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Passive Safety Features of KALIMER-600 Burner Reactor for Unprotected Under-cooling Events

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has been developing KALIMER (Korea Advanced LIquid Metal Reactor), which is a sodium-cooled, metallic-fueled, pool-type reactor. Sodium-cooled fast reactors (SFRs) have been regarded as the most promising nuclear power option, because they resolve a spent fuel storage problem through a proliferation-resistant actinide recycling. KAERI recently suggested a burner core design [1] for a transuranics (TRU) transmutation by changing the smearing fractions of the fuel rods in three fuel zones while maintaining the breakeven core geometry of KALIMER-600 (600 MWe). The cladding outer diameter and the cladding thickness of the fuel rods were not changed.

The present scoping analysis focuses on an assessment of the enhanced safety design features that provide passive and self-regulating responses to transient conditions and an evaluation of the safety margins during an unprotected overpower, loss of flow and under-cooling events. The analysis results show that the KALIMER-600 burner reactor provides larger safety margins with respect to the sodium boiling, fuel rod integrity, and structural integrity.

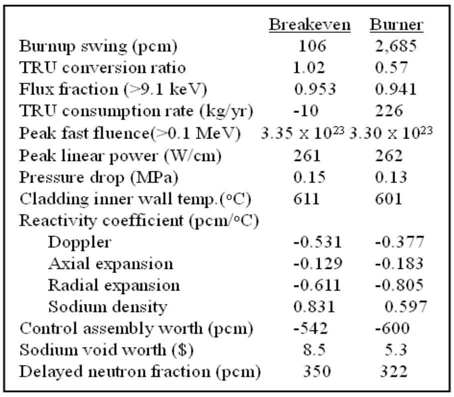
2. KALIMER-600 Burner Design

The KALIMER-600 burner core is configured to produce electricity for 332 effective full power days (EFPD) over a cycle with a five batch refueling scheme in order to avoid too high a burnup reactivity swing. In addition, three fuel assemblies were changed into control rod assemblies to accommodate the large burnup swing expected in the TRU burning environment. The TRU enrichment of the driver fuel was set to 30.0 w/o because of the current practical limitation of the U-TRU-10%Zr metal fuel database. The TRU conversion ratio was 0.57 and the burnup swing increased to 2,685pcm from 106pcm of the breakeven core.

The smearing fractions of the fuel rods in three fuel zones are changed while maintaining the cladding outer diameter and cladding thickness. The resulting fuel slug smearing fractions for the inner, middle, and outer core zones are 36%, 40%, and 48%, respectively. The fuel outer diameter of 0.9cm, the cladding thickness of 0.059cm, and the wire wrap diameter of 0.14cm are the same as the breakeven core. The fuel pin pitch is 10.50mm and the P/D ratio is 1.167. The fuel slug diameter for the inner, middle, and outer core zones are 4.692, 4.946, and 5.418mm, respectively. The gap region is assumed to be flooded with sodium even after a fuel swelling by 33%, and thus the core spectrum becomes softer when compared with the breakeven core.

The active core height is 94cm and the core diameter is 523cm. For the burner core, the outer assembly dimensions of the breakeven core were kept at an overall assembly height of 429.4cm and an assembly pitch of 18.31cm. The core performance parameters and reactivity coefficients for the burner core with an equilibrium cycle are provided in Table 1.

TABLE 1
Core Performance and Reactivity Coefficients



	Breakeven	Burner
Burnup swing (pcm)	106	2,685
TRU conversion ratio	1.02	0.57
Flux fraction (>9.1 keV)	0.953	0.941
TRU consumption rate (kg/yr)	-10	226
Peak fast fluence(>0.1 MeV)	3.35×10^{23}	3.30×10^{23}
Peak linear power (W/cm)	261	262
Pressure drop (MPa)	0.15	0.13
Cladding inner wall temp.(°C)	611	601
Reactivity coefficient (pcm/°C)		
Doppler	-0.531	-0.377
Axial expansion	-0.129	-0.183
Radial expansion	-0.611	-0.805
Sodium density	0.831	0.597
Control assembly worth (pcm)	-542	-600
Sodium void worth ($)	8.5	5.3
Delayed neutron fraction (pcm)	350	322

The favorable passive safety characteristic of the KALIMER-600 burner core is directly due to the usage of a metallic fuel. Since a metallic fuel has a high thermal conductivity, its operating temperature is relatively low, and consequently a relatively small amount of positive reactivity is needed to bring the core to a full power. Thus the negative reactivity needed to reduce the power is small because the positive reactivity inserted to raise the power is small in the metallic fueled core.

KALIMER-600 system has a highly reliable heat removal capability in the case of an unavailability of the main heat transport path. Two different types of decay heat removal systems are employed, one is a non-safety related Intermediate Reactor Auxiliary Cooling System (IRACS) and the other is a safety related Passive Decay heat Removal Circuit (PDRC) system. Figure 1 shows the configuration of the systems, IRACS and PDRC, available for a decay heat removal in the KALIMER-600 burner reactor. The PDRC system comprises two independent loops, and each loop is equipped with a single sodium-sodium decay heat exchanger (DHX), a single sodium-air heat exchanger (AHX) and a heat removing sodium loop connecting the DHX with the AHX. The non-safety related IRACS was not credited in the present analysis.

