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# Preliminary Safety Evaluation of KALIMER Under Transient Overpower Accident

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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) 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 system-wide LMR transient analysis code SSC-K.*

*The purpose of current work is to verify the logic of the reactivity feedback models developed and to evaluate the inherent safety characteristics of preliminary KALIMER conceptual design using a consistent set of reactivity coefficients for SSC-K simulations. This paper summarizes the preliminary analysis results produced by the SSC-K code for the transient overpower accident.*

## I. Introduction

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 [1]. The objective of the KALIMER Program is to develop an inherently and ultimately safe, environmentally friendly, proliferation-resistant and economically viable fast reactor concept. The initial KALIMER core consists of 20% enriched uranium metallic fuels, and the intermediate heat transfer system consists of two loops that contribute to the flexibility of plant operation and increase the reliability of decay heat removal by the normal procedures. KALIMER has inherent passive means of negative reactivity insertion and decay heat removal, sufficient to place the reactor system in a safe stable state for bounding anticipated transients without scram (ATWS) without significant damage to the core or reactor system structure. The reactivity control and shutdown systems result in extremely high shutdown reliability.

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, and the accommodation of ATWS without jeopardizing public safety. KALIMER utilizes the intrinsic negative reactivity feedback effect which is one of the most important inherent safety features of liquid metal reactors in hypothetical situations where reactor scram failures are postulated.

The SSC-K code, which is a main computational tool for the transient and safety analyses, includes models for reactivity feedback effects, pool thermal hydraulics and passive residual heat removal system which removes the residual heat from the containment vessel wall by an natural air flow. Reactivity feedback models account for the effects due to Doppler, sodium density, fuel axial expansion, core radial expansion, and control rod driveline expansion which considers the expansion of reactor vessel wall. A model also has been developed for a gas expansion module (GEM) in order to analyze its effect under loss of flow events [2].

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 drive lines 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 drive lines (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.

In order to enhance the negative reactivity feedback, gas expansion modules 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 inert 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].

In order to verify the logic of the reactivity feedback models and to assess the effectiveness of the inherent safety features in achieving the safety design objectives, a preliminary evaluation of unprotected transient overpower (UTOP) accident for the KALIMER design has been performed with a system-wide transient analysis code SSC-K.

## II. Uranium Metal Fueled KALIMER Design

The KALIMER core is designed to generate 392 MW (thermal) of power with a 12 months refueling cycle. The core utilizes a homogeneous core configuration with two driver fuel enrichment (< 20% $U^{235}$) zones that can allow a compact core and fuel shuffling. The core, shown in Figure 1 consists of 96 driver fuel assemblies, 42 radial blanket assemblies, 6 control rods, 1 self-actuated shutdown system (SASS) assembly, 6 gas expansion modules, 48 reflector assemblies, 120 shield assemblies, and 60 in-vessel storage spaces in an annular configuration. The in-vessel storage is located in the stainless steel shielding zone. There are no upper or lower axial blankets surrounding the core. The reference core has an active core height of 100 cm and a radial equivalent diameter (including control rods) of 208 cm. The core outer diameter of all assemblies is 344 cm. The core structural material is HT9, low irradiation swelling characteristics of which permits adequate nuclear and breeding performance in a physically small core.

The base alloy, binary (U-10%Zr) metal fuel is the fuel for the KALIMER as the driver fuel. The fuel pin is made of sealed HT-9 tubing containing metal fuel slug in columns. The fuel is immersed in sodium for thermal bonding with the cladding. A fission gas plenum is located above the fuel slug and sodium bond. The bottom of each fuel pin is a solid rod end plug for axial shielding. The driver fuel, blanket fuel, reflector, and shield assemblies use identical structural components with only the bundle and its mounting grid changing from one assembly type to the other.

The heat transport system of KALIMER is designed with the emphasis on economy, safety and reliability. A superheated steam cycle is implemented to have a high plant efficiency noting that high thermal efficiency reduces the heat discharge from the plant, resulting in less impact to the environment. IHTS consists of two loops and each loop has its own steam generator and related systems. The design feature enhances plant operation flexibility and safety. For safety, a large thermal inertia of the primary system is achieved by using a pool based primary system. Strong emphasis has been given to the prevention and mitigation of possible sodium-water reaction events to the IHTS piping routing and SG design. The system reliability is improved by using electromagnetic (EM) pumps which do not have moving parts for both of the primary and intermediate coolant pumping. The low momentum inertia of the EM pump is compensated by the coastdown inertia device. The device stores rotating kinetic energy when the EM pump runs normally but supplies electricity to the EM pump by converting the stored rotating kinetic energy to electricity at a pump power supply failure. The operating temperature and component size were determined to achieve the net plant thermal efficiency of 38.3%.

