IAEA Tec Mtg
Technical Meeting on Phenomenology and
Technologies Relevant to In-Vessel Melt Retention and
Ex-Vessel Corium Cooling
@SNERDI(SHANGHAI)

Improvement of Fuel-Coolant Interaction Models for Ex-Vessel Debris Coolability Evaluation

JAEA
Toshinori MATSUMOTO*, Ryuhei KAWABE,
Tomoyuki SUGIYAMA, Yu MARUYAMA

Background and Objectives

Background

- MCCI

Molten Core Concrete Interaction
Threats of CV failure

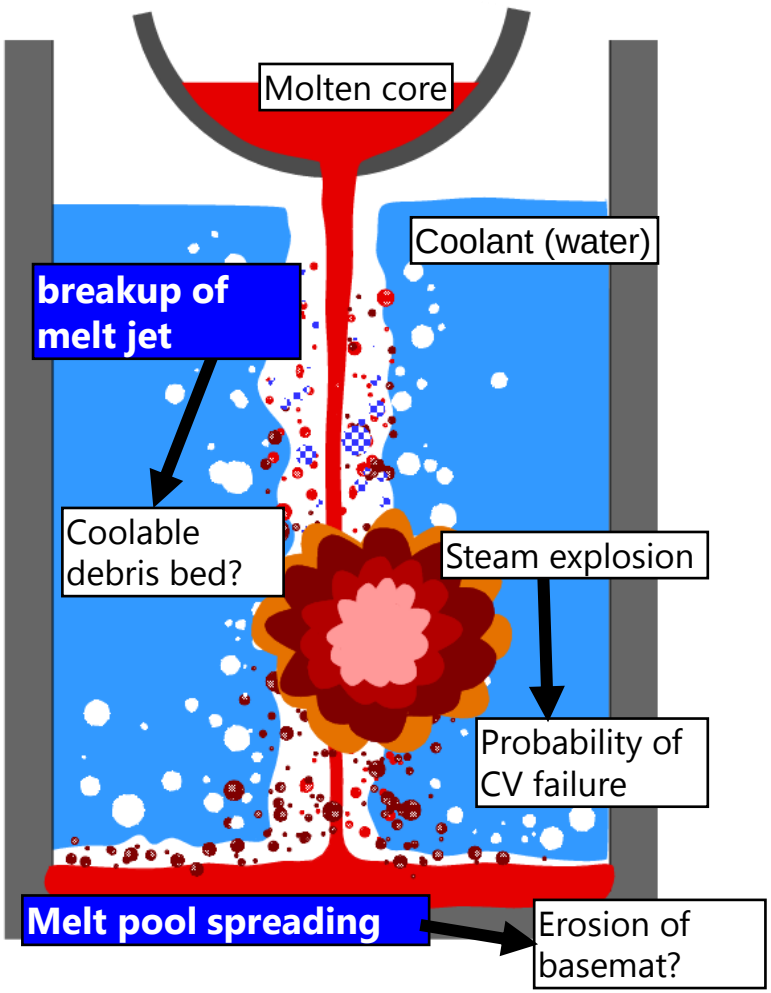
- Stabilization of MCCI

Requirement by specified current regulation of Japan

- Water injection into CV prior to the melt release from RPV to CV

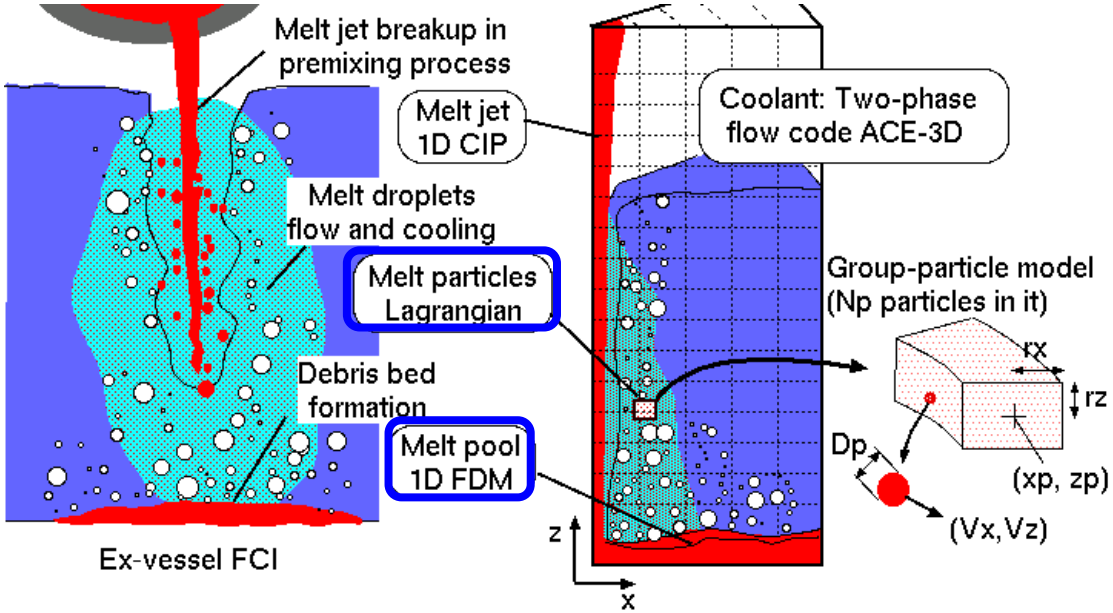
Objectives

- More realistic estimation of consequence of melt release into Cavity/ Pedestal space in CV
- Evaluation of probability of MCCI/ CV failure under various water depth conditions



