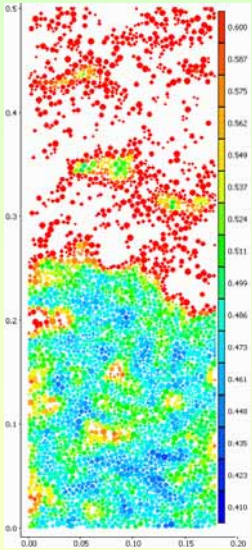
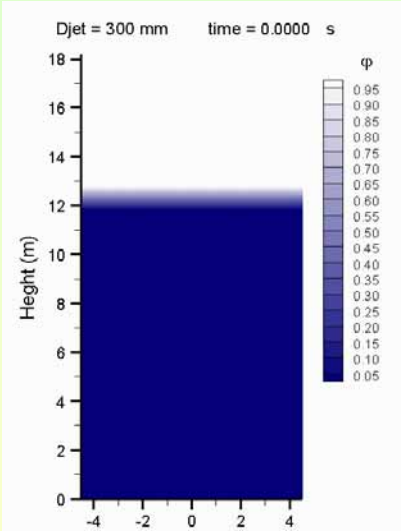
NKS-R ExCoolSE

Multiscale Phenomena of Severe Accident

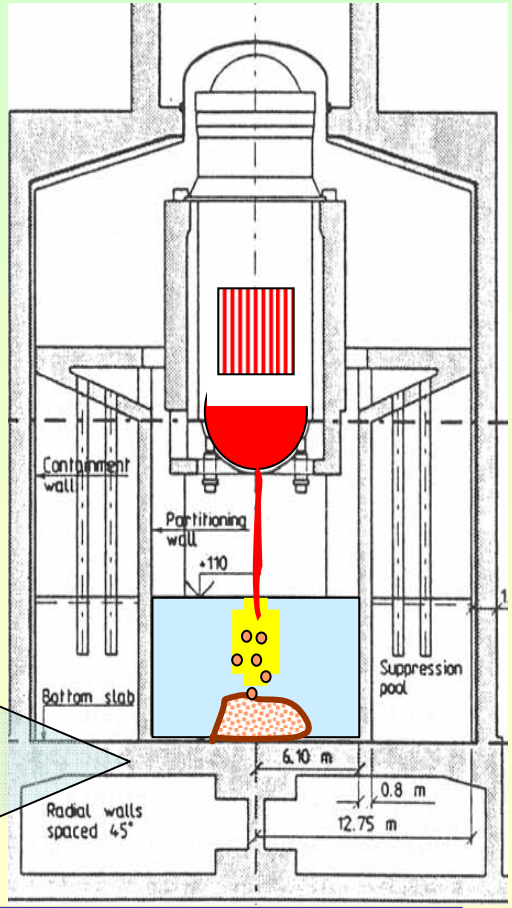
Pavel Kudinov, Weimin Ma, Chi-Than Tran, Roberta C. Hansson, Aram Karbojian, and Truc Nam Dinh

Division of Nuclear Power Safety (NPS), KTH
E-mail: pavel@safety.sci.kth.se





Experiment-Analysis-Application



Outline

- Severe accident in Swedish and Finnish type design of BWR
- Focus of the research
- Approach
- In-vessel coolability
- Steam explosion
- Debris bed formation and coolability
- Summary

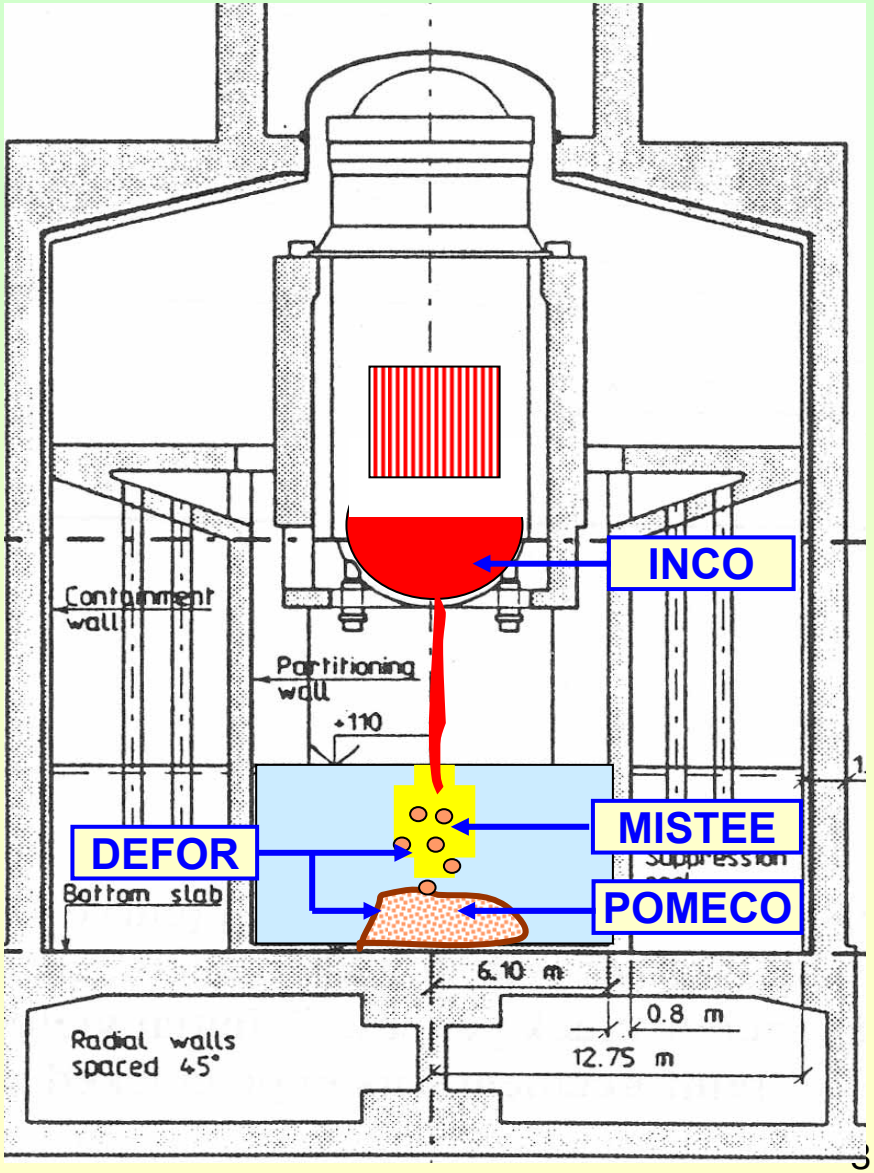
Focus
and Key questions

Addressing threats to containment integrity during a severe core melt accident

a) **<u>INCO</u>***: Is in-vessel retention achievable with CRGT cooling?*

b) **<u>MISTEE</u>***: Are large-scale steam explosions realistic?*

c) **<u>EXCO (DEFOR+POMECO)</u>***: Are the ex-vessel debris beds coolable?*



Approach

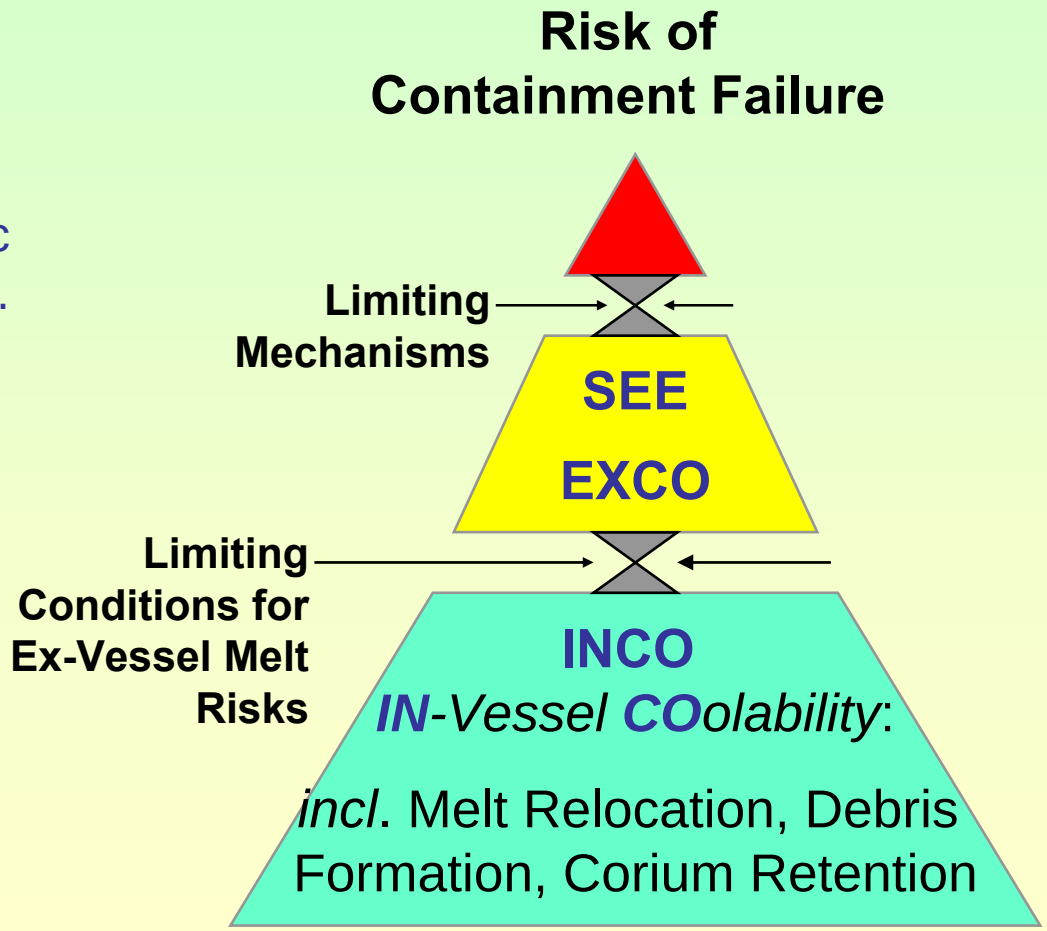
Big uncertainty exist both in scenario and physical phenomena of core melt accident

Approach:
Focus on **limiting physical mechanisms** which can reduce intrinsic uncertainty in scenario and phenomena.

