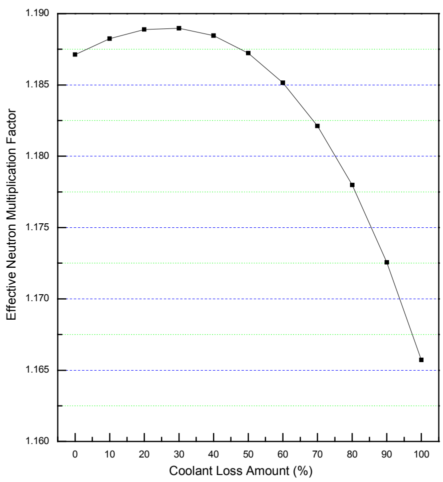

Figure 2. Criticality Calculations in the Reference Model

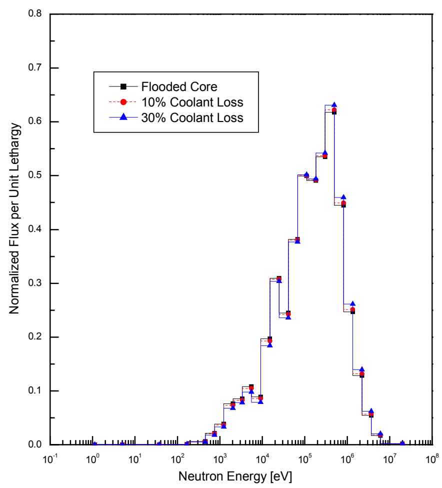

Figure 3. Neutron Spectra in the Reference Model

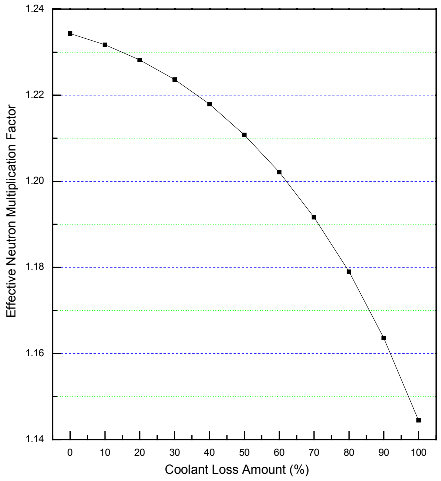

Figure 4. Criticality Calculations without Zr

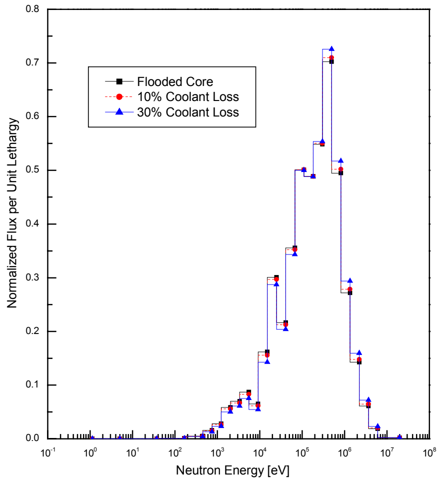

Figure 5. Neutron Spectra without Zr

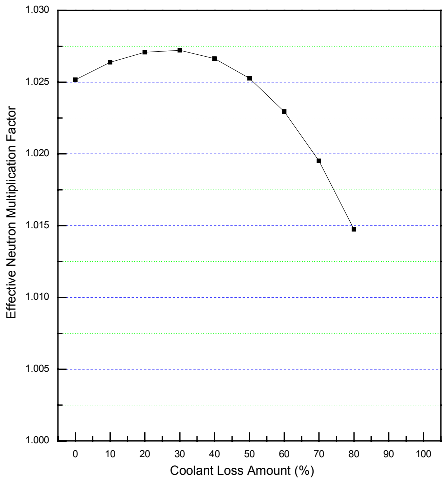

Figure 6. Criticality Calculations in the Case of Homogeneous Loading of B_4C

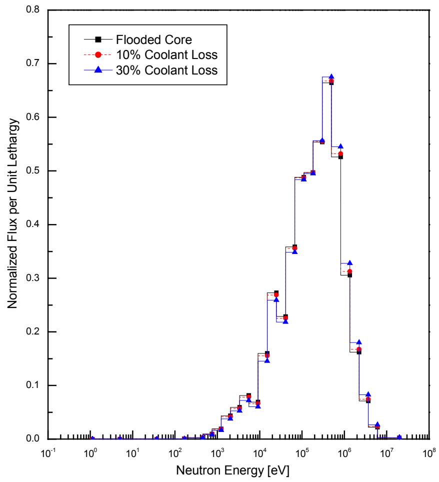

