Proceedings of the Korean Nuclear Society Autumn Meeting
Taejon, Korea, October 2000

An Effect of Gas Expansion Module on the Inherent Safety of the Korea Advanced Liquid Metal Reactor

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Abstract

The safety characteristics of the gas expansion module (GEM) in the Korea Advanced LIquid MEtal Reactor (KALIMER) are investigated using the system analysis code, SSC-K. The GEMs are passively activated through a pressure change in response to a loss of flow and require no operator action or active systems. The resultant void in the GEMs near the core periphery increases neutron leakage and introduces significant negative reactivity. The accident initiator considered is a loss of flow with failure of scram (ULOF). Various analyses of multiple faults such as loss of heat sink, transient overpower, or failure of GEMs with the ULOF are performed. It was found that the KALIMER design has inherent safety characteristics and is capable of accommodating various types of ULOF. The self-regulation of power without scram is mainly attributed to the inherent and passive reactivity feedbacks in conjunction with the GEMs.

1. Introduction

The Korea Atomic Energy Research Institute (KAERI) is developing the KALIMER (Korea Advanced LIquid MEtal Reactor) conceptual design [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 safety advantages of the KALIMER reactor concept are based on use of sodium cooling, metal fuel, and pool configuration. These features lead to an improvement of heat transfer characteristics, reactivity feedback response, and passive safety capability.

To evaluate the passive safety responses and safety margin in the conceptual KALIMER design, the consequence of failures of components or systems, such as the scram system or the pump power supply are analyzed. The main case considered in the present analyses is a unprotected loss of flow event (ULOF). The ULOF results from a loss of power to the primary sodium pumps. For the present analyses, the SSC-K [2] code is used, which is a main tool for analyzing a variety of off-normal conditions or accidents in the preliminary KALIMER design. The SSC-K code is under development at KAERI as a part of the KALIMER project.

A SHRT-45 experiment in the EBR-II [3] demonstrated the ability for a metal-fueled reactor to accommodate the loss of flow accident without scram with very benign consequence: no failure of fuel assemblies or core structures. In the Fast Flux Test Facility [4], the gas expansion modules (GEMs) added at the periphery of the oxide fueled core have been tested. In this paper, the inherent safety features adopted in the preliminary KALIMER design against loss of flow events with scram failure will be discussed.

2. KALIMER Reactor System

KALIMER is a liquid sodium cooled fast reactor plant. It has a net electrical rating of 150 MWe and the required core thermal output is 392 MWth. The schematic of KALIMER is shown in Fig.1. The primary heat transport system (PHTS) of KALIMER is a pool type and is constructed in a big sodium pool. The pool-type reactor provides the large thermal inertia of the system which yields slower transients, longer grace time in an accident, and eventually increases plant safety. The intermediate heat transport system (IHTS) consists of two loops and each loop has its own steam generator (SG) and related system, which contributes to the flexibility of plant operation and increases the reliability of decay heat removal by normal procedures.

The reactor vessel basically contains the entire inventory of primary sodium coolant. A vertical wall, called a reactor baffle, divides the primary pool into hot and cold pools. Cold sodium from the cold pool is pumped by the primary electro-magnetic (EM) pumps into the inlet plenum, and it flows into the hot pool through the core. The only primary piping used is from the discharge side of the inlet pump to the core inlet plenum. The IHTS is a conventional pipe system circulating sodium between the IHXs and the SGs. The SG is of once through type with a superheated steam cycle.

System reliability is improved by using EM pumps that do not have moving parts for both the primary and intermediate coolant pumping. As an EM pump has virtually no