Brief Description of JASMINE Code

- FCI: Fuel Coolant Interaction, simulation including steam explosion
- Premixing phase : melt jet (1D CIP), melt pool (1D FDM), particle group (Lagrange)
- Two-phase flow : water, vapor and non-condensable gas (two-fluid model, modified version of ACE-3D code)



Improvements of JASMINE

- Jet breakup particle diameter
  Rosin-Rammler distribution: Cumulative mass fraction function
- Melt pool crust formation
  Crust growth from top and bottom side of melt pool

Improvement relating with jet breakup

Cumulative mass fraction of breakup particles
(Moriyama, et. al., 2005)

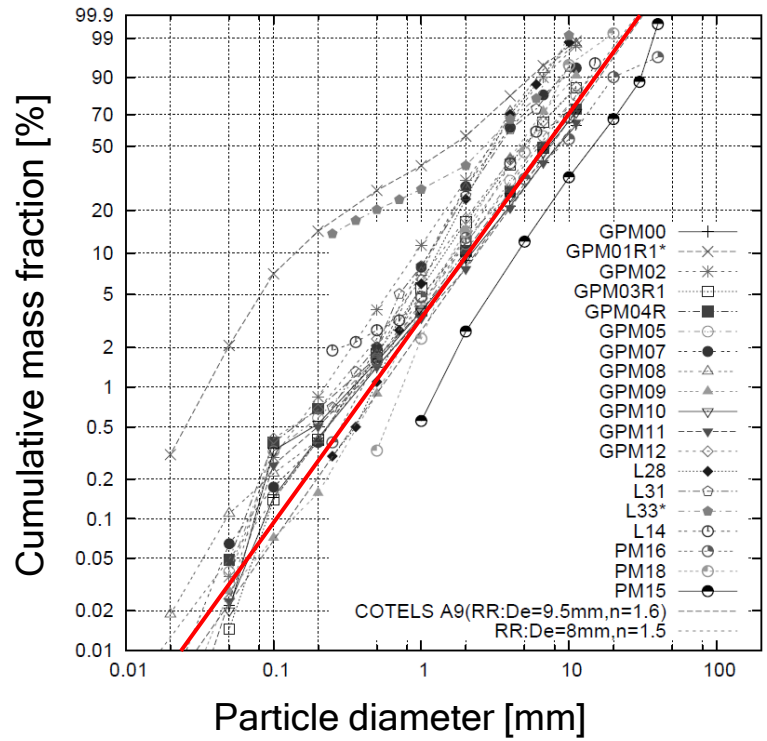
Rosin-Rammler distribution

Rosin-Rammler cumulative dist. function

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

Dp: Particle diameter
F: Cumulative mass fraction of particle (<Dp)
- Parameters of distribution

De: absolute size constant
n: distribution constant



Rosin-Rammler dist. function（De=9.5, n=1.6）
Y-axis: Scale mod. using（log(log(1/(1-F)))

Generation of diameter values of particles

Particle behavior in the code

- Mass: determined from jet breakup length.
- Particles diameter values are given when breakup particles discharged into water phase.
- Particle solidification by heat removal

Generation of values using Monte-Carlo method

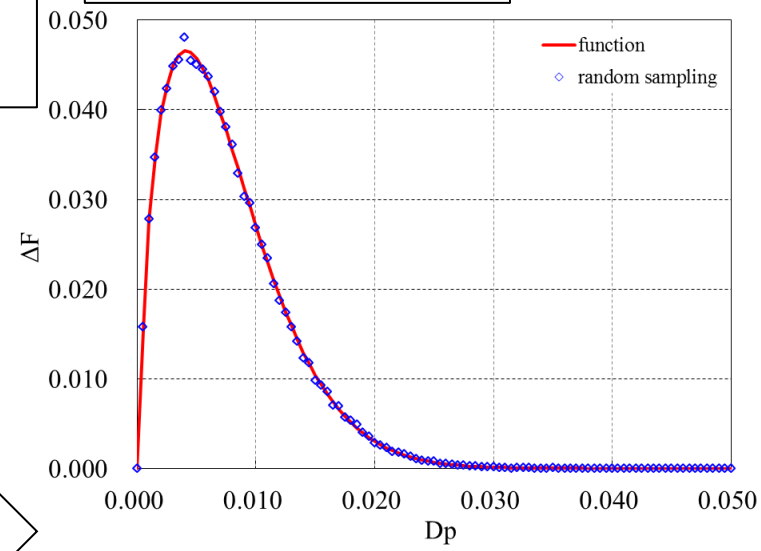
Uniform random numbers are applied for inverse function

$$F^{-1} = (-De(\ln(1-U))^{1/n}$$

(U: uniform random number)

Implemented in JASMINE code

Verification
n=1.5、De=0.008[m]



100,000 samples

- Simulation for Jet breakup experiment DEFOR-A

DEFOR-A experiment by KTH

(Jet breakup, agglomerated debris)

Over view of DEFOR-A test series

- Simulant material: Bi_2O_3+WO_3 (eutectic)
- 4 catchers: Collecting falling molten/solidified particles.