Key design parameters of KALIMER loaded with uranium metal fuel are summarized in Table 1 and Figure 2 show the heat balance of the KALIMER.

Table 1. Key Design Parameters of KALIMER (Uranium Core)

| | | | |
|---|---|---|---|
| **OVERALL** | | **PHTS** | |
| Net plant Power, MWe | 150 | Reactor Core I/O Temp., $^0$C | 386.2 / 530.0 |
| Core Power, MWt | 392 | Total PHTS Flow Rate, kg/s | 2143.1 |
| Gross Plant Efficiency, % | 41.5 | Primary Pump Type | Electromagnetic |
| Net Plant Efficiency, % | 38.3 | Number of Primary Pumps | 4 |
| Reactor | Pool Type | | |
| Number of IHTS Loops | 2 | | |
| Safety Shutdown Heat Removal | PSDRS | | |
| Seismic Design | Seismic Isolation Bearing | | |
| | | **IHTS** | |
| **CORE** | | IHX I/O temp., $^0$C | 339.7 / 511.0 |
| Core Configuration | Radially Homogeneous | IHTS Total Flow Rate, kg/s | 1803.6 |
| Core Height, mm | 1000 | IHTS Pump Type | Electromagnetic |
| Axial Blanket Thickness, mm | 0 | Number of IHXs | 4 |
| Maximum Core Diameter, mm | 3447 | Number of SGs | 2 |
| Fuel Form | U-10% Zr Alloy | | |
| Enrichments (IC/OC) for Equilibrium Core, % | 14.4 / 20.0 | **Steam System** | |
| Assembly Pitch, mm | 161.2 | Steam Flow Rate, kg/s | 155.5 |
| Fuel/Blanket Pins per Assembly | 271 / 127 | Steam Temperature., $^0$C | 483.2 |
| Cladding Material | HT9 | Steam Pressure, MPa | 15.50 |
| Refueling Interval, months | 12 | | |

