Asymptotic Safety Analysis of a Lead-Cooled TRU Transmuter

Yonghee Kim, Sang Ji Kim, and Tae Yung Song
Korea Atomic Energy Research Institute, Yuseong, Daejeon, Korea
E-mail address: yhkim@kaeri.re.kr

1. Introduction

For the transmutation of trasnuranics (TRUs), lead-cooled fast reactors (LFRs) are under investigation as an advanced transmuter option. When a fast reactor is designed as a TRU transmuter, there are some safety issues due to degraded core characteristics: 1) a relatively large reactivity swing, 2) a smaller delayed neutron fraction, 3) a reduced Doppler effect.[1]

In this paper, safety features of an LFR TRU transmuter are characterized for ATWS (Anticipated Transient Without Scram) scenarios by using an asymptotic safety analysis method, called balance of reactivity (BOR).[2]

2. Core Design and Characteristics

A 900 MWth LFR has been considered in this study.[1] The reactor core is divided into 3 zones and comprises 192 ductless hexagonal fuel assemblies with 13 tie rods (TRs), as shown in Fig. 1. Fuel is the conventional metallic alloy of U-TRU-Zr with a lead bonding. The coolant inlet and out temperatures are T_{in}=420 °C and T_{out}=540 °C, respectively.

A B_4C burnable absorber (BA) is used to reduce the burnup reactivity swing. The BA is loaded into the TRs with top/bottom cutbacks. A 75% B-10 enrichment is used in the inner core (IC) and a 45% one in the middle core (MC). No BA rods are utilized in the outer core (OC).

For a practical and proliferation fuel cycle, spent fuel reprocessing is based on the pyro-technology and the TRU feed is obtained by removing only 97% uranium from a PWR spent fuel and only 90% rare earth elements are removed from the spent fuel of the transmuter.

A one-year-cycle core has been designed to have a 310 effective full power days (EFPDs) with the DIF-3D[3]/REBUS-3[4] code systems. Two TRU enrichment is used, a low one for IC and MC and a high one for OC. For IC and MC, a 6-batch fuel management was utilized, while a 7-batch one was applied to OC.

Table I summarizes the major characteristics of an equilibrium core. The TRU support ratio of the core is ~1.0. The relatively small reactivity swing is largely attributed to the B_4C BA. The Doppler effect is rather small and shows the typical behavior of a metal-fueled core. The B_4C BA makes the coolant coefficient slightly more positive. Reactivity coefficients are similar at BOC and EOC. The control rod expansion coefficient was evaluated at an all-rod-out condition. The effect of control rod drive system expansion is noticeable.

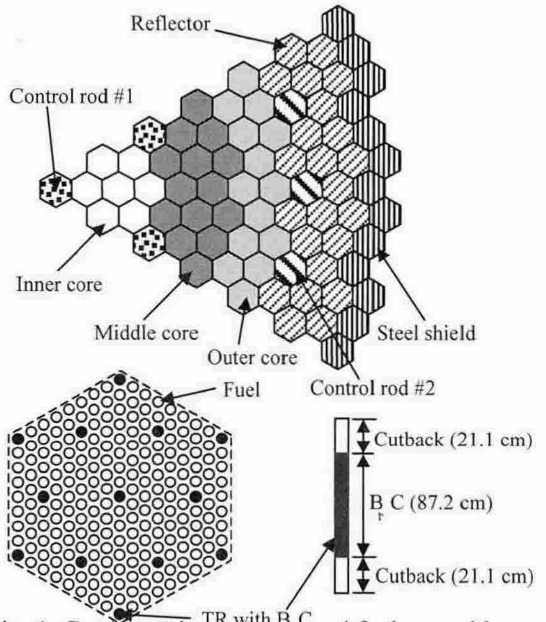

Fig. 1. Configuratio l fuel assembly.

Table I. Summary of core characteristics

Reactivity swing, pcm	905
β_{eff}, BOC/EOC	0.00313/0.00314
Neutron lifetime (BOC/EOC), μsec	0.538/0.551
Power density, W/cc	129
Power peaking, BOC/EOC	1.37/1.36
Fuel discharge burnup, a/o	9.0
TRU&U consumption, kg/cycle	92/196
Reactivity coefficients (BOC/EOC), pcm/°K Doppler, α_D Fuel axial expansion, α_H Coolant density, α_{Pb} Radial core expansion, α_R Control rod expansion, α_{CR}	$-4,855T^{-1.47}/-4,715T^{-1.46}$ -0.24/-0.25 0.059/0.064 -0.53/-0.54 -0.11/-0.12