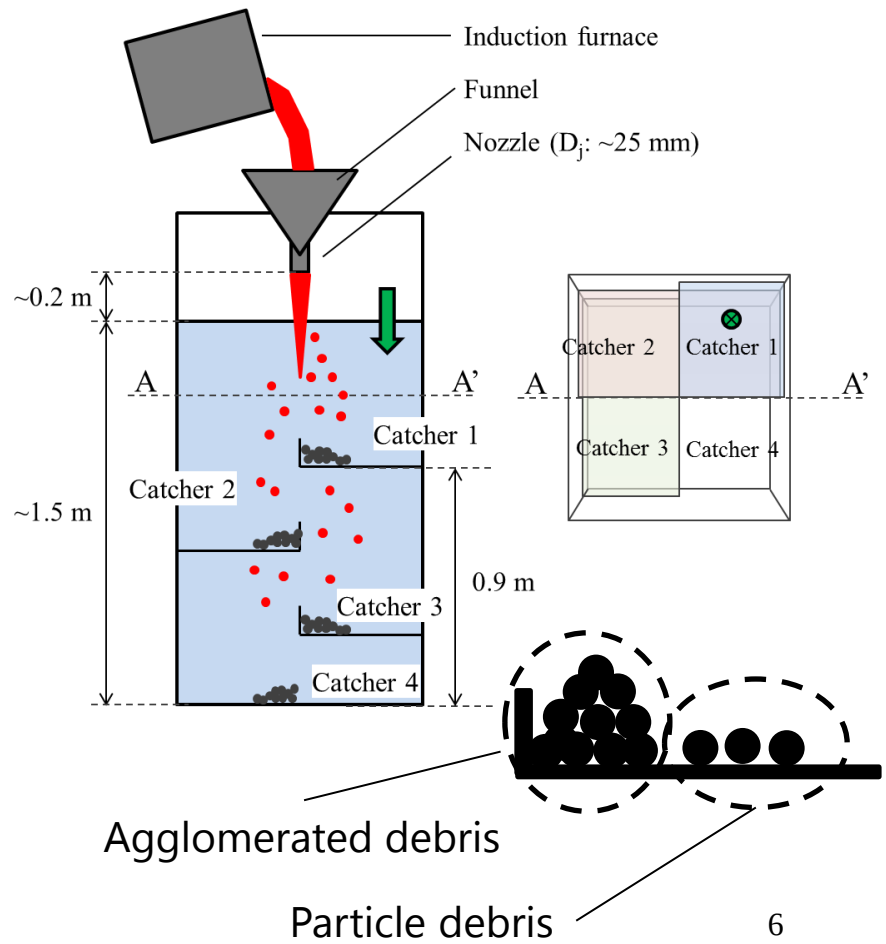
<u>Test parameters</u>

- Jet diameter, melt temperature
- Temperature of water pool
- 8 test cases

<u>Obtained data from tests</u>

- Cumulative mass fraction of particle debris at catcher height
- Mass fraction of agglomerated debris fraction at catcher height

Schema of DEFOR-A apparatus



Analyses of DEFOR-A tests

Calculation conditions

Calculation domain (2D axial symmetric)

- Calculation domain

  r: 1.37 [m], z: 2.7 [m]
- Pool area

  r: 0.268 [m], z: 1.51 [m]

Physical properties of simulant

- Simulant

  Bi_2O_3-WO_3 (Eutectic mixture)

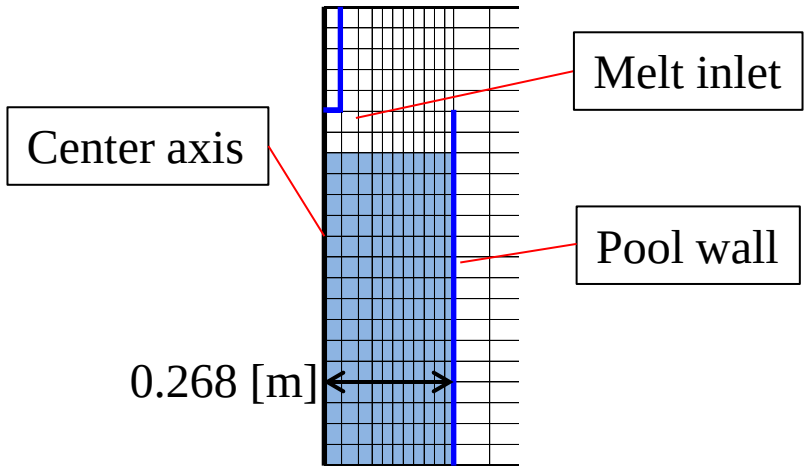
  Physical properties: accordance with the literature of DEFOR-A