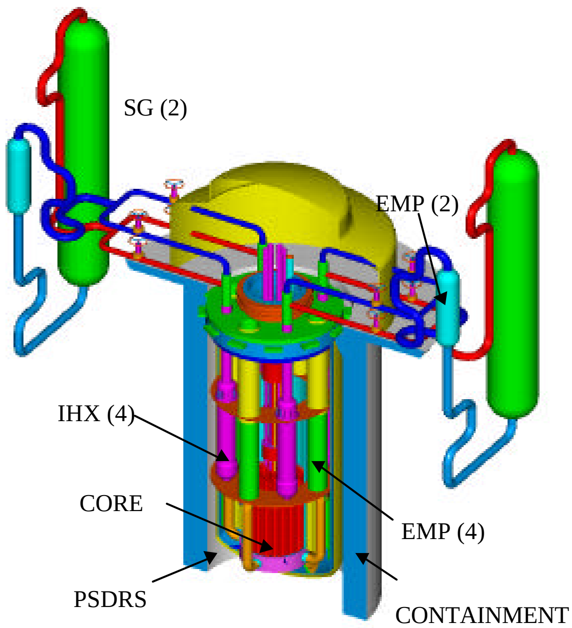

Fig.1 Schematic of the KALIMER Reactor Vessel

inertia, it is necessary to use a synchronous machine to provide an artificial coastdown. The safety-grade machine, which consists of flywheels coupled with motor-generator units, is operated continuously so that coastdown begins if there is a power loss or other pump malfunction. As the synchronous machine is coasting down, the rotational energy is converted to electrical power for the EM pumps, which then experience a gradual reduction in pumping power. Since the passive reactor shutdown requires some time to bring the fission power down, absence of pump coastdown can be a major safety concern. Therefore, the synchronous machine is a crucial safety component in the KALIMER design. Four synchronous machines are individually installed for the primary EM pumps.

The KALIMER core is designed with an 18-month refueling cycle. The core utilizes a heterogeneous configuration in the radial direction that corporates annular rings of internal blanket and driver fuel assemblies. The layout of the KALIMER breeder core is shown in Fig. 2. There are no upper or lower axial blankets surrounding the core. The active core height is 120.0 cm and the core outer diameter of all assemblies is 344.3 cm. The base alloy, ternary (U-Pu-10% Zr) metal fuel is used as the driver fuel. The fuel pin is made of a sealed HT-9 tube 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 KALIMER core includes 1 ultimate shutdown system (USS) assembly and 6 GEMs. For the safety margin in the event of a loss of primary coolant flow, GEMs are located at the periphery of the active core. A GEM has the same external size and configuration as the ducts of the other core assemblies. The GEMs are passively activated through a pressure change in response to a loss of flow and require no operator action or active systems. When the pumps are operating, sodium is pumped into the GEM, and the trapped helium gas is compressed into the region above the active core. In contrast, when the pumps are off, the helium gas region expands into the active core region, displacing the sodium in the GEM below the active core top. The resultant void near the core periphery increases neutron leakage and introduces significant negative reactivity.

The USS is included as a means to bring the reactor to the cold critical condition in the event of complete failure of the normal scram system. The inherent reactivity feedback brings the core to a safe but critical state at an elevated temperature. For this purpose the USS is located in the core center which drops the neutron absorber by gravity.

