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Inherent Safety Evaluation Models of SSC-K Code

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Abstract

The Korea Atomic Energy Research Institute (KAERI) is developing KALIMER (Korea Advanced LIquid Metal Reactor), which is a sodium cooled, 150 MWe pool-type reactor. The safety design of KALIMER emphasizes accident prevention by using passive processes, which can be accomplished by the safety design objectives including the utilization of inherent safety features to eliminate the need for diverse and redundant engineered safety systems.

KALIMER utilizes the intrinsic negative reactivity feedback effect which is one of the most important inherent safety features of liquid metal reactors (LMRs) even under hypothetical situations where reactor scram failures are postulated. In order to assess the effectiveness of the inherent safety features in achieving the safety design objectives, KAERI has been developing the reactivity feedback models for the metal core of KALIMER.

In addition to the existing models for Doppler, sodium density, fuel axial expansion and core radial expansion effects, a model for the control driveline and reactor vessel expansion has been newly developed and implemented into the system-wide LMR transient analysis code SSC-K. A model also has been developed for a gas expansion module (GEM), which is an empty hexagonal cross section duct located at the periphery of the core, in order to analyze its effect under loss of flow events.

This paper summarizes the modeling efforts of the CRDL expansion and GEM effects for the SSC-K code. Unprotected transient events have been simulated using the modified SSC-K code for the verification of the models developed.

I. Introduction

The next-generation reactor, including liquid metal reactors, should have inherent passive characteristics. The inherent passive safety features of the KALIMER design [1] preclude any significant damage under generic anticipated transients without scram (ATWS), such as unprotected loss of flow (ULOF), unprotected loss of heat-sink (ULOHS), and unprotected transient overpower (UTOP) events.

The reactor and core of KALIMER are designed to support passive reactivity control and natural circulation residual heat removal with ample margins for public safety [2]. A passive safety decay heat removal system (PSDRS) assures safety-grade decay heat removal by removing heat via circulating air passing the outside surface of the containment vessel.

The core is loaded with metal fuel which contributes to passive safety. High thermal conductivity of metal fuel and sodium bonding between fuel and cladding result in low fuel temperatures during operation. Low operating temperatures and the harder spectrum of metal-fueled cores as compared to oxide fueled cores reduce the positive Doppler reactivity feedback from fuel cooling, which reduces the amount of negative reactivity feedback required for the self-control of power during loss of cooling events. Axial thermal expansion of metal fuel also produces significant levels of reactivity feedback especially for the small core.

Thermal expansion of the drivelines due to the rise in core outlet temperature will cause the control rods to be inserted further into the core, providing a negative reactivity component. On the other hand, if the control rod drivelines (CRDLs) are supported on the vessel head, and if the core is supported by the vessel walls, as is the case for the KALIMER design, then heating the vessel walls will either lower the core or raise the control rod drive supports, leading to a positive reactivity component. Since the KALIMER design adopts a pool concept for which a large portion of the total length of the driveline is immersed in the hot pool of sodium, the effect of driveline expansion is important. It is also noted that the reference height of the KALIMER reactor vessel is 16.8 m and the vessel wall will heat up by the hot sodium which will be over-flown from the cold pool during transients and thus the expansion of the vessel wall needs to be considered with the CRDL expansion. Modified version of SSC-K code has been implemented with the model for the CRDL and reactor vessel expansion reactivity effect.

In order to enhance the negative reactivity feedback at the elevated temperatures, gas expansion modules (GEMs) can be added at the periphery of the core to provide a rapid negative reactivity feedback upon loss of primary flow. When the primary pumps trip and the pressure drops, the sodium within the GEMs at the active core elevation is displaced by the gas, thus increasing the leakage of neutrons from the core. The effectiveness of the GEMs in small fast reactors was demonstrated in the passive safety testing in the Fast Flux Test Facility (FFTF) [3]. A model for the analysis of the reactivity effects introduced by the GEM has been developed and implemented in to the SSC-K code.

