*Transactions of the Korean Nuclear Society Spring Meeting*
*Gyeongju, Korea, May 29-30, 2008*

# Numerical Analysis of Characteristics of a Particulate Debris Bed Coolability with Single Phase flow

Jewhan Lee[a*], Chungho Cho[b], Yong-bum Lee[b], Soon-heung Chang[a]
[a]*Korea Advanced Institute of Science and Technology, Gusungdong, Yuseong-gu, Daejeon 305-701, Republic of Korea*
[b]*Korea Atomic Energy Research Institute, 150 Deokjin-dong, Yuseong-gu, Daejeon 305-503, Republic of Korea*
[*]*Corresponding author: krazer@kaist.ac.kr*

## 1. Introduction

Designed on the basis of defense-in-depth concept, liquid metal cooled reactor, such as KALIMER-600 is unlikely to undergo the hypothetical core disruptive accident (HCDA). However in case of accident, there exists a possibility of re-criticality and vessel melting when core melt-down occurs. For this reason, the analysis on the ability of post-accident heat removal (PAHR) should be preceded. As a part of this, single phase flow coolability analysis of the particulate debris bed formed at the top of core catcher has been performed to achieve in-vessel fuel retention. The forming process of particulate debris bed is described and single phase cooling model with numerical results are presented.

## 2. Methods and Results

### *2.1. Formation of Particulate Debris Bed*

In case of HCDA condition, large amount of reactivity insertion is estimated, leading to a coolant dry-out. Then, the core melting is followed and it causes damage to the cladding materials. The molten fuel will be ejected and dispersed through the coolant flow channels. Nishimura et al. [1] conducted an experiment of molten aluminum dropping into a sodium pool and showed that the higher the temperature and the pressure at which molten fuel is ejected, the smaller the formed particle size is. Swift and Baker [2] and Rahman et al. [3] also agree with their own experiments in like manner. Based on these experiments, we can expect the formation of small particles when the fuel melts and the cladding is damaged, because of high pressure ejection of molten fuel due to the pressure of gas inside the fuel rod.

The behavior of molten fuel flowing down through the structure to the core catcher area can be described in two ways, according to the diameter of the sub-assembly channel. In the case of large channel diameter, molten core can reach the core catcher without any difficulties. In the case of small channel diameter, especially wire-wrap structure in KALIMER-600, molten core can stricture the sub-assembly channels and take much longer time to reach the core catcher. And also, the formed particle size is expected to be much bigger relatively. This paper is about to analyze the characteristics of single phase flow cooling by natural convection in early state of particulate debris bed formation.

### *2.2. Conduction-Only Cooling Model*

If we assume there is no natural convection, the temperature difference between top and bottom of the particulate debris bed which is cooled by conduction only can be expressed as follows.

$$\Delta T = \frac{QL}{2k} \tag{1}$$

where k is the conductivity of sodium and debris particles mixed bed. The coolable depth of bed by conduction alone is shown in Fig. 1. In Fig. 1 arrow-marked part is the coolable depth and the grey is the uncoolable part. For the case of inner core, inner+middle core, and whole core meltdown, it was only 2.8%, 1.5%, and 1.0% of the bed respectively. This indicates that it is impossible to cool the bed by conduction only.

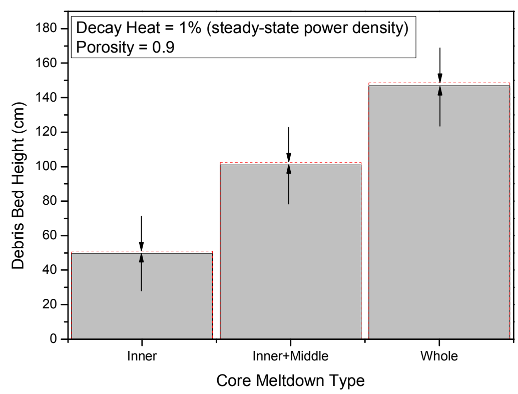


Fig. 1. The coolable depth by the conduction alone.

### *2.3. Single Phase Flow Cooling Model*

The pressure drop of porous medium which was created by the inter-reaction of molten core and coolant can be described by the terms of viscous resistance and inertial resistance. This is expressed as Forchheimer's equation.

