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권영민, 이용범, 장원표, 정관성, 한도희
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Inherent Core Safety of the Korea Advanced Liquid Metal Reactor

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1. Introduction

A liquid metal reactor (LMR) has the potential of enhanced safety utilizing inherent safety characteristics, transuranics (TRU) reduction and resolving the spent fuel storage problems through proliferation-resistant actinide recycling. Korea Atomic Energy Research Institute (KAERI) has been developing the conceptual design of KALIMER (Korea Advanced LIquid Metal Reactor, and the design target of KALIMER is to have the features of economically competitive, inherently safe, environmentally friendly, and proliferation-resistant fast reactor. The developed conceptual design of KALIMER can be used as a reference design for further LMR system design technology development and as one of the possible options for future LMR construction.

KALIMER has a net plant capacity of 150 MWe and it consists of of a reactor system, primary and intermediate heat transport systems, steam generation system, turbine/generator and related systems, instrument and control system, NSSS auxiliary systems, and other BOP systems. Fig. 1 shows the schematic of KALIMER system.

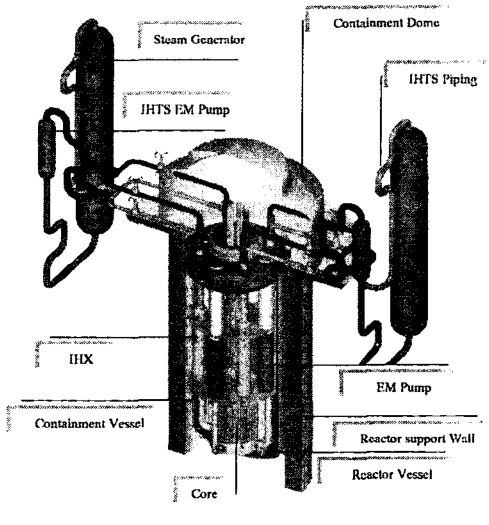

Fig. 1. Schematic of KALIMER System

2. Core Design of KALIMER

The KALIMER breakeven core system [1] is designed with 18 months refueling cycle. The core utilizes a heterogeneous configuration in the radial direction that corporates annular rings of internal blanket and driver fuel assemblies. The core layout, shown in Fig. 2, consists of 54 driver fuel assemblies, 24 internal blanket assemblies, 48 radial blanket assemblies, 6 control rods, 1 ultimate shutdown system (USS) assembly, 6 gas expansion modules (GEMs), 48 reflector assemblies, 54 B_4C shield assemblies, 72 shield assemblies, and 54 in-vessel storages (IVSs). There are no upper or lower axial blankets surrounding the core. Two clusters of the control rods are located in the annular ring of internal blankets in the driver fuel region. The active core height is 100.0 cm and the core outer diameter of all assemblies is 335.15 cm. The base alloy, ternary (U-Pu-10% Zr) metal fuel is used for the KALIMER as the driver fuel. The fuel pin is made of sealed HT-9 tubed 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. For safety margin in the event of loss of primary coolant flow, GEMs are included at the periphery of the active core. GEM has the same external size and configuration as the ducts of the other core assemblies. USS is included as a means to bring the reactor to cold critical condition in the event (Ultimate Shutdown System) of a complete failure of the normal scram system.

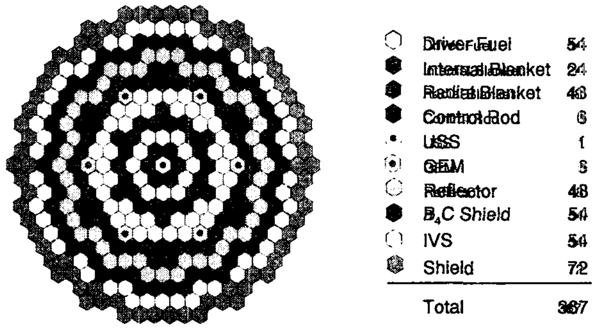

Fig. 2. KALIMER Breakeven Core Layout

3. Inherent Safety of KALIMER

3.1 Passive Safety System

The safety systems of KALIMER are based on passive system and KALIMER does not require active components in coping with accidents. It improves the reliability of KALIMER safety function. KALIMER also has other enhanced safety features such as using metallic fuel, USS, GEM in the core and Passive Safety Decay Heat Removal System (PSDRS). KALIMER accommodates unprotected anticipated transients without scram (ATWS) events without operator action, and without the support of active shutdown, shutdown heat removal, or any automatic system without damage to the plant and without jeopardizing public safety. Neither operator action nor offsite support is required for at least three days without violating core protection limits at an accident.

