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Preliminary Assessment of a Debris Bed Cooling Performance for Demonstration Sodium-cooled Fast Reactor

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1. Introduction

In the case of the sodium-cooled fast reactor such as KALIMER-600, Hypothetical Core Disruptive Accident (HCDA) attributed from mass nuclear fuel melting is unlikely to occur due to defense in depth concepts to meet requirements of redundancy and diversity.

Multiple faults such as loss of flow, loss of heat sink, or transient overpower without scram are to lead rising the power level until cladding failure as reactivity increasing. The fact that metallic fuel melts at a lower temperature than the cladding allows significant in-pin-fuel motion to occur prior to cladding failure. Also, the combination of Doppler and axial expansion feedback and negative feedback associated with the in-pin fuel relocation prevents the reactivity from reaching prompt critical. Finally, the resulting reactivity and power reductions help prevent fuel temperatures from rising more than the fuel melting temperature.

It is more difficult to occur HCDA in a metallic fueled core because reactor power and heat removal capability is maintained in balance by inherent safety characteristics

However, for the future design of sodium-cooled fast reactor, the evaluation of the safety performance and the determination of containment requirements may be worth considering due to the triple-fault accident sequences of extremely low probability of occurrence that leads to core melting.

For any postulated accident sequence which leads to core melting, in-vessel retention of the core debris will be required as a design requirement for the future design of sodium cooled fast reactor. Also, proof of the capacity of the debris bed cooling is an essential condition to solve the problem of in-vessel retention of the core debris.

Accordingly, evaluation of a packed debris bed cooling performance with single phase flow for demonstration sodium-cooled fast reactor was carried out for proof of the in-vessel retention of the core debris.

2. Concept of Core Catcher for Demonstration SFR

For the in-vessel retention of the core debris, control of melted core, and preventing the spread of the accident, concept of tray type core catcher is introduced. In the case of a pool type nuclear reactor, core catcher is installed beneath the core to ensure proper cooling and accumulation of core debris, typically. Fig. 1 shows the schematic diagram of a tray type core catcher installed at the bottom of the core structure.

Material of core catcher for demonstration SFR is the same as that of the internal structure that is STS316SS and diameter and chimney height of core catcher is 4.6m and 30.3cm, respectively.

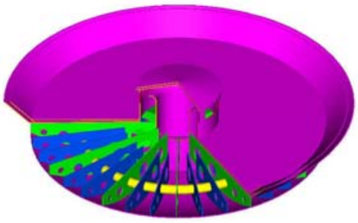

Fig. 1. Schematic diagram of a core catcher

3. Evaluation of a Debris Bed Cooling Performance

3.1 Cooling performance with Conduction alone

If the heat flows through the packed debris bed of Fig. 2 by conduction alone, the amount of heat transferred by conduction through upper surface was the same as the amount of heat generation of the packed debris bed. In this case, the temperature difference between the top and bottom of the packed debris bed can be expressed as follows.

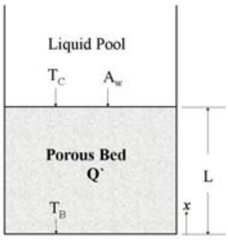

Fig. 2. Schematic diagram of a packed debris bed

$$-kA_w\frac{dT}{dx}=Q'V \qquad (1)$$

where k is the conductivity of the sodium and debris particles mixed bed, Q' is the heat generation rate per unit volume of the packed debris bed.

We predicted the coolable thickness of a packed debris bed based on Eq. (1) and the results was shown in Fig. 3. In this case, we assumed that the debris was accumulated on the core catcher uniformly. Also, the porosity and decay heat generation were 0.9 and 2% of norminal power density, respectively. In Fig. 3, coolable thicknesses of the packed debris bed with inner and whole core meltdown case were 42.7cm and 41.9cm respectively. In the case of the whole core meltdown, coolable thickness was about 15% of that of the packed debris bed. This is far less than the 277.6cm bed thickness so that it is concluded that the packed debris bed is not coolable by a conduction alone.

