How to Win the Uncertainty of Ex-vessel Corium Coolability in Pre-flooded Cavity.

Part 1: COOLAP-3 Development
Part 2: MELCOR-COOLAP Coupled Analysis

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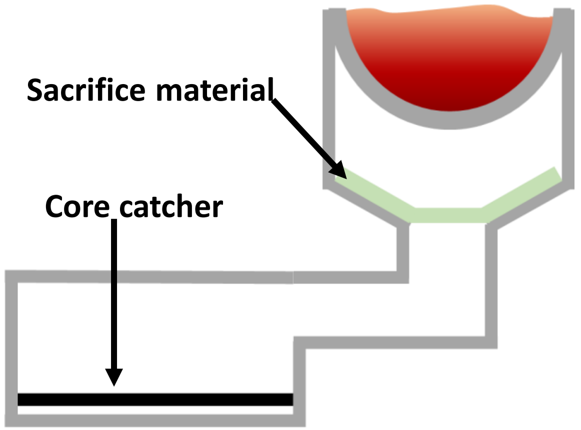
Background and objective

1. Ex-vessel corium cooling
2. Objective for COOLAP-3 code

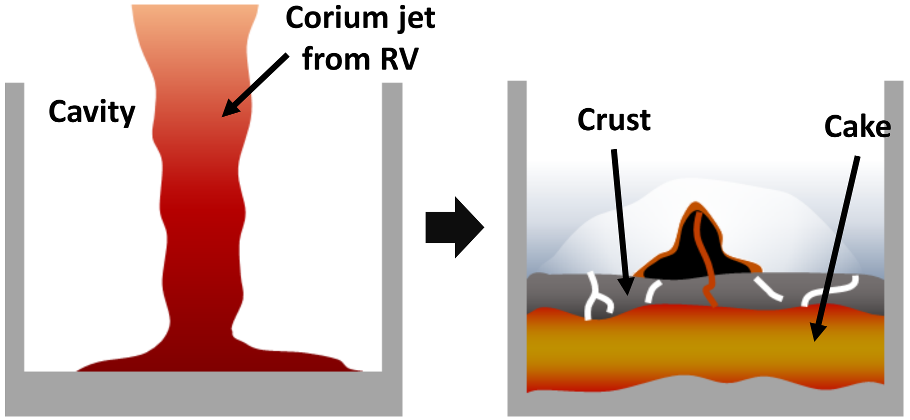
Ex-vessel corium cooling

- **Ex-vessel corium cooling strategies**

Mitigation Concept of EPR

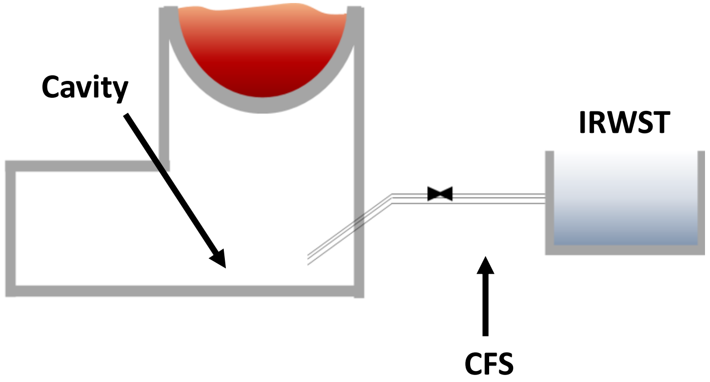


Top-flooding

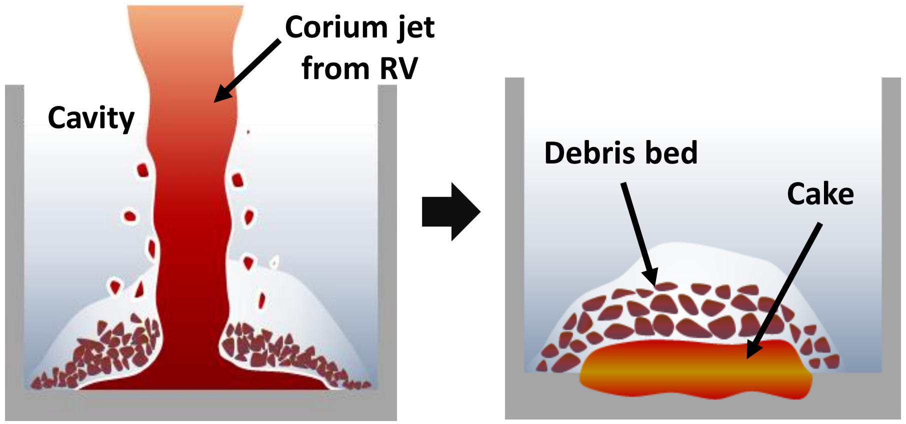


- Cooling process
  - Bulk cooling
  - Crust breach
  - Water ingression
  - Melt eruptions
- Pros and cons
  - Benign FCIs (Fuel-Coolant Interactions)
  - Low coolability (MCI↑)

Mitigation Concept of APR-1400



Pre-flooding



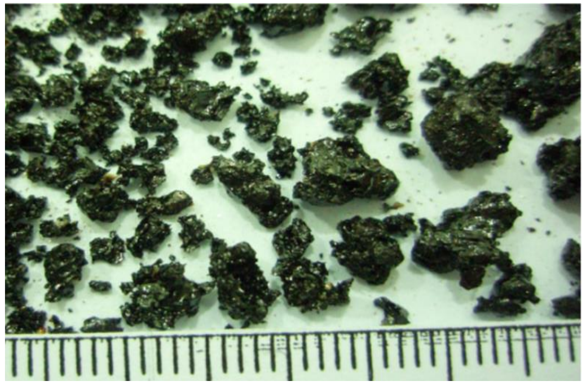
- Cooling process
  - Jet fragmentation
  - Debris bed & Cake formation
  - Dry-out in Debris bed
  - Cake top cooling
- Pros and cons
  - High coolability (MCI↓)
  - Energetic FCIs (steam explosion)