Phenomena are complex **multi-scale**

Feedback between different scales and stages of an accident – source of limiting mechanisms

Development validation and application of **simulation tools** to analysis of reactor scale phenomena in different accident scenarios



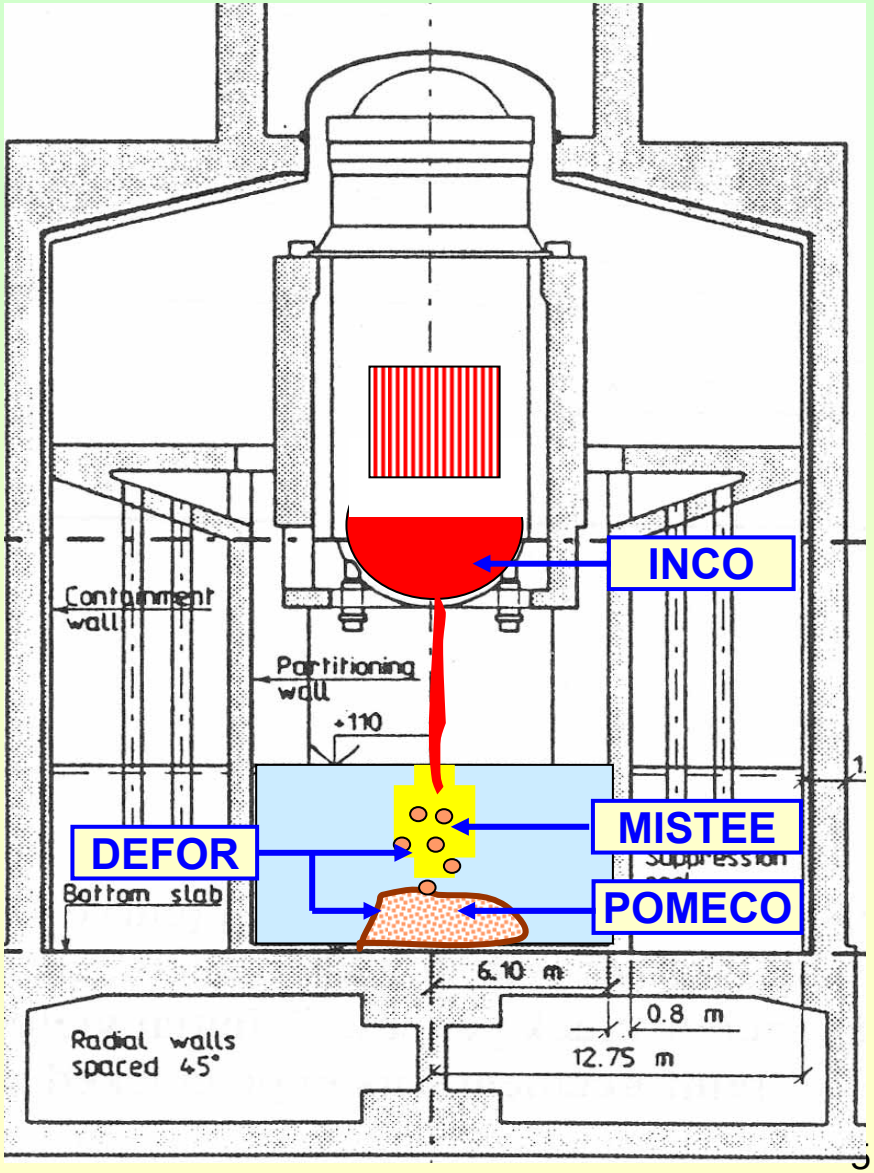
Focus
and Key questions

Addressing threats to containment integrity during a severe core melt accident

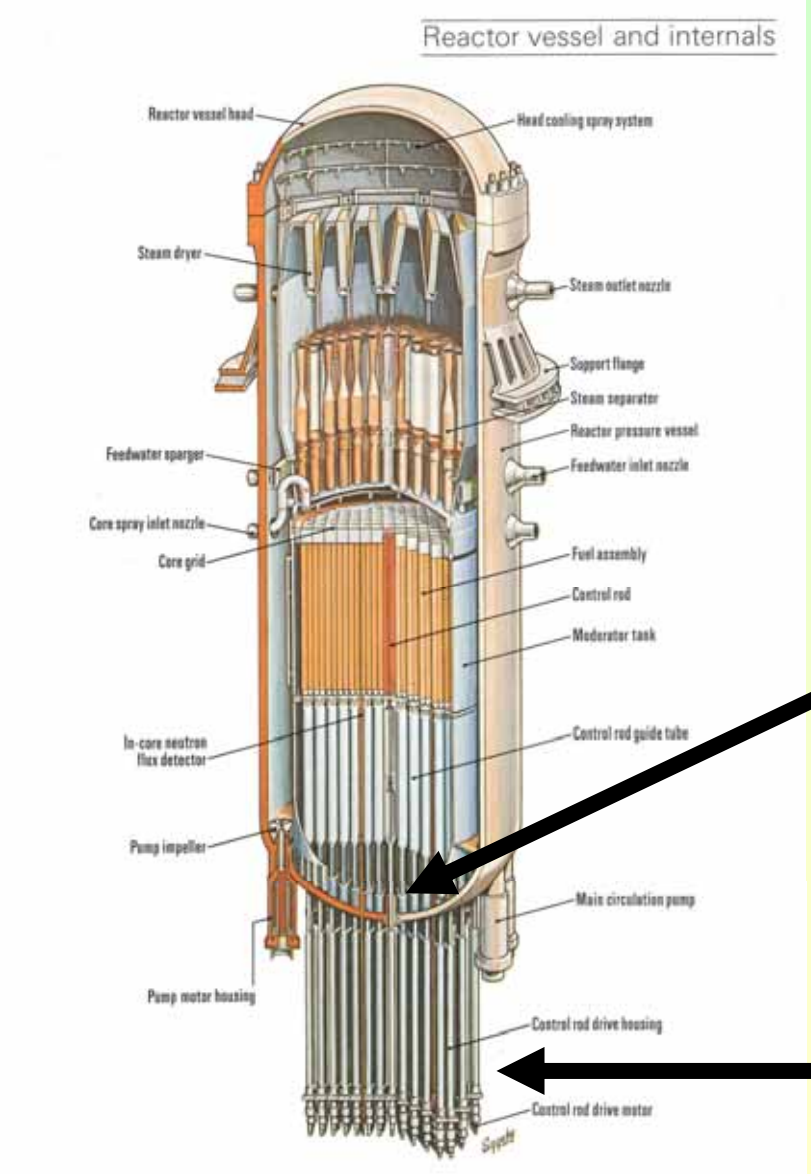
a) **<u>INCO</u>*: Is in-vessel retention achievable with CRGT cooling?***

b) **<u>MISTEE</u>*: Are large-scale steam explosions realistic?***

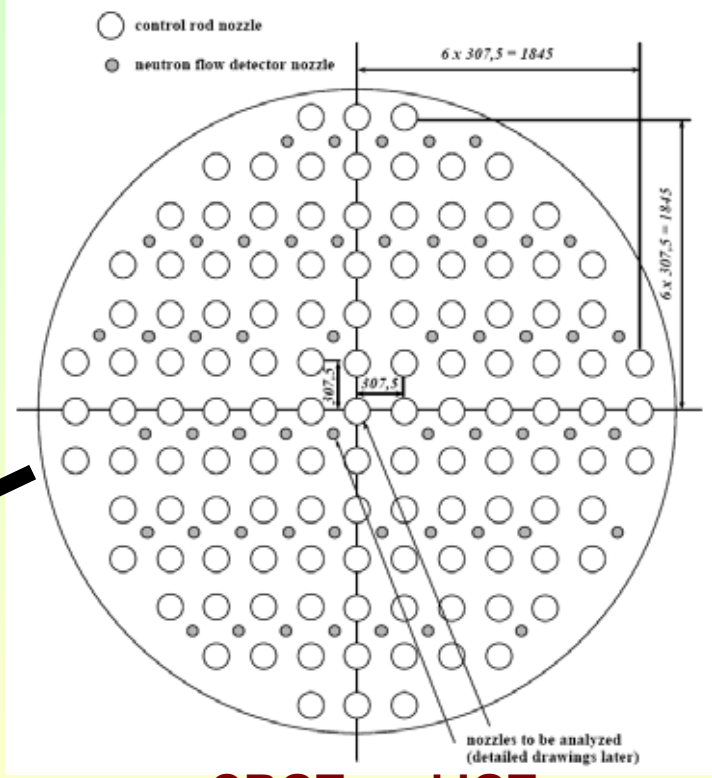
c) **<u>EXCO (DEFOR+POMECO)</u>*: Are the ex-vessel debris beds coolable?***



In-Vessel Coolability



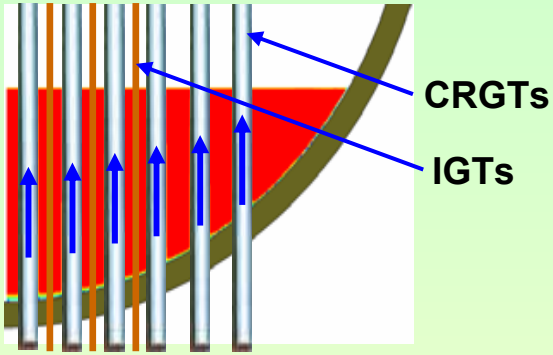
BWR lower head – complex geometry



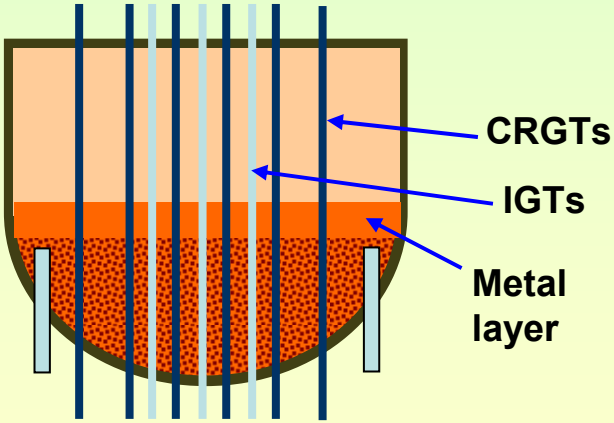
CRGT and IGT Arrangement:

- **CRGT: 121 (*124.5 mm*)**
- **IGT: 50 (*65.5 mm*)**

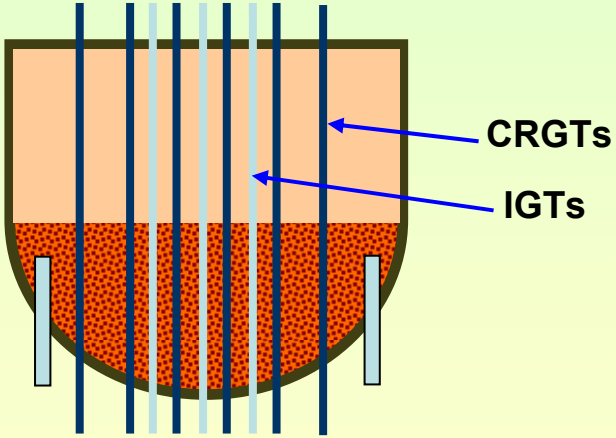
Melt Coolability by CRGT flow



Case 1: Homogeneous debris bed (melt pool)



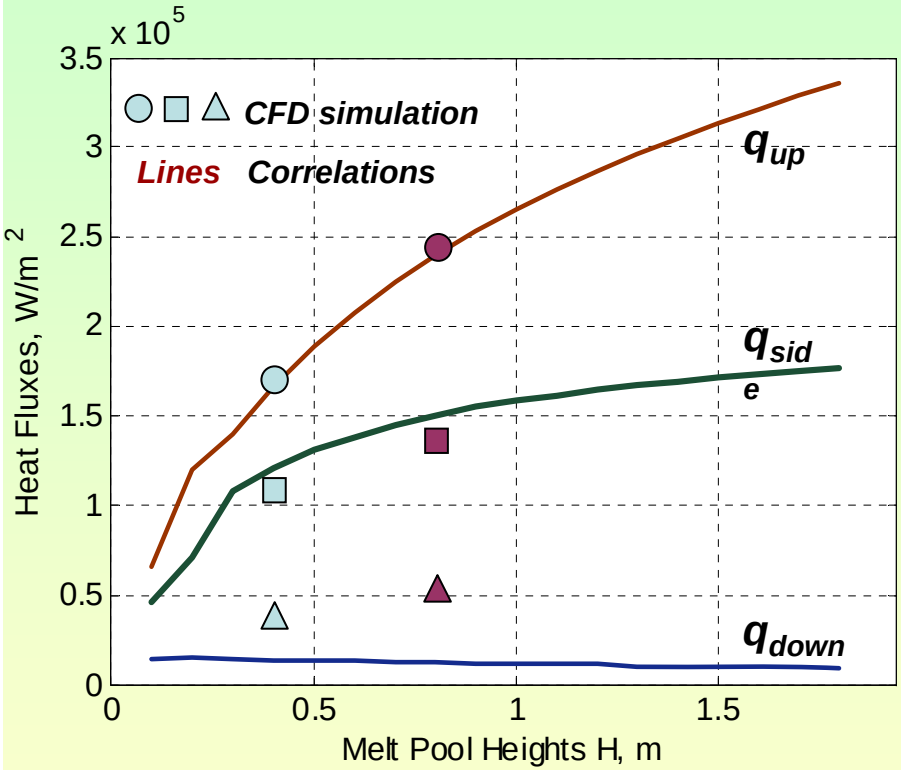
Case 2: Stratified heterogeneous debris pool



