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Reactivity Feedback Models for Safety Performance of Metal Core

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ABSTRACT

In the SSC (Super System Code), the reactivity feedback models of the Doppler effect and fuel axial expansion were modified to evaluate the safety performance of the metal-fueled core. The core radial expansion model was developed and implemented into the code as well. The transient analyses have been performed by the modified SSC for UTOP, ULOHS, ULOF/LOHS, and UTOP/LOF/LOHS events for one of the core design options being considered. Analysis results shows that the reactivity feedbacks can provide an inherent shutdown capability in response to key anticipated events without scram. Development of other reactivity feedback models and validation of these models against experimental data would make the SSC suitable for the assessment of the metal-fueled core safety performance.

I. INTRODUCTION

An important part of advanced reactor inherent safety is a reactor design that responds safely, usually by lowering its power level, during system transients. This characteristic is being sought after in the new ALMR (Advanced Liquid Metal Reactor) designs.(1) The approach of these plants is to use natural phenomena (like thermal expansion) for the basis of their safety rather than to use engineered or active safety systems. Recently, two experiments at EBR-II(2) using the metal fuel have successfully demonstrated this approach. The results of these tests demonstrated that natural processes such as negative feedback due to thermal expansion of reactor materials and natural circulation convection heat transfer to system components were enough to shut down EBR-II and maintain cooling without automatic action of control rods or operator action.

Presently, a modular, pool-type sodium cooled KALIMER(3) (Korea Advanced LIquid MEtal Reactor), whose program is now being led by KAERI (Korea Atomic Energy Research Institute), is in the initial conceptual design phase. In this study, the Super System Code(4) (SSC) was used to evaluate the safety performance of KALIMER design. Several modifications, which is concentrated on the inherent safety features of the metal fuel, were made to analyze the reactivity feedback mechanisms.

The transients analyzed by the SSC are the unprotected transient overpower (UTOP), the unprotected loss-of-heat-sink (ULOHS), the unprotected combined loss-of-flow (ULOF/LOHS), and the unprotected combined transient overpower (UTOP/LOF/LOHS) events. However, two unscrammed events, UTOP and ULOF/LOHS, are covered here.

II. DEVELOPMENT OF REACTIVITY FEEDBACK MODELS

Several reactivity feedbacks are important in the inherent shutdown response for the metal-fueled cores. A survey of several references(5,6) has identified the following contributions to the reactivity feedback effects : Doppler effect, sodium density/voiding, fuel axial expansion, core radial expansion, bowing, control rod drive-line expansion, and vessel expansion. These feedbacks respond according to their associated time constants to overcome the positive reactivity from the sodium density effect and any external source.

The radial expansion feedback model was added to the code by tracking the thermal expansion of the above core load pads and the grid plate expansion at the core inlet. The two thermally expanded segments were referenced from the steady state and averaged together to obtain the net radial feedback. The axial expansion feedback was modified by locking the fuel to the clad (since it swells to the clad after about 2% atom burnup) (6,7) and calculating the thermal strain as the weighted strain of the fuel and clad using Young's modulus and nominal cross-sectional area as the weighting factors. The Doppler feedback model was also modified by considering the characteristic of metal fuel for the reactivity coefficient. The sodium density feedback model was already present in the code and needed only a minor modification to accept the feedback. The bowing feedback was neglected because the complexity of this phenomena makes the mechanistic approach to determining the feedback worth of bowing very difficult with large uncertainties. The feedback effects of control rod drive-line expansion and vessel expansion also were not modeled in this study.

1. Doppler Reactivity Feedback Model

The Doppler coefficient is defined as the change in multiplication factor, *k*, associated with an arbitrary change in the absolute fuel temperature, *T*. Since this coefficient is found to vary as $1/T^{3/2}$ in a metal-fueled fast reactor,(8) this coefficient can be defined as

$$\frac{dk}{dT} = \frac{\alpha_D}{T^{3/2}}, \tag{1}$$

where α_D is a temperature independent Doppler parameter. Eq.(1) leads to the Doppler reactivity effect :

$$\rho_D = \sum_{JK} \rho_D^{JK} = 2\sum_{JK} \alpha_D^{JK} \left(\frac{1}{\sqrt{T_{ref}^{JK}}} - \frac{1}{\sqrt{T_{avg}^{JK}}} \right), \tag{2}$$

where

K = index of the fuel channel

J = index of the axial level in the fuel channel

α_D^{JK} = the node-weighted Doppler parameter

T_{ref}^{JK} = the reference fuel temperature at JK

T_{avg}^{JK} = the volume-averaged temperature at JK.

By definition, the reactivity is referenced to zero at the steady-state condition, i.e., before the transient begins.

