Analysis of Long-term Ex-vessel Debris Coolability with a Simple Model

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Introduction

- Ex-vessel Severe Accident

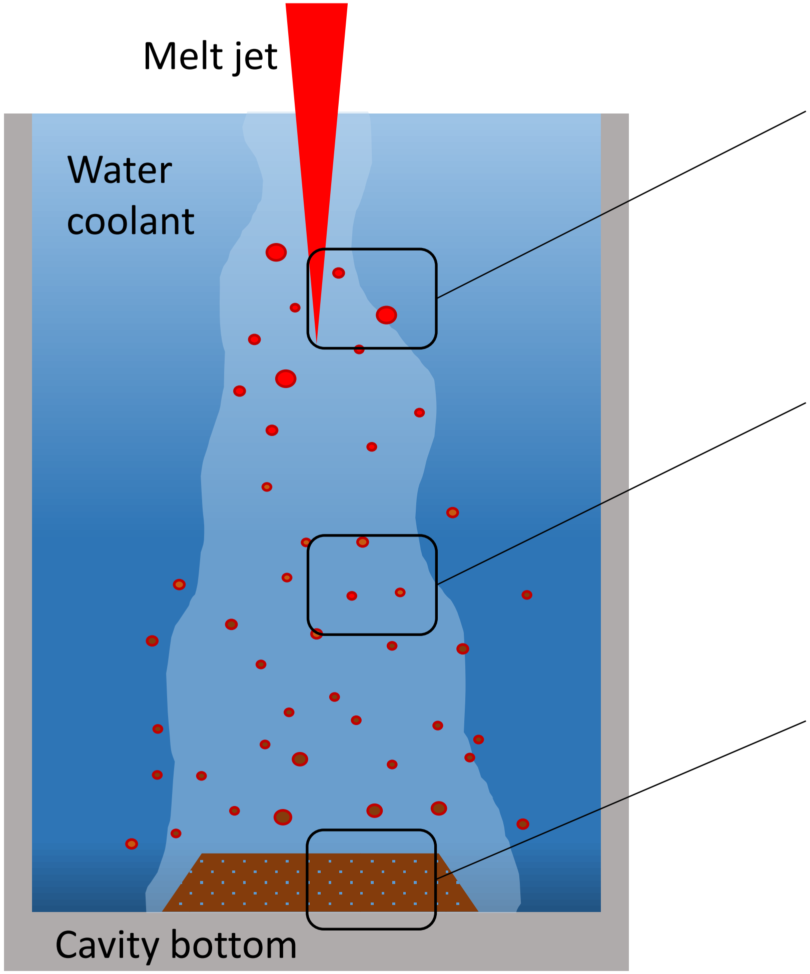

Fig. Scenario of ex-vessel severe accident in nuclear power plant

✓ Fuel Coolant Interaction (FCI)
- particle fragmentation
- steam explosion

✓ Particle sedimentation
- natural circulation
- two phase flow advection

✓ Debris particle bed
- **particle agglomeration**
- molten core-concrete interaction (MCCI)

Introduction

- Particle agglomeration in the FARO experiment

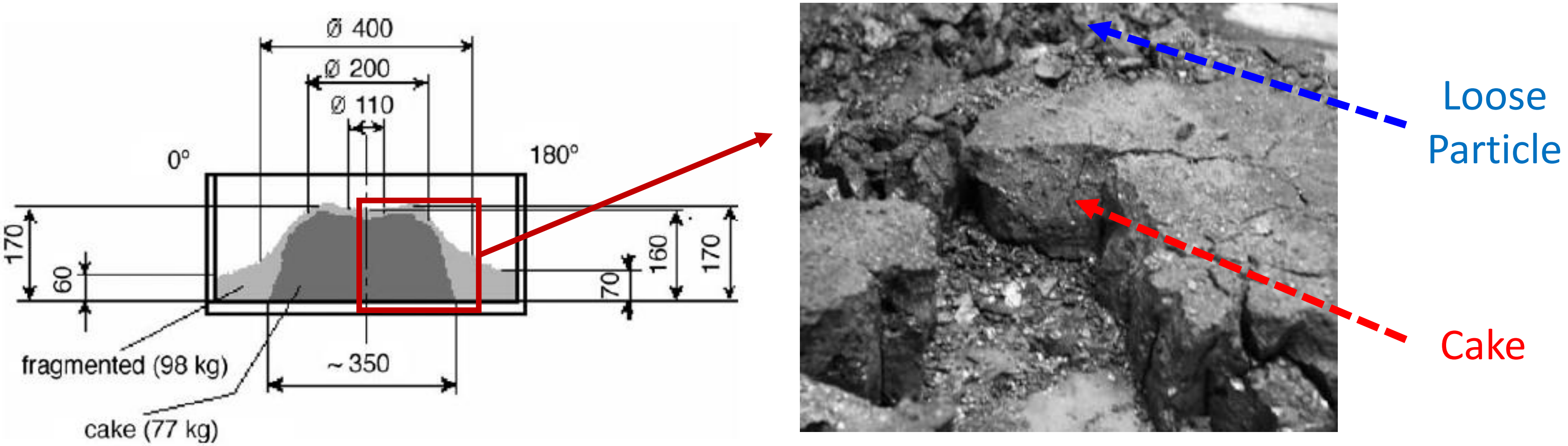

Fig. Configuration of debris bed in mm (left) and photographs of debris bed (right) in FARO L-28 test (Magallon, NED, 2006)