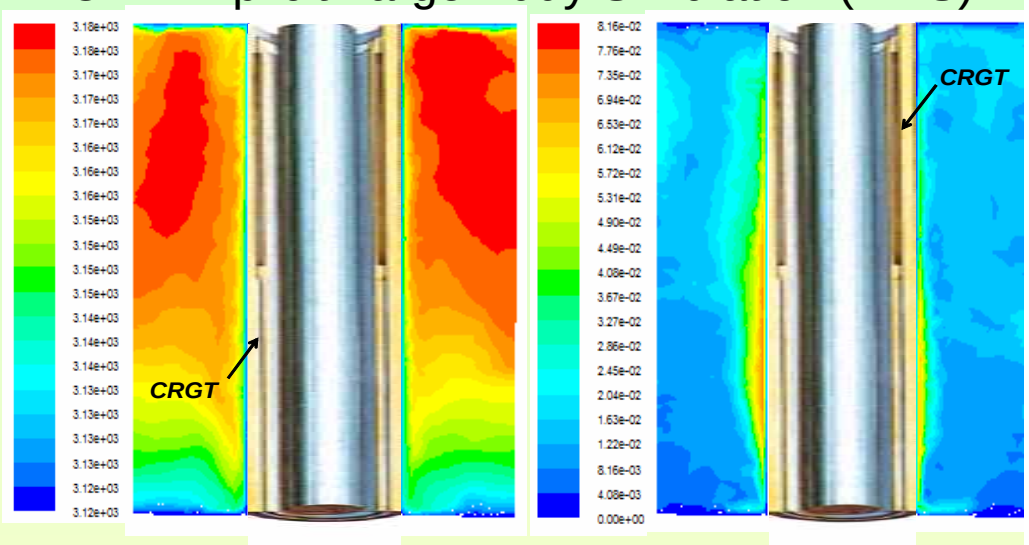
Case 3: Uniform heterogeneous debris pool

✓ IGT fail and plug is uncertain, in these cases we assume that IGTs are plugged

Separate Effect Study with CFD



CFD Implicit Large Eddy Simulation (ILES)

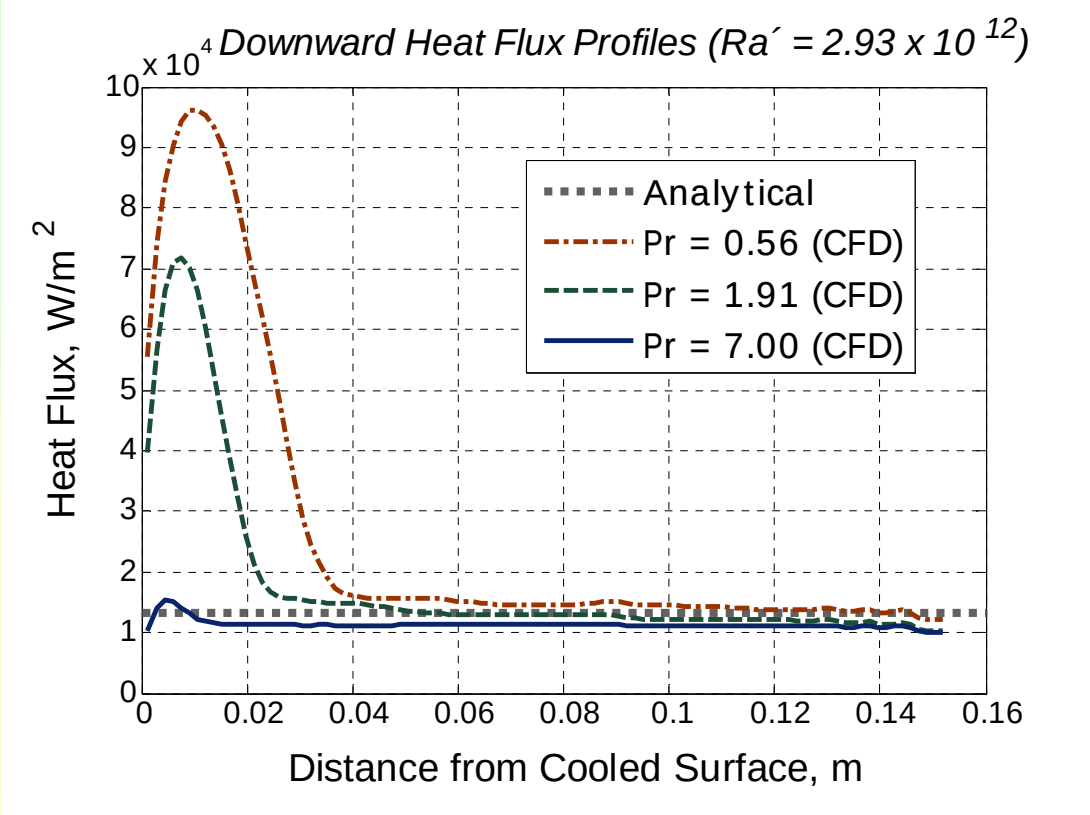


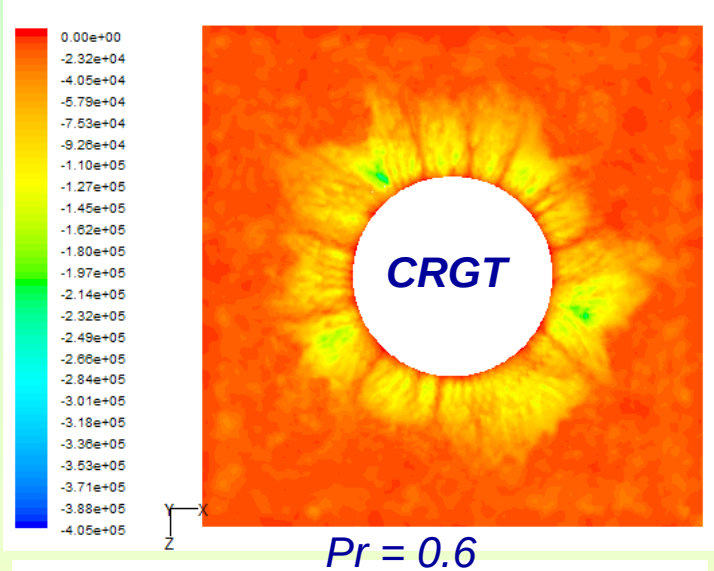
Temperature Velocity

- **Analytical model: Steinberner-Reineke correlations**
- **CFD study confirms the applicability of the selected correlations**
- **CFD simulations reveal the local effect of heat transfer (downward heat flux)**

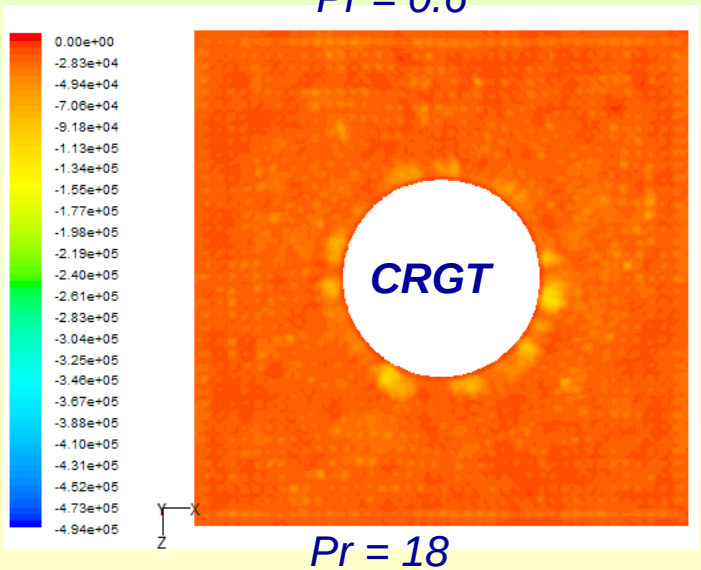
Enhancement of Local Heat Transfer due to Low Prandtl Number

Low Fluid Prandtl Number Effect





Pr = 0.6



Pr = 18

Direct CFD simulation of coolability in real geometry of BWR lower head is not practical.

Computationally effective and reasonably accurate model is necessary!

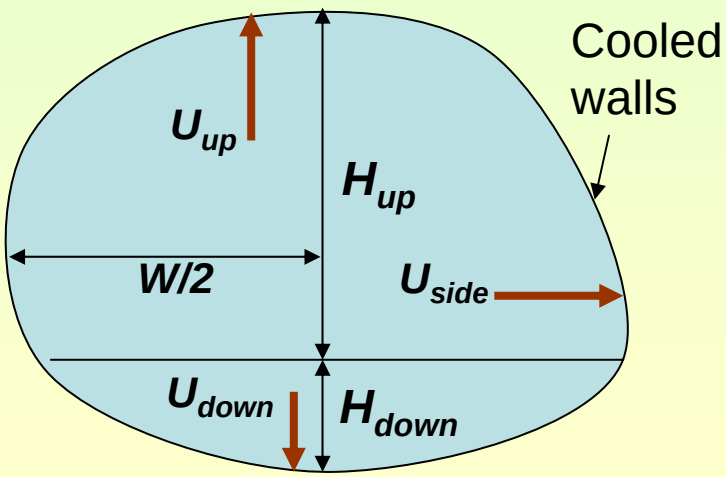
The Effective Convectivity Model (ECM and PECM)

The model (ECM/PECM) takes into account ***local effects***!