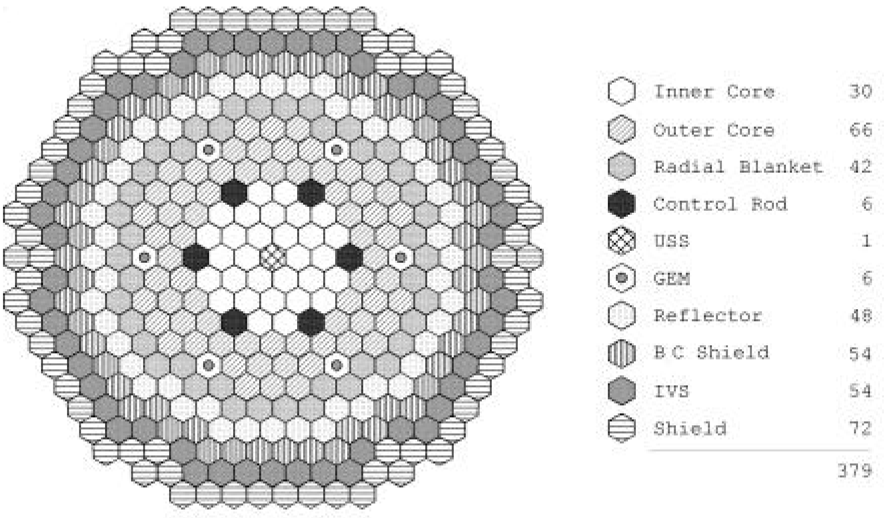


Figure 1. KALIMER Uranium Core Layout

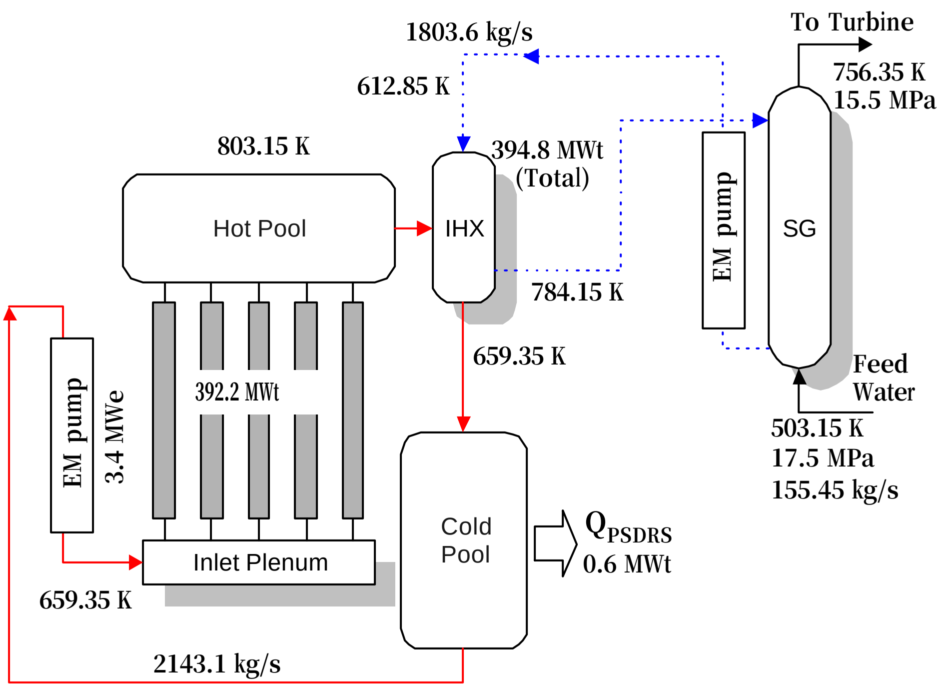


Figure 2. KALIMER Heat Balance

## III. Unprotected Transient Overpower (UTOP) Accident

### III.1 Identification of Causes and Accident Description

A transient overpower accident (TOP) in a liquid metal reactor (LMR) refers to an off-normal condition in which a reactivity insertion occurs. Because no core damage results unless the reactor protection system (RPS) failure occurs, the only TOP that is of safety concern is the postulated unprotected TOP (UTOP) case. Given the assumption of reactivity insertion occurring in an operating LMR, combined with the hypothesis of complete failure of RPS, the problem is to determine the intrinsic dynamic response of the reactor [4-6].

This event is initiated from full power and postulates that a malfunction in the reactivity controller causes the shim motor to continue to withdraw all of the control rods until the drivelines reach the rod stops and that the RPS either fails to detect the event or that the control rods fail to unlatch. It is assumed that the shim motors withdraw the control rods at a rate corresponding to 2 cents per second. It is also assumed that the rod stops are positioned to permit 20 cents of rod worth for power maneuvering before the stops must be reset. In order to account for uncertainties and to be conservative, a total of 30 cents has been adopted as the UTOP initiator for the analysis.

It is assumed that the primary and secondary sodium flows remain at rated conditions for this event and that the feedwater is sufficient to keep the sodium outlet temperature from the steam generator constant. The residual heat removal system is assumed not to function, which would have a minor effect on the analysis results.

Figure 3 shows the SSC-K representation of the KALIMER uranium core of which assemblies are represented by one of the seven channels. Active fuel region has a total of 10 axial slices and four radial nodes for fuel pellets of inner core, outer core, radial blanket and hot fuel channels.