✓ The effect of various parameters (melt composition, system pressure, water depth, subcooling temperature) was investigated

✓ The detail mechanism of cake formation is not shown…

✓ '**Particle sintering**' concept (Hwang et al., NED, 2016 [In Rev.])

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Research objective

- The effect of input parameters on the long-term ex-vessel cooling in reactor scale
    - ✓ Modification of the original Hwang’s model
    - ✓ Selection of input parameters and range
    - ✓ Parameter sensitivity tests on the long-term period (~ 50 hrs)

Modeling of Ex-vessel SA

1) Particle falling period

- ✓ Fully fragmented debris particle is assumed.

- ✓ Jet breakup length (L_b) using taylor-type correlation (Moriyama et al., JAERI-Research, 2005)

$$\frac{L_b}{D_{Ji}} = C_J N_\rho^{1/2}$$

L_b: jet breakup length
D_{Ji}:initial jet diameter
C_J: Jet breakup coefficient (~ 10)
N_ρ: ratio of melt to liquid water densities

- ✓ Falling time considering vapor flow effect (empirical correction factor from experiment data (Moriyama et al., ICONE23, 2015))

$$\Delta t_t' = \beta \Delta t_t$$
$$\beta = 1 - \exp(-\gamma d_p)$$

$\Delta t_t'$: falling time considering vapor flow
Δt_t: falling time without vapor flow
γ: fitting parameter for effective transit time
d_ρ: particle diameter

Modeling of Ex-vessel SA

1) Particle falling period **(modified)** → **Particle falling time data**

- ✓ Generalization of ‘particle size distribution’

Test-specific

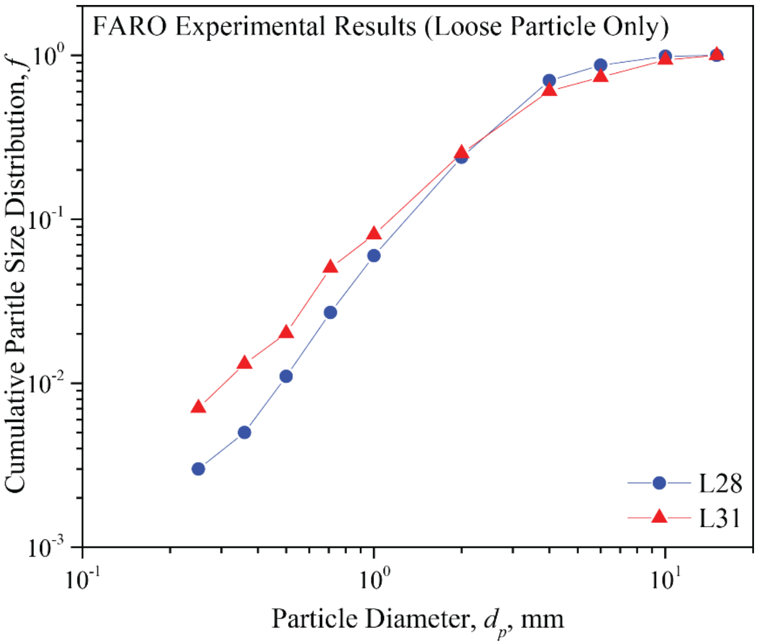


Fig. Cumulative particle size distribution in FARO L-28 and L-31 tests (Hwang et al., NED, 2015)

$$F = 1 - \exp\{-\left(\frac{D_p}{D_e}\right)^n\}$$

$$D_e = \frac{D_{MM}}{(log2)^{\frac{1}{n}}} \qquad n = 1.5$$

F: cumulative mass fraction of particles smaller than a diameter D_p

D_{MM}: mass median diameter

D_e: absolute size constant

n: Rosin-Rammler distribution constant

Modeling of Ex-vessel SA

2) Bed formation period

- ✓ Heat transfer in water pool (film boiling + radiation)
- ✓ Heat conduction only in inner part (assumption)
- ✓ Phase change using enthalpy method
  (Voller et al., Int. J. Heat Mass Transf., 1981)