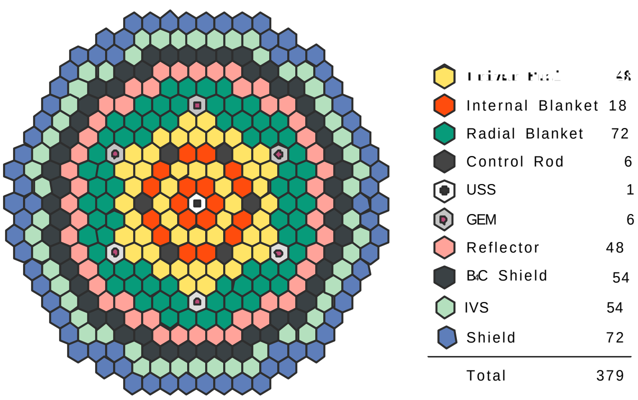

Fig.2 KALIMER Breeder Core

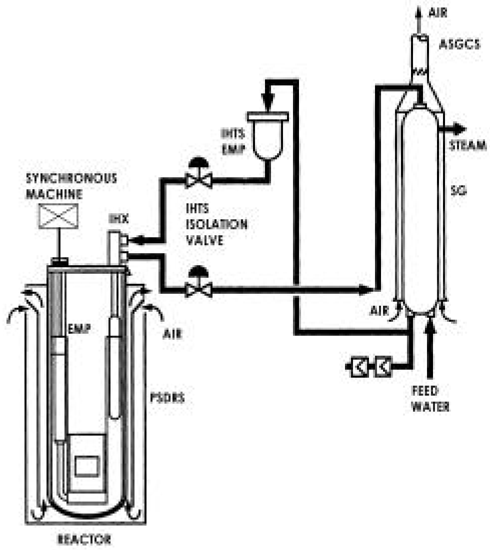

Fig. 3 Schematic Diagram of the PSDRS

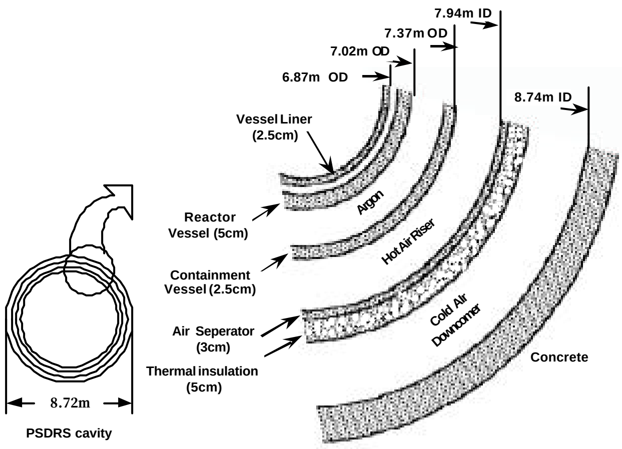

Fig. 4 Cross-sectional Flow Areas of the PSDRS

3. Passive Safety Decay Heat Removal System

In the KALIMER design, decay heat from the reactor is normally removed by two loops of the IHTS. In the rare event that the IHTS becomes unavailable during power operation, the core heat is removed by the highly reliable safety-grade backup of the passive decay heat removal system (PSDRS). Fig. 3 shows the schematic of the PSDRS and Fig. 4 shows the cross-section flow areas o the PSDRS. Since the PSDRS utilizes natural convection between the containment vessel and surrounding air and operates continuously, it requires no emergency power and no operator action for its operation following the defined design basis events. The gap between the reactor vessel and the containment vessel is filled with argon gas and thus radiation heat transfer prevails due to the high temperature of these walls. Atmospheric air comes in from the inlets located at the top of the containment, and flows down through the annulus gap between the air separator and the concrete silo. It then turns back upward passing through the other annulus gap between the containment outer surface and the air separator and finally flows out through the stack with raised temperature by the energy gained from cooling the containment vessel.

The significance of the PSDRS in the KALIMER design is that it plays the role of the only heat removal system under a total loss of heat sink accident. For this reason, its function is crucial to prevent core damage, so that performance analysis as well as realistic modeling of the system may be a key issue to provide essential knowledge for a safety evaluation of the KALIMER design. The key design parameters of the KALIMER loaded with metallic fuel are summarized in Table 1.

Table 1. Key design parameters of KALIMER

Overall		Cladding Material	HT9
Net plant Power, MWe	150	Refueling Interval, months	18
Core Power, MWt	392		
Gross Plant Efficiency, %	41.5	**PHTS**	
Net Plant Efficiency, %	38.3	Reactor Core I/O Temp., ^{0}C	386.2 / 530.0
Reactor	Pool Type	Total PHTS Flow Rate, kg/s	2143.1
Number of IHTS Loops	2	Primary Pump Type	Electromagnetic
Safety Shutdown Heat Removal	PSDRS	Number of Primary Pumps	4
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	1200	IHTS Pump Type	Electromagnetic
Axial Blanket Thickness, mm	0	Number of IHXs	4
Maximum Core Diameter, m	3447	Number of SGs	2
Fuel Form	U-Pu-10% Zr Alloy		
Enrichments (IC/OC) for Equilibrium Core, %	14.4 / 20.0	**Steam System**	
		Steam Flow Rate, kg/s	155.5
Assembly Pitch, mm	161.2	Steam Temperature., ^{0}C	483.2
Fuel/Blanket Pins per Assembly	271 / 127	Steam Pressure, MPa	15.50

4. Methodology of Analysis

The SSC-K [2] computer program was used for the analysis of the ULOF. The SSC-K is a best-estimate system code for analyzing a variety of off-normal conditions or accidents of a pool-type sodium-cooled fast reactor. The SSC-K is under development at KAERI on the basic framework of SSC-L [5] as a part of the KALIMER project, which was originally developed at Brookhaven National Laboratory to analyze loop-type liquid metal reactor (LMR) transients. Most modification of the SSC-L were made in order to analyze the thermal hydraulic behavior within the pool-type reactor. The PSDRS model [6] was also developed to predict the heat removal rate by this system and it was coupled with the SSC-K code.

Since the SSC-L code was originally designed to analyze oxide fuel LMRs, substantial modification has been made to facilitate modeling of the metal fuel used in KALIMER. Reactivity changes are calculated for control rod scram, the Doppler effect in the fuel, sodium voiding or density changes, fuel thermal expansion, core radial expansion, thermal expansion of control rod drives, and vessel wall thermal expansion. In addition to the reactivity model, the GEM model has been developed in order to analyze its effect under loss of flow events.

