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A Simple Reactivity Feedback Model Accounting for Radial Core Expansion Effects in the Liquid Metal Fast Reactor

Young Min Kwon, Yong Bum Lee, Won Pyo Chang, Dohee Hahn

Korea Atomic Energy Research Institute
150 Deokjin, Yusong, Daejon, Korea 305-600

Abstract

The radial core expansion due to the structure temperature rise is one of major negative reactivity insertion mechanisms in metallic fueled reactor. Thermal expansion is a result of both the laws of nature and the particular core design and it causes negative reactivity feedback by the combination of increased core volume captures and increased core surface leakage. The simple radial core expansion reactivity feedback model developed for the SSC-K code was evaluated by the code-to-code comparison analysis. From the comparison results, it can be stated that the radial core expansion reactivity feedback model employed into the SSC-K code may be reasonably accurate in the UTOP analysis.

1. Introduction

An advanced liquid metal fast reactor (LMFR) has the potential of enhanced safety utilizing inherent safety characteristics, transuranics reduction and resolving spent fuel storage problems through proliferation-resistant actinide recycling. The advanced design highly emphasizes inherent safety, which maintains the core power reactivity coefficient to be negative during all modes of the plant status and under accidental conditions as well. These effects result from either the law of nature, or both the law of nature and core design.

The components of reactivity feedback considered in a typical metallic fueled LMFR core are shown in Fig. 1, in which the effects of Doppler, sodium density (or void), fuel axial expansion, radial core expansion and control rod driveline expansion are illustrated. Temperature affects reactivity in a number of ways. The temperature of the structure affects the dimensions of the reactor and sometimes the relative positions of the various parts. Changes in core dimension occur during normal operation and might occur during off-normal transients.

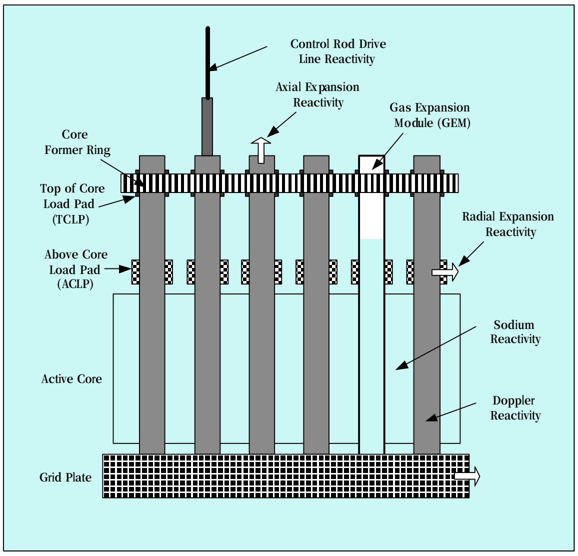

Fig.1 Reactivity components in a metallic fueled core

The structure that supports the core expands radially if the inlet sodium temperature increases, thus causing a radial expansion of the core. For these reasons, it is important to understand the reactivity effects caused by changes in core dimensions due to radial core expansion. Radial fuel expansion may increase fuel pin diameters slightly but will have relatively little effect on radial expansion of the core. Bulk core radial expansion is governed primarily by the structure and, hence the coolant temperature, together with the influence of the radial restraint system.

The objective of this paper is to evaluate the simple radial core expansion reactivity feedback model employed into the SSC-K [1] code, which has been used to analyze the preliminary safety analyses [2] for KALIMER conceptual design [3].

2. KALIMER Core Restraint System

Void swelling in the metallic fuel pin leads to appreciable swelling in the assembly ducts. Both fluence and temperature are responsible for this spatial problem. Because of assembly duct swelling, initial gaps (generally less than 1 mm) among assemblies are required. If the gap were not supplied, the core would dilate radially during irradiation and would soon cause unacceptable misalignment of control rods and assembly handling heads. Then, refueling, which must be done in opaque sodium, would become very difficult. Therefore the core restraint system is necessary by the design requirements: (a) to allow clearance between assembly ducts to accommodate swelling, (b) to constrain the core to resist bowing due to swelling and thermal gradients.