Single enthalpy conservation equation for an internally heated volume:

$$\frac{\partial}{\partial t}(\rho h) = \nabla \cdot \left(\frac{k}{C_p} \nabla h \right) - \frac{\partial(\rho \Delta H)}{\partial t} - \nabla \cdot (\rho U_{x,y,z} h) - \nabla \cdot (\rho U_{x,y,z} L) + Q_v$$

Characteristic velocities $U_{x,y,z}$ (U_{up}, U_{side} and U_{down}) are solved instead of u

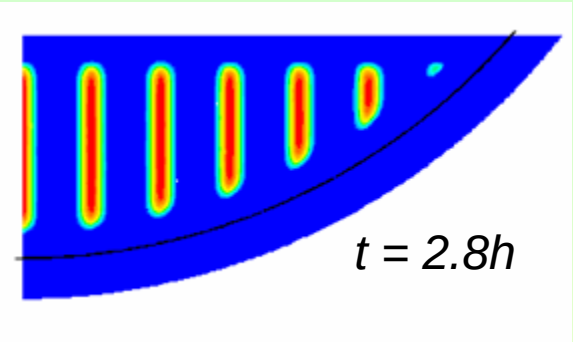


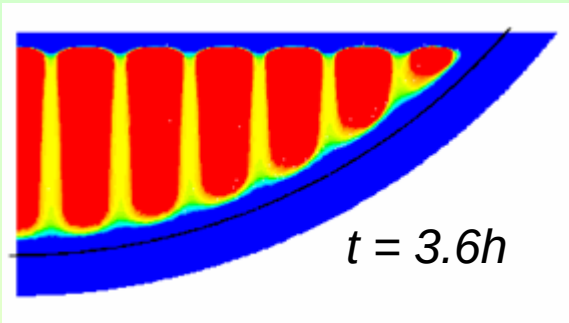
$$\begin{cases} U_{up} = \dfrac{\alpha}{H_{pool}} \times \left(Nu_{up} - \dfrac{H_{pool}}{H_{up}} \right) \\ U_{down} = \dfrac{\alpha}{H_{pool}} \times \left(Nu_{down} - \dfrac{H_{pool}}{H_{down}} \right) \\ U_{side} = \dfrac{\alpha}{H_{pool}} \times \left(Nu_{side} - \dfrac{2 \times H_{pool}}{W_{pool}} \right) \end{cases}$$

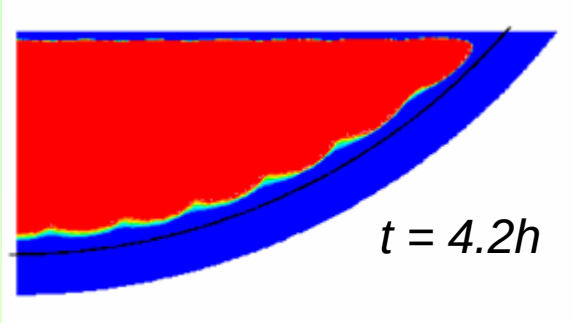
✓ **The Nu_{up}, Nu_{side} and Nu_{down} are determined from correlations and the BL model**

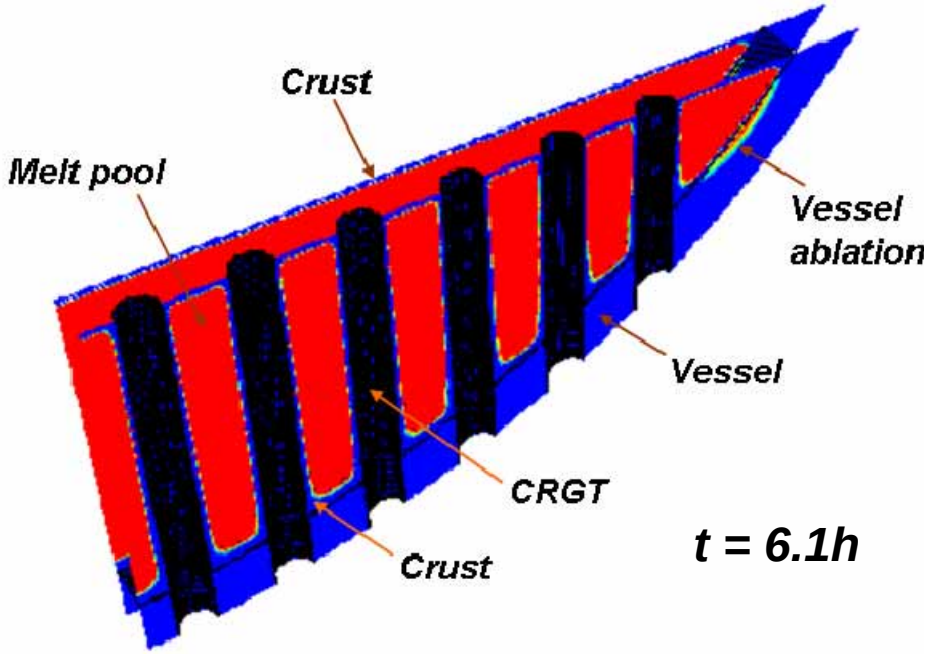
PECM Simulations in Real Geometry of a BWR Lower Head

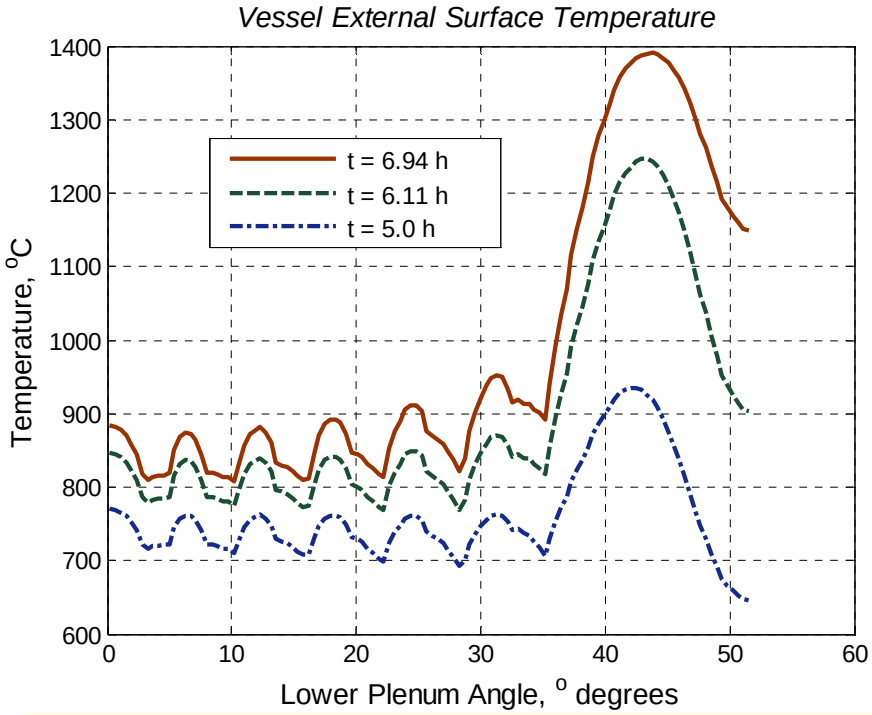
Melt Pool Development (H = 1m)











In-vessel Melt Coolability Multiscale Approach

- ***Local effects*** are captured in ***CFD*** simulations of unit volume geometry

- ***Effective models*** (ECM/PECM) for simulation of ***large scale*** real geometry are developed with taking into account of ***local effects***

- Application of the effective models shows considerable ***influence of small scale effects on large scale*** melt pool heat transfer and vessel failure mode

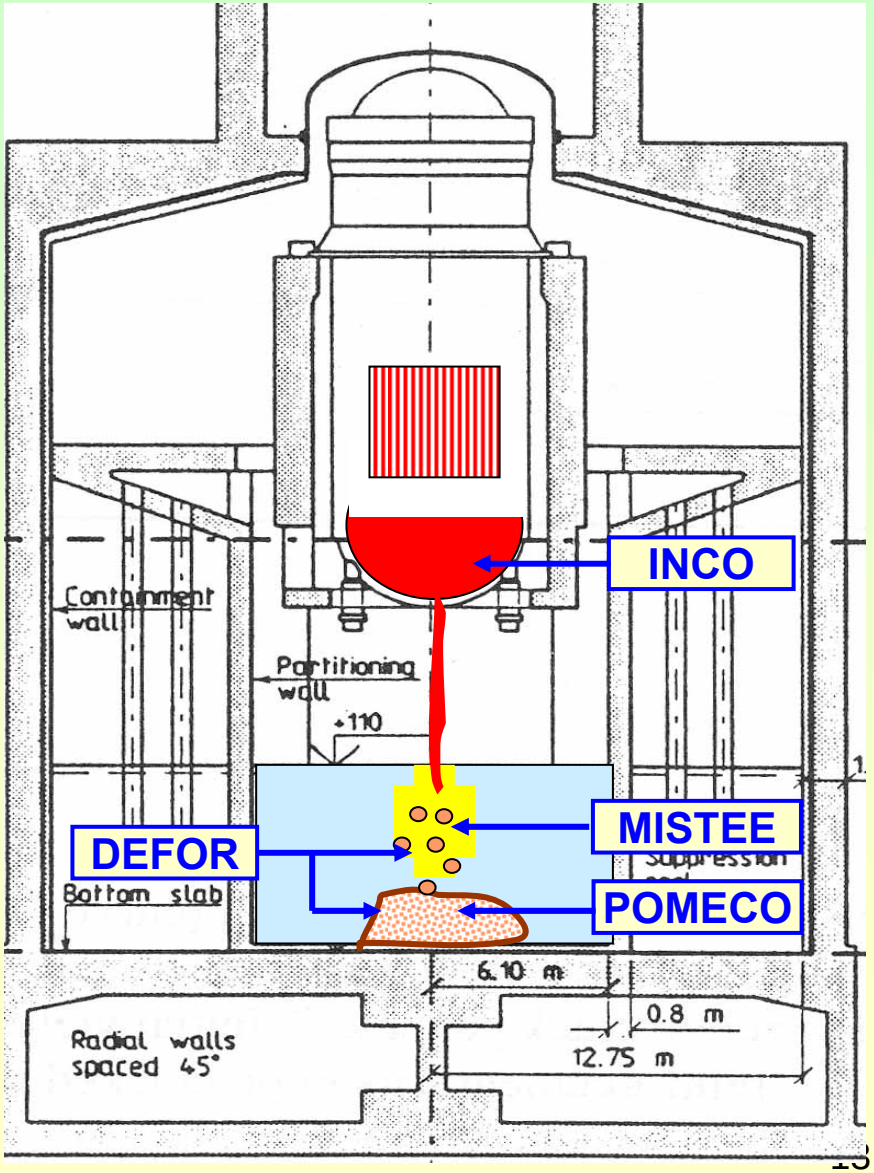
Focus
and Key questions

Addressing threats to containment integrity during a severe core melt accident

a) <u>INCO</u>*: Is in-vessel retention achievable with CRGT cooling?*

b) <u>MISTEE</u>***: Are large-scale steam explosions realistic?***

c) <u>EXCO (DEFOR+POMECO)</u>*: Are the ex-vessel debris beds coolable?*



Steam explosion

High temperature liquid contacts with cold and volatile liquid.

Rapid heat transfer between the high temperature liquid (e.g., molten materials) and cold liquid (e.g., water)

Explosive vapor generation, strong shock waves.

Hydrodynamic loading to the surrounding system.

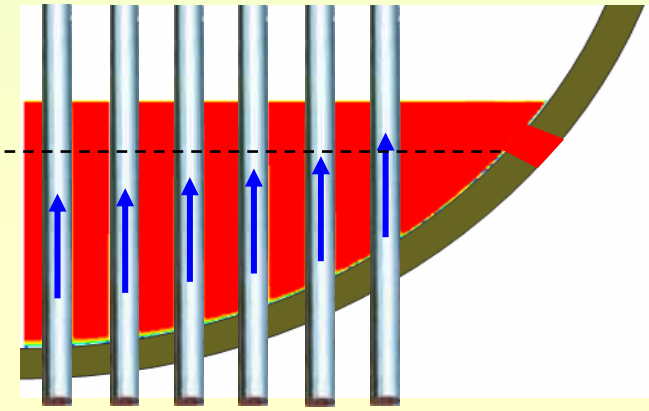
Steam Explosion Impact
Connection INCO → MISTEE

In case of slow dripping of the melt through small opening(s), the mass of the melt available for explosion will be limited.