A full plant SSC-K model for KALIMER was simulated. For the core, several channels are used to represent the drivers, the radial blanket, the control assemblies, the reflector assemblies, the shield assemblies, in-vessel storage assemblies (IVS), and a hot driver assembly. Ten nodes are used to represent the active core, and four nodes for the gas plenum in the axial direction. Each axial segment is divided radially into five sections that represent fuel, gap, clad, sodium coolant, and structure sections. Thermal expansions are accounted for in the fuel and clad, but those of the coolant channel flow area and the structure are not considered. The peak power channel is used to calculate the hot channel response. Thermal power generation is represented by neutron kinetics and decay heat equations. A specified fraction of the total reactor power is generated in the fuel, cladding, blanket and sodium. The axial variation of power generation is governed by the input axial power profile.

The KALIMER EM pump has not been designed in detail and the performance characteristics of the EM pump are not available at present, therefore the mechanistic model for pump coastdown operation cannot be used in this analysis. The coastdown curve of the KALIMER EM pump is directly embedded into the SSC-K code as function of flow vs time. Therefore, the pump flow behaves as the coastdown curve after the pump trip. Natural circulation also takes into account thermally driven density changes in all parts of the primary, intermediate, and water/steam loops with elevation changes. The SSC-K SG model provides heat transfer based on subcooled, boiling or superheat conditions. Perfect separation is assumed for fluid leaving the steam drum. Feedwater from the nozzles is considered as the boundary conditions.

Since the KALIMER design has not yet been completed, most of the plant data are preliminary. When there are uncertainties involved in the design, conservative assumptions are used for the analysis following the conventional accident analysis methods. Some over simplified characteristic values or unrealistic values for unavailable data are used only when they guarantee conservatism. The following assumptions are made in the present analysis; (1) The transient is initiated from the full-power condition. (2) The transient is initiated by all the primary pump trips followed by coastdown. (3) Although ULOF would normally lead to a scram due to a high flux-to-flow ratio, it is assumed that the reactor protection system (RPS) fails to detect the mismatch or that the control rods fail to be inserted. (4) The thermal conductivity used is the reduced case in order to account for uncertainties in the data and to reflect the fuel behavior under irradiation. (5) The balance of the plant side is simply modeled because its contribution does not have an effect on the analysis results.

The ULOF event considered in this analysis is categorized into extremely unlikely event, which has an extremely low probability and is not considered in licensing analyses for current generation light water reactors. According to the top-tier requirements [1] for the KALIMER program, KALIMER should have provisions to ensure adequate prevention and protection against those events that have the potential for large release, core melt, or reactivity excursion.

The acceptance criteria [7] for KALMIER safety analysis are shown in Table 2. For the highest

Table 2. KALIMER Safety Criteria

Event category	Core Average Outlet Temperature, oC		Cladding Peak Temperature, oC		Coolant Peak Temperature, oC		Fuel Peak Temperature, oC
	Short-term	Long-term	Short-term	Long-term	Pump on	Pump off	
Moderate frequency events (ME)	540	540	650	635	1070	960	955
Infrequent events (IE)	565	565	650	635	1070	960	955
Unlikely events (UE)	650	650	790	704	1070	960	1070
Extremely unlikely events (XE)	760	700	790	704	1070	960	1070

temperature period of the short-term transient (< 1 hr), the most likely cladding mid-wall failure mechanism is expected to be stress-rupture due to weakening of the HT-9 cladding at high temperature. For the longer period of the transient (> 1 hr) at lower temperatures, the most likely cladding failure mechanism is formation of low-melting point eutectic between the cladding and the metal fuel. The containment function of the vessel structures and boundaries is protected by limiting their temperatures. Besides thermal damage protection, the criteria also preclude dynamic loads on the vessel by ensuring that the margins are maintained relative to fuel melting and sodium boiling. These physical phenomena should be avoided since they are considered as necessary initial events in the development of any severe dynamic loading.

5. Analysis Results

5.1 ULOF Only

The ULOF is initiated by a trip of the EM pumps followed by their coastdowns at full power. Two cases of the ULOF with and without the GEMs are examined. The power transients for both cases are plotted in Fig.5. For the case with GEMs, the power immediately begins to drop and reaches the decay heat level by about 100 seconds since there is enough negative reactivity insertion due to the GEMs. Without the GEMs, the power gets higher and decreases somewhat slowly. The reactivity feedback for two cases respond differently in the power reduction. With the GEMs, the negative reactivity is enough to drive the core in subcritical as shown in Fig.6, and the power rapidly transitions down to the decay heat level as shown in Fig.5. The GEMs reach their full worth by 20 seconds, and the worth remains throughout the entire transient.