Diameter of breakup particles

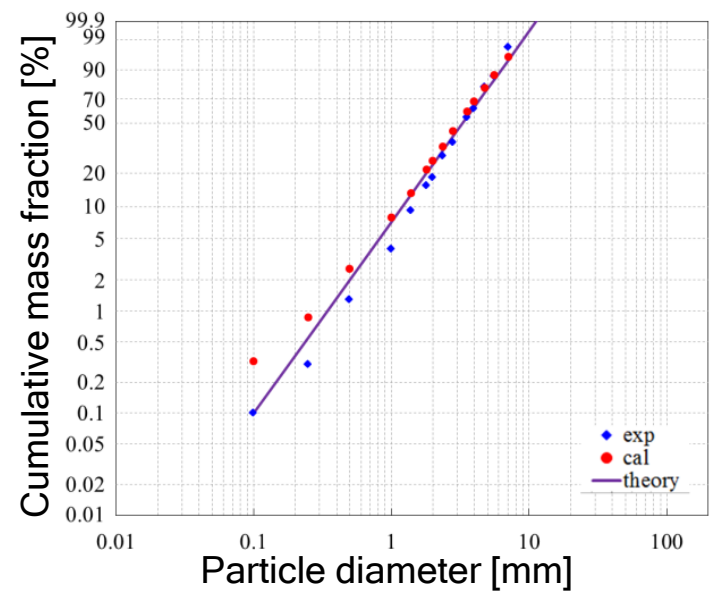
- Rosin-Rammler distribution

Parameters De and n: Fitting with the average distribution of all DEFOR-A experiments

De = 4.0, n = 1.87



Calculation domain

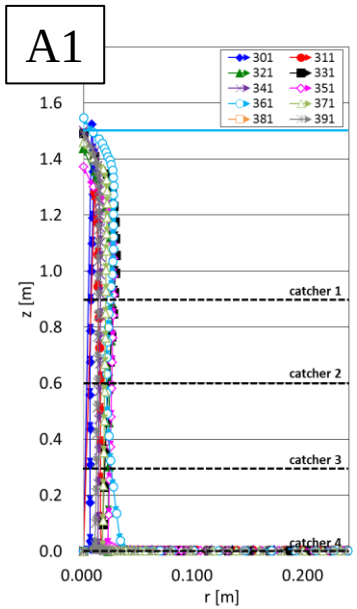


Rosin-Rammler dist. function

Y-axis: Scale mod. using (log(log(1/(1-F)))

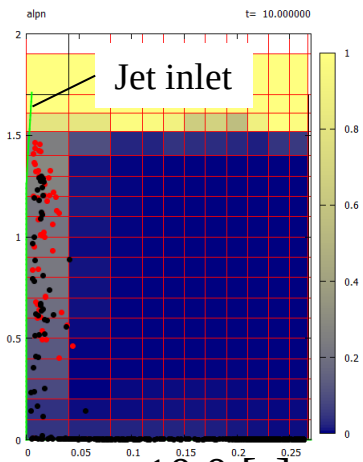
Distribution of void fraction and particle groups

	A1	A2
Test conditions	Jet diameter = 10 [mm] Subcooling = 27 [K] Superheat = 110 [K]	Jet diameter = 20 [mm] Subcooling = 7 [K] Superheat = 103 [K]



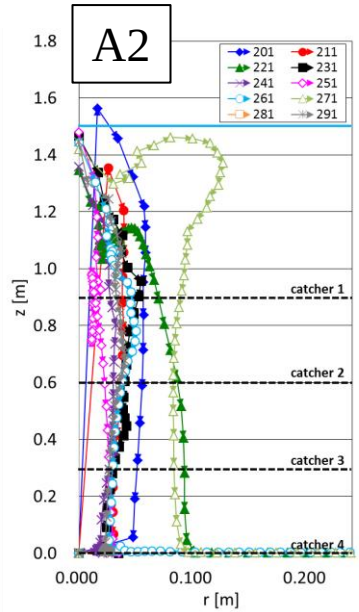
Track of particle gr.

- Liquid particle group
- Solid particle group

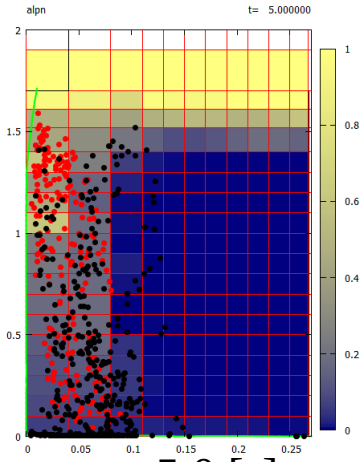


t = 10.0 [s]

Void fraction, particle gr. distribution



Track of particle gr.