Figure 7. Neutron Spectra in the Case of Homogeneous Loading of B_4C

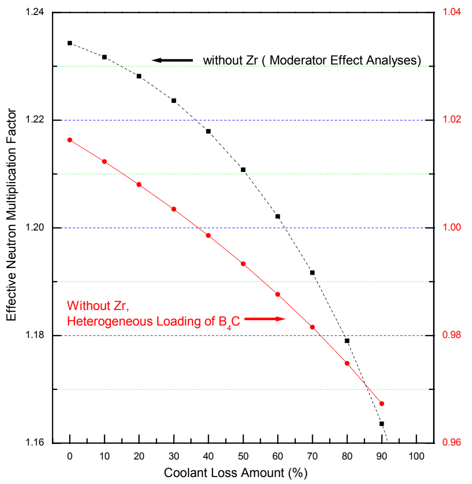

Figure 8. Criticality Calculations in the Case of Heterogeneous Loading of B_4C

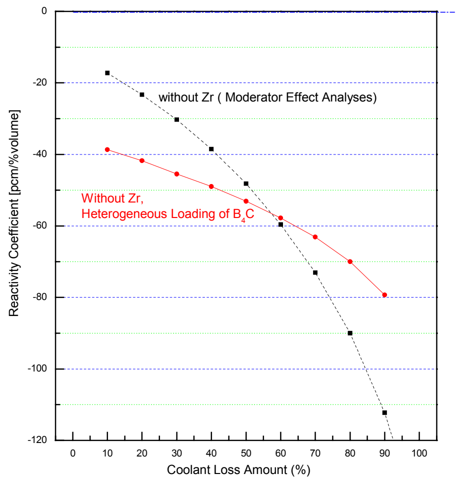

Figure 9. Reactivity Coefficients in the Case of Heterogeneous Loading of B_4C

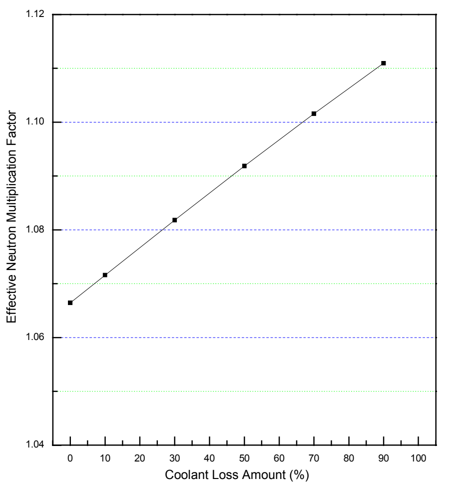

Figure 10. Criticality Calculations in the Case of Homogeneous Loading of ^{238}U

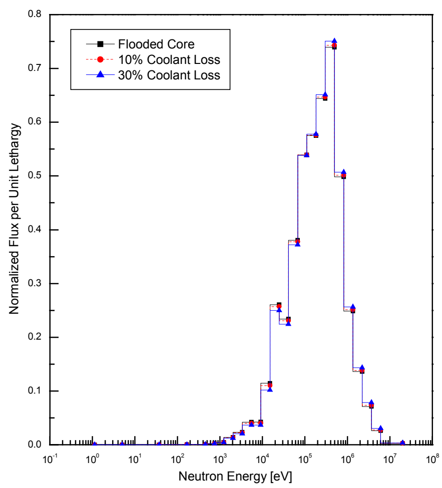

Figure 11. Neutron Spectra in the Case of Homogeneous Loading of ^{238}U