In order to assess the effectiveness of the inherent safety features based upon the negative reactivity feedbacks in achieving the safety design objectives of passive safety, a preliminary analysis of ULOF/LOHS performance has been attempted for a small metal core design [4].

II. Control Rod Driveline Expansion Effect

Since KALIMER is a pool type reactor, about 9.3 m of control rod driveline is immersed into the hot pool of sodium. About 15 m of reactor vessel wall will be in contact with the hot sodium when the sodium in the hot pool overflows into the cold pool during heat up transients. Considering the length of control rod driveline and reactor vessel walls which are in contact with the hot sodium, and the large temperature difference of sodium between normal operation and accident conditions, it is important to model the reactivity effects of CRDL expansion in view of passive safety.

A simple one node treatment is used for calculating the temperature of the control rod drives as

$$M_{cr}\ C_p^{cr}\ \frac{dT_{cr}}{dt} = h_{cr}\ A_{cr}\ (\ T_{Na}^{cr} - T_{cr}\ ) \qquad (1)$$

where

- M_{cr} = mass of the control rod drives, kg
- C_p^{cr} = specific heat of the control rod drives, J/kg K
- T_{cr} = temperature of the control rod drives, K
- t = time, sec
- h_{cr} = coefficient of heat transfer between coolant and the control rod drives, W/m^2 K
- A_{cr} = area of heat transfer between coolant and the control rod drives, m^2
- T_{Na}^{cr} = temperature of coolant in the upper plenum region, K

For the calculation of T_{Na}^{cr}, one zone perfect mixing model or tow-zone mixing model for the upper plenum is used.

For the expansion of reactor vessel,

$$M_{vs}\ C_p^{vs}\ \frac{dT_{vs}}{dt} = h_{vs}\ A_{vs}\ (\ T_{Na}^{vs} - T_{vs}\ ) \tag{2}$$

where the parameters are defined similar to the case of control rod drives.

Time dependent temperatures of control rod drives and reactor vessel wall calculated from Equations (1) and (2), respectively, are used to calculate the effective linear expansion as

$$\Delta Z = \Delta Z_{cr} - \Delta Z_{vs} \tag{3}$$

Reactivity introduced by the thermal expansion can then be calculated based upon the control rod worth in $\Delta k / k$ per unit length of insertion into the core.

III. Gas Expansion Module

Due to the lack of detailed design data, including dimensions, sodium levels at various operating regimes, mass of Helium gas inside GEM, and GEM reactivity worth as a function of sodium level, a simplified model has been developed first in order to study the effectiveness of GEM under LOF accident conditions.

The GEMs provide a rapid negative reactivity feedback upon loss of the primary flow to reduce power to flow ratio. The GEMs are hollow assembly ducts, which are open to flow at the bottom but are closed at the top. The GEMs are filled with vessel cover gas before insertion into the core, and this gas is compressed as the GEMs are filled with sodium. As is shown in Figure 1, with the primary pumps on, the high pressure in the inlet plenum compresses the gas captured in the GEMs and raises the sodium level in the GEMs to above the active core. When pumping power is lost and the pressure drops, the gas expands, displacing the sodium in the GEMs to below the active core. The resultant void near the core periphery increases neutron leakage and introduces significant negative reactivity.

In order to calculate the sodium level in the GEM, the following equations are solved. The total length of the GEM is occupied by the Helium gas and primary sodium as

$$h_g + h_l = h_t \tag{4}$$

where

h_g = axial length of Helium gas in GEM, m
h_l = axial length of sodium in GEM, m
h_t = total axial length of GEM, m