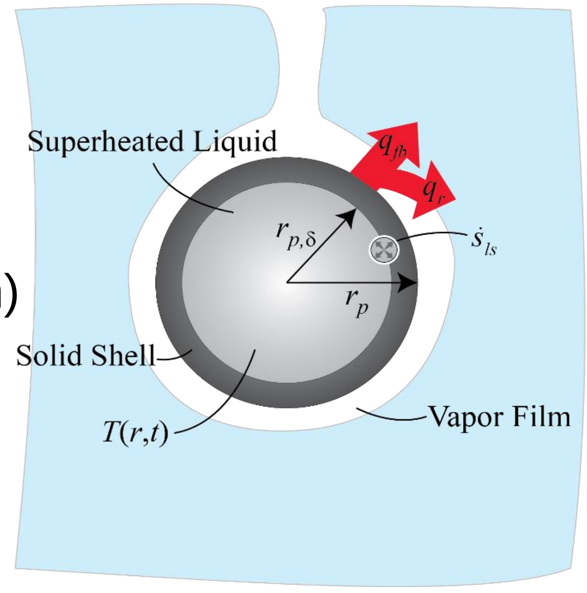


Fig. Heat transfer in water pool
(Hwang et al., NED, 2015)

$$\frac{\partial h}{\partial t} = \frac{\alpha}{r^2}\left[\frac{\partial}{\partial r}\left(r^2 \frac{\partial T}{\partial r}\right)\right]$$

$$h = \begin{cases} c_p T, & T < T_{sl} \\ c_p T_{sl} + \Delta h_{sl}/2, & T = T_{sl} \\ \Delta h_{sl} + c_p (T - T_{sl}), & T > T_{sl} \end{cases}$$

h_{sl}: specific enthalpy of fusion
T_{sl}: solid-liquid phase change temperature
α: thermal diffusivity
r: radial direction coordinate

Modeling of Ex-vessel SA

2) Bed formation period

✓ the criteria for particle remelt (~ Normalized excessive enthalpy)

$$\Delta h_{ex}^{*} = \frac{\frac{1}{V}\int_{V} h\,dV}{c_p T_{sl} + \Delta h_{sl}}$$

average enthalpy of each particle size

enthalpy of fusion

- $\Delta h_{ex}^{*} \geq 1$
  → remelting phase (Remelting)
- $\Delta h_{ex}^{*} < 1$
  → remain solid particle (loose particle)

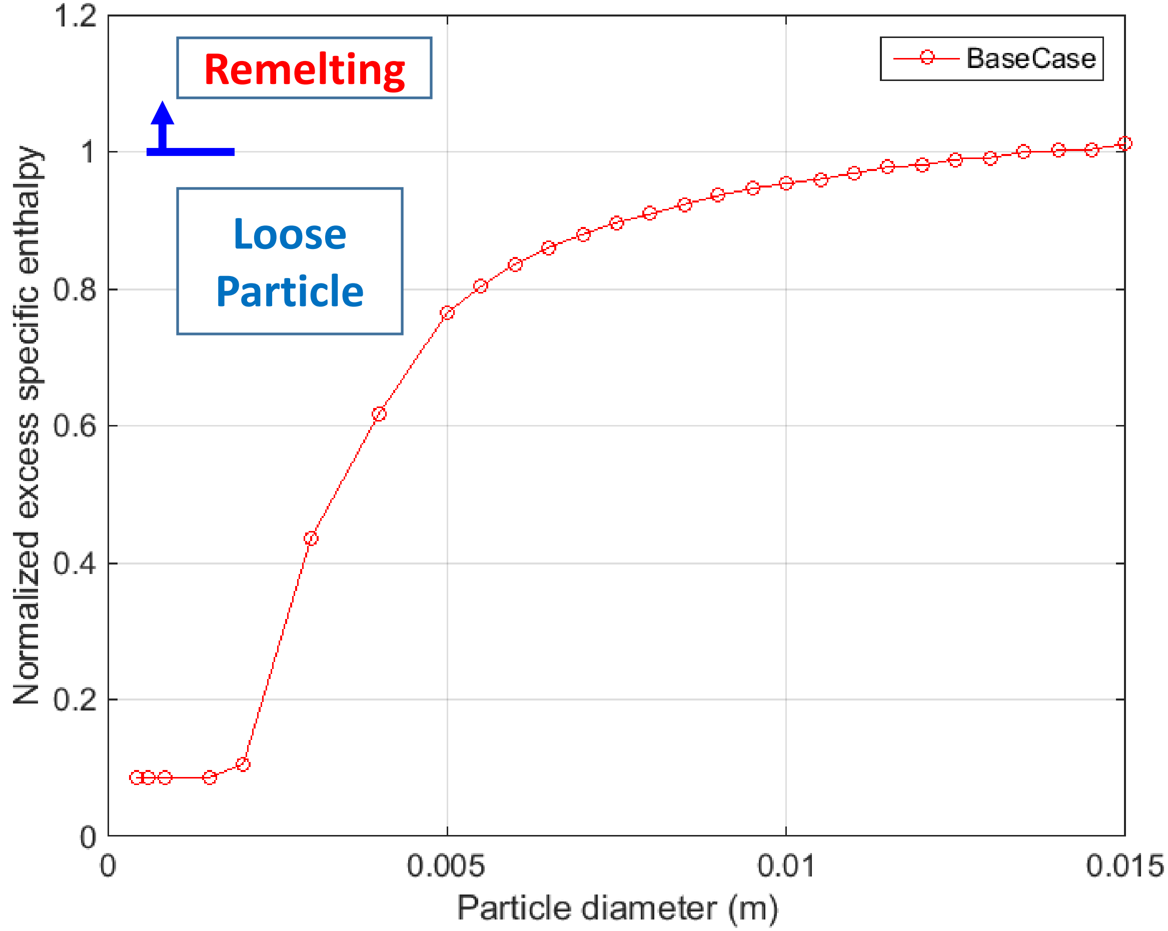
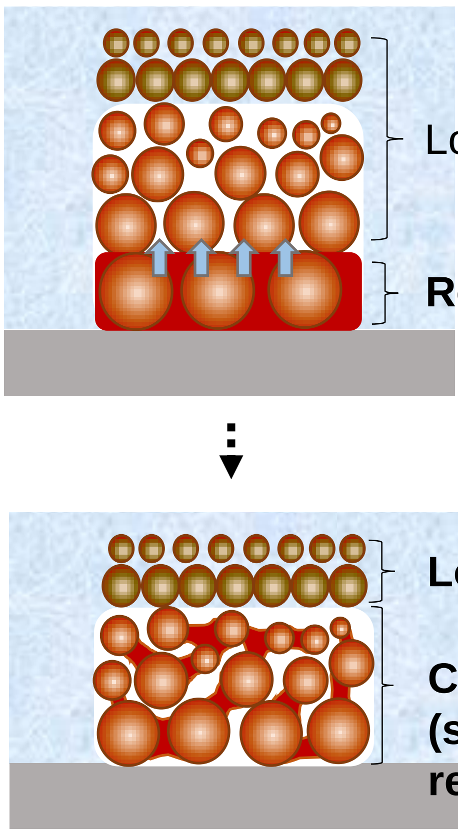