Figure 2 illustrates the KALIMER core restraint system. The KALIMER core assemblies are held by their nosepieces in the receptacles, and by the top of core load pads (TCLP) near the top of the assemblies which are surrounded by a core former ring attached to the core barrel. The separation of the assemblies is maintained by the above core load pads (ACLP) at an elevation above the active core. Positioning of the handling sockets is also maintained by the TCLPs. The ACLPs above the core are not restrained by a former ring attached to the core barrel. Thus, the core assemblies are free to bow as dictated by temperature differences and their metallurgical condition. Load transfer is through the core assembly load pads to the former ring and the core barrel. The core former ring is made of HT9 and is supported horizontally and vertically by the core barrel. The grid plates and load pads are made of stainless steel and HT9, respectively.

In the vertical direction, core restraint is provided by the combination of assembly weight and hydraulic balance. The bottom ends of the receptacles for these assemblies have hydraulic communication with the inlet plenum as shown in Fig. 2. The inlet plenum receives primary sodium from the primary pipes and distributes it to the core via the nosepiece receptacles. The receptacles are located in a triangular pitch to match the core array map. The receptacles participate in the core orificing.

3. Radial Core Expansion Reactivity

3.1 KALIMER reactivity calculation

The reactivity feedback effect of radial core expansion was calculated utilizing the DIF3D code. The DIF3D code performed the neutron flux and adjoint solution calculations. Global feedback coefficients were determined by the results from direct flux computations for the