2. Axial Expansion Reactivity Feedback Model

The reactivity worth is determined from the difference between the initial fuel length and the elongated length at any given time. The axial expansion coefficient, *dk/dz*, can be defined as

$$\frac{dk}{dz} = \frac{\alpha_A}{z}, \tag{3}$$

where α_A is an axial expansion parameter.

The fuel elongations can be calculated by using an average strain, weighted with Young's modulus as the following$^{(6,7)}$

$$\xi = \frac{\xi_f Y_f A_f + \xi_c Y_c A_c}{Y_f A_f + Y_c A_c}, \tag{4}$$

where

ξ = strain ($\Delta l / l$)

Y = young's modulus

A = nominal cross-sectional area

f = fuel

c = clad.

The axial expansion reactivity can be obtain as the following :

$$\rho_A = \sum_{K} \rho_A^K = \sum_{K} \alpha_A^K \ln\left(1 + \xi^K\right) \cdot \tag{5}$$

3. Radial Expansion Reactivity Feedback Model

The radial dimension of the core is largely determined by the assembly spacing. This spacing is determined by the grid plate below the core and by two sets of load pads above the core.$^{(6,7)}$ The radial expansion coefficient, *dk/dr*, can be defined as

$$\frac{dk}{dr} = \frac{\alpha_R}{r}, \tag{6}$$

where α_R is an axial expansion parameter.

The reactivity worths for the ACLP and the grid plate, respectively, can be found as follows :

$$\rho_{AP} = \alpha_R \ln\left(1 + \xi_{AP}\right), \tag{7}$$

$$\rho_{GP} = \alpha_R \ln\left(1 + \xi_{GP}\right), \tag{8}$$

where ξ_{AP} and ξ_{GP} are their respective strains ($\Delta r / r$).

The coefficients supplied for radial expansion were calculated using a uniform increase over the core radius. However, the ACLP responds to the core exit sodium temperature while the grid plate responds to the core inlet temperature. This causes non-uniform expansions and the worth for each component must be weighted. From geometrical considerations, the split is W_{AP} from ACLP and W_{GP} from grid plate. Hence, the radial expansion reactivity can be calculated as

$$\rho_R = \alpha_R \ln\left(1 + W_{AP}\xi_{AP} + W_{GP}\xi_{GP}\right), \tag{9}$$

where

W_{AP} = the geometrically weighting factor of the ACLP

W_{GP} = the geometrically weighting factor of the grid plate.

III. ANALYSIS OF UNPROTECTED TRANSIENT EVENTS

The transient responses to various unscrammed events(7) were evaluated using the SSC with the developed reactivity feedback mechanisms. Two unscrammed events are covered here. The first event, UTOP, is the more likely event and forms the basic beyond-design-basis event. The other less likely event, combined ULOF/LOHS, was also analyzed. The initial conditions for all transients were taken to be the normal operating conditions (full power and flow) at the end-of-equilibrium burnup cycle, and all analyses were conducted on the basis of best-estimate phenomenological modeling assumptions.

1. UTOP Accident

The accident initiator for the unprotected transient overpower accident is assumed that a malfunction in the reactivity controller causes the shim motor to continue to withdraw all control rods from the core and that the Reactor Protection System (RPS) fails to scram the reactor. This event inserts 35¢ of reactivity into the core at 2¢/sec. It is assumed that the primary and secondary sodium flows remain at rated conditions for this event and that the steam generators continue to reject the equivalent of nominal power, and additional power acts to raise the secondary sodium return temperature, and thence the primary sodium temperature. The relative power and core flow rate curves calculated by the SSC are shown in Figure 1. As shown in Figure 2, the total reactivity reaches a maximum of 16¢ and that the sodium density adds about 11¢. Figure 3 shows that the maximum fuel and maximum sodium temperatures, which were found to be 1313K and 1161K, respectively, have some margins to their respective safety limits.

2. ULOF/LOHS Accident

The unprotected loss-of-flow accident with LOHS is assumed that the power supplied to the primary and secondary loop pumps is lost at time zero and the LOF circulation causes a stoppage in heat removal through the intermediate loop. In addition, it is also assumed that there is a failure to scram the reactor, so that the reactor power changes only in response to the reactivity feedbacks introduced as a result of the electrical power loss. In this plant design, the primary pumps coast down according to their inertial characteristics only. Current analysis of this event is performed without the RVACS model and limits the early stage of the event. The power history and core flow rate calculated by the SSC are shown in Figure 4. The core flow rate coasts down, corresponding to the coastdown curve of the primary loop pumps. Figure 5 shows the reactivity feedbacks. The sodium density feedback calculated by the SSC is an average of about 9¢. In Figure 6 the sodium temperature starts to decrease after it reaches a peak temperature of about 1168K. This analysis shows that sodium boiling is avoided with substantial margin in the short-term transient. In the long term the reactor power will equilibrate to any available heat sink, if a heat removal system is modeled, with the inlet temperature elevated above the initial state.