The KALIMER design highly emphasizes on the 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. Fig, 3 illustrates the components of reactivity feedback considered in the KALIMER core.

3.2 Doppler Feedback

Doppler is the direct result of the laws of nature. As the fuel temperature rises, more neutrons are parasitically absorbed in the resonance energy range. This has the effect of removing active neutrons from the core and reducing reactivity. Doppler feedback is also the fastest acting feedback mechanism. Fuel temperature is instantly affected by the core power level and is a practically instantaneous indicator of the power excursion. Doppler feedback removes the reactivity as the temperature rises and can thus help limit the extent of the power-increase excursion. As the fuel temperature drops with the power reduction, Doppler adds reactivity and tends to increase the core fission power. Doppler feedback in metallic fuel is a smaller negative factor than it is for oxide fuel because of the harder neutron energy spectrum.

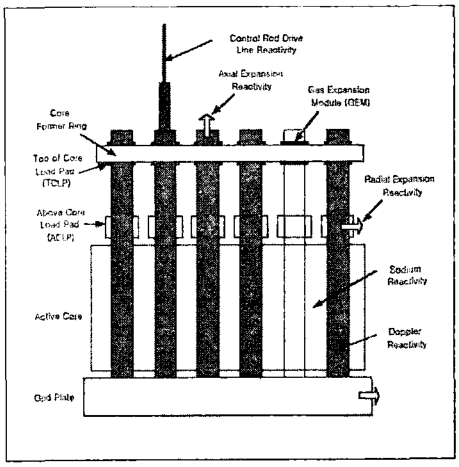

Fig. 3. Reactivity Feedback Components in a Metallic Fueled Core

3.3 Core Radial Expansion

The thermal expansion of the core structures results in a slower feedback mechanism. Thermal expansion is a result of both the laws of nature and the particular core design. It causes negative feedback for temperature increases by the combination of increased core volume captures and increased core surface leakage. 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. The radial dimension of the core is determined largely by the assembly spacing. The spacing is determined by the grid plate at the bottom of the core and by two set of load pads above the core, which are shown in Fig. 3. Radial thermal expansion of the core support structure is a slow feedback mechanism. As the temperature of the coolant returning to the core inlet plenum rises, the core support structure heats and expands radially. As the result, spreading of the core leads to a negative reactivity feedback

3.4 Fuel Axial Expansion

Metallic fuel expands significantly as it heats. Fuel thermal expansion is a fast feedback mechanism. Radial fuel slug expansion is accommodated within the pin and the fuel bundle lattice and does not affect the reactivity. Then the axial expansion is controlled by the expansion of the cladding, since the metallic fuel has little strength. Axial fuel expansion increases the core height and does affect the core reactivity, primarily decreases the effective density of the core materials by increasing the core surface area. The axial expansion increases the probability that a neutron will escape the core, giving a significant negative reactivity feedback. While the geometric change also affects neutron captures within the core, the overall effect is a rapid negative reactivity feedback contribution from the fuel temperature increase.

3.5 Sodium Density/Void Feedback

Thermal expansion of the sodium coolant produces a reactivity feedback effect. The thermal expansion of the sodium results in fewer sodium atoms being within the core so fewer neutrons are parasitically captured by the coolant, which results in positive reactivity feedback effect. Off-setting this effect leads to increased leakage of neutrons from the core because there are fewer sodium atoms to scatter them back into the core. Reduced neutron collision with the sodium atoms also tends to harden the neutrons energy spectrum. For a small LMR, the neutron leakage effect is dominant compared to the neutron spectrum hardening. For the larger KALIMER reactor, the hardened spectrum neutrons created in the center of the core are unable to escape from the core. but the feedback effects from the hardened spectrum are small compared to absorption and leakage effects. For a sodium-cooled, mixed plutonium-uranium core, the net feedback effect from the coolant thermal expansion is positive. As long as the sodium is subcooled, this contribution is modest, however in the extremely unlikely event that the sodium is voided from the entire core, this feedback effect is significant.