The reactivity feedbacks for the axial and radial expansion are positive since their temperatures become lower than the reference ones due to the GEMs. The GEMs retain the power and temperatures down. The control rod drive line (CRDL) reactivity feedback turns slightly positive due to vessel expansion. The usual positive reactivity feedback from sodium density becomes negative because the average sodium temperature is decreased from the reference value which is the temperature at the nominal operating condition. Without the GEMs, since the core heats up significantly as the sodium flow rate reduces, the Doppler, axial expansion, radial expansion, and control rod drive line reactivity feedbacks initially turn negative, except the sodium reactivity feedback which is positive. The reactivity feedbacks without the GEMs behave as shown in Fig.7. The net reactivity feedback is initially negative, but the power level is later reestablished at 16 percent of the rated power by 600 seconds as shown in Fig.5.

The pool temperatures for both cases are shown in Fig.8. The fuel temperature distribution in the hot pin with the GEMs is shown in Fig.9. The reduction of core flow due to the pump trips causes an initial peak centerline temperature before the power begins to fall. However, the peak fuel temperatures satisfy the safety criteria for the case with the GEMs. The fuel temperatures ultimately decrease, and fuel damage is not a concern for this event. However, the case without the GEMs shows that the peak cladding temperature exceeds the acceptance limit as shown in Fig.16. The sodium levels for the pools and the GEM are shown in Fig. 10, where the cold pool level increases rapidly due to the pump trip, and it overflows the top of the reactor baffle that is a divider for the cold and hot pools.

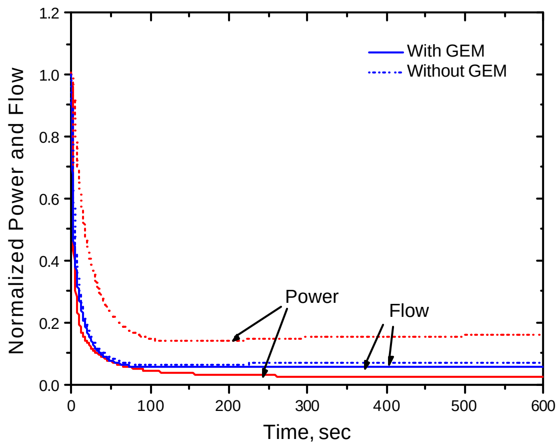

Fig.5 Power and flow fraction (ULOF)

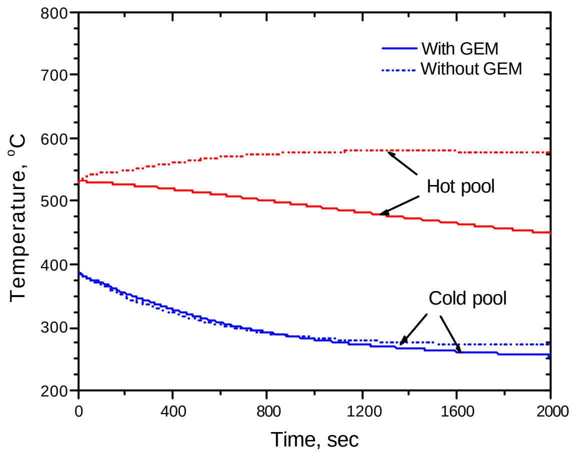

Fig.8 Hot pool temperatures (ULOF)

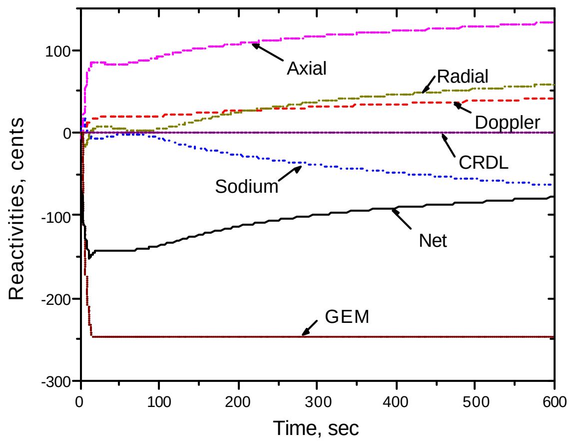

Fig.6 Reactivity w/ GEMs (ULOF)