Fig. Normalized excessive enthalpy according to particle size

Modeling of Ex-vessel SA

2) Bed formation period → The fraction of cake

✓ The prediction of cake fraction from experimental data (**sintering**)



1) Remelting liquid smears into particle region.
2) Some fraction of loose particle are sintered by remelt liquid
3) The fraction of cake (or loose particle can be predicted through the sintering process.

Fig. Comparison between cake fraction from experiment and remelt liquid from numerical prediction

Modeling of Ex-vessel SA

3) Long-term cooling period

- ✓ **Local volume average** calculation on loose particle & cake

$$\frac{\partial < h >}{\partial t} = \frac{< k >}{< \rho >}\frac{\partial^2 < T >}{\partial z^2}$$

k: thermal conductivity
ρ: density of debris particle
z: vertical direction coordinate
<>: local volume average

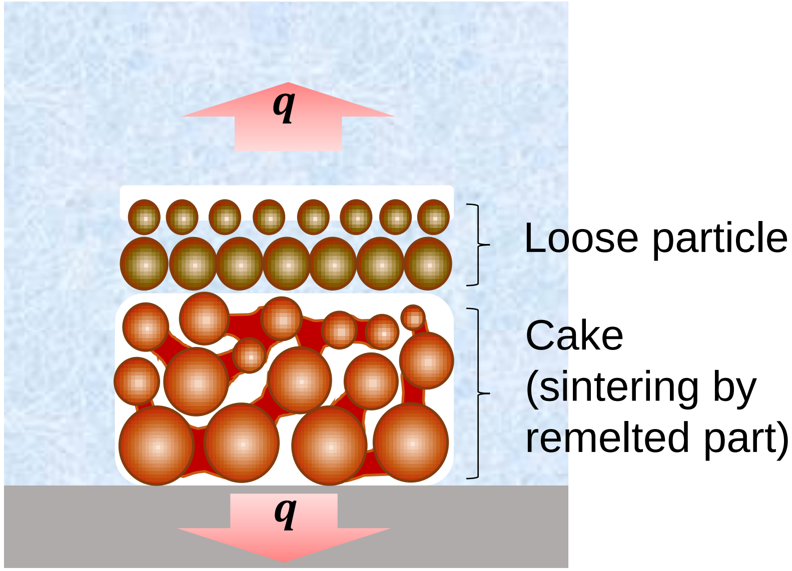


Fig. Long-term cooling period

- ✓ **Pool-boiling correlations** for plain surface was assumed in top surface.
- ✓ The **radiant thermal conductivity** for porous medium (Kaviany, 1995) is considered in cake thermal conductivity

$$< k > = < k_s > + < k_r >$$

Modeling of Ex-vessel SA

3) Long-term cooling period

✓ Porosity reduction model **(modified)**

- Originally fixed the porosity of loose particle and cake with same value (0.3 ~ 0.6 assumed)
- Cake porosity decreases by the volume of remelt liquid