Dynamical impact on structures = Mass of **available for explosion** melt * Energy Conversion Ratio

Limiting factors:
- ❖ Rupture size (vessel wall or IGT failure)
- ❖ Rupture position (limited amount of melt)

Limiting factor:
- ❖ Coolant state

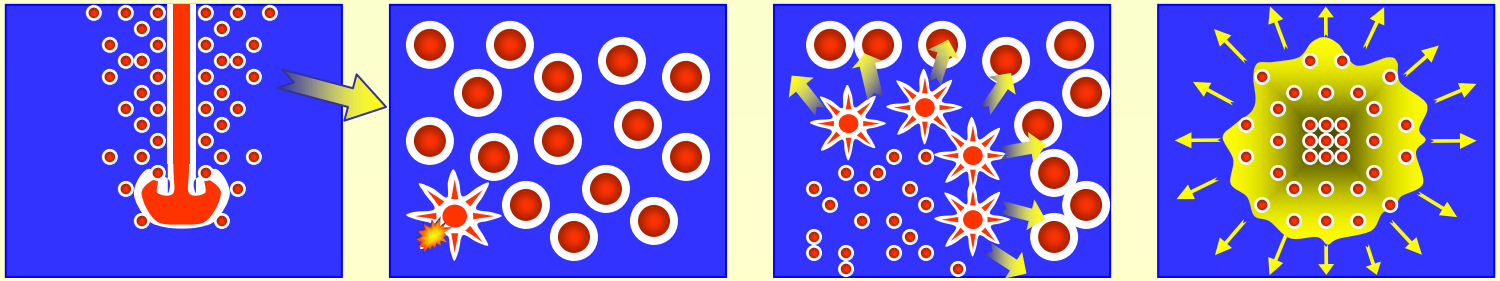


INCO → **SEE**

Limiting factors:
- ❖ Melt composition
- ❖ Melt superheat

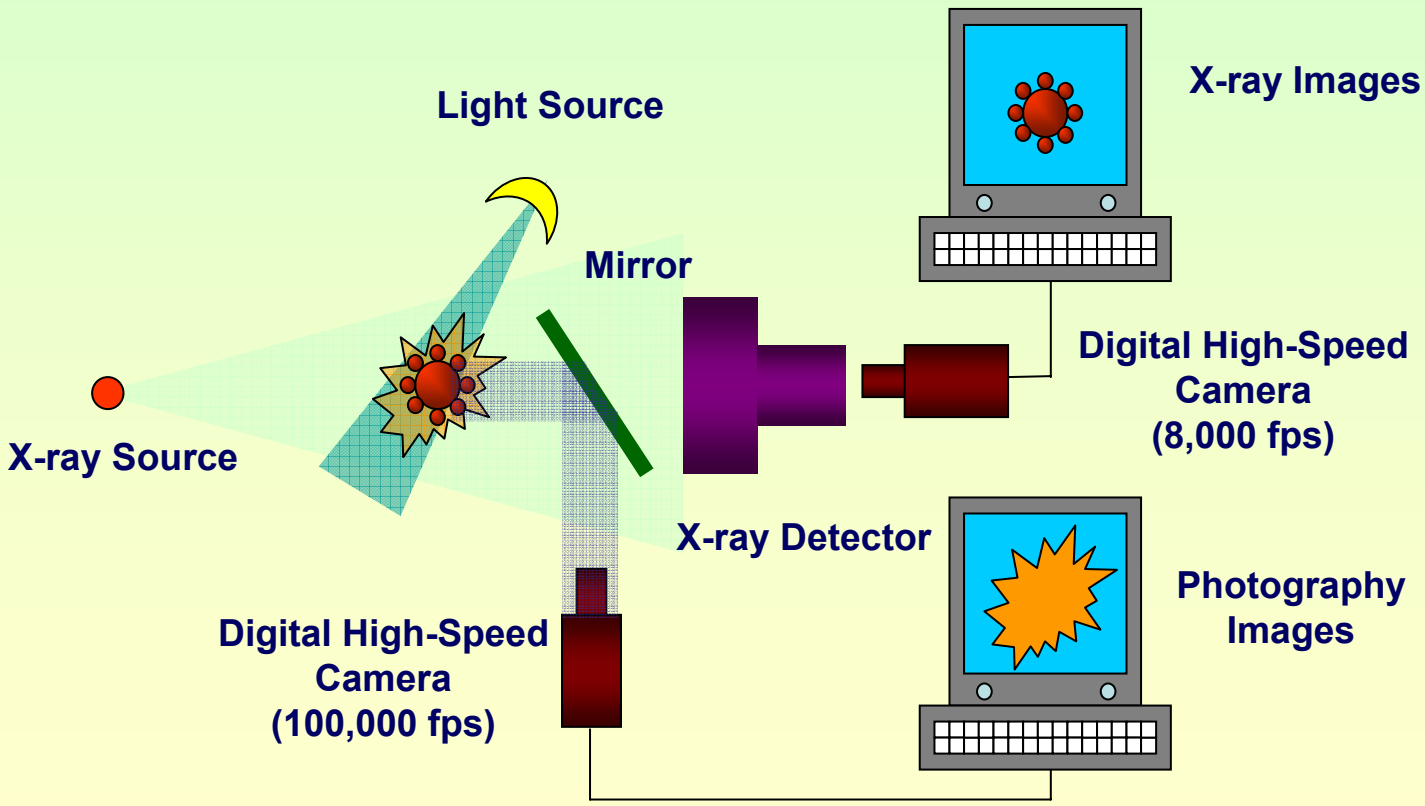
Steam Explosion Phenomena

- Vapor explosion consists of various sequential multiphase and multi-component phenomena in scales of
  - **Mixing phase**
    - Jet impingement (Jet breakup and penetration) in air and coolant
  - **Triggering phase**
    - bubble dynamics (interfacial instability)
  - **Propagation/Escalation phase**
    - shock wave generation, propagation and escalation (detonation)
    - heat transfer and fluid flow in porous media
    - jet fragmentation
  - **Expansion phase**
    - expansion of multiphase, multi-component mixture
    - agglomeration and solidification of melt
    - structure response by impact



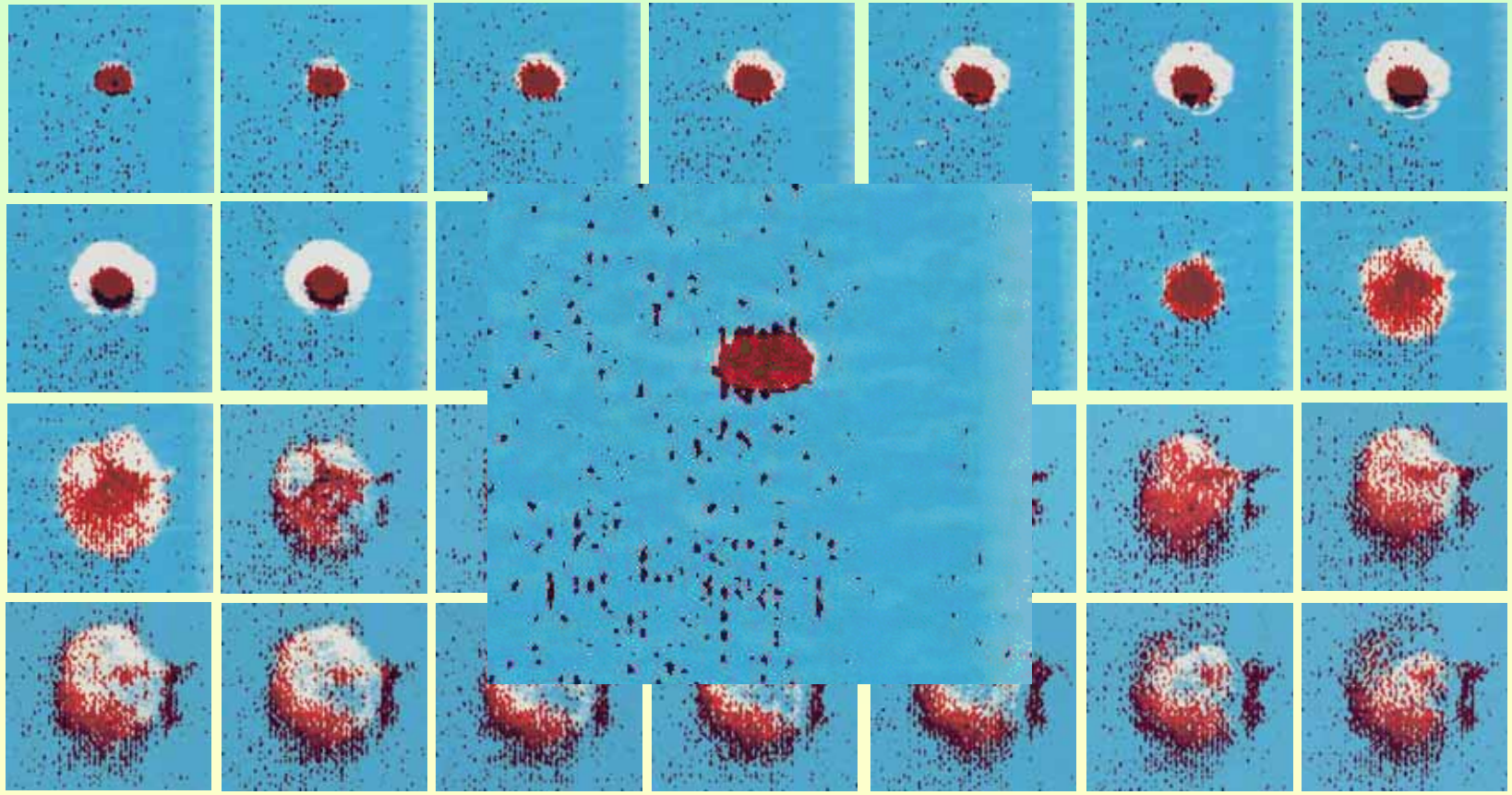
MISTEE Facility

Study of ***Micro Interactions*** in Steam Explosion (MISTEE)
with Simultaneous High Speed Acquisition Radiography and Photo Images (SHARP)



Micro-scale Phenomena of Steam Explosion

Micro-scale determines energy **conversion ratio** and thus **energetics of large scale** steam explosion