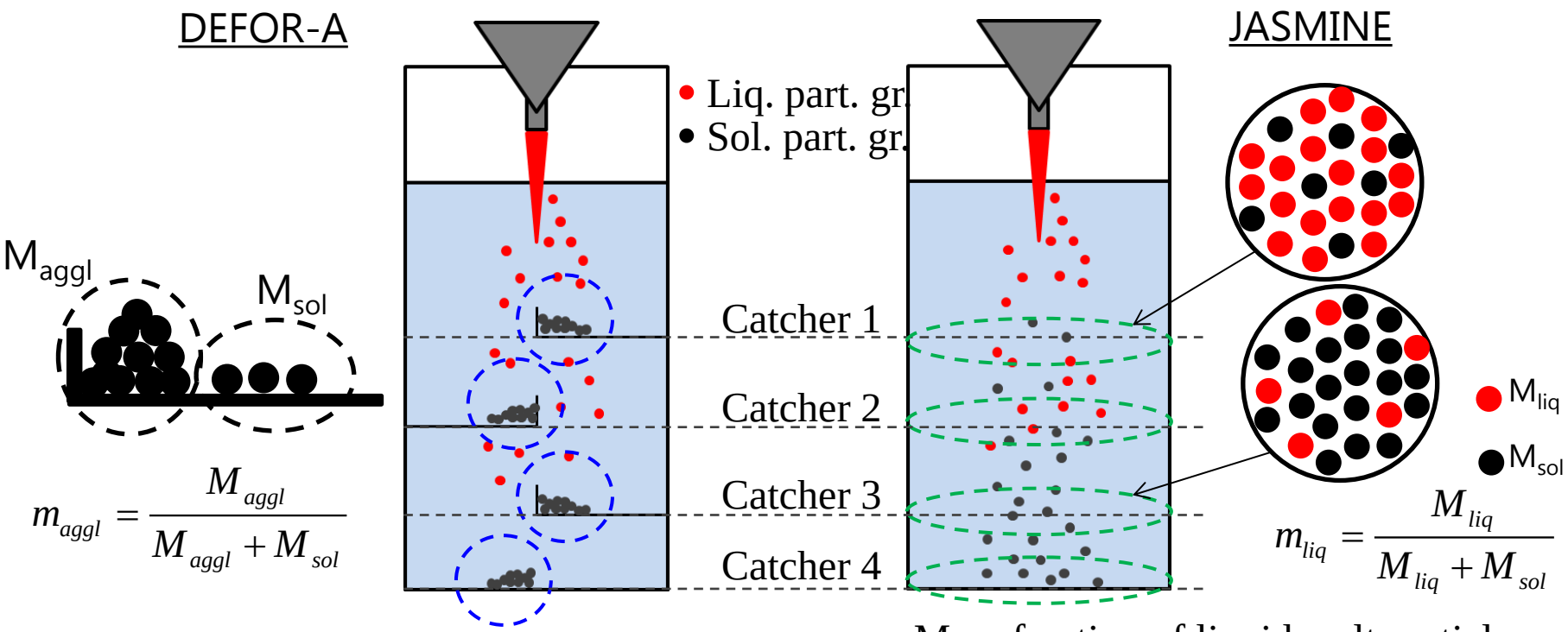
t = 5.0 [s]

Void fraction, particle gr. distribution

Analyses results correspond qualitatively with the observation of tests

Mass fraction of agglomerated debris 1

- Assumption: Two values from experiment and calculation have correlation.



$$m_{aggl} = \frac{M_{aggl}}{M_{aggl} + M_{sol}}$$

$$m_{liq} = \frac{M_{liq}}{M_{liq} + M_{sol}}$$

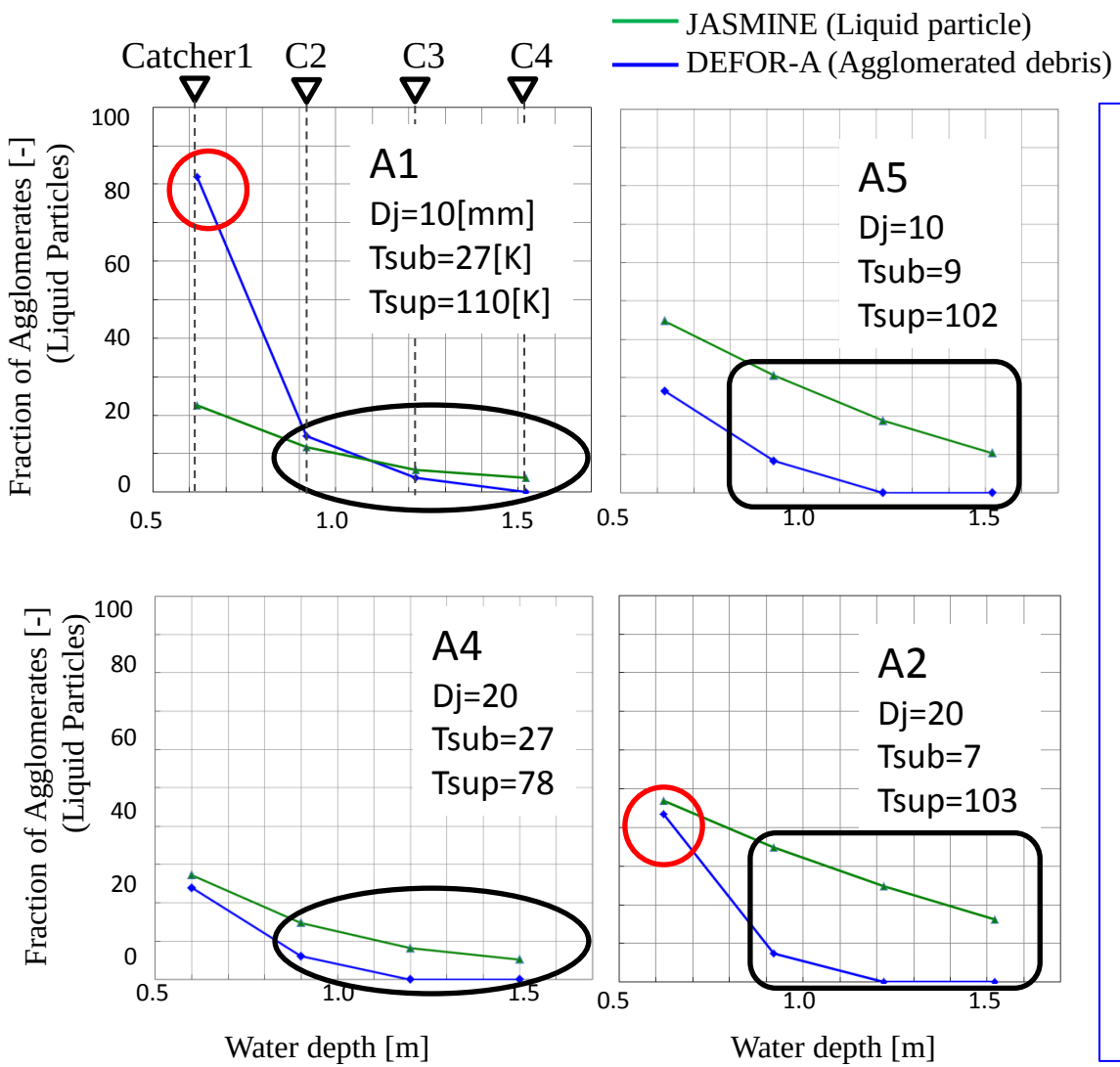
m_{aggl}: Mass fraction of agglomerated debris