✓ Decay heat model (Shwageraus et al., IYNC08, 2008) **(modified)**

$$\frac{\boldsymbol{P(t_s)}}{\boldsymbol{P_0}} = 1.250 \times 10^{-1} \times \boldsymbol{t_s}^{-0.2752} \quad \text{for} \quad 10^2 \le t_s \le 10^6 \ s$$

P_0: constant power for an infinite period before shut down
t_s: time duration after shutdown

Input parameters & Ranges

- 10 initial/boundary conditions & 5 model parameters

Initial/Boundary condition parameter*1	Range	Basecase
Water temperature [K], **WT**	300 ~ 350	300
Jet diameter [m], **JD**	0.2 ~ 0.28	0.2
Jet velocity [m/s], **JV**	6 ~ 12	6
Water pool depth [m], **WD**	3.5 ~ 5.6	5.6
Melt initial temperature [K], **MT**	2900 ~ 3400	3150
Melt mass [t], **MM**	120 ~ 145	145
Porosity, **PO**	0.3 ~ 0.6	0.45
Accumulation area [m^2], **AA**	21 ~ 84	42
Duration after shutdown [hr], **TAU**	2 ~ 20	2
Loose particle conductivity [W/mk], **KLP**	490 ~ 1100	676.75
Model parameter	**Range**	**Basecase**
Jet breakup constant, **CJB*2**	0.5 ~ 0.9	0.7
Vapor velocity constant, **CV*3**	172.3 ~ 220.6	172.3
View factor, **VF*4**	0.1 ~ 0.5	0.3
Sintering effect constant, **CS*5**	5 ~ 20	12
Particle size constant, **CD*6**	1.428 ~ 0.572	1

*1 Ranges are defined based on **APR1400**.

*2 Modifies **the particle starting position** in the jet breakup length.

*3 Modifies the fitting parameter (γ) in the **vapor flow effect**.

*4 Modifies the view factor in **the radiation heat transfer**.

*5 Modifies the fraction of cake by **sintering effect** using the constant for proportionality.

*6 Modifies the **mass median diameter** (D_{MM} → D_{MM} / CD)

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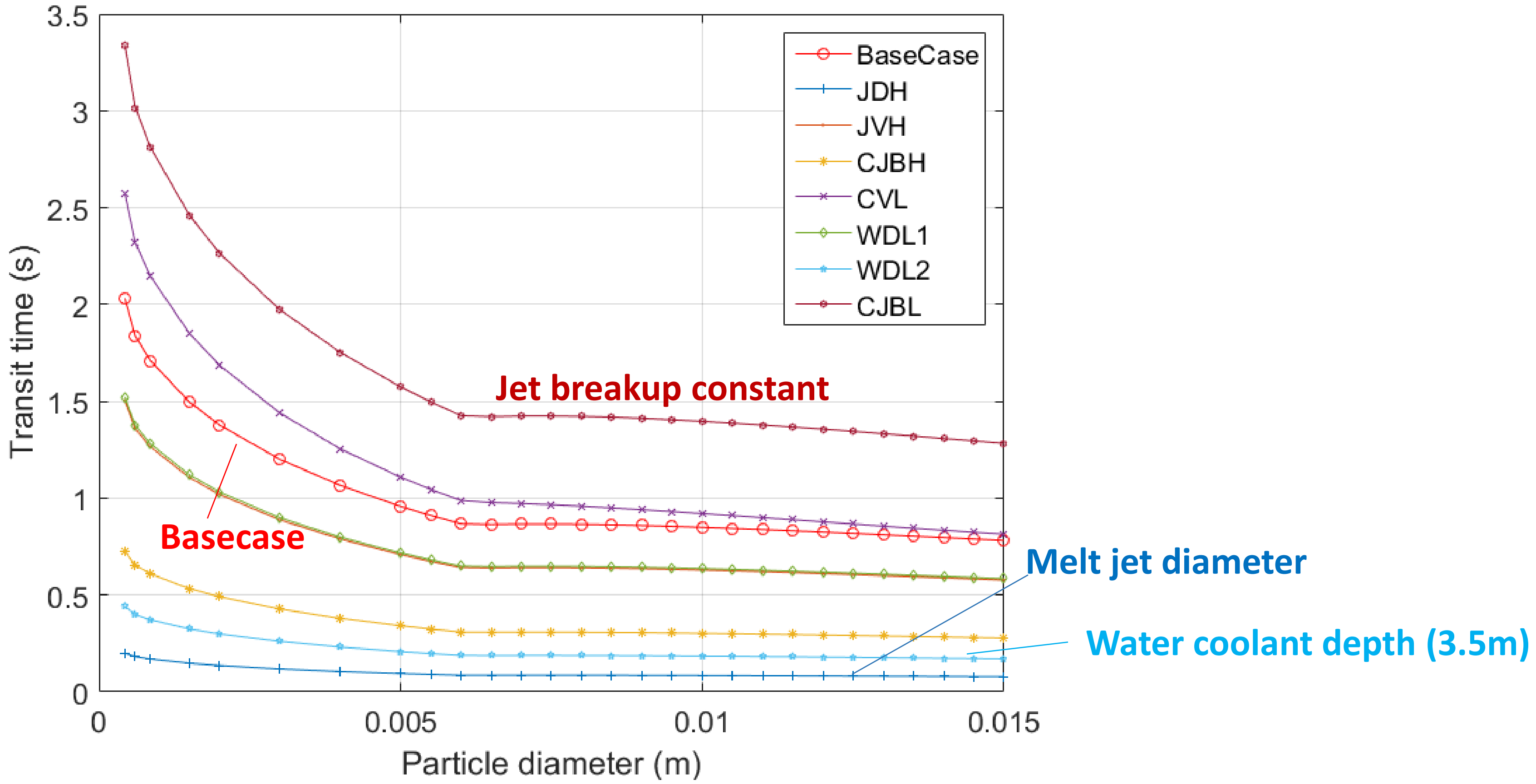
Results: Particle falling period