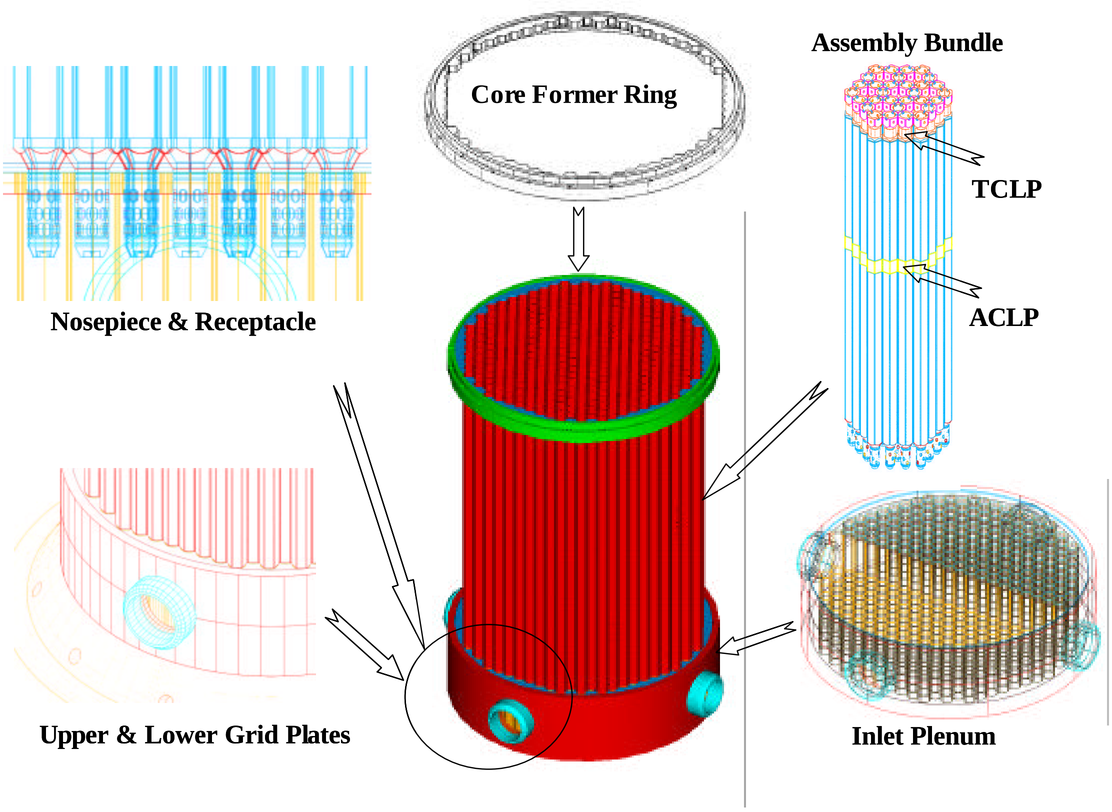

Fig. 2 KALIMER core restraint system

unperturbed and perturbed systems. The uniform radial core expansion due to the structure temperature rise is one of major negative reactivity insertion mechanisms in metallic fueled reactor. Uniform radial expansion coefficients (dk/k)(R/dR) for constant material mass are computed by uniformly increasing the core size by a constant fraction without changing the material mass. That is, isotopic number densities are reduced accordingly to reflect the core size change. Then,

$$(\mathrm{dk/k}) / (\mathrm{R/dR}) = \frac{\mathrm{k(radially\ expanded)} - \mathrm{k(reference)}}{\mathrm{k(reference)} \cdot \mathrm{(fractional\ radial\ expansion)}}$$

The effect of such a growth in the volume and outer surface area of the active fuel region of the core is not only to increase the parasitic neutron captures in the extra coolant with the core volume but also to increase the loss of neutrons from the core region through the surface area. Both effects lead to the removal of the reactivity from the core. The radial expansion coefficients are estimated to be –143 pcm/(% radial expansion) and –141 pcm/(% radial expansion), respectively for BOEC and EOEC [3]. The radial expansion coefficients are insensitive to the burnup and degree of radial expansion. It should be noted that the uncertainties for the reactivity components are large due to the state of insufficient knowledge about the core during conceptual design.

3.2 Reactivity feedback model

The locations of TCLP, ACLP, and grid plates are shown in Fig. 2. The TCLPs are restrained at the core edge by the core former ring. The ACLPs are not restrained at the core edge. The nosepieces of assemblies are inserted into the receptacles, which are fixed by the upper grid plate. This restraint system is called the limited free bow design [4]. Figure 3 illustrates the concept of the limited free bow core restraint system adopted in the KALIMER design, which behaves like a passive device. Such a configuration results in the active core region of the fuel assemblies bowing radially outward from the core centerline in response to the temperature gradients generated in the ducts at power as shown in Fig. 3.

According to the KALIMER core design, the radial dimension of the active core is largely determined by the assembly spacing. As the core heats up there is radial expansion of the fuel assemblies and core support structures which tends to effectively increase the pitch-to-diameter ratio of the fuel lattice. The assembly spacing is determined by the grid plate at the bottom of the core and by two sets of load pads above the core.

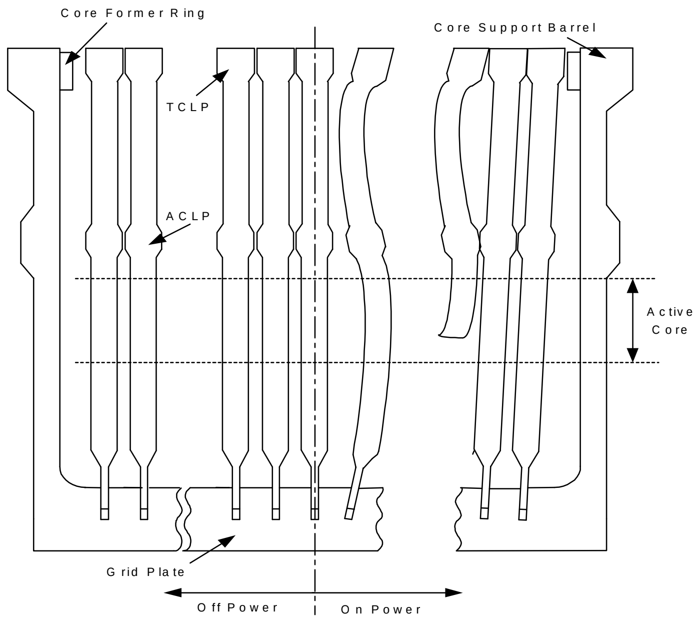

Fig. 3 Limited free bow core-restraint concept

3.2.1 Model 1

In the SSC-K code, the radial expansion reactivity coefficient, dk/dr, can be defined as

$$\frac{dk}{dr} = \frac{a^R}{r}$$

where a^R is a radial expansion coefficient in units of *Dk*. This equation is integrated to yield

$$r^R = a^R \ln\left(\frac{r}{r_o}\right)$$

where r and r_o are the radial dimension of core at transient temperature and at the initial steady-state temperature, respectively.