Interrelated progression of the bubble and molten material

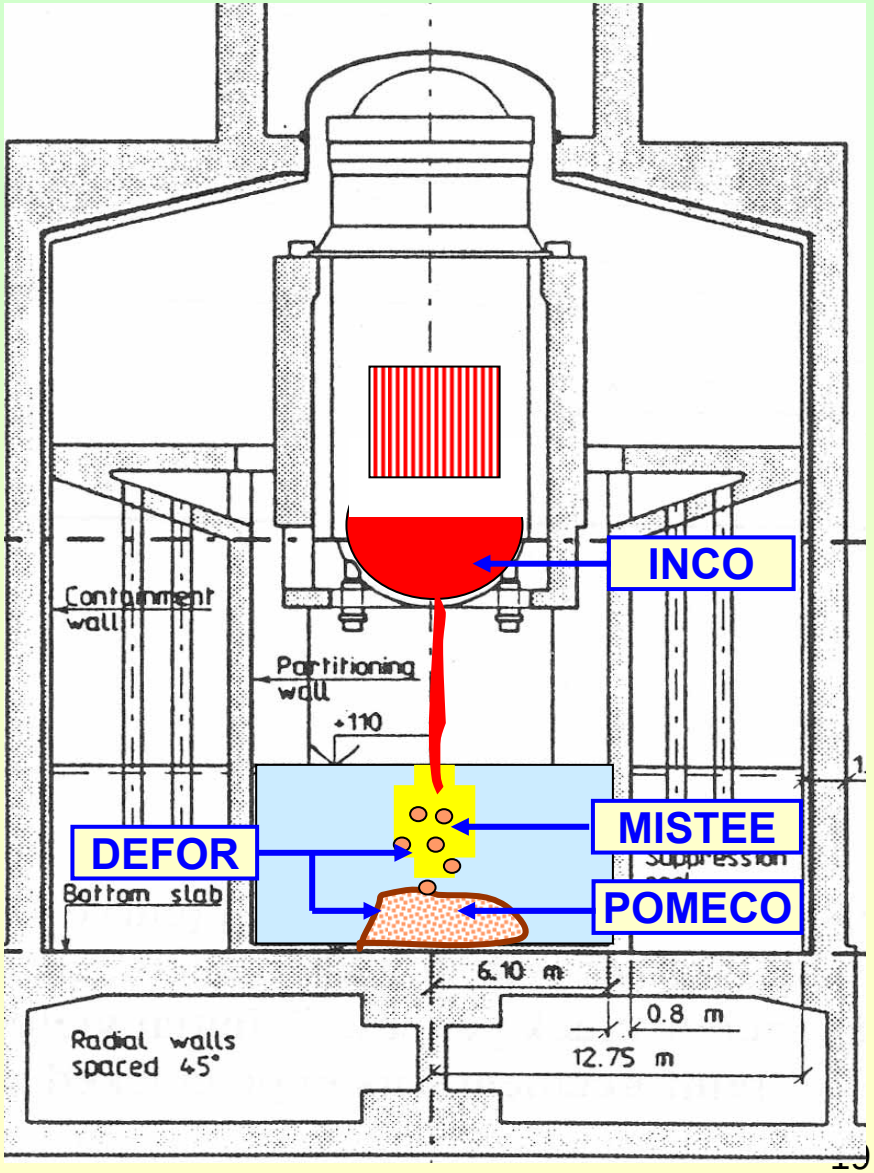
Focus
and Key questions

Addressing threats to containment integrity during a severe core melt accident

a) <u>INCO</u>*: Is in-vessel retention achievable with CRGT cooling?*

b) <u>MISTEE</u>*: Are large-scale steam explosions realistic?*

c) **<u>EXCO (DEFOR+POMECO)</u>***: Are the ex-vessel debris beds coolable?*



Problem Decomposition in Severe Accident Analysis

Fuel Coolant Interaction (FCI)

Debris Bed Coolability

How ?

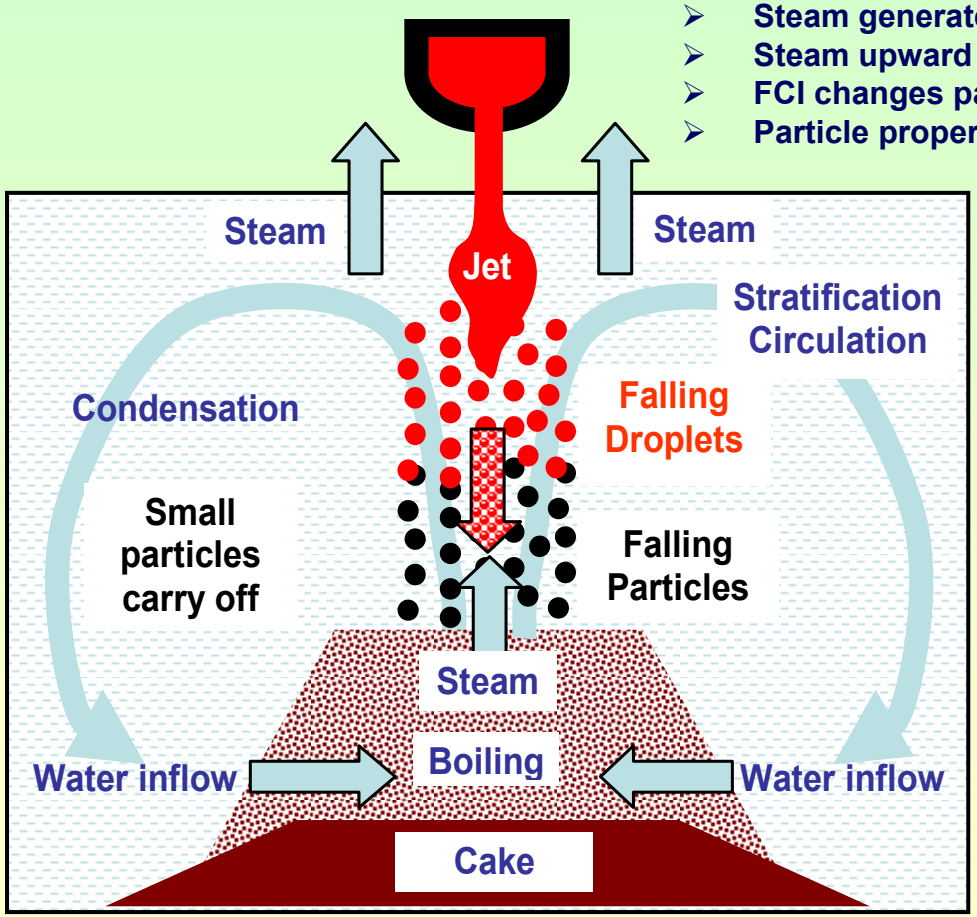
Data

Gap in knowledge

Data

Debris Bed Formation in a LWR Severe Accident

- The cooling of the debris bed is provided by heat transfer to the water that ingresses into the porous bed interior
- Steam generated inside debris bed is escaping upwards
- Steam upward flow changes conditions for FCI
- FCI changes particle properties (size distribution and morphology)
- Particle properties affect the debris bed coolability phenomena



Debris formation
- Sizes distribution
- Morphology

Jet fragmentation

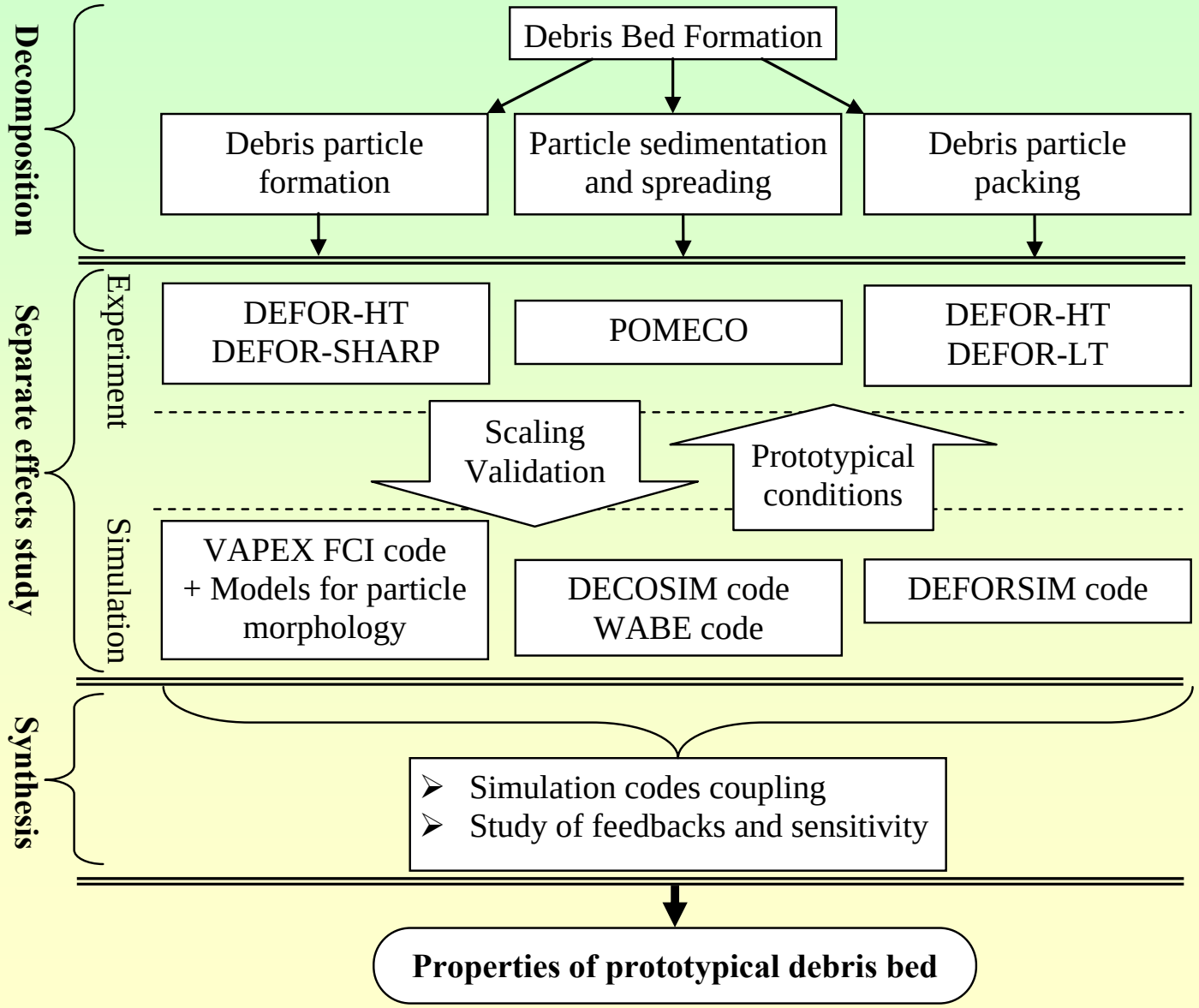
DEFOR Phenomena
- Sedimentation
- Packing
- Levitation and carry off
- Shape of debris bed
- Porous media properties
  - Porosity (void fraction)
  - Pores size distribution
  - Pore morphology
  - Non-homogeneity
  - Non isotropy

Feedback

Coolability Phenomena
- Boiling inside debris bed
- Steam / water flow
  - Inside debris bed
  - Outside debris bed

Strong **feedback** between FCI, debris bed formation and coolability

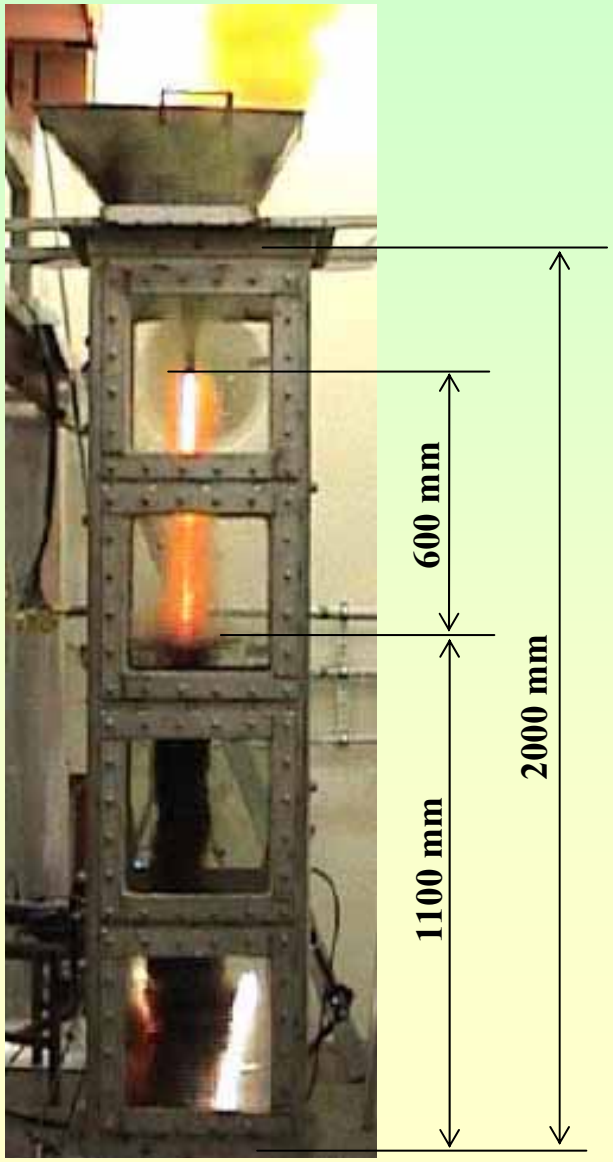
DEFOR research program
"To Fill the Gap in Knowledge"