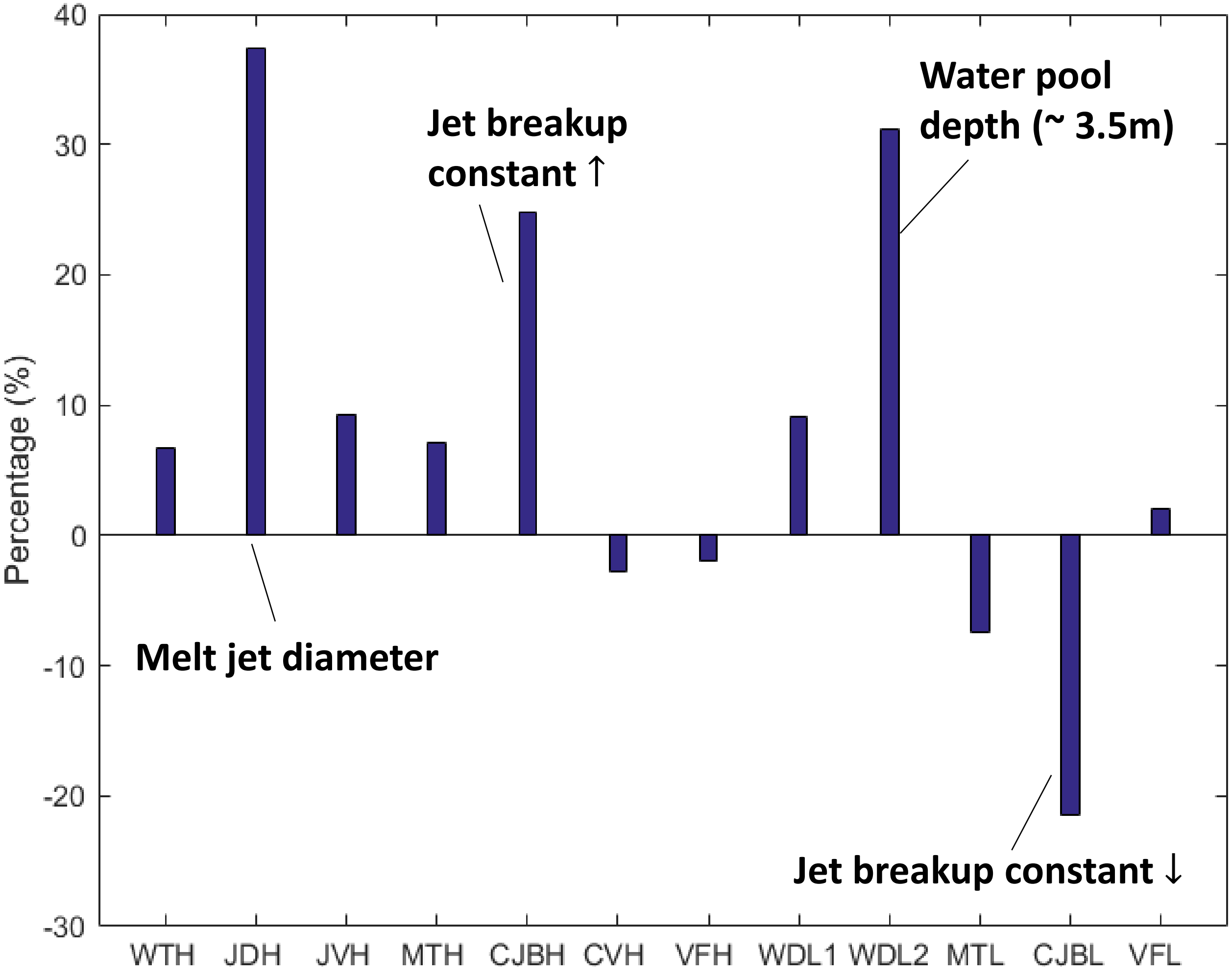
- **Falling time according to debris particle size**



- Melt jet diameter (JDH), water pool depth (WDL2), and jet breakup constant (CJBH, CJBL) show large variation with Basecase.