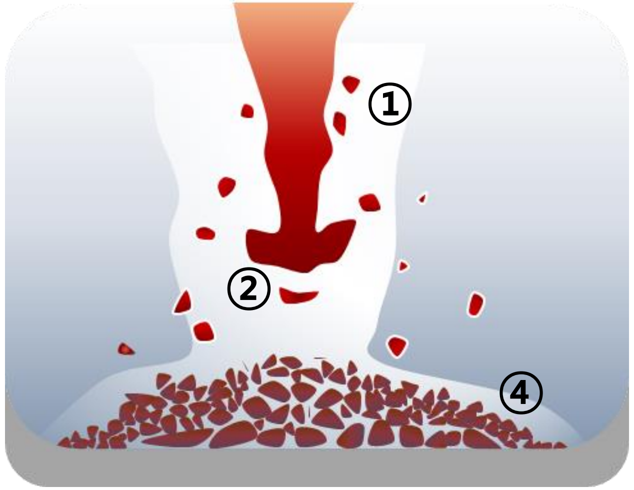
Ex-vessel corium cooling

- **Ex-vessel corium behavior in pre-flooded cavity**

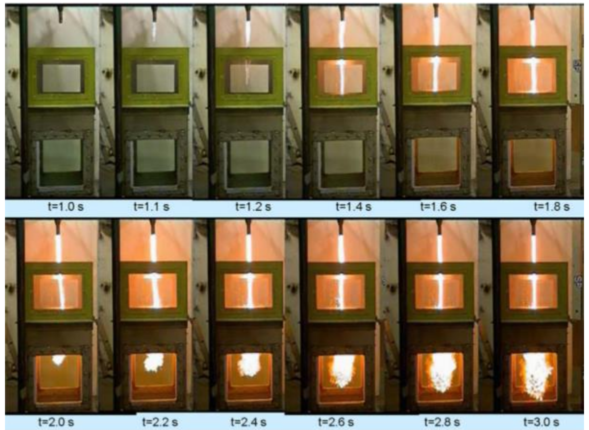
Non-energetic Phenomena in Pre-flooded Cavity

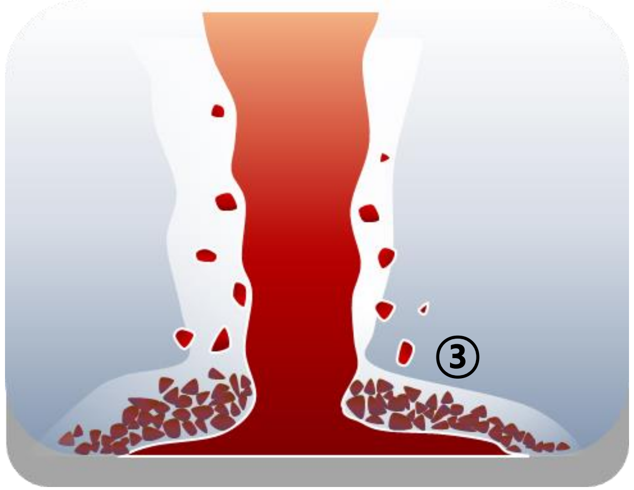
① Jet fragmentation





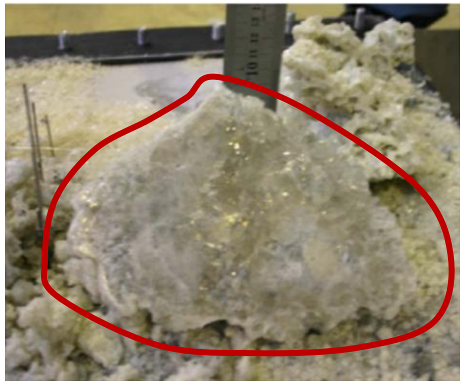
② Jet breakup





③ Cake & debris bed formation

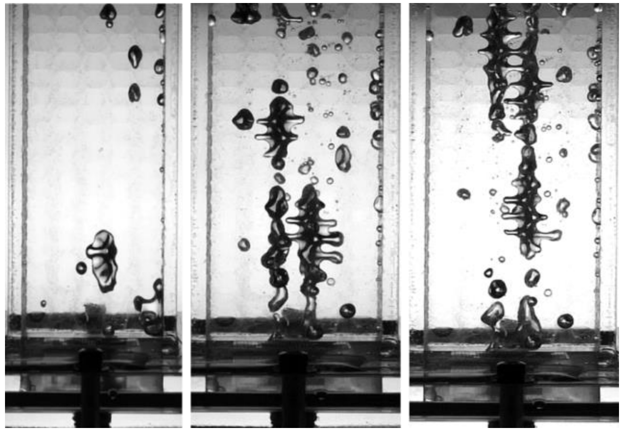
DEFOR-E
(A. Karbojian, 2009)



Cake

Debris bed

④ Two-phase in debris bed

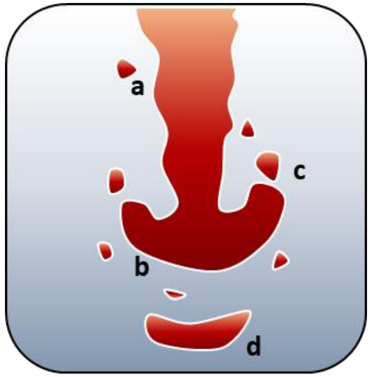


Index matching
(Vishal, 2022)