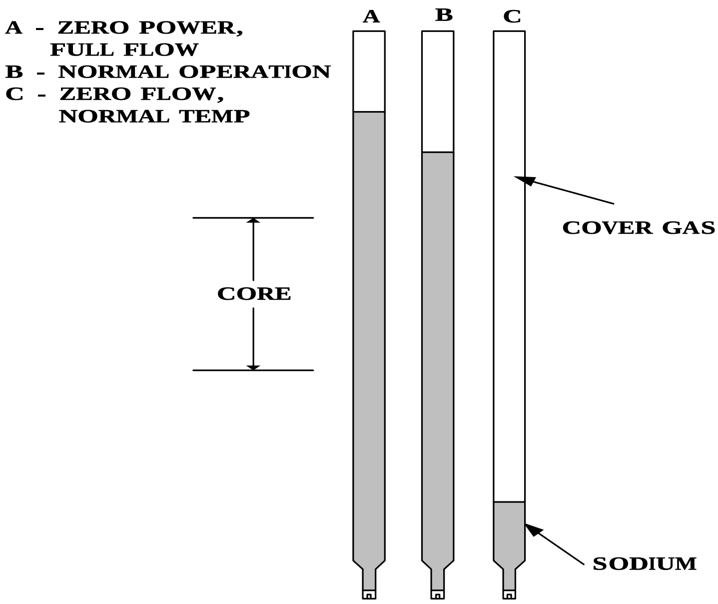

Figure 1. Schematic of gas expansion module

Since there is no sodium flow through the GEM, the pressure of sodium at the core inlet plenum can be expressed as

$$P_g + r\, g\, h_l = P_i \tag{5}$$

where

P_g = GEM gas pressure, Pa
P_i = pressure of sodium at core inlet plenum, Pa
= (pressure of sodium at bottom of core)
– (gravitational pressure drop along the orifice inlet zone)
r = average density of sodium in GEM, kg/m^3
g = gravity, m/s^2

The equation of state for ideal gas is applied for the Helium gas in the GEM as

$$P_g\ A\ h_g = \left(\frac{M_g}{W_g}\right) R\ T_g \tag{6}$$

where

A = cross sectional area of GEM, m^2
M_g = mass of Helium gas in GEM, kg
W_g = melecular weight of Helium gas, kg/mole

R = universal gas constant, J/K mole
T_g = temperature of Helium gas in GEM, K

Unknowns in the Equations (4) to (6) are h_g, h_l, and P_g.

The average density of sodium in GEM, r, is assumed to be the density corresponding to the average temperature of sodium in adjacent subassemblies. The gas temperature, T_g, closely follows the GEM duct temperature which is determined by considering the heat transfer between the neighboring subassemblies and the GEM. For simplicity, the gas temperature is assumed to be the average of the temperatures of duct walls of adjacent subassemblies.

Equations (4) to (6) can be rearranged to give a quadratic equation for the axial length of Helium gas in GEM, h_g, which is calculated at each time step. The worth of the GEMs when the sodium level is equal to, or greater than, the top of the core is zero. When the level reaches the bottom of the core, the maximum worth of GEM is inserted. Intermediate values of reactivity are interpolated linearly from the sodium level in the GEMs.

Currently the sodium density inside the GEM is assumed to be the axial average of the neighboring channels. Sensitivity study is needed to investigate the effect of sodium density on the sodium level. If needed, the GEM model will be modified so that the axial sodium density can be calculated considering inter-assembly heat transfer.

The temperature of the GEM gas is assumed to the average of the structural temperature of neighboring channels. Improvement of the current GEM model can be achieved by calculating the GEM gas temperature as

$$c_p \ M_g \ \frac{dT_g}{dt} = Q \tag{7}$$

where

c_p = specific heat of GEM gas, J/kg*K
Q = heat from conduction from neighboring channels, watts

IV. ULOF/LOHS Evaluation

One of the options being considered for the KALIMER reactor core is the design which utilizes a homogeneous core configuration with six GEM subassemblies as shown in Figure 2. A test run has been performed in order to verify the GEM model and to study the effectiveness of GEM under ULOF/LOHS conditions for which all of the primary pumps are assumed to coastdown and the heat transfer through the intermediate heat exchanger is assumed to be stopped. Although this would normally result in a scram due to a high flux-to-flow ratio soon after the initiation of the transient, it is assumed that either the reactor protection system (RPS) fails to detect the mismatch or the control rods fail to insert

