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Assessment of the KALIMER-600 Burner Reactor Responses to an Unprotected Overpower Transient

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1. Introduction

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. KALIMER-600[1] is a sodium-cooled pool-type fast reactor with an electricity output of 600MWe and it uses U-TRU-10%Zr metal fuel. For extending the KALIMER-600 capability to a TRU transmutation, many core designs have been searched with a variation of the intra-assembly configuration from the breakeven core. Among the various promising design options for the burner core, the core design by changing the smearing fractions of the fuel rods was selected as a reference one for safety analyses. The purpose of this paper is to evaluate the safety performance characteristics provided by the passive safety design features in the KALIMER-600 burner reactor by using a system-wide safety analysis code, SSC-K[2]. The present scoping analysis focuses on an assessment of the enhanced safety design features that provide passive and self-regulating responses to unprotected overpower transient conditions.

2. KALIMER-600 Burner Reactor Concept

The KALIMER-600 breakeven core was originally configured to produce electricity for 540 effective full power days (EFPD) over a cycle with a four batch refueling scheme. However, for the burner core concept, a cycle length of 332 EFPD and a five batch refueling scheme were selected 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.

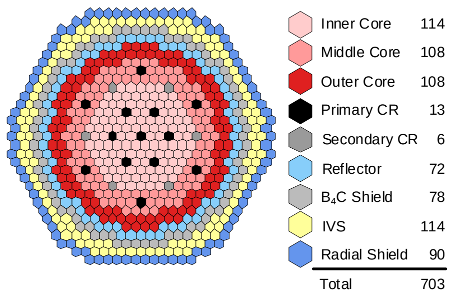

Fig. 1 Core Layout of the KALIMER-600 Burner Core

For the burner core concept selected for the present analysis, 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 is divided into three different zones as shown in Fig.1: inner, middle, and outer core zones composed of 114, 108, and 108 fuel assemblies, respectively. 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 overall length of a metal fuel pin is 360cm including the lower shield of 96.75cm and the upper gas plenum of 153.71 cm. The core performance parameters and reactivity coefficients for the burner core with an equilibrium cycle are provided in Table 1.

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.

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

3. Unprotected Overpower Transient

The UTOP event is initiated at a full power by a possible malfunction of the reactivity controller due to either a reactor protection system failure to detect the transient or control rods failure to unlatch, which causes the shim motor to withdraw the control rods until the drivelines reach the rod stops. Since the detailed design for maneuvering the control rods under an accident condition is not determined yet, a maximum reactivity of a 73¢ insertion during 15 seconds was analyzed, which case just meets the safety acceptance criteria. A total of 40¢ during 15 seconds was utilized as the UTOP initiator of the KALIMER-600 breakeven core.

It is assumed that the primary and secondary sodium flows remain constant at the rated conditions, and the feed water is sufficient to maintain a constant sodium outlet temperature because of the SG operation. The power and flow transients during the initial 1000 seconds are shown in Fig. 2. The reactor power reaches a peak of 2.26 times the rated power at 30.0 seconds and then slowly decreases to seek an equilibrium with the available heat sink provided by the coolant system heat capacity and the heat rejection by the SGs. The power begins to level off at 0.76 times the rated power by 1000 seconds. As shown in Fig. 3, the net reactivity rises initially with the inserted reactivity, but it soon peaks and falls as the negative feedbacks counter the only positive feedback from the coolant density reduction. The net reactivity eventually decreases to near zero, and in the long term, begins a slow, low-amplitude, negative-to-positive oscillation as the reactor power adjusts to the system heat rejection rate.