Objective for COOLAP-3

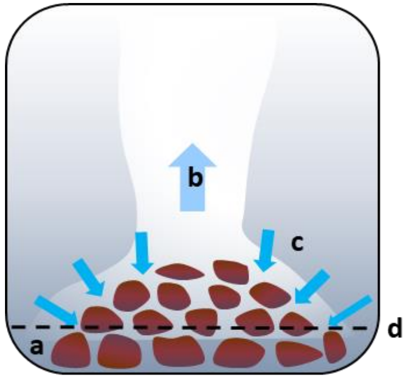
▪ Uncertainty of Severe Accident

Complexity of Phenomena



Jet breakup

a. K-H instability
b. R-T instability
c. Vortex stripping
d. Coarse breakup

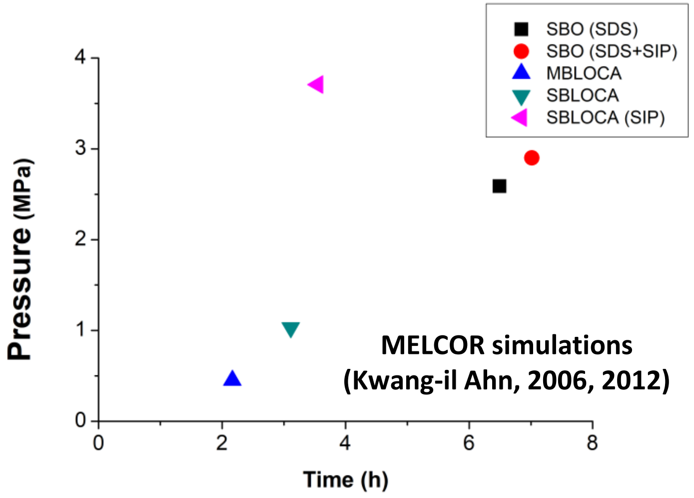


Debris bed cooling

a. Nonhomogeneous structure
b. Steam outflow
c. Water inflow
d. Quench front

Various of physical models describing phenomena

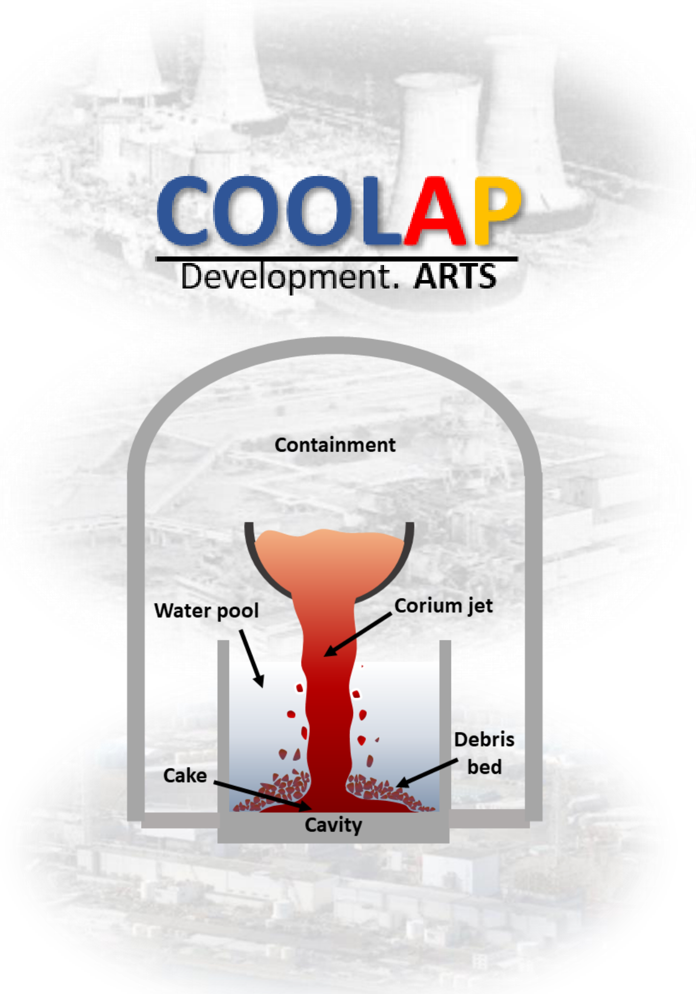
Uncertainty of Initial Condition



➡ Decay heat? Jet velocity?

- RCS pressure
- Time at RV failure
- RV hole ablation
- Corium temperature
- Cavity water pool depth

} Uncertainty



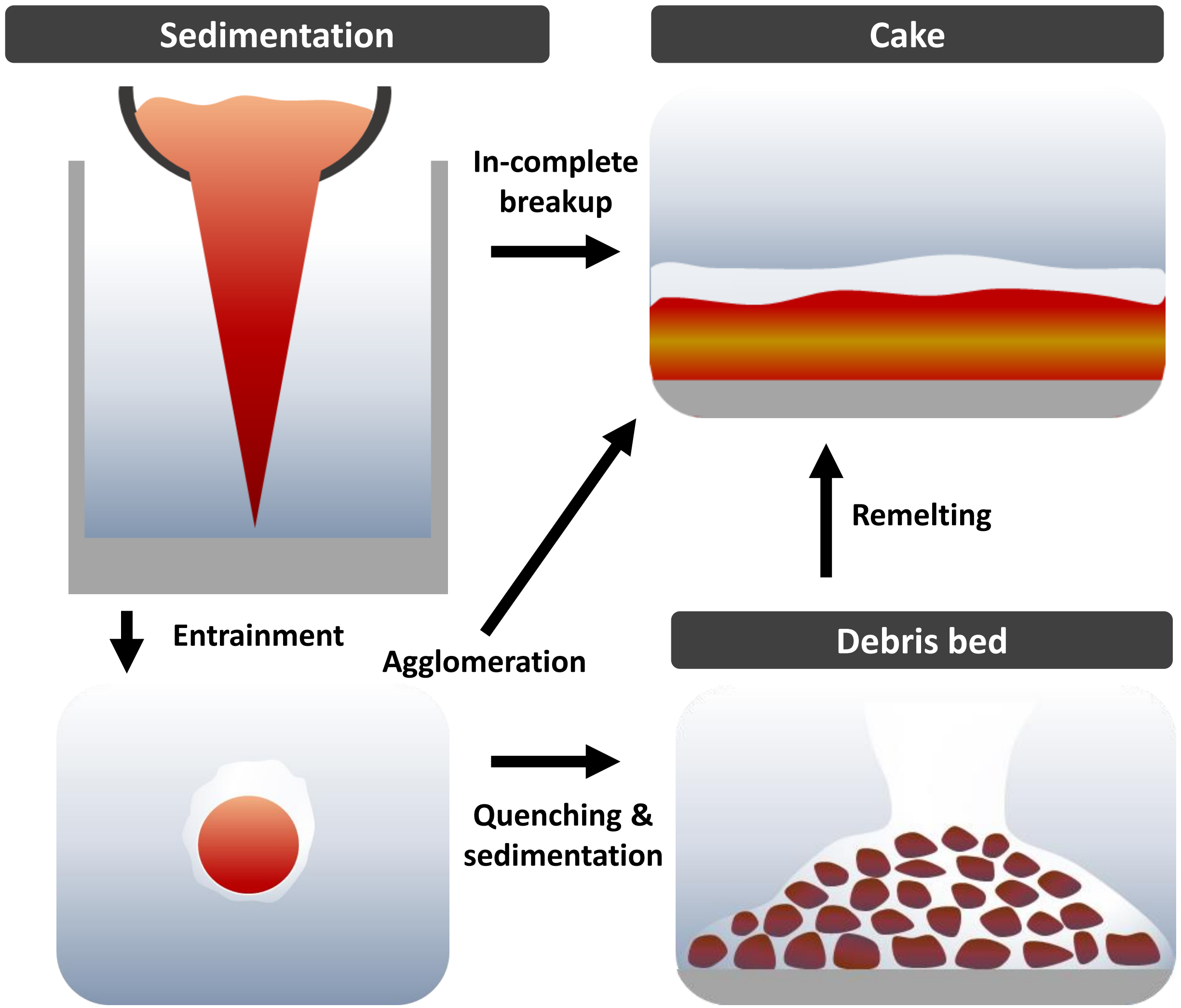
- Testing various of physical models
- Overcoming uncertainty