By definition, the effective strain, x, can be expressed as $x = (r - r_o)/r_o$, thus

$$r^R = a^R \ln(1+x)$$

The coefficients, a^R, for radial expansion effect, are calculated assuming a uniform increase over the core radius as described in section 3.1.

It is assumed that the radial core expansion reactivity is determined solely by thermal expansions of the grid plate and the ACLP, with all regions having the same thermal expansion coefficient. The displacement of the core mid-plane is sufficient to estimate the reactivity feedback from the radial core expansion. All of the subassembly load pads are in contact throughout the transients. However, the ACLP responds to the core exit sodium temperature while the grid plate responds to the core inlet temperature. This causes non-uniform expansion and the worth for each component must be weighted. From geometrical considerations, the split is W_{ACLP} for the ACLP and W_{GP} for the grid plate. It is assumed that W_{ACLP} and W_{GP} are 35% and 65%, respectively, in the KALIMER design.

The radial expansion reactivity can be calculated as

$$
\begin{aligned}
r^{R} &= a^{R} \ln\left(1+W_{GP}x_{GP}+W_{ACLP}x_{ACLP}\right) \\
&= a^{R} \ln\left(1+W_{GP}x_{GP}+W_{ACLP}\sum_{K} N^{K}x^{K}_{ACLP}\right) \\
&= a^{R} \ln\left(1+W_{GP}a_{GP}\left(T_{GP}-T_{GP}(0)\right)+W_{ACLP}a_{ACLP}\sum_{K} N^{K}\left(T^{K}_{ACLP}-T^{K}_{ACLP}(0)\right)\right)
\end{aligned}
$$

where

K = index of the fuel channel

N^K = number of subassemblies in K-th channel as shown in Fig. 4

x^{K}_{ACLP} = strain for ACLP of channel K

a_{ACLP} = thermal expansion coefficient of the ACLP

a_{GP} = thermal expansion coefficient of the GP

$T^{K}_{ACLP}(0)$ = initial steady state temperature of the ACLP at K-th channel

T^{K}_{ACLP} = volume-averaged temperature of the ACLP at K-th channel

$T_{GP}(0)$ = initial steady state temperature of the GP

T_{GP} = temperature of the GP

3.2.2 Model 2

The another simple model [5] employed into the SAS4A/SASSYS-1 [6] code also assumes that the expansion of the grid plate is assumed to be proportional to the rise in the subassembly inlet temperature above its initial steady-state value. The expansion at the ACLP is assumed to

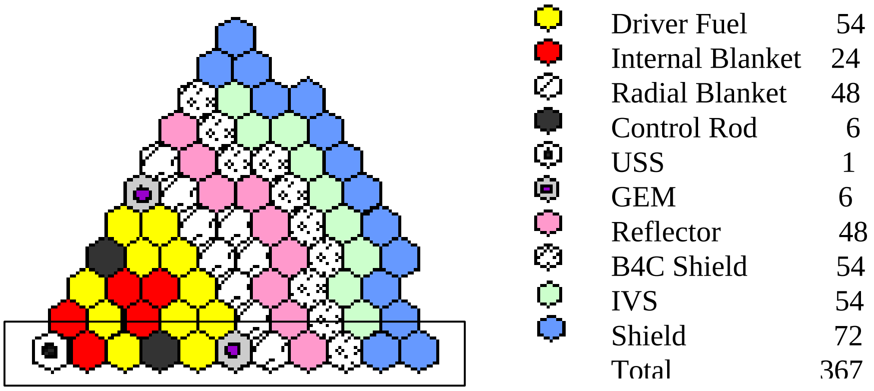

Fig. 4 1/6 configuration for KALIMER breakeven core be proportional to the change in the average structure temperature at this location.