Figure 3 shows the fractional power and core flow during a ULOF/LOHS. Reduction of the core flow is due to the coastdown of primary electromagnetic pumps, and the reactor power decreases to about 6 % of the rated power due to negative reactivities including contributions from GEMs. When there were no GEMs in the core, there occurred a sodium boiling at about 37 seconds into the transient since the reactor power decreases rather slowly and power-to-flow ratio increases.

The temperatures of core outlet sodium and fuel rapidly increase immediately after the initiation of the transient due to the initial large drop in core flow. The reactor power decreases and the core flow decreases gradually after the initial large drop, which results in a decrease in temperatures. Since the current version of SSC-K code does not have a model for the residual heat removal system, there is a slow increase in the above core average sodium temperature with time.

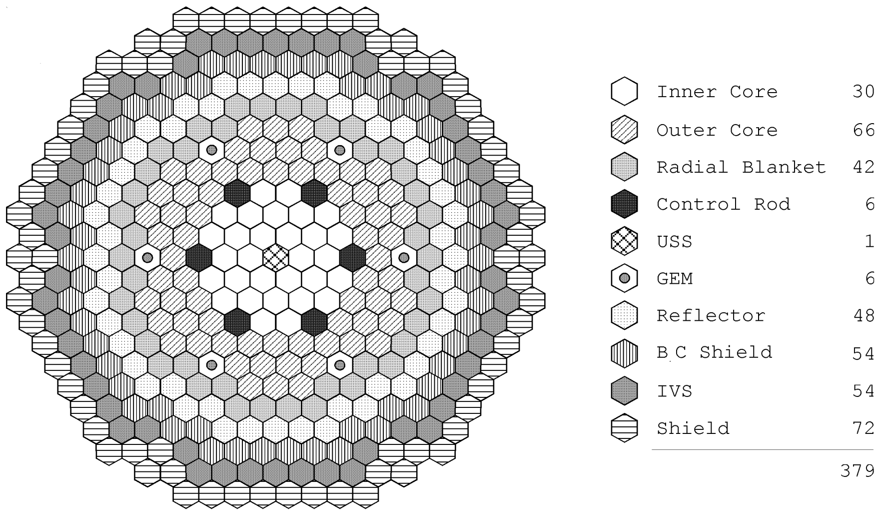

Figure 2. KALIMER Core Layout

Reactivity changes during the transient are shown in Figure 4. In addition to the contributions shown in the Figure, fuel axial and core radial expansion effects also have been modeled and these effects are included in the total reactivity. The net reactivity is always negative during the course of the transient, which results in a power decrease. The reactivity effect of GEM is the largest of all contributions and a maximum of –69 cents, which is the GEM reactivity worth when the sodium level inside GEM is at or below the bottom of core, is inserted at about 570 seconds after initiation of the transient.

Reactivity due to the CRDL expansion is also shown in the Figure 4. Due to the increase in core outlet sodium temperature, the CRDL expands and negative reactivities are inserted. However, from about 100 seconds into the transient, temperature of sodium in the cold pool, which is in contact with the reactor vessel wall, increases and the reactor vessel starts expanding. Thus the reactivity inserted becomes less negative and eventually becomes positive with time.

Level of sodium inside GEM decreases similar to the reactor core flow coastdown as shown in Figure 5. During the initial steady state the sodium level is at 3.4 m and the GEM reactivity is zero. The sodium level reaches the top of core at 2.46 m at 4 second into the transient when the negative reactivity starts to be introduced. The Helium gas inside the GEM is initially pressurized at 6.3×10^5 Pa. The gas volume expands with the pressure decrease at the bottom of GEM duct caused by the loss of pumping power, which results in the sodium level decrease.