3.6 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 that 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 outward and spoil the neutronic efficiency of the core. Since the duct region is heated and bowing is in and above the core and the duct is thin and has a small heat capacity, bowing feedback tends to occur within a few seconds of the start of the transient. Thermal bowing is a rapid feedback mechanism. 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 removal of the reactivity from the core. But it is difficult to accurately calculate. 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.

3.7 Control Rod Driveline and Vessel Expansions

Thermal expansion of the control rod driveline results in a slow effect on the core reactivity. Particular reactor structural design is the primary determinant in the magnitude, timing and sign of the net feedback from this mechanism. During the temperature increase transient, the hot sodium discharged into the reactor upper plenum heats and extends the length of the driveline. The expansion will cause the control absorber bundle to move toward the core mid-plane, which by itself gives a negative feedback. Since the control rod drives attach to the top of the reactor vessel and the core attaches to the bottom of the vessel, the expansion of the reactor vessel as it heats pulls the control rods out of the core somewhat. This is a positive feedback. The net feedback due to this mechanism may be either positive or negative depending on the particular transient. This effect is not a safety factor early in a transient since its time constant is relatively large.

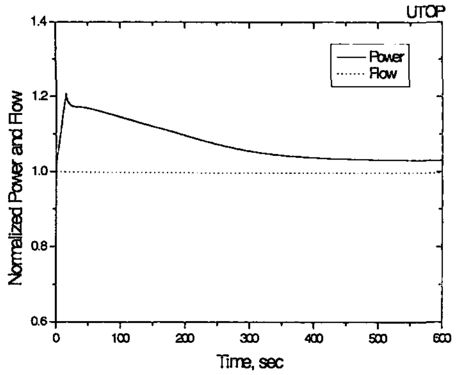

Fig. 4. Power and Flow during a UTOP

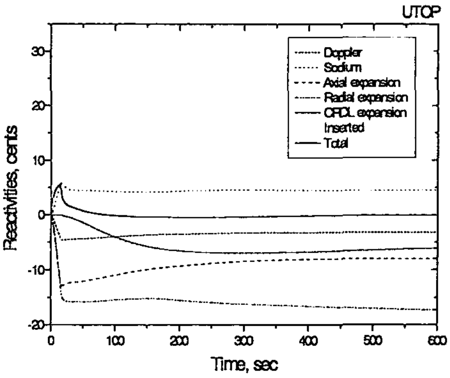

Fig. 5. Reactivity during a UTOP

4. Analysis of Unscrammed Events

The transient responses of the KALIMER system to three major unscrammed events, UTOP (Unprotected Transient OverPower), ULOF (Unprotected Loss of Flow) and ULOHS (Unprotected Loss of Heat Sink), were evaluated using SSC-K codes [2]. For all of the unprotected events, evaluation of reactivity feedback is a major consideration. Detail safety analysis for these events are presented in Ref. [3].

The UTOP is assumed to insert 2 cents per second for 15 seconds, for total of 30 cents, representing the withdrawal of all the control rods. The power reaches a peak of 1.21 times the rated power at 15 seconds into the transient, and begins to level off at 1.03 times the rated power by 7 minutes, as shown in Fig. 4. The reactivity components are shown in Fig. 5. The initial increase in the core power is limited by Doppler and fuel expansion feedbacks so that the total energy generated can be dissipated to the coolant with sodium temperature below boiling, and with cladding and fuel temperatures that satisfy short term fuel integrity criteria.