Results: Debris bed formation period

- **Fraction of remelt liquid** (~ **Normalized excess specific enthalpy**)
- **Comparison with 'basecase' on 5mm particle region**

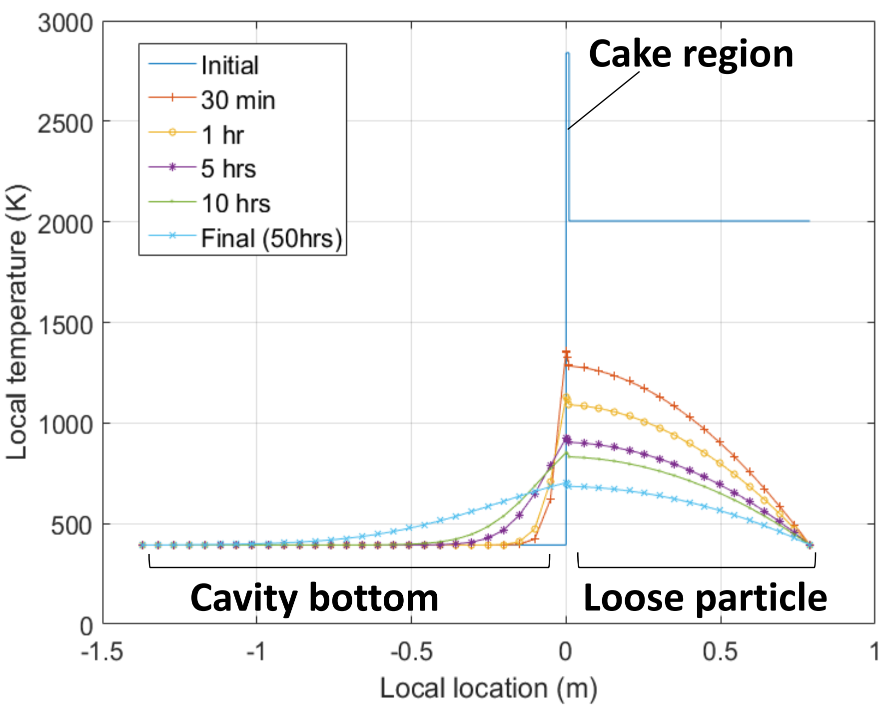


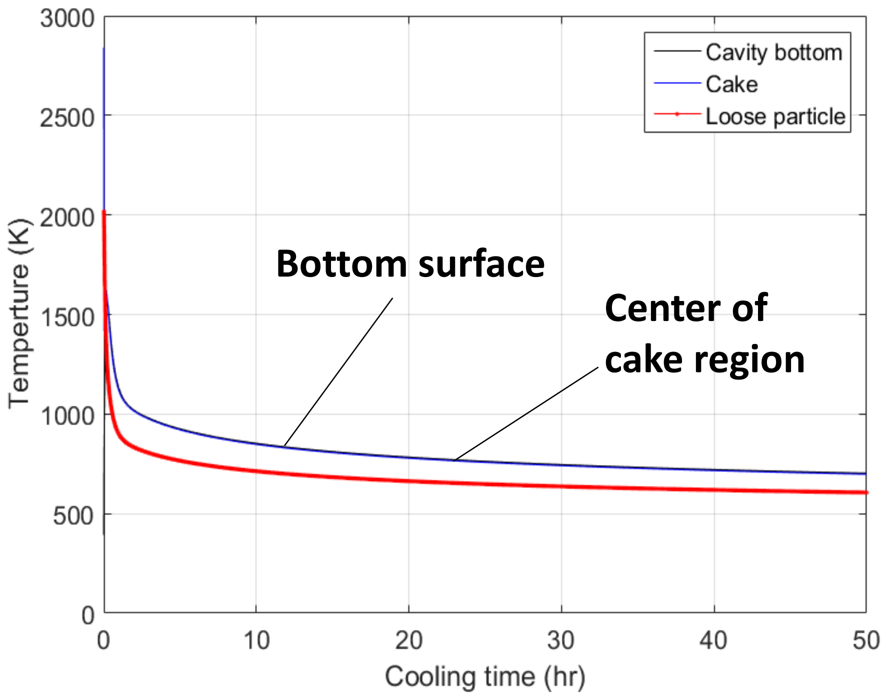
- Melt jet diameter, Jet breakup constant, and water pool depth still show large variation with basecase.

- Other input cases show the variation less than 10%.