The radial expansion reactivity feedback is calculated from

$$r^{R} = C_{re}[\Delta T_{in} + \frac{XMC}{XAC}(\Delta T_{SLP} - \Delta T_{in})]$$

where

C_{re} = coefficient, \$/K

DT_{in} = changes in coolant inlet temperature

XMC = distance from nozzle support point to core mid-plane

XAC = distance from nozzle support point to the ACLP

DT_{SLP} = changes in average structure temperature at ACLP location

The thermal expansion of the core structures results in a slower feedback mechanism. The feedback is slow because the hot fuel must increase the cladding temperature first and then the coolant. The coolant must then transport the heat to the load pad planes and heat the ducts/load pads. The heat capacities of the materials and the sodium transit times thus cause the feedback to be delayed by roughly a minute. Also the radial thermal expansion of the grid plates is a slow feedback mechanism, because it need time delay the temperature of the coolant returning to the core inlet plenum rises, the grid plates heat and expand radially.

3.2.3 Bowing effect

The radial power profile across the core gives a tendency of temperature decrease in the radial direction. The side of the assembly duct facing the core center is hotter than the side away from the core center, so the differential thermal expansion of the duct tends to cause the assembly to take a shape that is convex to the core centerline. Interactions between adjacent assemblies and the core restraint boundaries force the core to deflect outwardly as shown in Fig. 3. Therefore, the effect always leads to the removal of the reactivity from the core. KALIMER uses the limited free bow restraint system and the load pads are placed in such a manner as to assure a negative contribution during power production.

It is noted that a bowing effect was intentionally left out in the SSC-K reactivity models, because it is considered to omit the bowing effect is conservative. The quantification of the radial bowing is very difficult and the feedback is always negative when the temperatures are rising. Although the Model 2 in section 3.2.2 was not explicitly set up to account for subassembly bowing or flowering of the core, but the user can set arbitrary values for C_{re} and XMC/XAC. Therefore, if the bowing reactivity effect is proportional to DT_{SLP} or to DT_{SLP} - DT_{E}, then bowing reactivity can be accounted for by adjusting C_{re} and XMC/XAC.

4. UTOP Analysis for Test Runs

An unprotected transient overpower (UTOP) was selected for the test runs. The main concern of the present UTOP analysis is to evaluate the system response by nuclear-kinetic effects that involve inherently shutting the core down to acceptable power levels. The UTOP results when positive reactivity is inadvertently inserted into the core and there is a complete failure of reactor protection system. The accident initiated at a full power. It was assumed to insert 2 cents per second for 15 seconds, for a total of 30 cents, representing the withdrawal of all the control rods.

The reactivity feedback models for radial core expansion described in section 3.2 were compared by running both the SSC-K (Model 1) and the SAS4A/SASSYS-1 (Model 2) codes. The evaluation was performed in two steps: first the individual reactivity models of SSC-K and SAS4A/SASSYS-1 codes were compared separately, and then integral effect of the separate models was compared for the UTOP event. It should be noted that only the results relating to the radial core expansion are presented in this paper. The comparison of other reactivity effects is included in Reference [7].

Because of model difference between the SSC-K and the SAS4A/SASSYS-1 codes, adjustment on the reactivity feedback model was conducted through the user input in the SAS4A/SASSYS-1 calculation. The SAS4A/SASSYS-1 code provides multiplication factors as the user input for the purpose of adjusting the amount of reactivity feedback effect against experimental data. Figures 5 and 6 show comparison of reactivity and core power for the 30 cents UTOP event, where only the radial core expansion reactivity model was considered with deactivation of other reactivity models. It was found that the separate reactivity model comparisons demonstrate good agreements between Model 1 and Model 2.