The ULOHS is assumed to begin with a sudden loss of the normal heat sink by IHTS and steam generators. The only heat removal is conducted by the PSDRS. The reactivity feedback is shown in Fig. 6. Uncooled sodium re-enters the core and begins to heat the core structures, core support structures, and the driveline. The resulting

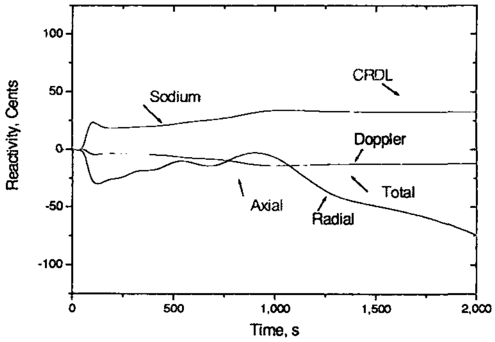

Fig. 6. Reactivity during a ULOHS

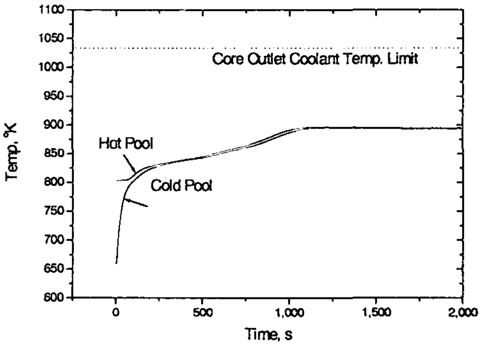

Fig. 7. Pool Temperatures during a ULOHS

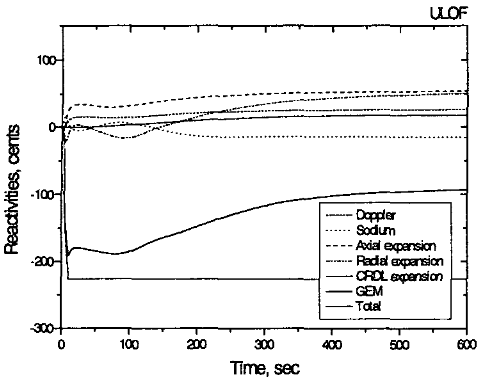

Fig. 8. Reactivity during a ULOF

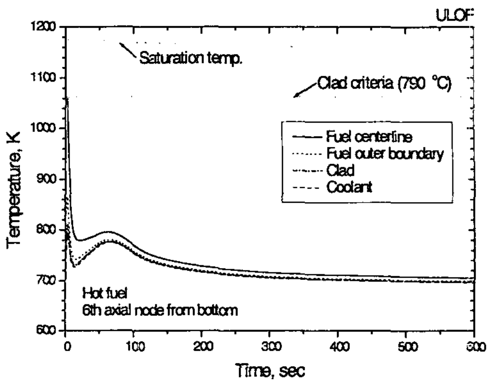

Fig. 9. Peak Fuel Temperatures (ULOF)

thermal expansions tend to reduce core power as the coolant and core heat up. The loss of cooling in the IHX results in a rapid increase of the cold pool temperature within a short time. As illustrated in Fig. 7, the cold pool temperature reaches almost the same value as that in the hot pool within about 500 sec. and so does the core inlet temperature. Thereafter, the temperature increases very slowly because of the large heat capacity of sodium in the pool as well as PSDRS heat removal.

For a loss of flow accident, the power to flow ratio is the key parameter that determines the consequences of the accident. The power immediately begins to drop and reaches a decay heat level since there is enough negative reactivity insertion due to GEMs as shown in Fig. 8. The fuel temperature distribution in the hot pin 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 and ultimately the fuel temperatures decrease.

5. Conclusion

The inherent safety features of the KALIMER core were evaluated. The SSC-K calculations for the three major unscrammed events in KALIMER were carried out. Although the analysis is preliminary in nature, it has been shown that the KALIMER design has inherent safety characteristics and is capable of accommodating unscrammed events. The self-regulation of power without scram is mainly due to the inherent and passive reactivity feedback. Safety margins appear to be significant for all three events. It can be said that the margins for the inherent safety must be large to compensate for the uncertainties in the reactivity feedbacks.

Acknowledgement

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