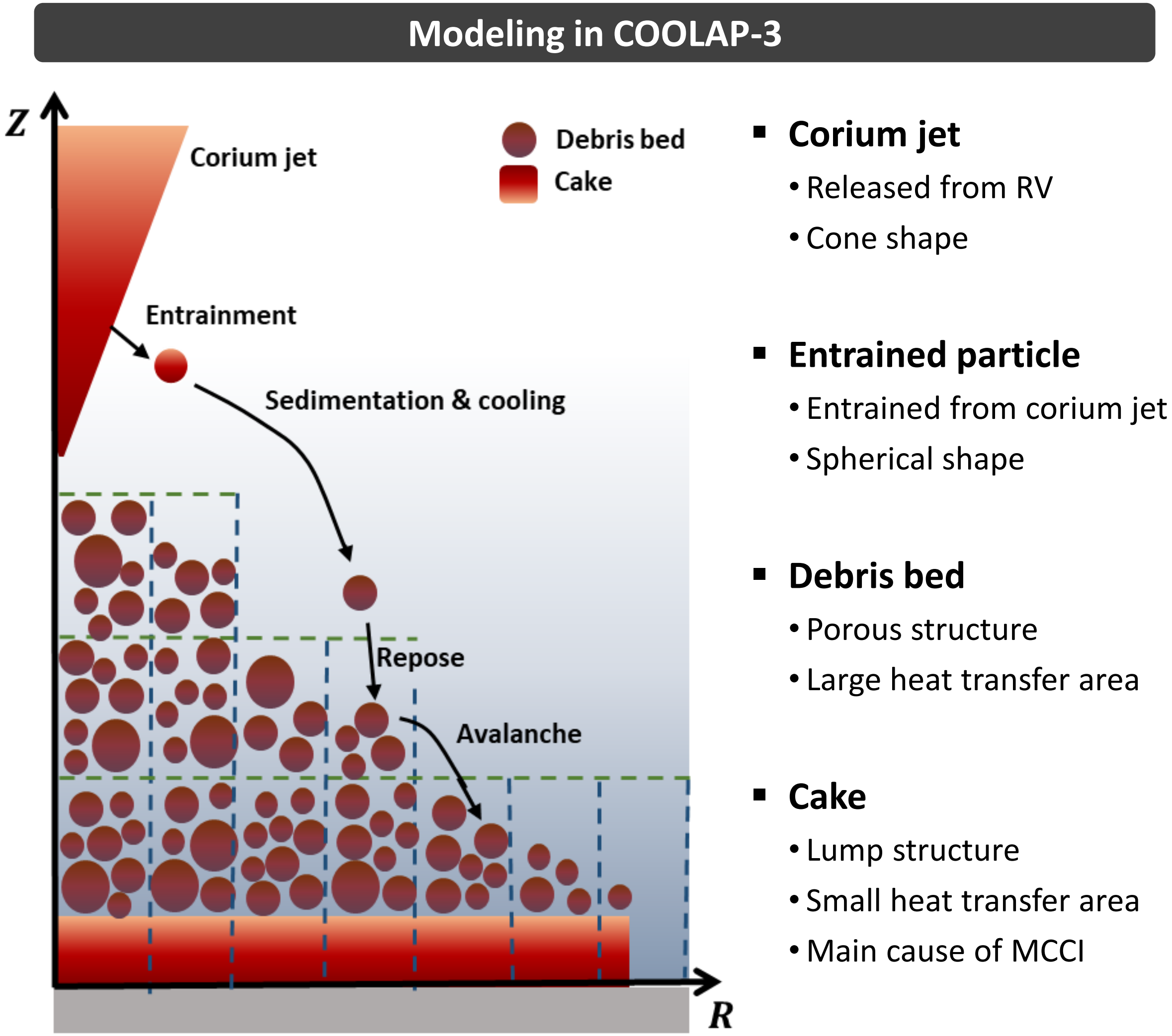
COOLAP-3 Modeling Concept

1. Cooling of corium in pre-flooded cavity
2. Validation: FARO L28 and L31

Cooling of corium in pre-flooded cavity

- **Corium behavior in COOLAP-3**

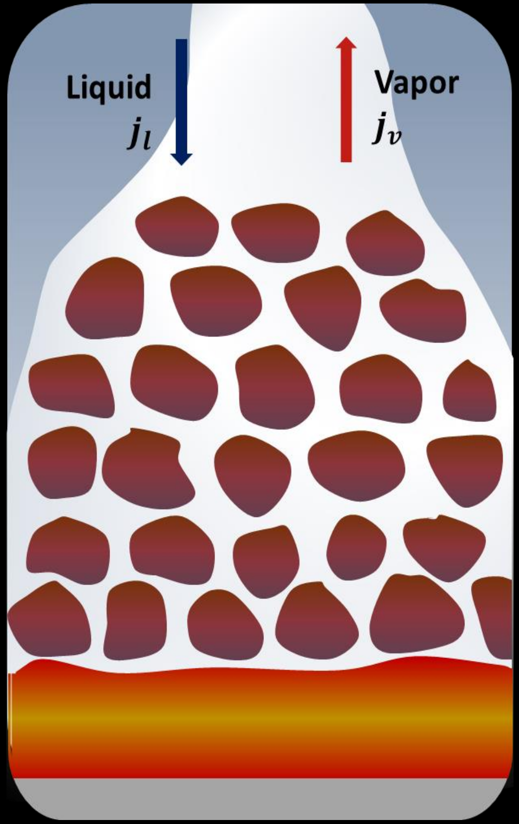




- **Corium jet**
  - Released from RV
  - Cone shape
- **Entrained particle**
  - Entrained from corium jet
  - Spherical shape
- **Debris bed**
  - Porous structure
  - Large heat transfer area
- **Cake**
  - Lump structure
  - Small heat transfer area
  - Main cause of MCCI

|Dryout in debris bed

- **Debris bed heat transfer limit**
  - 2-Phase Counter-Current Flow Limit
  - Heat transfer from debris bed is limited by **Dryout**. ($\dot{q}_d \leq \dot{q}_{dhf}$)

