Molten Fuel Relocation Behavior during a Severe Accident in KALIMER-600

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1. Introduction

Preliminary safety analyses of the KALIMER-600 design have shown that the design has inherent safety characteristics and is capable of accommodating double fault initiators such as ATWS events without boiling coolant or melting fuel [1]. For the future design of liquid metal reactor, however, the evaluation of the safety performance and the determination of containment requirements may require consideration of tripe-fault accident sequences of extremely low probability of occurrence that leads to fuel melting. For any postulated accident sequence which leads to core melting, in-vessel retention of the core debris will required as a design requirement for the future design of LMR. For sodium-cooled core designs with metallic fuel, one of the major phenomenological modeling uncertainties to be resolved is the potential for freezing and plugging of molten metallic fuel in above- and below-core structures and possibly in inter-subassembly spaces.

In this study, scoping analyses were carried out to evaluate the penetration depths in the coolant channels by molten fuel mixture during the unprotected loss-of-flow accidents in the core of the KALIMER-600. It is assumed in the analyses that a solid fuel crust would start to form upon contact with the coolant channel structure temperature of which is below the fuel solidus.

2. Methods and Results

2.1 Analysis Methods

The sequence of the accident initiated by an abrupt loss of flow accompanied by failure of all reactor scram system is used as the reference accident sequence in this study for the analysis of molten fuel freezing and plugging in a sodium voided coolant channel. Upon cladding failure in a sudden loss-of-flow transient, molten fuel released at near midplane elevations would be blown biaxially through coolant channels toward the core ends.

Previous analyses show that the fuel moves past the upper end of the core with a velocity less than 10 m/s and with fuel temperatures around 1300℃. Temperatures near the center of the core are less than 1500℃ when fuel begins to leave the core. Cladding within the core boundaries generally would be so hot as to preclude refreezing at those elevations. Upon entering cooler regions above and below the core, rapid cooling, refreezing and plugging in principle could occur. Cladding within the core boundaries generally would be so hot as to preclude refreezing at those elevations. Upon entering cooler regions above and below the core, rapid cooling, refreezing and plugging in principle could occur [2,3].

It is assumed in the analyses that a solid fuel crust would start to form upon contact with the coolant channel structure, temperature of which is below the fuel solidus. The analysis results would predict if the coolant channels would be plugged by the freezing molten fuel in the inlet lower shield or in the outlet, fission-gas-plenum region of the sodium-voided pin channel. In contrast to uranium dioxide fuels, the process would be one of desuperheating and refreezing the fuel. For temperatures of interest, the fuel-wall contact temperature would be below the fuel solidus such that a solid fuel crust would start to form upon contact. So long as significant melt superheat persisted (more than as few tens of degrees) crust growth would be limited by the convective heat transfer. Later, when superheat neat the flow front had been reduced sufficiently, conductive heat transfer from the crust would exceed the convective heating from the melt and the crust could grow to plug the channel completely.

The current KALIMER-600 design features a continuation of pin geometry below and above the active core as in the KALIMER-150 design. The inlet/outlet channels are defined by a continuation of the in-core cladding to form shield rods and fission gas plena, which are typical of many LMR designs. The channel hydraulic diameter at the top and bottom ends of the active core of the KALIMER-600 is estimated to be 4.15 mm. Meanwhile, a special, large-flow-diameter endfittings are employed for the inlet shielding in the IFR design, for which the hydraulic diameter is as much as 2.5 cm [1].

2.2 Analysis Results

Table 1 shows the results of parametric studies of plugging depths calculated using the model described above. Major parameters of variation include the initial melt velocity, pin channel configuration and melt temperature, among others. First, two different initial velocities of the melt were used; 10m/s and 1.0 m/s, representing the upper limit of melt velocity in the abrupt loss of flow and gravity flow of the melt, respectively.

Table 1. Penetration Distances (cm)

Melt Velocity	Channel Configuration	Melt Temperatures(^{o}C)		
		1,500	1,320	1,140
10 m/s	KALIMER Inlet D = 0.4 cm T_w =350 ^{o}C	64.4	52.3	10.0
	KALIMER /IFR Outlet D = 0.4 cm T_w =500 ^{o}C	70.0	57.9	15.6
	IFR Inlet D = 2.5 cm T_w =350 ^{o}C	1,030	906	489
1.0 m/s	KALIMER Inlet D = 0.4 cm T_w =350 ^{o}C	11.9	7.89	1.92
	KALIMER /IFR Outlet D = 0.4 cm T_w =500 ^{o}C	14.3	10.2	1.92
	IFR Inlet D = 2.5 cm T_w =350 ^{o}C	303	239	35.8

Note : D = channel hydraulic diameter,
T_w = channel wall temperature

Also, a number of cases were analyzed for the different pin channel conditions of the IFR and KALIMER designs. Initial fuel temperatures corresponding to radially peak, average, and minimum power location were used: 1,500, 1,320, and 1,140 ^{o}C, respectively. Structural wall temperatures used for channel inlet and outlet are 350 and 500 ^{o}C, respectively.

The results shown above indicate that the coolant channels would be plugged by the freezing molten fuel in the inlet, lower shield region with its length about 112 cm as well as in the outlet, fission-gas-plenum region for the KALIMER-600 design. For the IFR design, the outlet region of the same length and hydraulic diameter as the KALIMER design would be also plugged but complete penetration of the inlet, large-diameter lower-shielding region is highly likely for all radial regions. The initial fuel temperatures are characteristic of those predicted for a sudden loss-of-flow transient. Any milder transient, which leads to a cooler, lower velocity melt would be more plugging prone, even in large diameter inlet channels.

3. Conclusion

The analysis results predict that the coolant channels would be plugged by the freezing molten fuel in the inlet lower shield as well as in the outlet, fission-gas-plenum region for the KALIMER-600 design. The melt will probably emerge from the assembly by meltthrough of the assembly. It will take some time for the melt to reach the core support structures. Thus, the amount of decay heat to be assumed in considerations of fuel coolability would be reduced for the KALIMER-600 design.

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