3. Analysis of Unprotected Under-cooling Events

Two typical under-cooling ATWS events, ULOF and ULOHS, are analyzed by the safety analysis code, SSC-K [2] and it is assumed that the reactor scram systems fail to operate. The ULOF event is initiated by all 2 primary pumps trip at a full-power condition and following coastdown. The heat generated in the core is assumed to be removed through the normal heat removal path. The coastdown flow rate gradually decays following a pump trip. The natural circulation flow rate by SSC-K is 8.0 % of the rated flow and the power reaches 13.3 % of the rated power by about 1000 seconds.

As shown in Fig. 1, a fast insertion of a negative reactivity reduces the power, while maintaining the power-to-flow ratio favorable. The rapidly falling net reactivity reaches a peak value of -36.0 ¢ at 55 seconds and then begins to increase. The positive feedback by the sodium density during the initial phase of the transient is offset by other negative feedback components.

Figure 2 shows the temperatures of the fuel centerline, fuel outer surface, cladding, sodium, and duct structure in the hot channel. The rapid increase of the fuel temperatures in the early phase of the transient is attributed to the power-to-flow mismatch, and subsequent gradual drops of those temperatures result from the negative feedback effects. The peak fuel centerline temperature (797.2^{o}C) is 273^{o}C below the fuel melting temperature. The maximum cladding temperature (772.8^{o}C) is below the threshold for an eutectic formation. The peak sodium temperature in the hot channel (768.5^{o}C) is significantly below the sodium boiling point.

The ULOHS event is assumed to start with a loss of the heat rejection capability at all of the SGs, with the primary and intermediate loop pumps continuing to run. The only heat removal is conducted by the passive heat removal system of the PDRC.

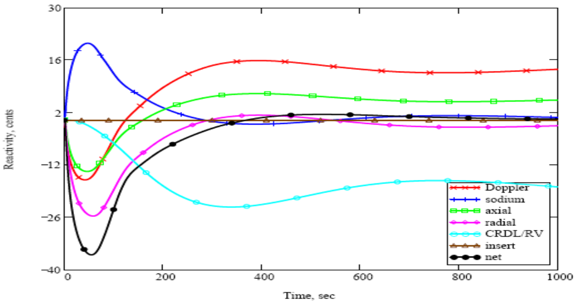


Fig. 1 Reactivity Feedbacks during a ULOF

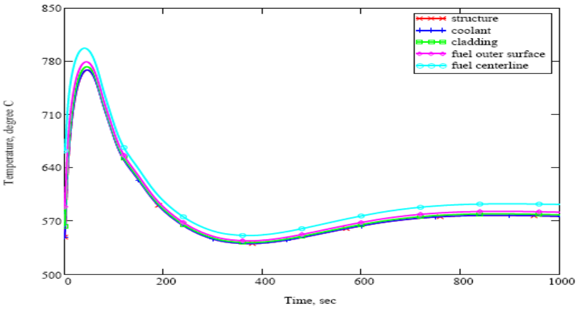


Fig. 2 Core Temperatures during a ULOF

As shown in Fig. 3, the power immediately drops due to the negative reactivity feedbacks in response to an increased core inlet temperature, and then it slowly decreases to seek an equilibrium with the available heat sink provided by the coolant system heat capacity and the heat rejection by the PDRC. The power reaches a 2.7% of the rated power by about 600 seconds. The net reactivity drops initially by about 600 seconds, and then it approaches a constant reactivity of -15.1 ¢. The core maintains a subcritical shutdown condition. The fuel temperatures in Fig. 4 ultimately reach a quasi-equilibrium condition as the core heat generation rate is balanced with the heat removal rate by the PDRC.

As a result, the KALIMER-600 burner design concept has inherent safety characteristics and is capable of accommodating the under-cooling ATWS events. The self-regulation of the power without a scram is mainly due to the inherent and passive reactivity feedbacks in conjunction with the passive decay heat removal. Severe accident conditions are prevented by wide margins, with the peak coolant temperatures significantly below the boiling point in the hot channel assembly.

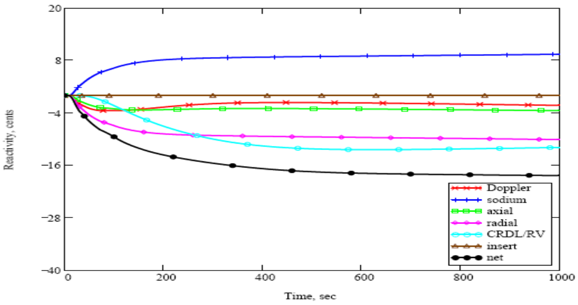


Fig. 3 Reactivity Feedbacks during a ULOHS

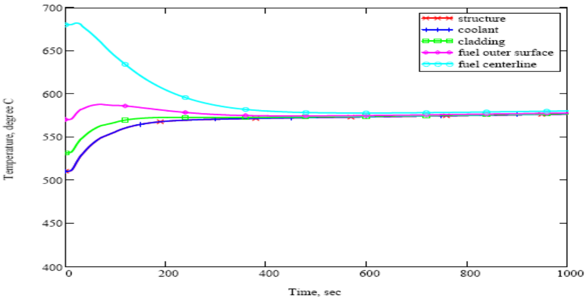


Fig. 4 Core Temperatures during a ULOHS

REFERENCES

[1] H. Song et al., “Effects of Conversion Ratio Change on the Core Performance in Medium to Large TRU Burning Reactors,” ICAPP’09, Tokyo Japan, May 2009.

[2] Y. M. Kwon et al., “SSC-K Code Users Manual, Rev.1,” KAERI/TR-2014/2002.