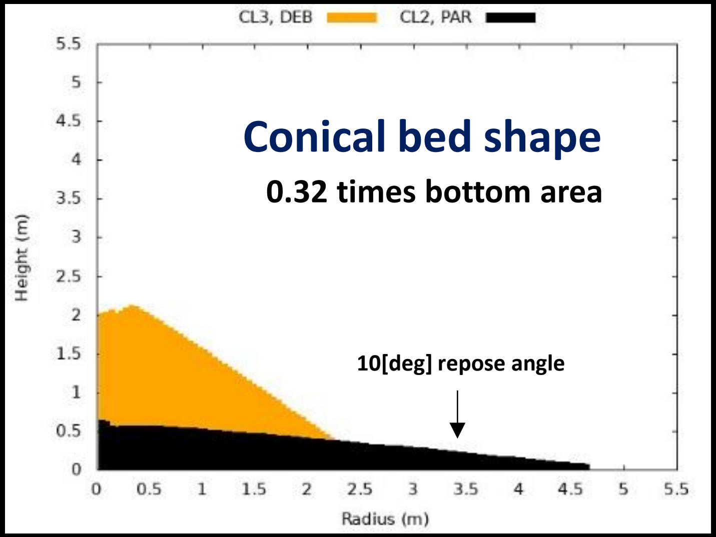


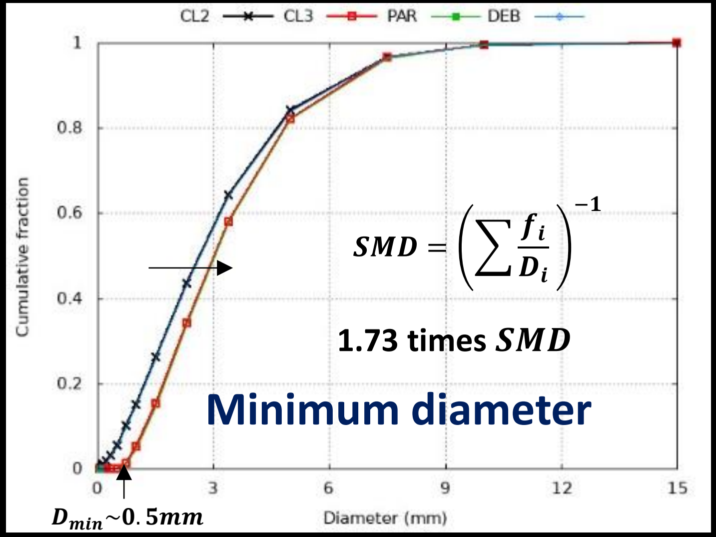
Lipinski-type vertical 1-D DHF equations

- **Mass**
  - $j_v = \frac{q''_{dhf}}{\rho_v h_{fg}}$
  - $j_l = -\frac{q''_{dhf}}{\rho_v h_{fg}}$
- **Momentum**
  - $\frac{dP_v}{dz} = -\rho_v g - \frac{\mu_v}{K_{r.v}K} j_v - \frac{\rho_v}{\eta_{r.v}\eta} |j_v| j_v - \frac{F_i}{\varepsilon\alpha}$
  - $\frac{dP_l}{dz} = -\rho_l g - \frac{\mu_l}{K_{r.l}K} j_l - \frac{\rho_l}{\eta_{r.l}\eta} |j_l| j_l + \frac{F_i}{\varepsilon(1-\alpha)}$
- **Closure relation (Ergun, 1952)**
  - **Permeability**: $K = \frac{\varepsilon^3 D_p^2}{150(1-\varepsilon)^2}$
  - **Passability**: $\eta = \frac{\varepsilon^3 D_p}{1.75(1-\varepsilon)}$

$$\dot{q}_{dhf} = \int_{A_{btm}} q''_{dhf}\, dA$$

- **Model effect: 1000MWe-type NPP**





Validation: FARO L28, L31

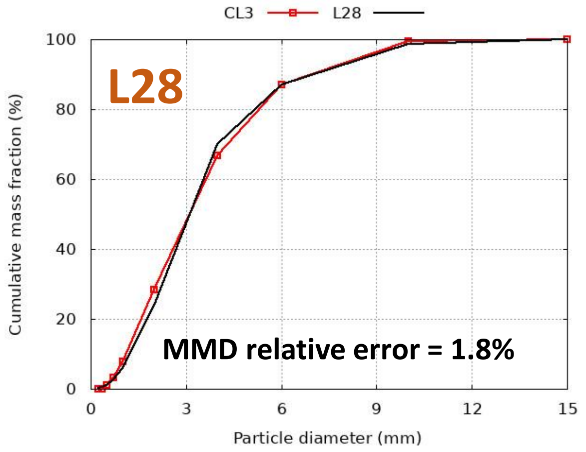
Characteristics of corium debris bed generated in large-scale fuel-coolant interaction experiments (D. Magallon, 2006)

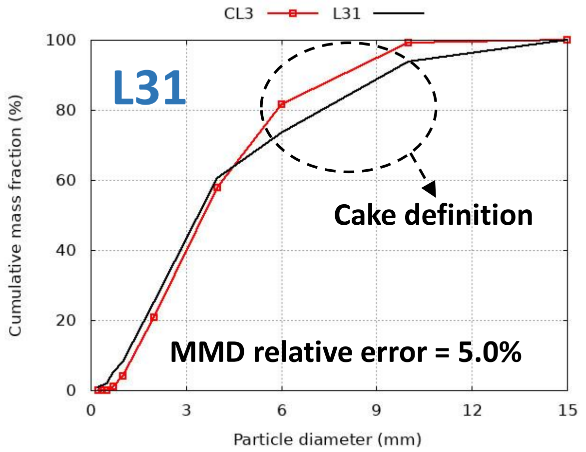
Test condition

Input	L28	L31
Melt material	UO_2/ZrO_2 (80/20wt%)	
Melt mass (kg)	**175**	**92**
Melt initial temperature (K)	3052	2990
Melt release height (m)	2.33	2.22
System pressure (MPa)	**0.51**	**0.22**
Water temperature (K)	**423**	**291**
Debris catcher area (m^2)	**0.3959**	**0.1302**