- Mass fraction of aggl. debris
  Collected at catchers

m_{liq}: Mass fraction of liquid melt particles

- Mass fraction of liq. melt particles
  Rate of liquid particles to whole particles which crossed the height of catchers

Mass fraction of agglomerated debris 2



- Mass fraction of liquid particle > Agglomerated debris

  Influence of the inconsideration of attachment of neighboring particles in calculation

- Mass fraction of agglomeration debris are larger at catcher 1in cases of A1 and A2

  Confirmation of complete of jet breakup at the height of catcher 1 is needed (Influence of catcher bend?)

- Larger gaps exist at smaller subcooling cases

  Void region have large influence on cooling of melt particles

Crust Formation Model

Implemented crust formation model

<u>Crust formed at upper surface (Top crust)</u>

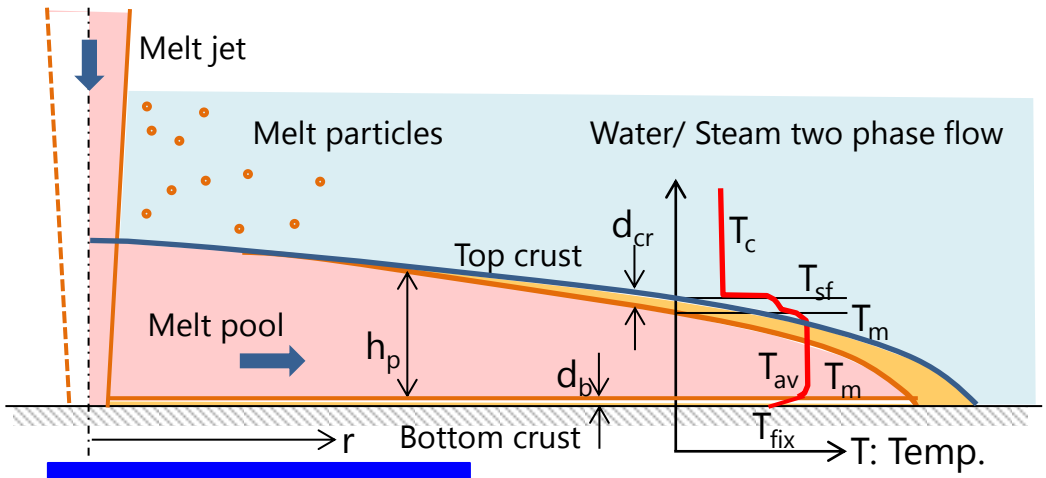
- Assumed to float on the liquid phase of melt due to pore in solid phase. (though density of solid > liquid)

<u>Horizontal direction moving</u>

- Moving of top crust is stopped when the leading edge of the melt pool is fixed
- Crust layer does not move without cracking or deformation under the 2D axial symmetric system.
- Crust moving velocity is equivalent to liquid phase

Implemented melt pool model

(Pool consists of 3 layers of top and bottom crust and molten pool)



Heat conduction

<u>Top crust</u>

Thermal conduction + water sinking into crust
(up surf: boiling heat transfer
dn surf: convective heat transfer)