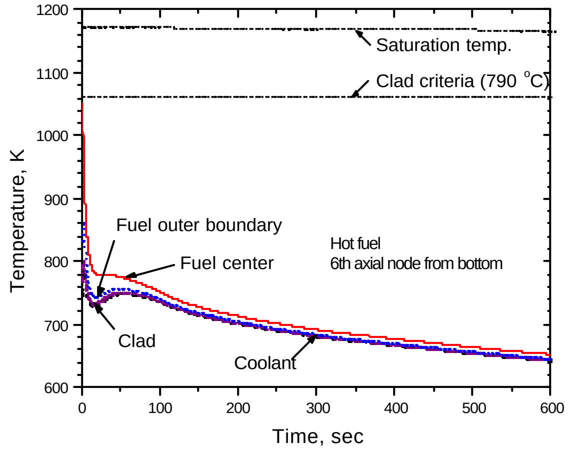

Fig.9 Fuel temperatures (ULOF w/ GEMs)

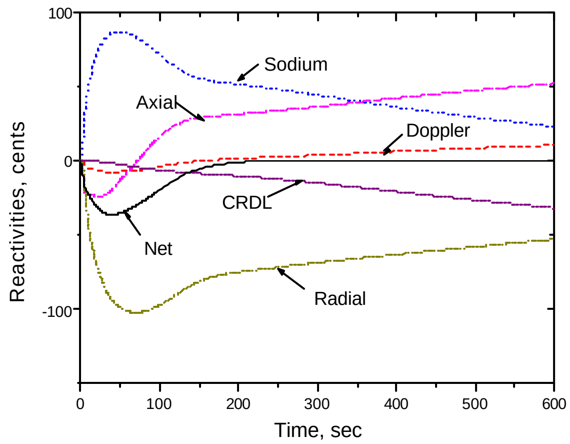

Fig.7 Reactivity w/o GEMs (ULOF)

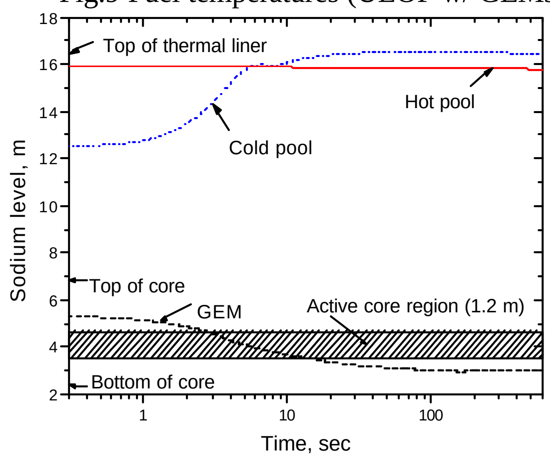

Fig.10 Sodium levels (ULOF w/ GEMs)

5.2 ULOF Combined with LOHS

A ULOF transient is assumed to simultaneously occur in combination with a loss of IHTS cooling, which has an extremely low probability. The IHTS flow is assumed to instantaneously stop as the primary pump trips. Figure 11 shows the sodium pool temperatures during the ULOF/LOHS. The IHX outlet temperature rapidly increases to that of the hot pool as soon as the IHX flow terminates. The slow heatup of sodium results from the large thermal capacities of the sodium pools and the metal mass.

The rapid insertion of the negative reactivity reduces the power, keeping the power-to-flow ratio favorable, so that the heat generated in the fuel can be removed without damaging the fuel as shown in Fig. 12. As long as enough coolant flow is available to remove the generated heat, the fuel temperatures can be maintained at an acceptable level. The rapid increase of fuel temperature in the first few seconds is attributed to the power-to-flow mismatch, and the subsequent rapid drops of those temperatures results from the quick negative reactivity feedback of the GEMs. The fuel temperatures rise again due to the power-to-flow mismatch and reach peak values when natural circulation flow is established at the decay heat power level.

The highest peak fuel temperature of 1050 K (777 °C) occurs at the beginning of the transient, because tripping of the pumps triggers a quick response from the GEMs, which brings the power down before the system begins to heat up. The fuel temperatures drop very quickly. In the fuel temperatures, Fig. 12 indicates that the temperature continues to increase slightly after 2000 seconds, because the core generated heat and the decay heat removal by the PSDRS are not yet balanced. The PSDRS

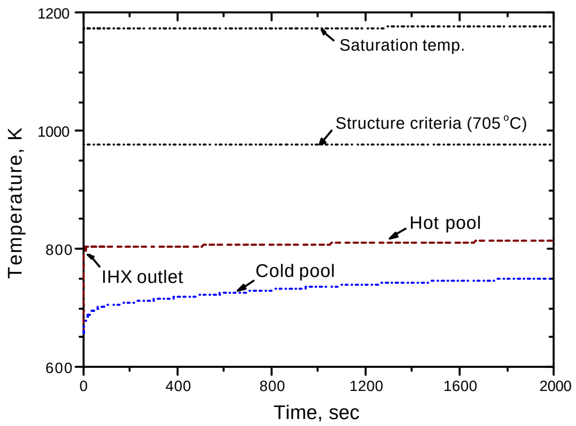

Fig.11 Hot pool temperatures (ULOF/LOHS)