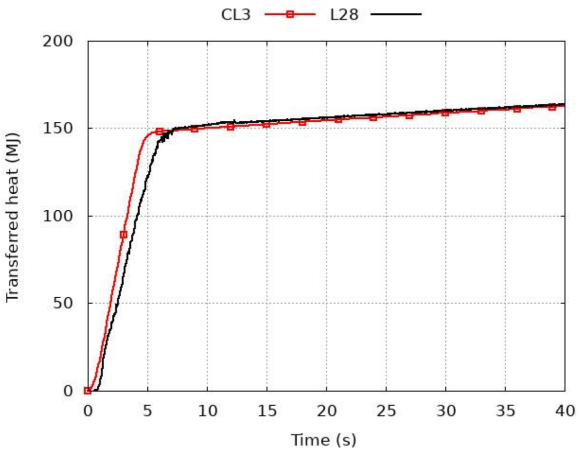
- **L28 condition**
  - Large debris catcher ($0.40m^2$)
  - High system pressure (0.51MPa)
  - Low subcooling ($\Delta T_{sub} = 2.6K$)
- **L31 condition**
  - Small debris catcher ($0.13m^2$)
  - Low system pressure (0.22 MPa)
  - High subcooling ($\Delta T_{sub} = 105.4K$)

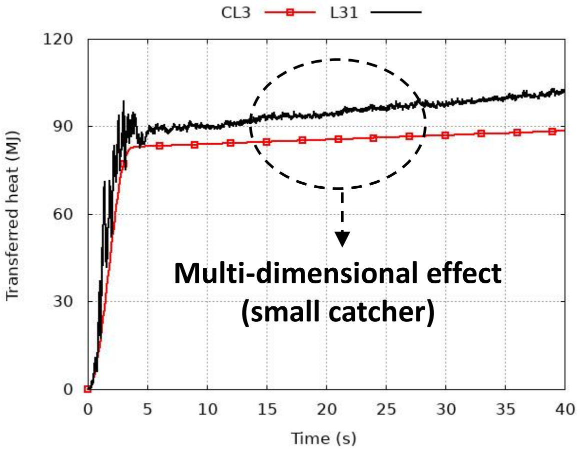
Particle diameter distribution





Released heat





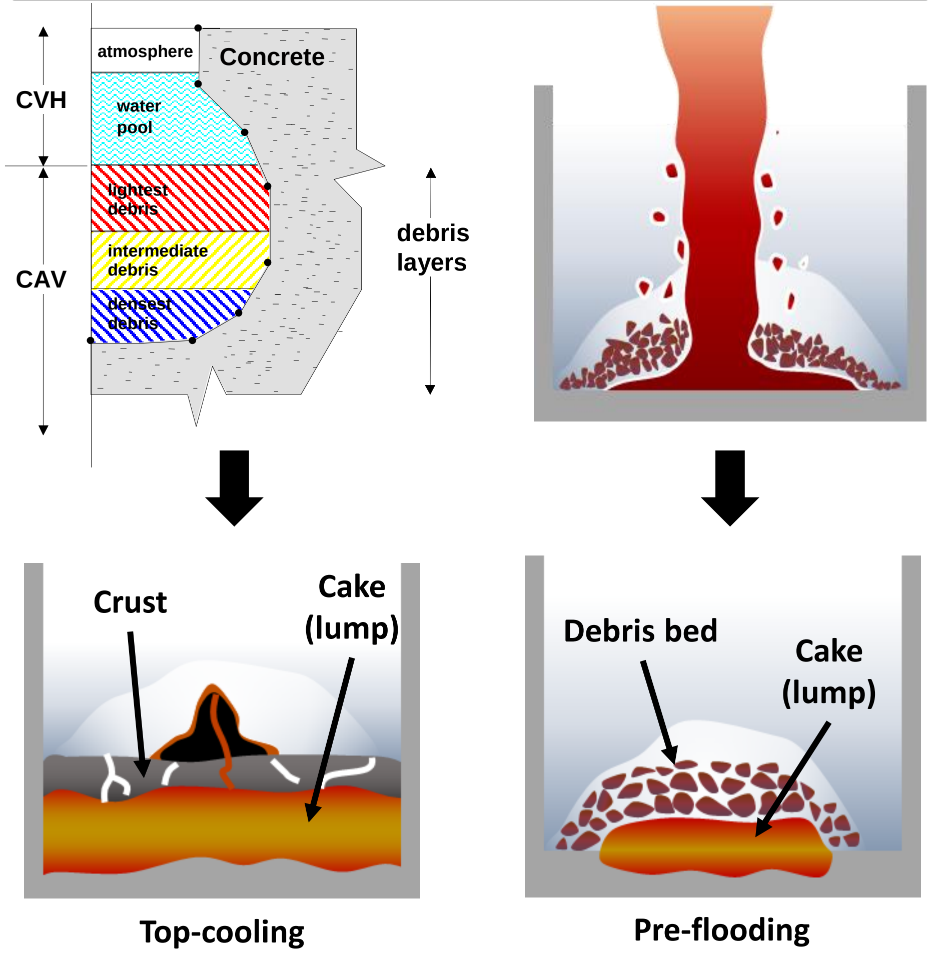
Application of COOLAP-3 to Uncertainty Analysis