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

Based on this equation, Ergun [4] developed a popular equation.

$$\frac{\Delta P}{L} = \frac{150\mu}{\phi_p^2 d_p^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} V + \frac{1.75\rho}{\phi_p d_p} \frac{(1-\varepsilon)}{\varepsilon^3} V^2 \qquad (3)$$

where P is the pressure, L is the debris bed depth, μ is dynamic viscosity, ρ is the density, ε is the porosity of debris bed, d is the equivalent particle diameter, φ is the sphericity of particle and V is the superficial velocity. Macdonald et al. [5] and Hardee and Nilson [6] derived a way that we can estimate the temperature difference between top and bottom of the particulate debris bed formed in the core catcher.

### *2.4. Results*

For calculation, we used the boundary conditions as shown in Table 1. In the Fig. 2, the result of the analysis with 3 different core meltdown types, which are inner, inner+middle, and whole is shown.

Table 1. Boundary conditions

| | Inner | Inner+Mid. | Whole |
|---|---|---|---|
| Power Density (W/cm$^3$) | 179 | 171 | 152 |
| Molten Pool Depth (cm) | 5.12 | 10.24 | 14.85 |
| Debris Bed Height (cm) | 51.2 | 102.4 | 148.5 |
| Porosity(ε) | 0.9 | | |
| Equivalent Diameter ($D_e$) | 0.18cm | | |
| Roughness (N) | 2.75 | | |
| Theremal Exp. Coeff. (β) | 0.00031 K$^{-1}$ | | |
| Gravitational Accel. (g) | 981 cm/s$^2$ | | |
| Density (ρ) | 0.78 g/cm$^3$ | | |
| Specific Heat (C) | 1.26 J/gK | | |
| Temp. at the bottom | 550°C | | |
| Boiling Temp. | 920°C | | |

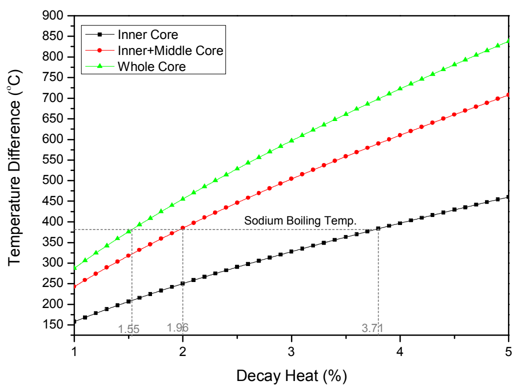


Fig. 2. Debris bed coolability with variation of core meltdown type.

In the case of inner core meltdown, the decay heat of top part reaching boiling point is about 3.71%. For inner+middle and whole core meltdown, the decay heat is 1.95% and 1.55% respectively. The required delay time for debris bed cooling is about 40 sec, 17 min, and 45 min respectively considering the decay heat per time.

In case of KALIMER-600, molten fuel is estimated to reach the core catcher in about 20 minutes, because of wire-wrap structured sub-assemblies and complicated orifices. The corresponding decay heat is about 2% of the normal operation. Therefore it is possible to cool down the inner and inner+middle core meltdown case, but the whole core meltdown case.

## 3. Conclusions

In this study, we performed a coolability analysis of the particulate debris bed, which is accumulated at the core catcher, with single phase flow when the HCDA occurs. Modified Ergun's equation was used to see the temperature difference of the debris bed. The result showed that inner and inner+middle core meltdown cases were coolable. To extend this study, experimental data will be needed and other means of verification will be needed. Furthermore, two phase flow analysis will be needed if the single phase flow cooling fails.

## REFERENCES

[1] Satoshi Nishimura et al., Transformation and Fragmentation Behavior of Molten Metal Drop in Sodium Pool, Nuclear Engineering and Design, Vol 237, Issue 23, pp2201-2209, 2007.

[2] Swift D. L., Baker Jr. L., Experimental Studies of the High Temperature Interaction of Fuel and Cladding Materials with Liquid Sodium, ANL-7120, pp839-847, 1965.

[3] Rahman et al., Experimental Investigation of Molten Metal Freezing on to a Structure, Experimental Thermal and Fluid Science, Vol. 32, Issue 1, pp198-213, 2007.

[4] S. Ergun, Fuel Flow Through Packed Columns, Chemical Engineering Science, 1952.

[5] I. F. Macdonald et al., Flow Through Porous Media – the Ergun Equation Revisited, Industrial and Chemical Engineering Vol. 18, 1979.

[6] H. C. Hardee and F. H. Nilson, Natural Convection in Porous Media with Heat Generation, Nuclear Science and Engineering, Vol. 63, pp119-132, 1977.