Results: Long-term cooling period

- **50 hours calculation for each input cases**
- **gradually decreasing trend with having maximum temperature in cake region**

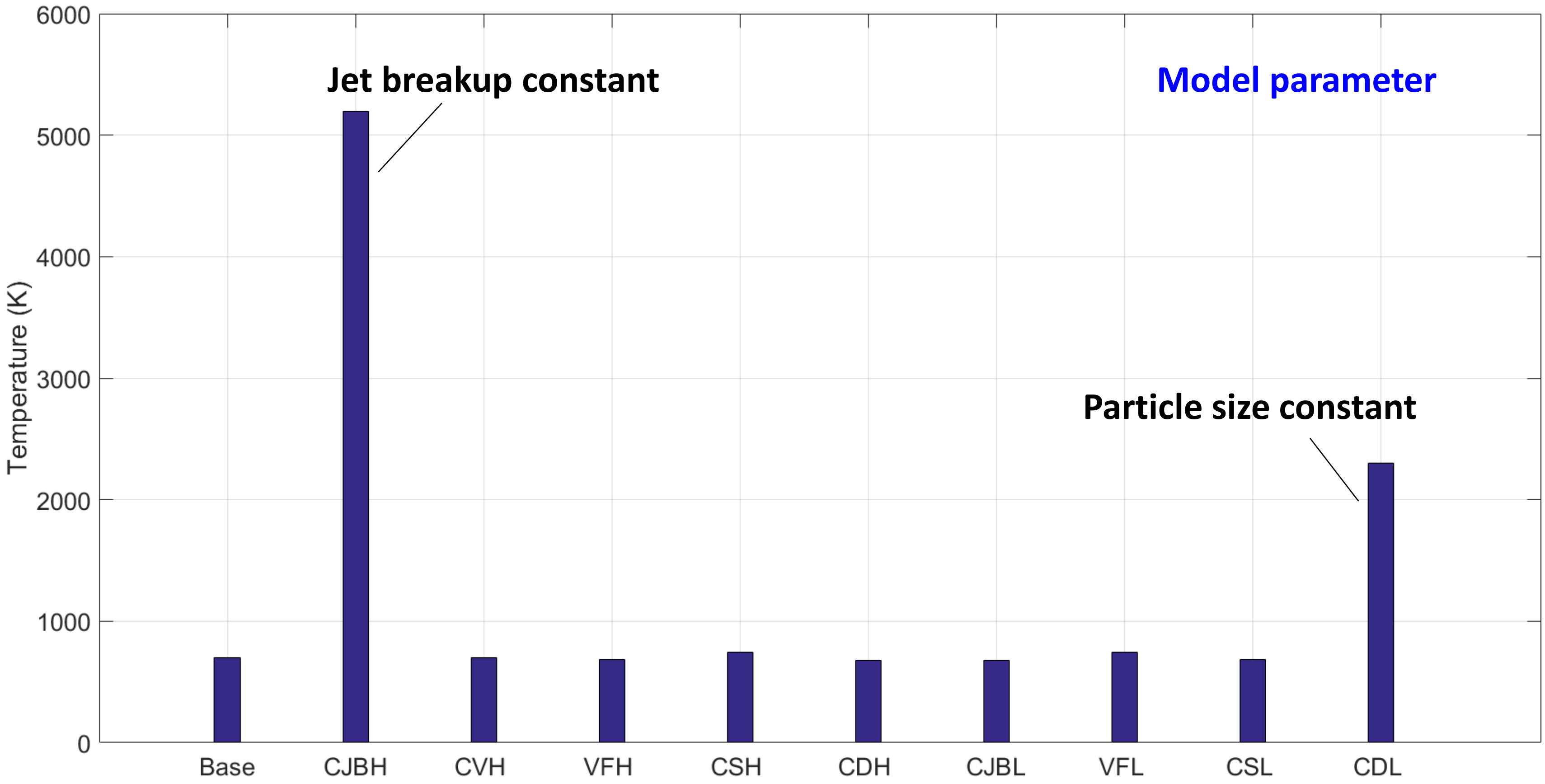




Spatial temperature distribution (left) and the history of temperature (bottom surface, centers of the cake and loose particle debris) (right) for the basecase

Results: Long-term cooling period

- Maximum temperature at 50 hrs (for 15 input parameters)



- Melt jet diameter, water pool depth, debris particle accumulation area, jet breakup constant, and particle size constant show high maximum temperature

Conclusions

- The effect of input parameters on the long-term ex-vessel cooling in reactor scale was investigated.
- The application of particle distribution model and decay heat model to Hwang's model was performed.
- From the results, the effect of **melt jet diameter**, **water pool depth**, **debris particle accumulation area**, **particle starting position (~ jet breakup constant), and particle size distribution (~ size constant)** is larger than other input parameters.
- Further uncertainty studies for above input parameters for the quantification of accident scenario.

Thank you ☺