1. Methodology: MELCOR-COOLAP framework
2. Result: Containment pressure, cavity ablation depth

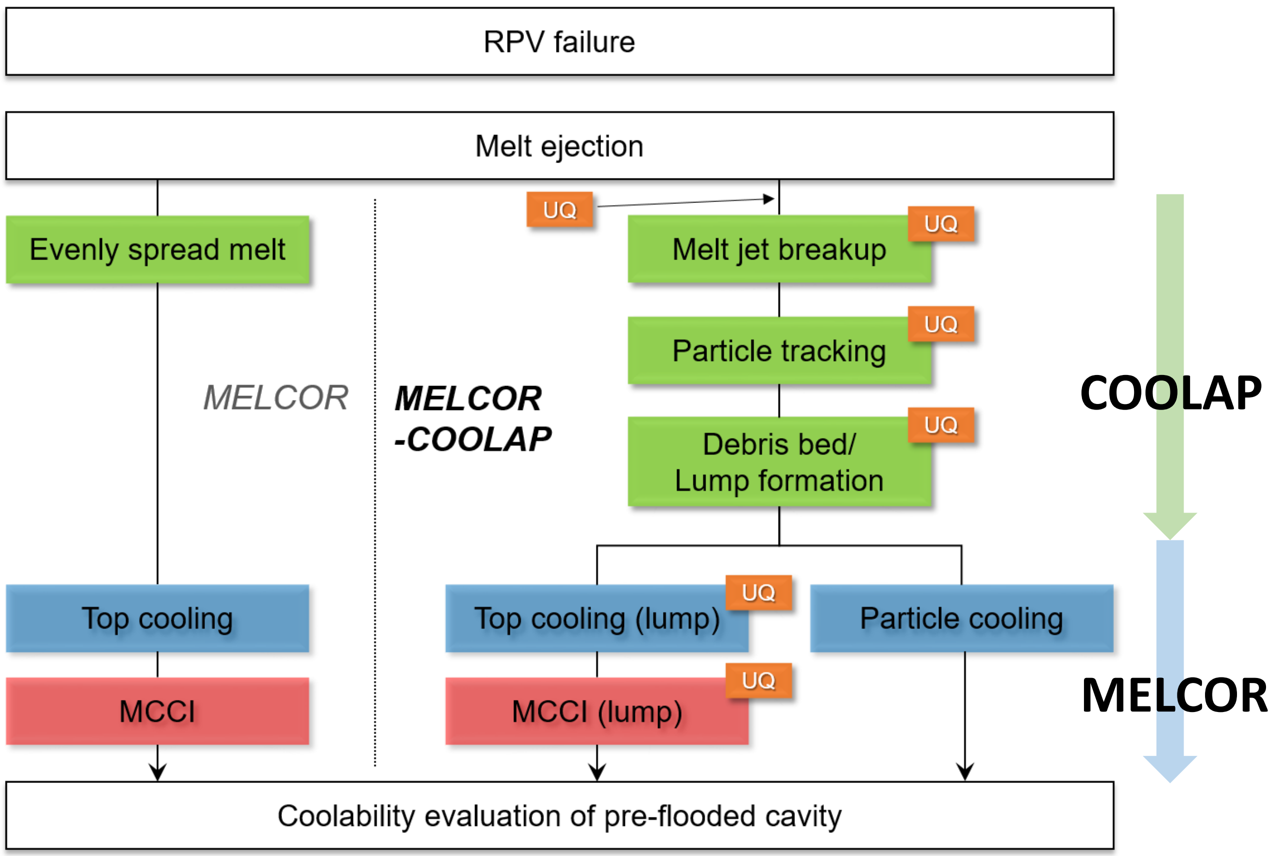
Methodology: MELCOR-COOLAP framework

- **MELCOR-COOLAP coupling framework**

MELCOR-2.2 CAV Package & COOLAP



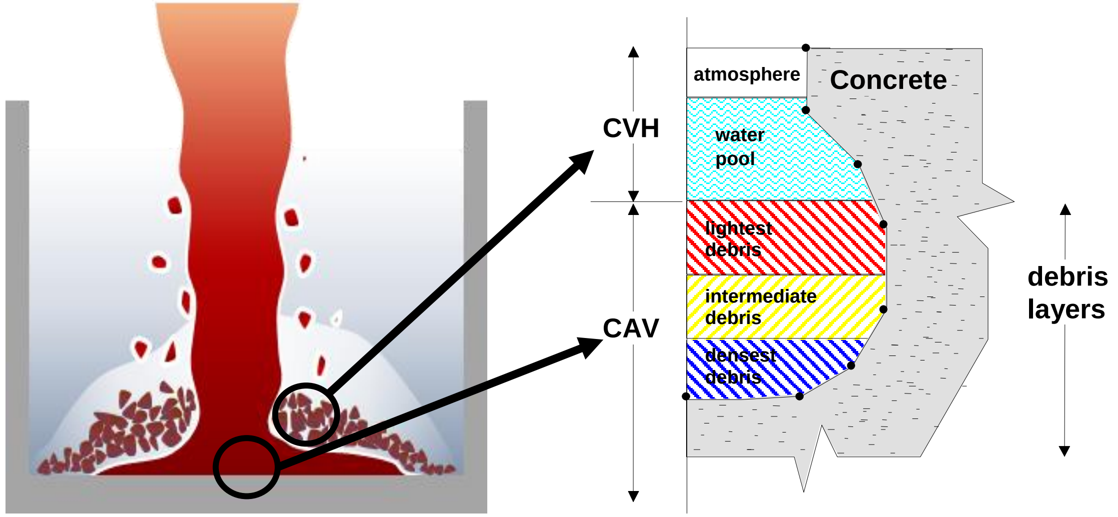
MELCOR-COOLAP Framework



Result: Containment pressure, cavity ablation depth

- **MELCOR-COOLAP vs MELCOR single**

COOLAP-3 → MELCOR

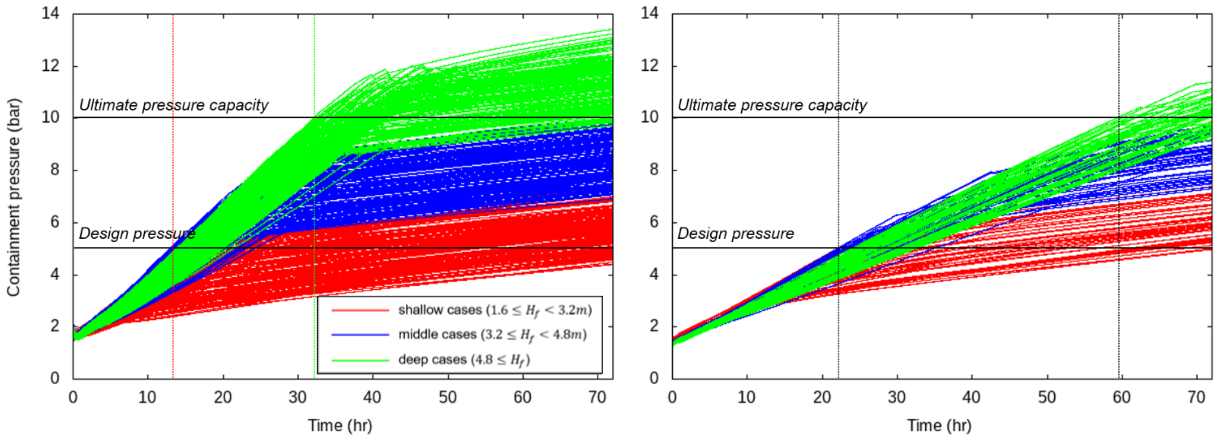


COOLAP-3: RV failure – 1h

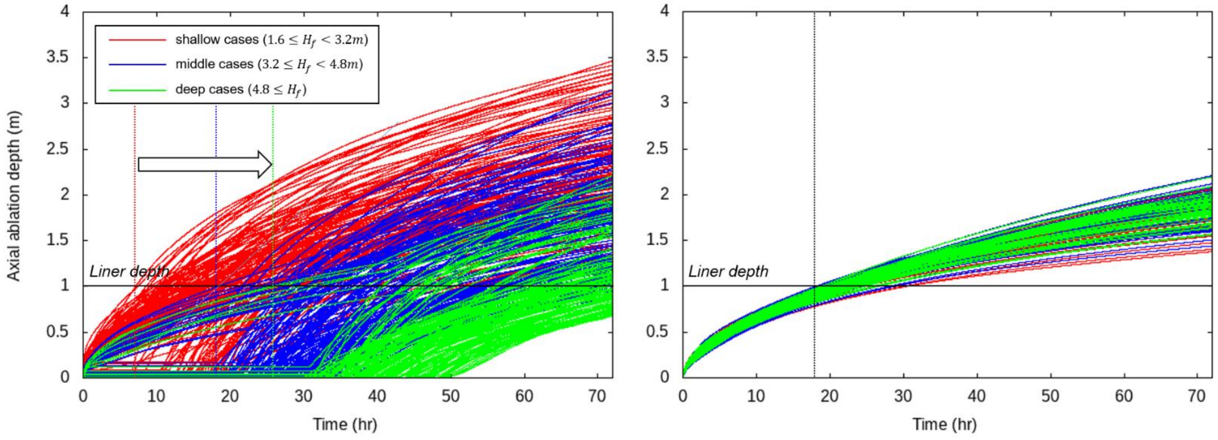
MELCOR: 1h – 72h

- **Gap (MEL → MEL-CL)**
  - All Cake → Cake + debris bed
  - Totally spreading → Spreading according to model
- **Result**
  - Conservative pressure increase
  - Ablation reflecting phenomena in pre-flooded cavity

Containment Pressure (MEL-CL, MEL)