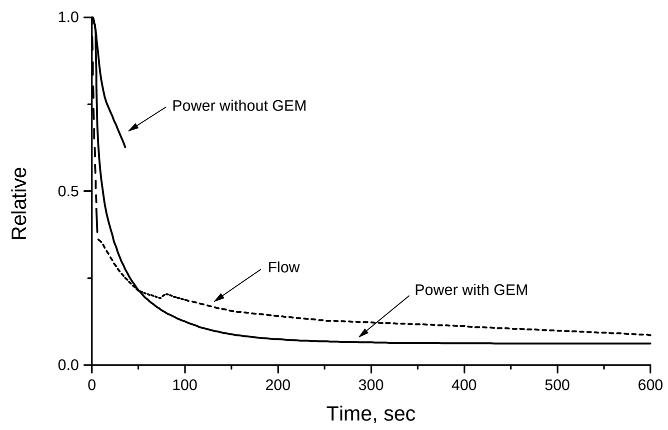

Figure 3. Power and flow during a ULOF/LOHS

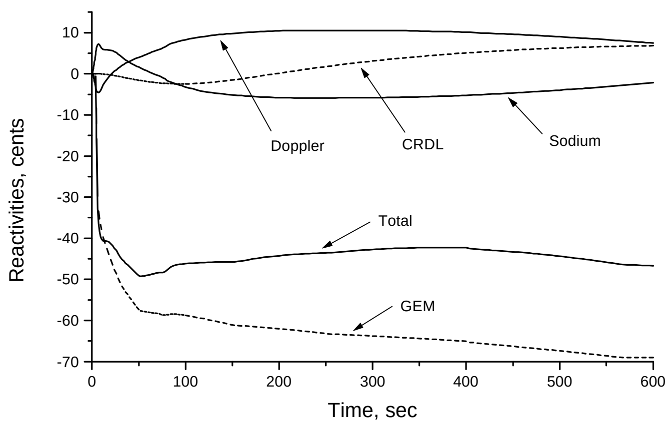

Figure 4. Reactivities during a ULOF/LOHS

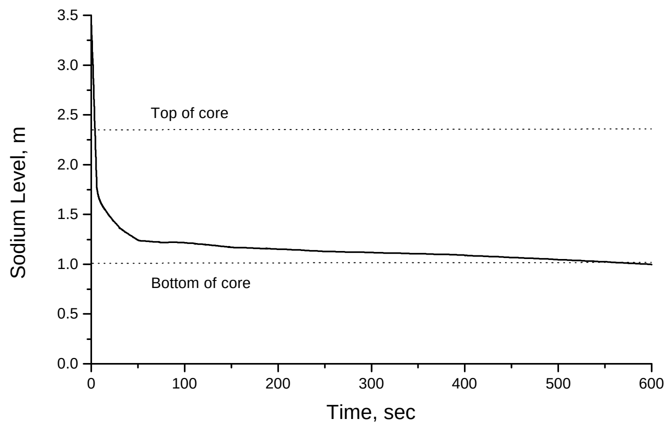

Figure 5. Level of sodium inside GEM during a ULOF/LOHS

V. Conclusions

Improvement of the KALIMER design and assurance of the enhanced safety can be achieved by the preliminary evaluation of ATWS performance of KALIMER core options from the initial concept study phase. In addition to the reactivity feedback models for Doppler, sodium void, fuel axial and core radial expansion effects which have already been developed for the SSC-K code, models for CRDL expansion and GEM have been newly developed and verified through the simulation of existing design data.

One node CRDL expansion model coupled with upper plenum model for CRDL temperature and with cold pool model for reactor vessel temperature will be used for the analysis of long-term transient such as LOHS events for the evaluation of inherent safety characteristics. A GEM model will be used for the optimization and safety improvement of core designs especially under LOF and pipe break accident conditions

Acknowledgements

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