For the UTOP analysis of integral effect with all the reactivity models, the component

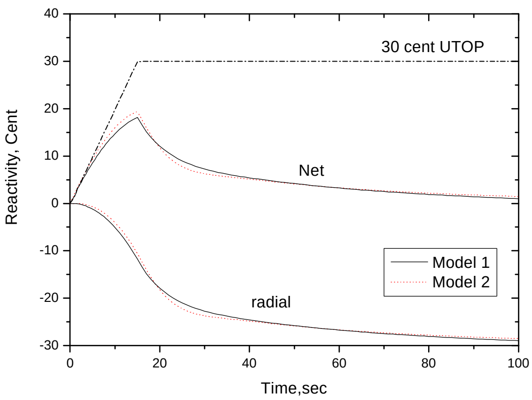

Fig. 5 Comparison of separate model (reactivity)

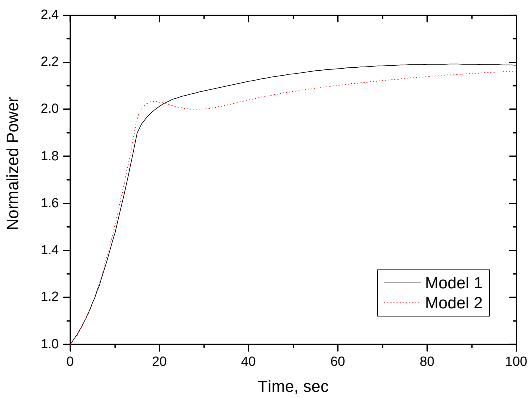

Fig. 6 Comparison of separate model (power)

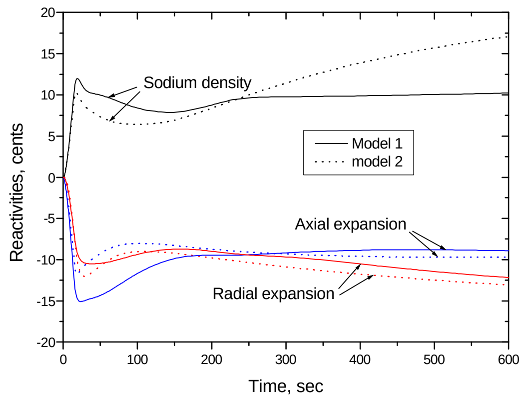

Fig. 7 Reactivities of sodium density, fuel axial and radial core expansion during a 30cent UTOP

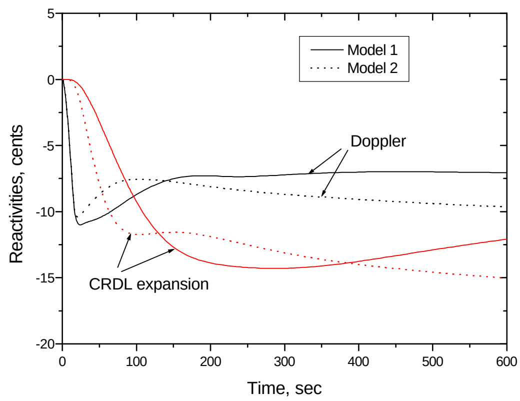

Fig. 8 Doppler and CRDL Expansion Reactivities during a 30cent UTOP

reactivities predicted by the SSC-K and SAS4A/SASSYS-1 codes follow the general trend. Individual comparisons of reactivity component between two calculations are shown in Figs. 7 and 8. The component reactivities are generally similar; however the reactivities of sodium density, CRDL expansion and radial expansion, predicted by the SAS4A/SASSYS-1 code show a similar trend but with different magnitude with those by the SSC-K code. The higher sodium temperatures cause the thermal expansion of radial core expansion, which inserts negative feedback into the core. The radial expansion adds negative reactivity that eventually limits the power increase and contributes to the power reduction that follows.

5. Summary

The simple radial core expansion reactivity feedback model developed for the SSC-K code was evaluated by the code-to-code comparison analysis. From the comparison results, it can be stated that the radial core expansion reactivity feedback model employed into the SSC-K code may be reasonably accurate in the UTOP analysis. However a more detailed modeling based on a mechanistic approach to calculate the radial core expansion is needed in the future.

Acknowledgement

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