Cavity Ablation Depth (MEL-CL, MEL)



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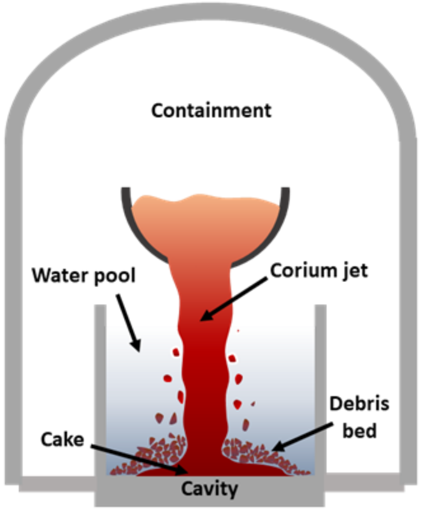
Summary

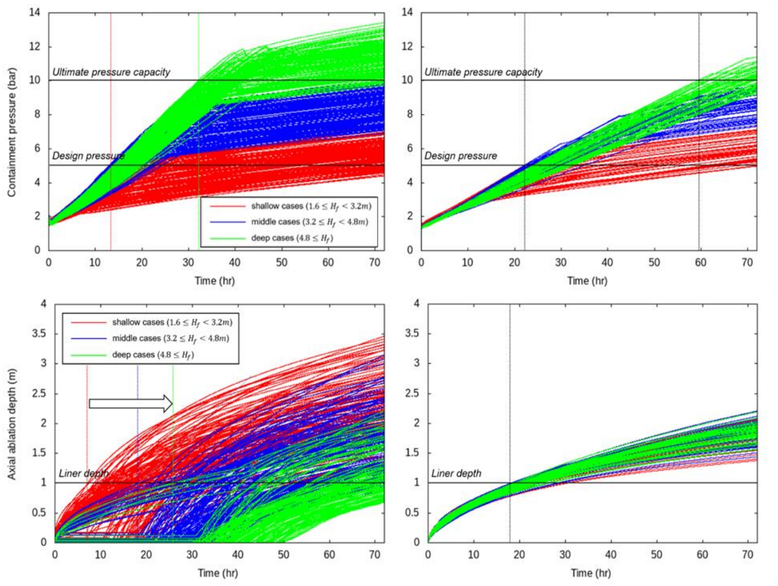
Code Development

COOLAP
Development. ARTS



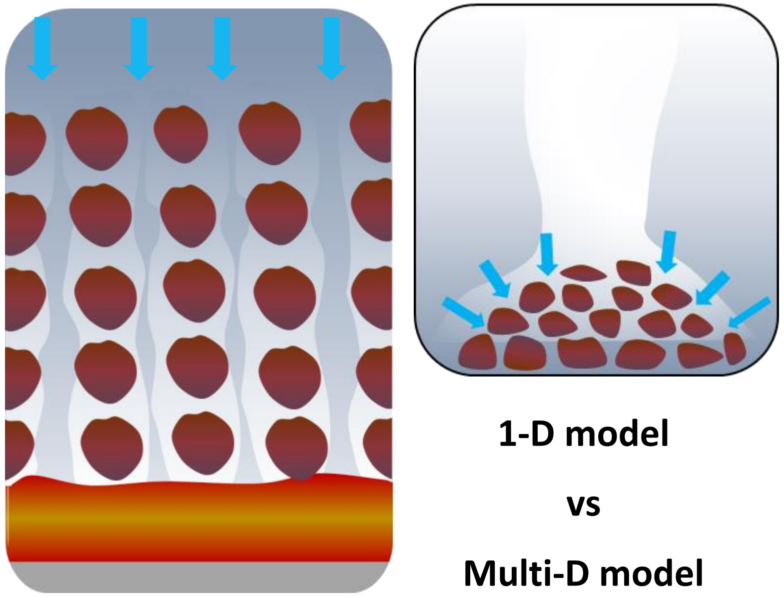
- **Objective: Evaluation of ex-vessel coolability**
- **Code update: COOLAP-2 → COOLAP-3**
  - Particle size distribution
  - Debris bed shape
- **Validation with FARO L28 and L31**

Application to Uncertainty Analysis



- **MELCOR-COOLAP framework**
  - Containment pressurization
  - Molten Core-Concrete Interaction
- **Possible to reflect phenomena in pre-flooded cavity**

Future Work



1-D model

vs

Multi-D model

- **Possibility of underestimation of DHF**
- **Multi-dimensional water ingression**

Thank you for listening!