DEFOR program
Research Instruments

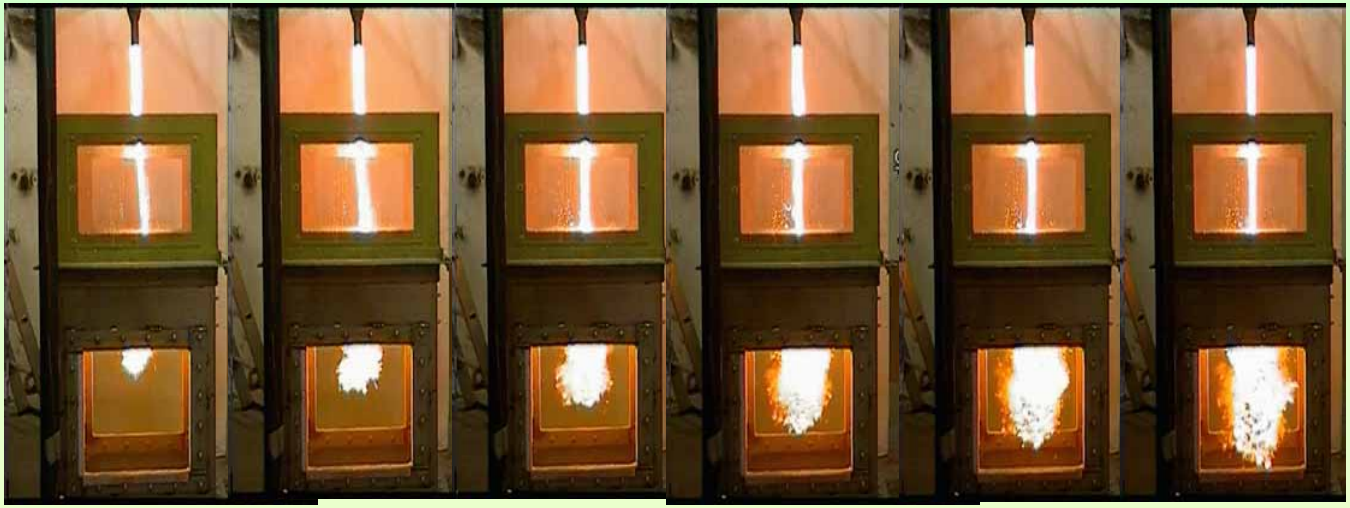
	Research Instrument	Objectives	Research method	References
Experiment	**DEFOR-E**	**Obtain first-cut information on integral picture of the debris formation after FCI**	**Scoping experiments with medium amount (2.5-7 liters) of binary-oxide melts, at 1000-1400 °C**	**Karbojian et al. (2007, 2009)**
	DEFOR-S	**Separate effect study of the coolant state and melt composition influence on debris formation and packing**	**Snapshot experiments with small amount (~1 liter) of heavy, binary-oxide, ceramic-type melts, at ~1000-1400 °C**	**Kudinov et al. (2007, 2008a, 2009)**
	DEFOR-SHARP	Study of the debris particle formation phenomena, melt material and coolant temperature effects	Experiments in SHARP facility on single melt droplet and small jets of heavy, binary-oxide, ceramic-type melts	-
	DEFOR-LT	**Study of coolant flow influence on packing and resulting properties of the debris bed**	**Low temperature experiments with different shape and size distribution of particles**	**Budu (2008)**
	POMECO	Quantification of drag and heat transfer in the debris bed of prototypical properties	Experiments with prototypical shape, size distribution of particles and porosity of the bed	-
Simulation	**VAPEX**	**Development of debris agglomeration mode map. Prediction of pre-deposition state of the debris after FCI.**	**Solving multi-field equations (water, vapor, melt jet, and debris) in FCIs**	**Dombrovsky et al. (2008); Davydov & Kudinov (2009)**
	WABE	**Prediction of the flow, heat transfer, and coolability of the decay heated debris bed**	**Solving porous media two-fluid equations with different semi-empirical closures for heat and momentum exchange**	**Ma, Buck, Bürger & Dinh (2007), Ma & Dinh (2007)**
	DECOSIM	**Prediction of transient heat transfer in the growing bed and in the pool. Prediction of particle spreading by the flow in the pool**	**Solving porous media two-fluid equations in the bed, and turbulent two-fluid free flow equations in the pool. Lagrangian description of debris particles trajectories**	**Yakush, Kudinov & Dinh (2008, 2009)**
	DEFORSIM	**Prediction of packing phenomena, from micro-scale particle-particle interaction to averaged macro-scale properties of the bed**	**Discrete element method equations for single particle dynamics. Multiscale "gap-tooth" for prediction macro scale debris bed properties**	**Kudinov & Dinh (2007, 2008)**

DEFOR-HT (High Temperature) experimental program



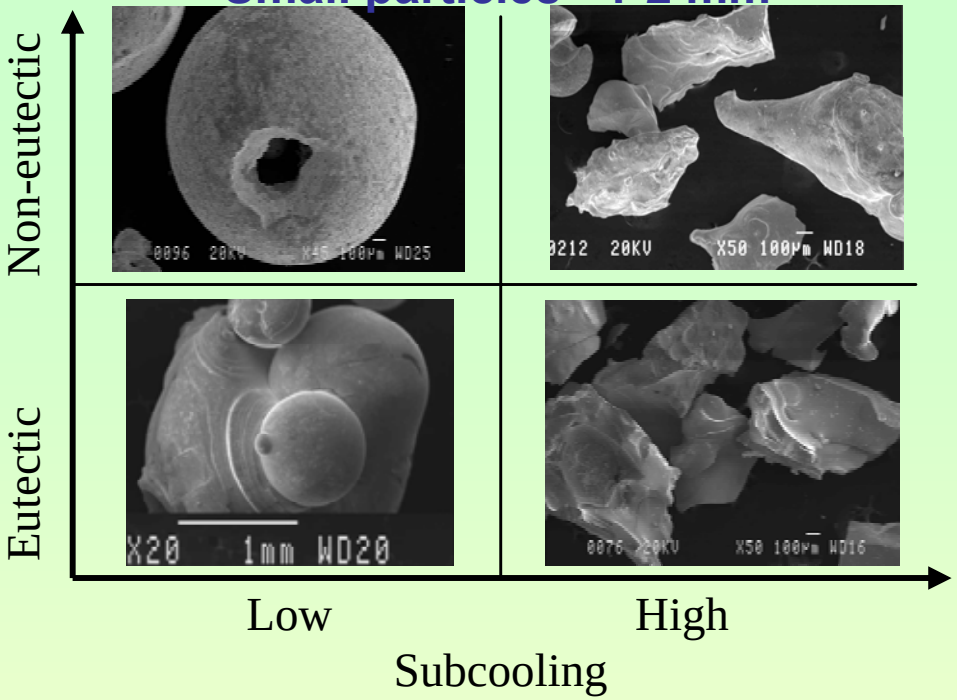
Containment: 4x4x4 m,
5 bar max pressure

Debris Bed Formation in FCI

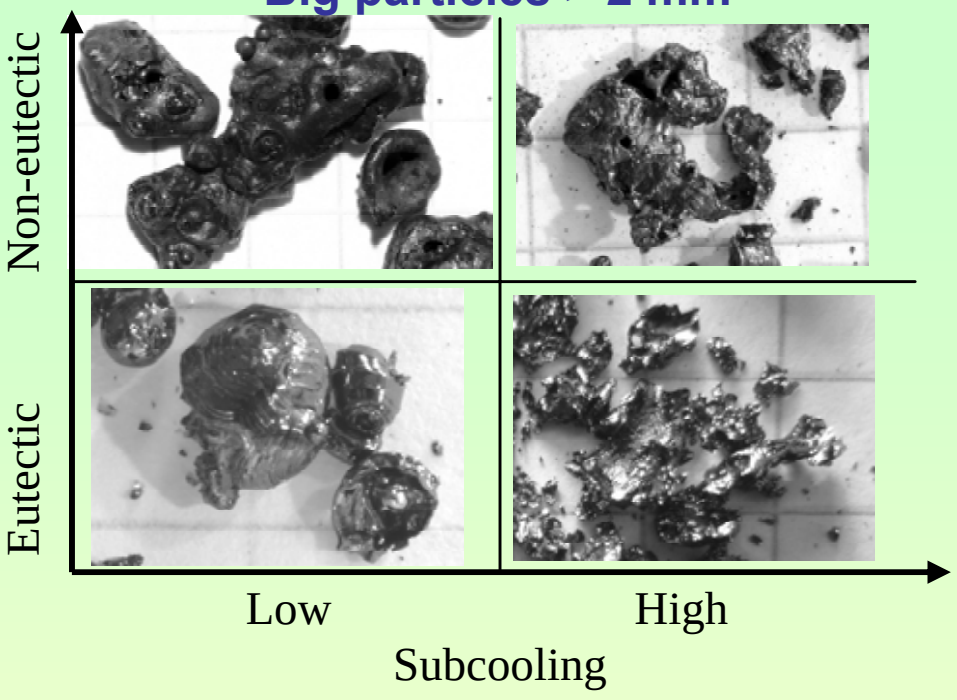


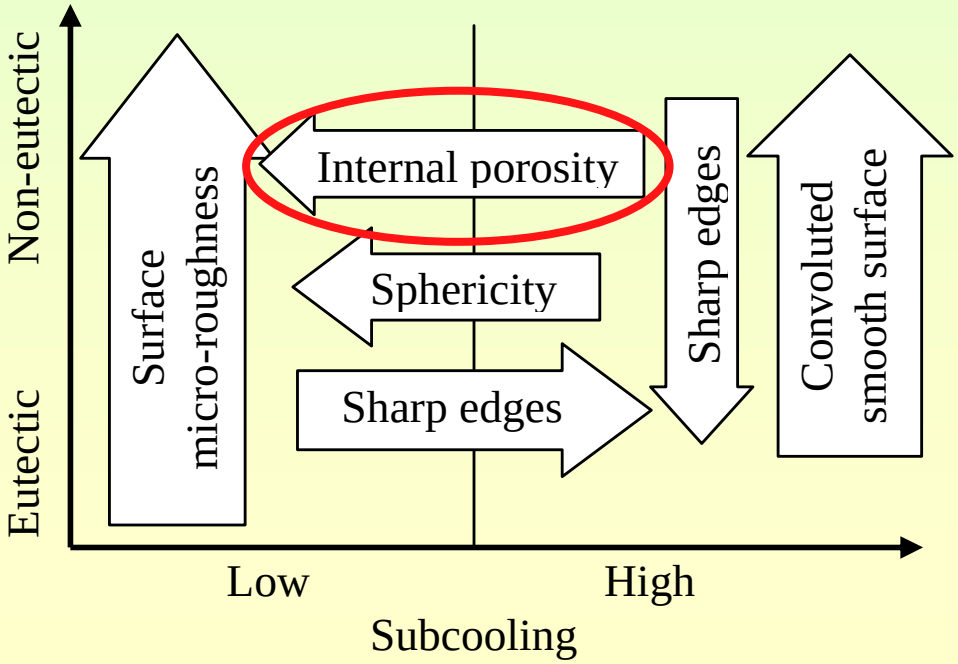
t=2.0 s t=2.2 s t=2.4 s t=2.6 s t=2.8 s t=3.0 s