<u>Bottom crust</u>

Thermal conduction

(up surf: convective heat transfer

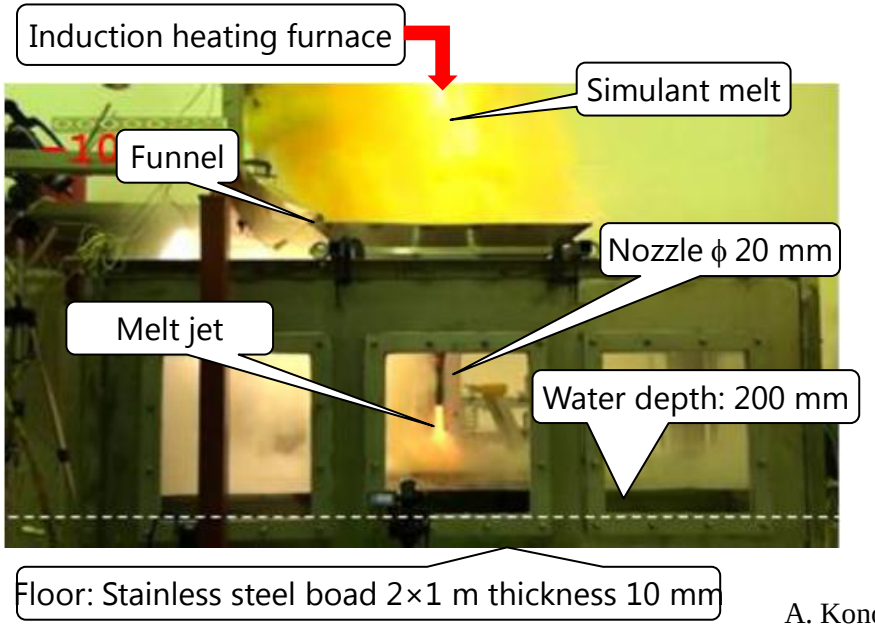
dn surf: Constant temp./ Adiabatic boundary)

PULiMS Experiment by KTH

Calculation target cases

Run No.	Simulant	Mass of Melt	Superheat of Melt	Providing Duration	Area of Cake
E1	Bi_2O_3+WO_3	23.4 kg	136 K	10 s	0.14 m^2
E4	Bi_2O_3+WO_3	46.9	70	12	0.30

PULiMS apparatus



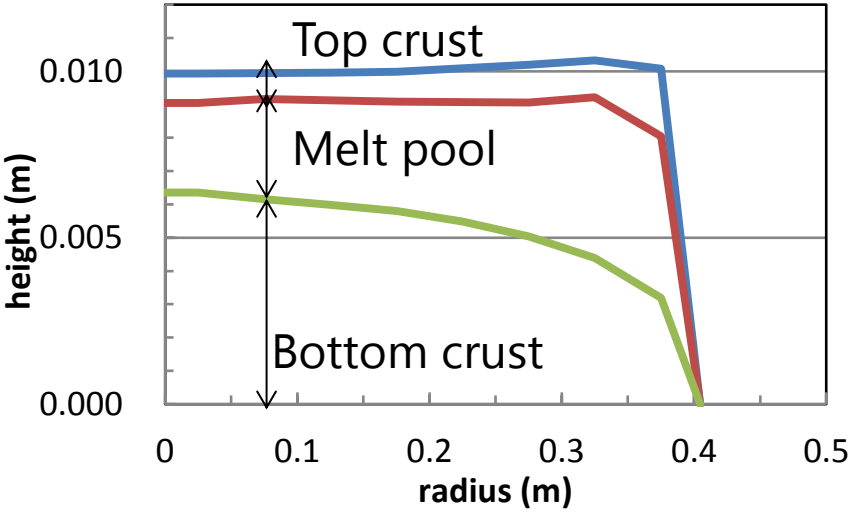
Physical properties of simulant

	UO_2-ZrO_2 70-30 wt%	Bi_2O_3-WO_3 43-57 wt%
Melting temp. (K)	2811	1143
Density (kg/m^3)	7121	7811
Thermal conductivity (W/m K)	3.6	5.3
Specific heat (J/kg K)	680	280

A. Konovalenko, et al., NUTHOS-9, Kaohsing, Taiwan, Sep. 2012, N9P0303

Comparison of Analyses and Experiments

Thickness of crust and melt pool (E4 exp. 20 s)



Layers of solidified simulant (E4 exp.)

3 layers structure including pores

- Bottom crust form after reaching leading edge of melt pool
  -> Thickness of the crust decline at periphery region
- Top crust have opposite circumstance of bottom (due to the moving with melt pool)

Summary of analyses of PULiMS exp.

Run No.	Exp. conditions		Results of exp. and cal.				Rate of spreading area cal/exp
	Melt mass (kg)	Super heat (K)		Melt Spreading (m)	Area of melt (m2)	Average thickness (m)	
E1	23.4	136	Exp.	0.43 × 0.32	0.14	0.031	**2.1**
			Cal.	0.61	0.292	0.0089	
E4	46.9	70	Exp.	0.711 × 0.471	0.30	0.030	**1.7**
			Cal.	0.81	0.518	0.0097	

Summary & Future Work

Improvement of particle diameter distribution in JASMINE code

- Implementation of Rosin-Rammler distribution as the distribution of jet breakup particle diameter.
- Analytical results for DEFOR-A experiment show that the prediction with the current code have larger deviation in larger steam generation cases.
- Further improvement: consideration of detachment of liquid particles on the floor

Improvement of melt spread model of JASMINE code

- Implementation of crust formation model (Melt pool consists of 3 layer structure)
- Shallow water equation is adopted as governing equation for Melt pool
- Spreading area was overestimated, according to analytical results of PULiMS tests
- Further improvement: consideration of gas phase generating inside melt phase, thermal conduction with the floor.