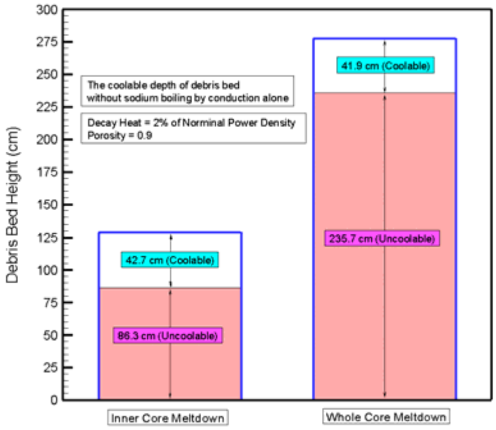

Fig. 3. Coolable thickness with core meltdown type

3.2 Cooling performance with Single Phase Flow

It is well known that the pressure loss during one-dimensional flow through a packed bed of granular material is given by the sum of two terms: a viscous energy loss term, proportional to the fluid velocity, and an inertial loss term, proportional to the velocity squared, i.e., it is represented by Eq (2) so called Forchheimer equation.

$$\frac{\Delta P}{L}=\frac{\mu}{a}v+\frac{\rho}{b}v^2 \qquad (2)$$

Where △P is the piezometric pressure loss, L is the packed bed height, v is the superficial fluid velocity, and a and b are empirical parameter.

One form of the Eq. (2) widely used by chemical engineers was given by Ergun[1]. Macdonald[2] introduced the modified Ergun equation additionally considering the roughness of particle surface. Also, Hardee and Nilson[3] derived an analytical model of a single phase convective roll cell using a first order approximate technique.

Macdonald's equation and Hardee and Nilson's convective roll cell model can be combined to form Eq. (3) which can determine unknown v in Eq. (2), the superficial fluid velocity.

$$v^3+\frac{180\mu(1-\varepsilon)}{R\rho D_e}v^2-\frac{Q'L\beta g D_e\varepsilon^3}{R\rho C(1-\varepsilon)}=0 \qquad (3)$$

where L is the debris bed thickness, μ is dynamic viscosity, D_e is the equivalent particle diameter, R is the roughness of particle surface, g is the acceleration of gravity, and β is the thermal expansion coefficient.

For evaluation of the ability of post accident heat removal with demonstration SFR, the sensitivity studies were performed with porosity, equivalent diameter, and roughness.

Calculation results show that 21 sets (inner core meltdown: 5 sets, whole core meltdown case: 16 sets) among 300 sets were uncoolable by single phase flow because sodium temperature above the debris bed exceed the sodium boiling temperature. Table 1 shows uncoolable parameter sets of whole core meltdown case.

Table 1. Uncoolable parameter sets of whole core meltdown case

	D_e (cm)	ε	R	ΔT (℃)
Inner Core Meltdown	0.09	0.5	1.8	602.443
	0.09	0.5	2.275	621.384
	0.09	0.5	2.75	638.942
	0.09	0.5	3.375	660.327
	0.09	0.5	4	680.11
	0.09	0.6	1.8	408.178
	0.09	0.6	2.275	425.965
	0.09	0.6	2.75	442.11
	0.09	0.6	3.375	461.413
	0.09	0.6	4	478.981
	0.18	0.5	1.8	382.208
	0.18	0.5	2.275	402.79
	0.18	0.5	2.75	421.193
	0.18	0.5	3.375	442.921
	0.18	0.5	4	462.485
	0.27	0.5	4	384.903

4. Conclusions

We performed a preliminary evaluation of cooling performance of a particulate debris bed, which is accumulated on a core catcher with a single phase flow when an HCDA occurs.

Results of the sensitivity studies showed that the coolability of the packed debris bed depended on how large the debris diameter and porosity were.

For accurate evaluation of cooling performance of a debris bed, experimental data such as debris generation mechanism will be needed and two phase flow analysis will be needed because the single phase flow cooling fails.

REFERENCES

[1] Ergun, S. , Fluid Flow through Packed Columns, Chemical Engineering Progress, 38, 9-94, 1952.

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[3] H. C. Hardee and F. H. Nilson, Natural Convection in Porous Media with Heat Generation, Nuclear Science and Engineering, Vol. 63, pp 119-132, 1977.