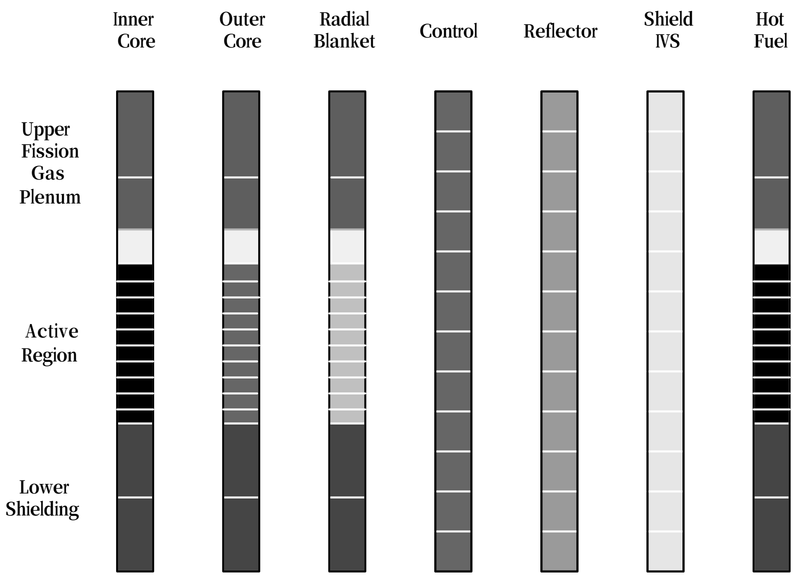


Figure 3. SSC-K Representation of KALIMER Uranium Core

## III.2 Analysis of Effects and Consequences

The UTOP transient results for power and flow, reactivity feedbacks and temperatures are shown in Figures 4 through 7.

The power reaches a peak of 1.43 times the rated power at 32 seconds into the transient, and begins to level off at 1.09 times the rated power by 7 minutes, as shown in Figure 4.

The increase in power raises the average core outlet sodium temperatures from a normal value of 803 K to a peak of 867 K and then the temperature is reestablished at around 842 K, which is 39 K above the initial temperature, as shown in Figure 5. The peak fuel temperature increases from 874 K to a peak of 984 K which is below the threshold for eutectic formation. The peak sodium temperature is 896 K which is below boiling point. The equilibrium temperatures reestablished after the initial phase of UTOP, where the core remains hotter indefinitely to offset the increased reactivity, limits the maximum reactivity insertion during the event.

The changes in the reactivity are shown in Figure 6. The net reactivity starts out positive because of the reactivity from the control rods being removed, but turns downward once the negative reactivity feedbacks increases enough to counter the positive insertion. The rise in fuel temperatures first increases the Doppler absorption of the neutrons and then triggers the fuel's elongation. Higher sodium temperatures create a harder neutronic spectrum, which generates a positive reactivity feedback. The higher sodium temperatures cause the thermal expansion of the control rod driveline and radial expansion, which are negative feedbacks. The control rod drive lines have a large time constants and are slow to act compared to radial expansion. The radial expansion adds the crucial amount of reactivity that eventually limits the power increase to 1.43 times rated power and contributes to the power reduction that follows. Although the reduced power decreases the worth of Doppler, sodium and axial expansion, the control rod driveline and radial expansion effects cause the total reactivity to become slightly negative and re-stabilize the power near 1.43 times the rated level.

Predicted fuel temperature distribution from the SSC-K code for the $8^{h}$ axial fuel node from the bottom of hot driver is shown in Figure 7.

Although the design meets the performance limits for ATWS events with margin, the limiting condition appears to be the clad temperature at the elevated equilibrium conditions. This temperature must remain below the 978 K limit to prevent eutectic formation because the reactor could be in that state indefinitely. Although the cladding temperature may exceed the eutectic formation temperature during the power ascent phase of the UTOP with a larger insertion reactivity, the clad attack may be small because of the short duration of the elevated temperature condition.