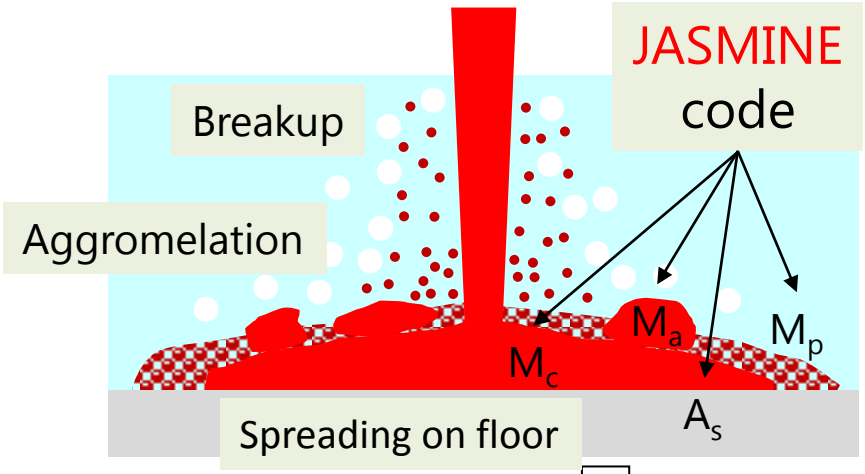
Future work: Our target

- Assessment of probabilities of MCCI starting (success of cooling) in CV
- Deterministic/ Stochastic assessment

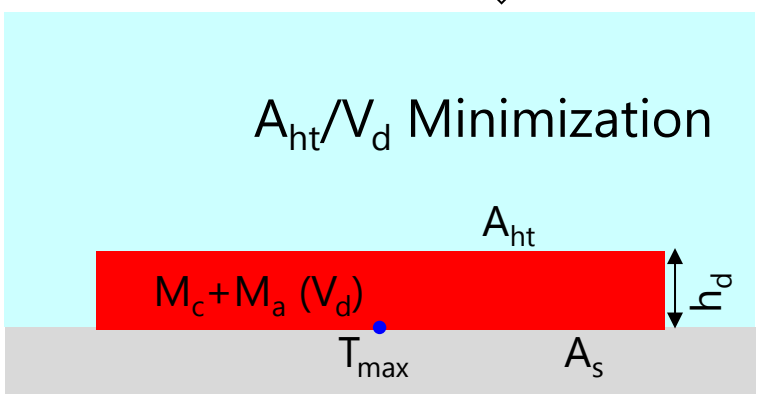
  JASMINE will be used as deterministic simulation in the procedure.

Assessment of MCCI/CV Failure Probability

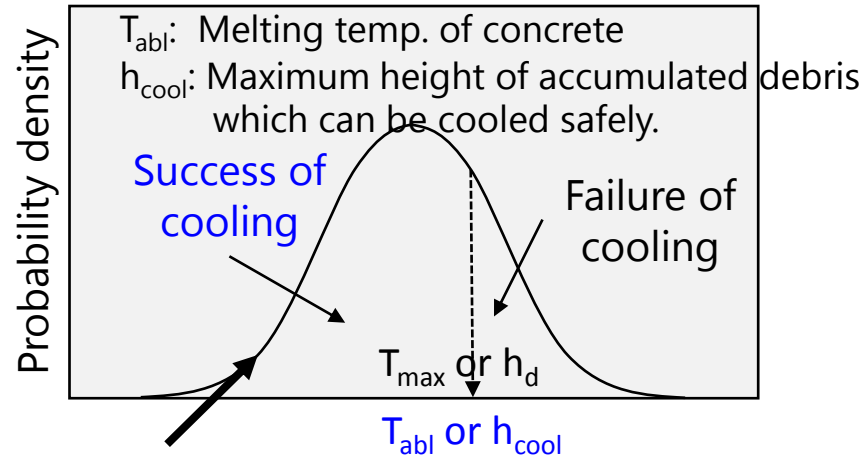
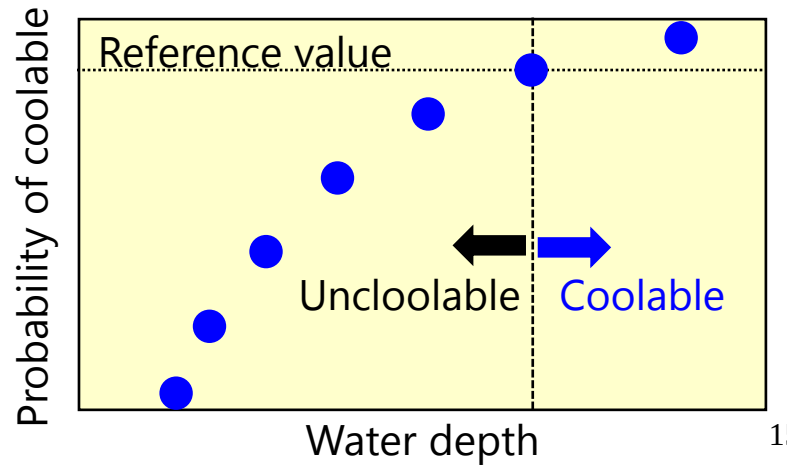
Mechanistic approach



Conservative approach



Evaluation procedure considering uncertainty



Probability density of Tmax or hd
Tmax or hd differ depending on the uncertainty of mass, temp. and composition of molten core, water level inside Ex-vessel and physical models in the code.