3. Safety Analysis with Balance of Reactivity

In the BOR method, it is assumed that the reactor core asymptotically approaches to a new critical state after a limited transient. The BOR method is based on the following two equations,

$$\rho = (P-1)A + (P/F-1)B + \delta T_{in} C + \delta\rho_{ex} = 0,$$

$$\delta T_{out} = \delta T_{in} + (P/F-1)\Delta T_c ,$$

where P and F are normalized power and flow rate, respectively, and δT_{in} = change in coolant inlet temperature, $\delta\rho_{ex}$ = external reactivity, δT_{out} =change in outlet temperature, ΔT_c =coolant temperature rise, respectively. The coefficients A, B, and C are represented by using the reactivity coefficients α_D, α_H, α_{Pb}, α_R, and α_{CR}:

$$A = (\alpha_D + \alpha_H)\Delta T_{FC},$$

$$B = (\alpha_D + \alpha_H + \alpha_{Pb} + 2\alpha_R + \alpha_{CR})\Delta T_c / 2,$$

$$C = (\alpha_D + \alpha_H + \alpha_{Pb} + \alpha_R + \alpha_{CR}),$$

where ΔT_{FC} is difference between average fuel temperature and average coolant temperature. For the lead-cooled core in this paper, $\Delta T_{FC} \approx 150$ °C.

With the BOR method, four ATWS cases were analyzed for the lead-cooled core: TOP (Transient of Over-Power), LOHS (Loss of Heat Sink), LOF (Loss of Flow), and CIT (Chilled Inlet Temperature).

The analysis is performed only for the BOC condition in this paper. Parameters A, B, and C are temperature-dependent since the Doppler coefficient depends on fuel temperature. In this paper, non-linear and linear BOR analyses are compared. In the linear BOR, the Doppler effect is evaluated at the nominal fuel temperature of 900 °K, and they are A=-0.22β_{eff}, B=-0.30β_{eff}, C=-0.00332β_{eff}/°K.

For TOP, two reactivity insertion accidents are considered: 0.3$ and 0.4$. In this case, the inlet temperature remains fixed at short/intermediate state. It is assumed that, in an asymptotic state, the inlet temperature would increase enough to reduce the power back to the initial value.

In LOHS, the negative reactivity by the inlet temperature rise is balanced by the positive reactivity resulting from the power decrease to almost near zero-level. In the LOF accident, it is assumed that the inlet temperature does not change while the coolant flow coasts down to a natural circulation level (F_{NC}=0.1). For the CIT case, an inlet temperature decrease of 80 °C is assumed. The coolant flow rate remains constant at the initial value.

Tables II and III summarize the results of the BOR analysis. It is clearly observed that the core responds rather safely to the LOHS, LOF, CIT cases. However, it is observed that the coolant temperature could be excessively high for a big reactivity insertion case. Both nonlinear and linear BOR methods provide similar results.

Table II. Responses to ATWS accidents (Nonlinear BOR)

TOP	$\delta\rho_{ex}$ = 0.4$	P=1.82, T_{out} =639 °C (S/I*)
		P≈1.00, T_{out} =665 °C (A**)
	$\delta\rho_{ex}$ = 0.3$	P=1.61, T_{out} =613 °C (S/I)
		P≈1.00, T_{out} =633 °C (A)
LOHS		P≈0.00, T_{out}=578 °C
LOF	10% F_{NC}	P=0.16, T_{out}=617 °C
CIT (δT_{in} = -80 °C)		P=1.51, T_{out}=521 °C

* Short/Intermediate, ** Asymptotic

Table III. Responses to ATWS accidents (Linear BOR)

TOP	$\delta\rho_{ex}$ = 0.4$	P=1.77, T_{out} =632 °C (S/I*)
		P≈1.00, T_{out} =660 °C (A**)
	$\delta\rho_{ex}$ = 0.3$	P=1.58, T_{out} =609 °C (S/I)
		P≈1.00, T_{out} =630 °C (A)
LOHS		P≈0.00, T_{out}=578 °C
LOF	10% F_{NC}	P=0.16, T_{out}=614 °C
CIT (δT_{in} = -80 °C)		P=1.51, T_{out}=521 °C

4. Conclusions

The ATWS accidents have been analyzed by the BOR method for a TRU-loaded LFR core with a TRU support ratio of ~1.0. For LOHS, LOF, CIT cases, the core responses are considered to be acceptable in terms of the core power and the coolant temperature. However, the core might be susceptible to the TOP accident, depending on the magnitude of the inserted reactivity. For a better safety, the reactivity swing of the core needs to be reduced further.

REFERENCES

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