Figure 4 shows the temperatures of the fuel centerline, fuel outer surface, cladding, sodium, and duct structure at the hot assembly. Those temperatures are taken from the 8th axial node out of a total of 10 axial nodes for the active fuel region. Fig. 4 indicates that temperatures on a nominal basis, by not considering the uncertainties such as the engineering peaking factors. As a result, the peak fuel centerline temperature of 985°C occurs at the 6th axial node at 31 seconds into the transient, which is 85°C lower than the fuel melting temperature (1070°C). The cladding temperature reaches a maximum level of 786.7°C at 32 seconds in the 8th axial node, which is slightly lower than the threshold for an eutectic formation (790°C). The sodium coolant temperature is significantly lower than the boiling point (1055°C) as shown in the Fig. 4. Therefore, no fuel damage, no center-line melting, and no cladding failure are expected during a UTOP with a 73¢ reactivity insertion. As long as the core outlet temperature of the KALIMER-600 burner core remains below the threshold for a coolant boiling or cladding failure, the net negative reactivity will decrease the power to a decay heat level and eventually establish an equilibrium between the available heat rejection and the reactor power.

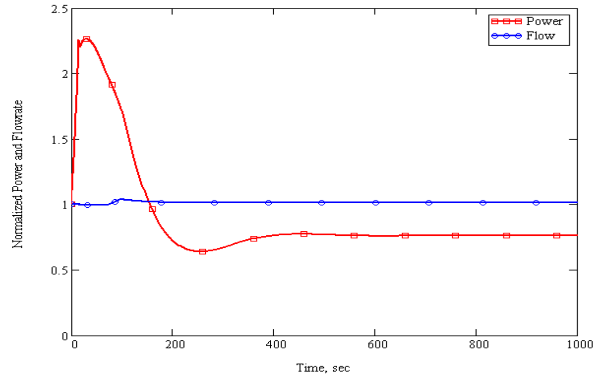

Fig. 2 Normalized Power and Flow

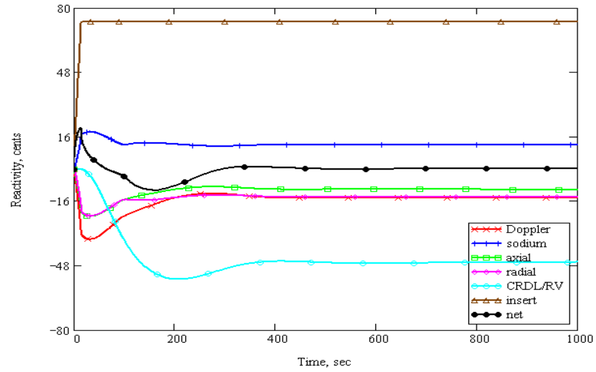

Fig. 3 Reactivity Feedback Components

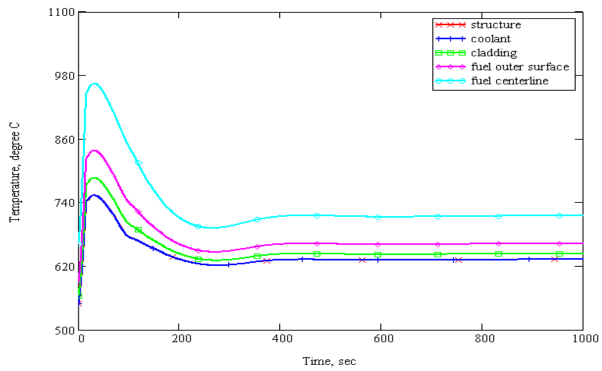

Fig. 4 Hot Assembly Temperatures

The main concern for the UTOP analysis is to evaluate the system response by the neutron-kinetic and thermal-hydraulic effects that inherently involve shutting the core down to acceptable power levels, which avoids a coolant boiling and fuel damage. The best defense against a UTOP vulnerability is to ensure that only small reactivity insertions are possible. In the KALIMER-600 burner design, this is achieved through a control rod stop system (RSS), which limits the potential magnitude of the UTOP initiators.

REFERENCES

[1] Y. M. Kwon, “KALIMER-600 Design Data for the Plant Safety Analysis,” SFR-SA-500-DD-01-2008, Rev.00, KAERI Internal Report, Nov. 11, 2008.

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