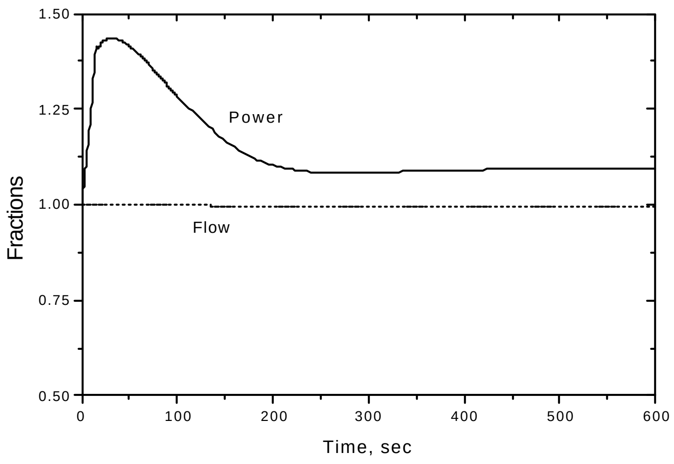


Figure 4. Power and flow during a 30 cent UTOP

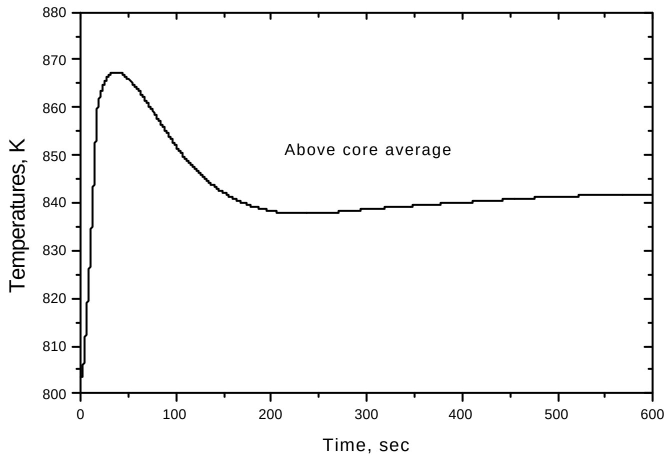


Figure 5. Above core average sodium temperature during a 30 cent UTOP

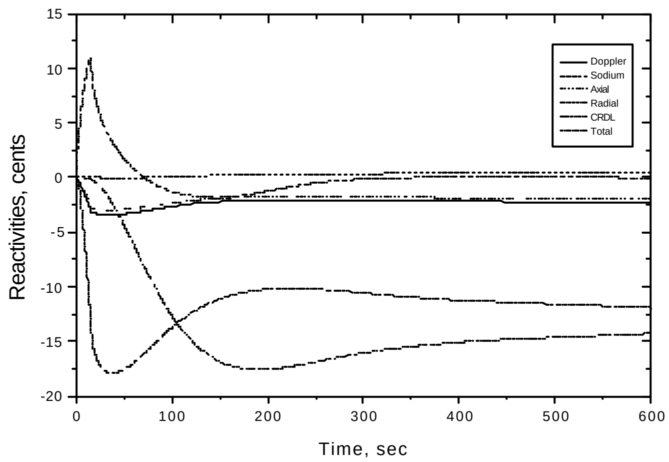


Figure 6. Reactivities during a 30 cent UTOP

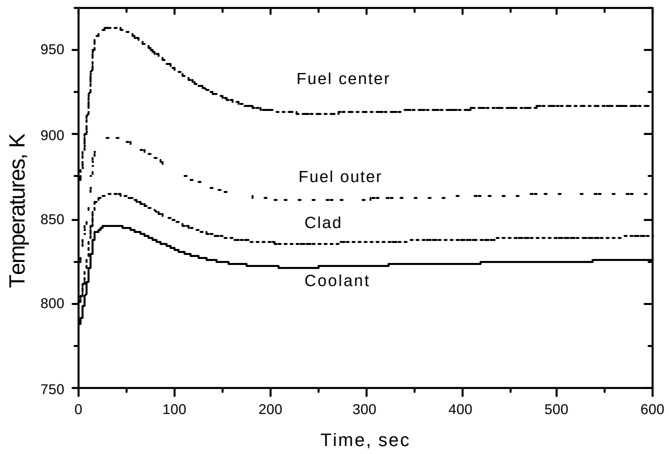


Figure 7. Fuel temperature distribution for the $8^{th}$ axial fuel node from bottom of hot driver for a 30 cent UTOP

## IV. Conclusions

It is noted that the computed power, reactivity and temperatures under the UTOP accident condition need to be viewed as a preliminary analysis results for the logic verification of the SSC-K models. Although the analysis is preliminary in nature, the 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 development phase.

Reactivity feedback models of SSC-K code for Doppler, sodium density, fuel axial expansion, core radial expansion and control rod driveline expansion effects produces physically consistent results, which shows that the code is capable of modeling the phenomena properly.

Future work includes the code-to-code comparison runs which will serve as an attempt to validate the code without resorting to the experimental data.

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## References

[1] C.K. Park, et al, "KALIMER Design Concept Report," KAERI/TR-888/97 (1997. 7.)
[2] D. Hahn, et al, "Reactivity Feedback Models for SSC-K," KAERI/TR-1105/98 (1998. 6.)
[3] D.M. Lucoff, "Passive safety testing at the Fast Flux Test Facility," *Nuclear Technology*, **88**, 21 (1989)
[4] G.J. Van Tuyle, et al, "Evaluation of 1990 PRISM Design Revisions," NUREG/CR-5815 (1992)
[5] G.L.Gyorey, et al, "Safety and licensing of the PRISM liquid metal reactor," *Nucl. Engr & Design*, **137**, pp. 181-189 (1992)
[6] U.S. NRC, "Preapplication Safety Evaluation Report for the PRISM Liquid Metal Reactor," NUREG-1368 (1994)