IV. CONCLUSIONS

Main focus of this study was to develop and implement key reactivity feedback models in the existing LMR system transient code SSC in order to assess the inherent safety characteristics of KALIMER core design option. The SSC calculations on the two beyond-design-basis events described above show that the reactivity feedbacks can provide an inherent shutdown capability in response to key ATWS events. The safety performance of the metal-fueled core from the results emphasizes to prevent accidents by using passive and natural processes, which can be accomplished by the utilization of inherent reactivity feedback characteristics for the unprotected events without the operation action, and without the support of active shutdown, shutdown heat removal, or any action system.

Development of other reactivity feedback models, including the bowing, control rod drive-line and vessel expansions, and validation of these models against experimental data would make the SSC code suitable for the assessment of the metal-fueled core safety performances.

Imperfections in the prediction of reactivity coefficients affect the accuracy of calculations of reactivity feedback and associated power and temperature trajectories. As the calculation of reactivity, power, and temperature trajectories during the transients provides important information for the safety design of LMRs, the possible impact of reactivity coefficient uncertainties requires special attention.

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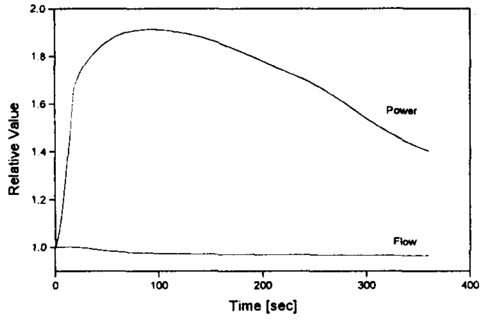

Figure 1. Power and Core Flow Rate during UTOP

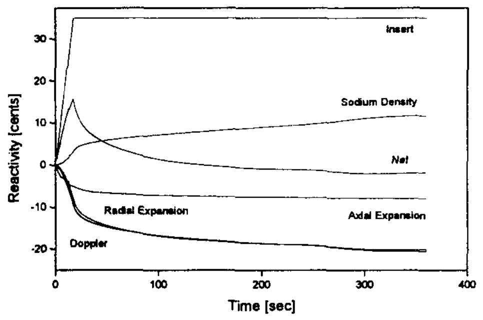

Figure 2. Reactivity Feedbacks during UTOP

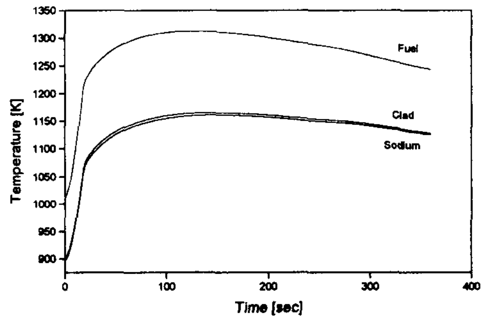

Figure 3. Peak Temperatures during UTOP

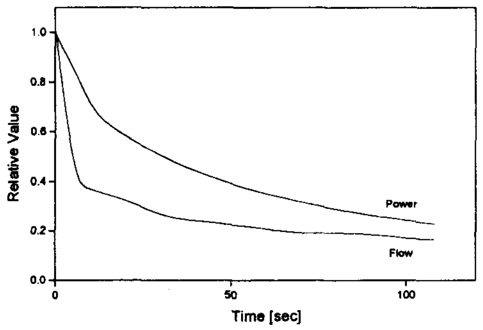

Figure 4. Power and Core Flow Rate during ULOF/LOHS

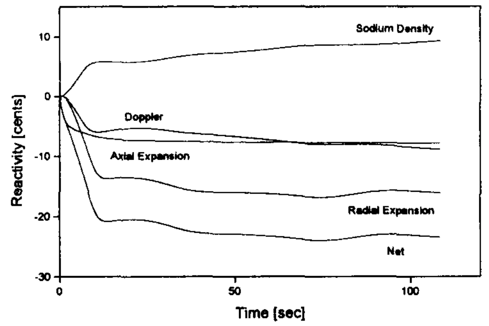

Figure 5. Reactivity Feedbacks during ULOF/LOHS

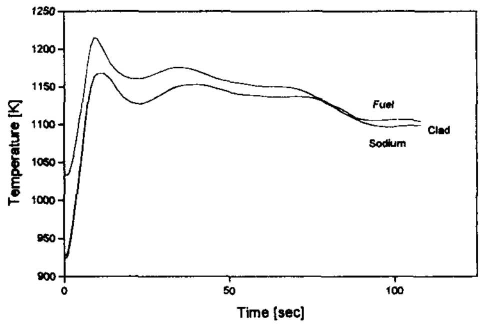

Figure 6. Peak Temperatures during ULOF/LOHS