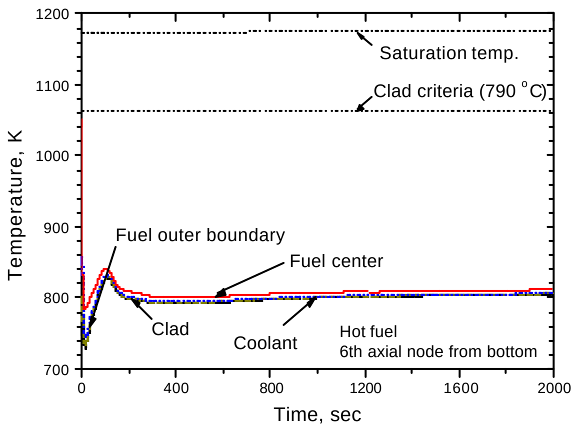

Fig.12 Fuel temperatures (ULOF/LOHS)

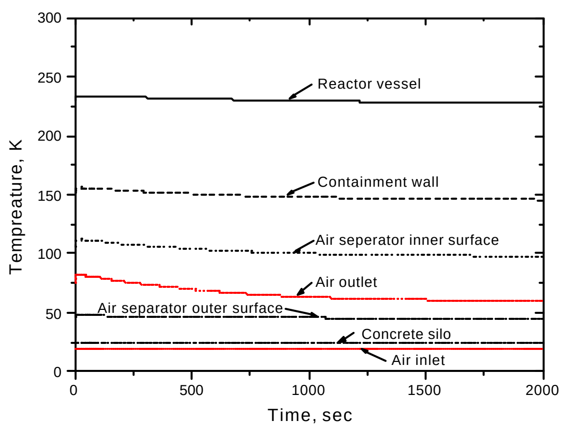

Fig.13 PSDRS temperatures (ULOF/LOHS)

has enough capacity to remove the decay heat level, thus, the temperatures appearing in Fig. 12 would eventually decrease. The temperatures of the structural walls and air flow in the PSDRS are presented in Fig. 13.

For the analysis results from the ULOF/LOHS transient, strong inherent negative reactivity feedback with rising temperature brings the reactor to a stable equilibrium state with the core outlet sodium temperature that is below the long-term structural design limit, fuel temperature below eutectic formation, and local coolant temperature well below sodium boiling.

5.3 ULOF Combined with TOP

The ULOF/TOP transient is assumed to begin with the simultaneous withdrawal of the control rods. The initial conditions are the same as the UTOP case with the primary pumps trip. This event is initiated from full power and postulates that a malfunction in the rod controller system causes withdrawal of all the control rods until the drivelines reach the rod stops. It is assumed that a total of 30 cents is inserted into the core during 15 seconds. The IHTS sodium flow remains at the rated conditions and normal feedwater is supplied to the SGs.

In this event, the initial response comes mostly from the GEMs. The flow decrease with reactivity increase heats up the system quickly. Addition of negative reactivity by the GEMs at the beginning holds down the power-to-flow ratio, and the core heat is removed by sufficient flow. The GEMs dominate the other reactivity feedbacks, causing the power to decrease. The power level rapidly increases up to around 4 percent of the rated power at the initial stage as shown in Fig.14. At about 200 seconds, the power and flow begin to stabilize, and natural circulation is established. For the UTOP only case (Hahn et al., 2000b), the peak power reaches 1.16 times the rated power at 15 seconds into the transient, and begins to level off at 1.06 times the rated power by 6 minutes. Fig.15 shows the various temperatures in the hot pin at the 6th axial node from the bottom. No fuel damage is predicted for this case because of the negative reactivity feedbacks

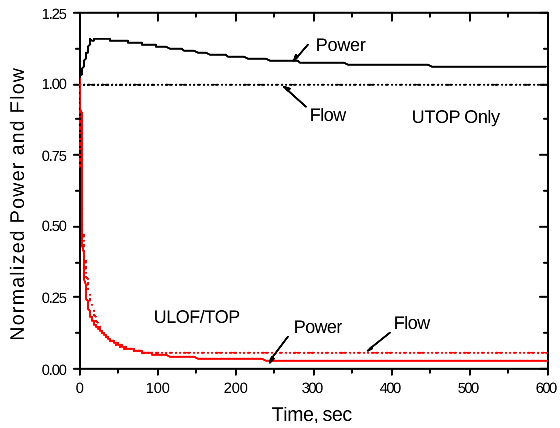

Fig.14 Power and flow (ULOF/TOP)

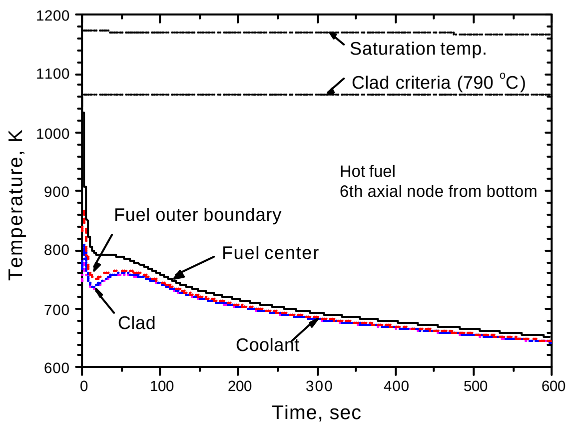

Fig.15 Fuel temperatures (ULOF/TOP)

from the GEMs following a loss of flow.

Final shutdown can be achieved by the USS by releasing the neutron absorbing balls containing Boron-10 from the container at the closure head, which fall by gravity into an open assembly in the center of the core. The shutdown action itself can be completed in a few seconds once initiated. The USS provides a means of bringing the reactor to cold subcritical conditions following various ULOF events.

6. Conclusion

KALIMER safety analyses have been performed to evaluate the plant response, performance of certain inherent safety features, and margin to plant safety limits under accidents. Although the emphasis here is on its application to the ULOF among ATWS events, SSC-K can be utilized for a variety of other objectives (Hahn et al., 2000b).

It has been demonstrated through the present analyses that the KALIMER design has inherent safety characteristics and is capable of accommodating not only a ULOF, but also accidents of a ULOF with multiple faults. These events have an extremely low probability and are not considered in licensing analyses for current generation reactors. The self-regulation of power without scram is mainly due to the inherent and passive reactivity feedbacks in conjunction with the GEMs. The GEM effect during a loss of flow event appears to be highly effective. The GEMs reduce the power so quickly that the fuel actually cools down and does not heat up. It is believed that using the GEMs will significantly improve the KALIMER response to a ULOF events.

The main advantage of the KALIMER design for loss of flow events is that it is hardly

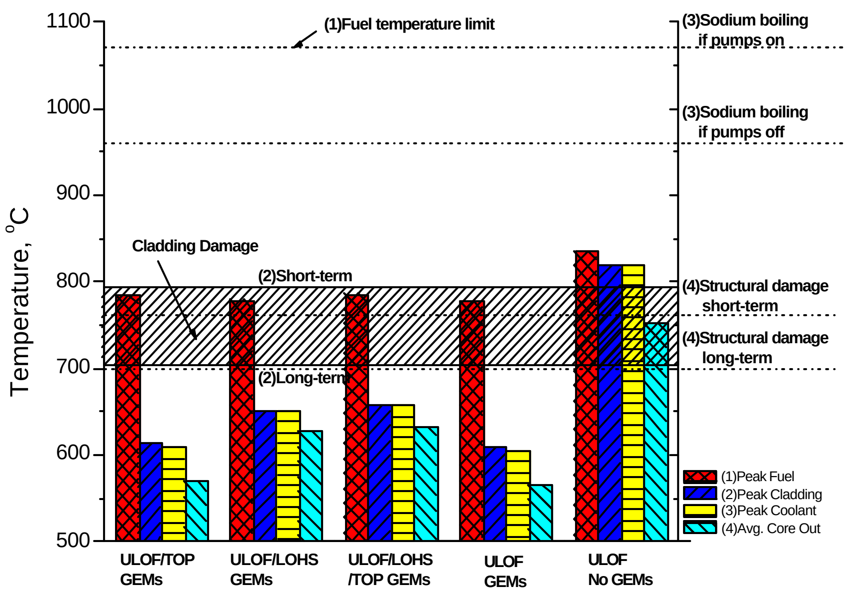

Fig.16 Peak Temperatures for Variations of the ULOF

possible to approach or exceed prompt criticality in the initiation phase of the transient. For most of the calculated event sequences following ULOF events, core configuration eventually maintains the cooling capability. A summary of the resultant peak temperatures predicted by the SSC-K code for the ULOFs under various conditions is presented in Fig.16.

Acknowledgement

This work was performed under the long-term nuclear research and development program sponsored by the Korea Ministry of Science and Technology.

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