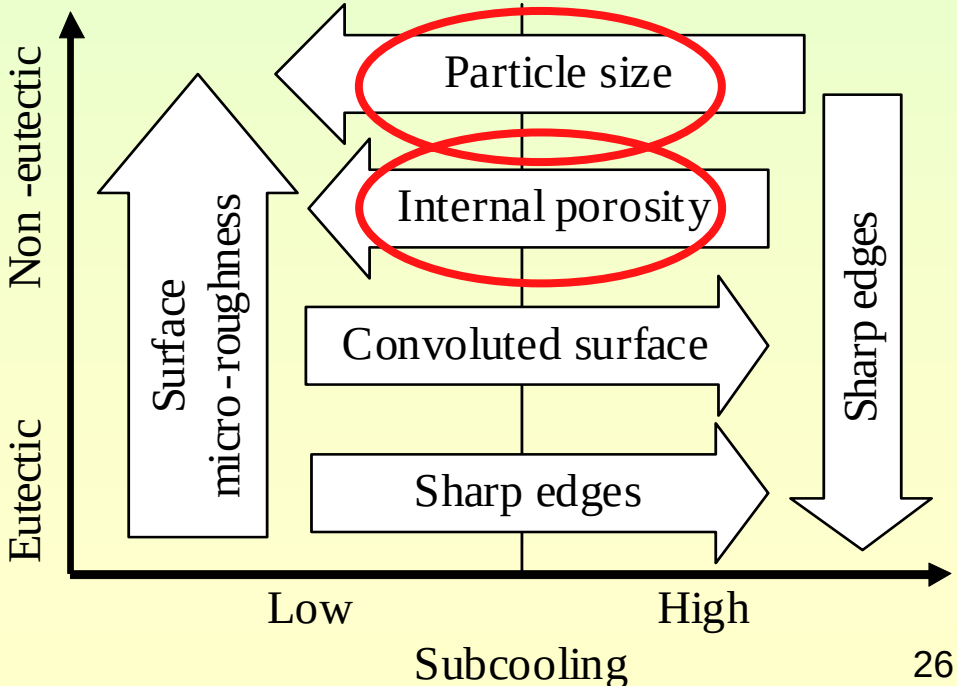
Small particles <1-2 mm



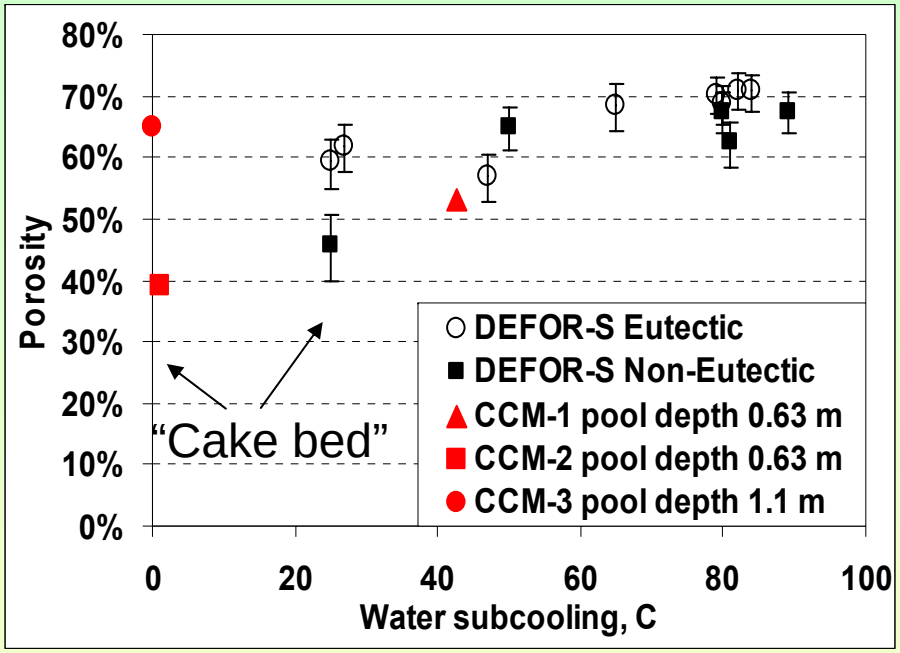
Big particles > 2 mm

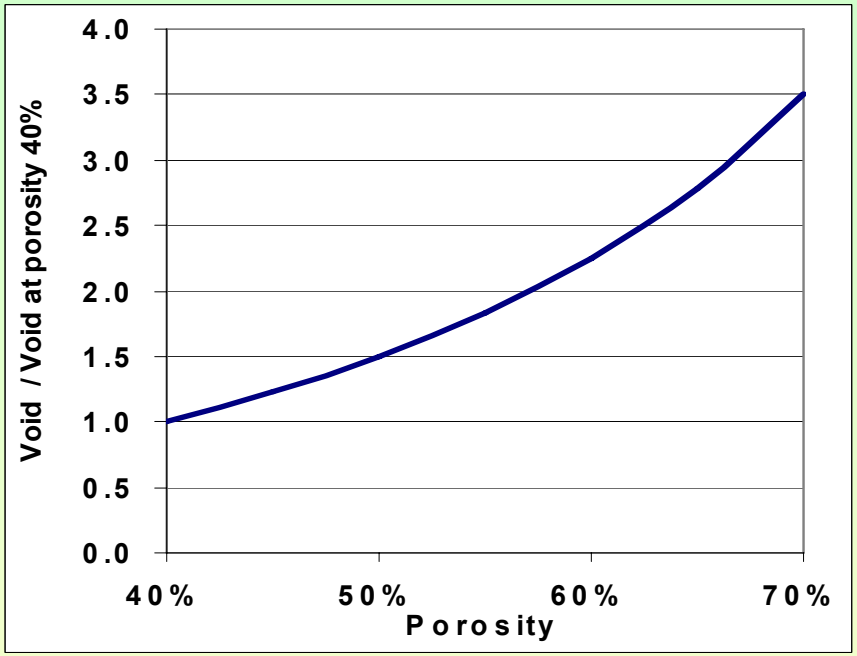






Summary of DEFOR-HT Findings





- Normally, assumed porosity for coolability calculations is **40%**
- **Averaged porosity of debris bed in DEFOR is high ~60-70% and insensitive to melt composition or water subcooling.**
- **Q:** ***Why porosity is so high, and will it be the same high for corium?***

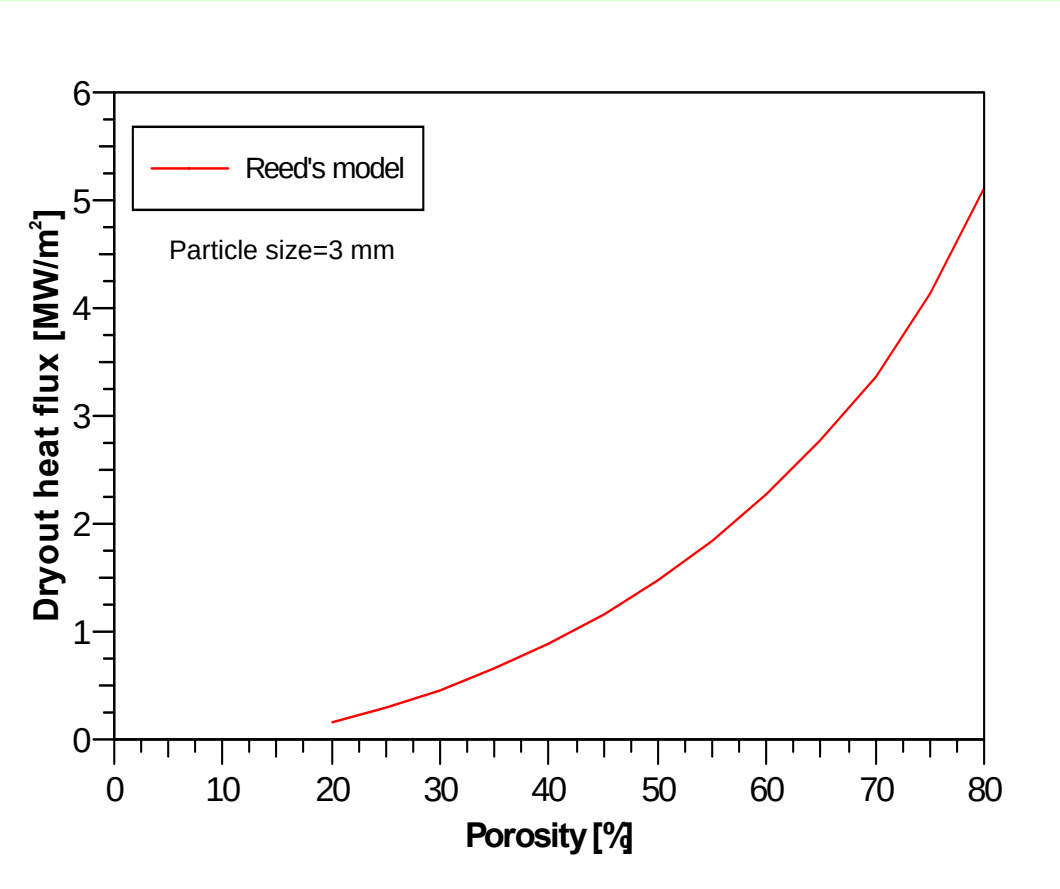
Coolability enhancement of high-porosity bed

ε ≈ 0.5-0.7 in DEFOR

$$\frac{DHF(\varepsilon=0.5)}{DHF(\varepsilon=0.4)}=\frac{1.48}{0.9}=1.6$$

$$\boxed{\frac{DHF(\varepsilon=0.6)}{DHF(\varepsilon=0.4)}=\frac{2.26}{0.9}=2.5}$$

$$\frac{DHF(\varepsilon=0.7)}{DHF(\varepsilon=0.4)}=\frac{3.37}{0.9}=3.7$$



Increase in coolability due to higher porosity 2-3 times!

Particle Dynamics and Packing Discrete Element Method (DEM)

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{V}_i \qquad m_i \frac{d\mathbf{V}_i}{dt} = \mathbf{F}_i$$

$$\frac{d\boldsymbol{\theta}_i}{dt} = \mathbf{w}_i \qquad I_i \frac{d\mathbf{w}_i}{dt} = \mathbf{T}_i$$

Discrete Element Method (DEM) is the most popular and well developed, approach for numerical study of **particle dynamics** with taking into account of:

- viscoelastic particle-particle collisions
- hydrodynamic effects

$$\mathbf{F}_i = \mathbf{F}_{i,contact} + \mathbf{F}_{i,gravity} + \mathbf{F}_{i,buoyancy} + \mathbf{F}_{i,drag}$$

$$\mathbf{F}_{i,contact} = \sum_{j=1,\, j\neq i}^{N} \mathbf{F}_{ij} \qquad \mathbf{F}_{ij} = \mathbf{F}_{\mathbf{n}ji} + \mathbf{F}_{\mathbf{t}ji}$$

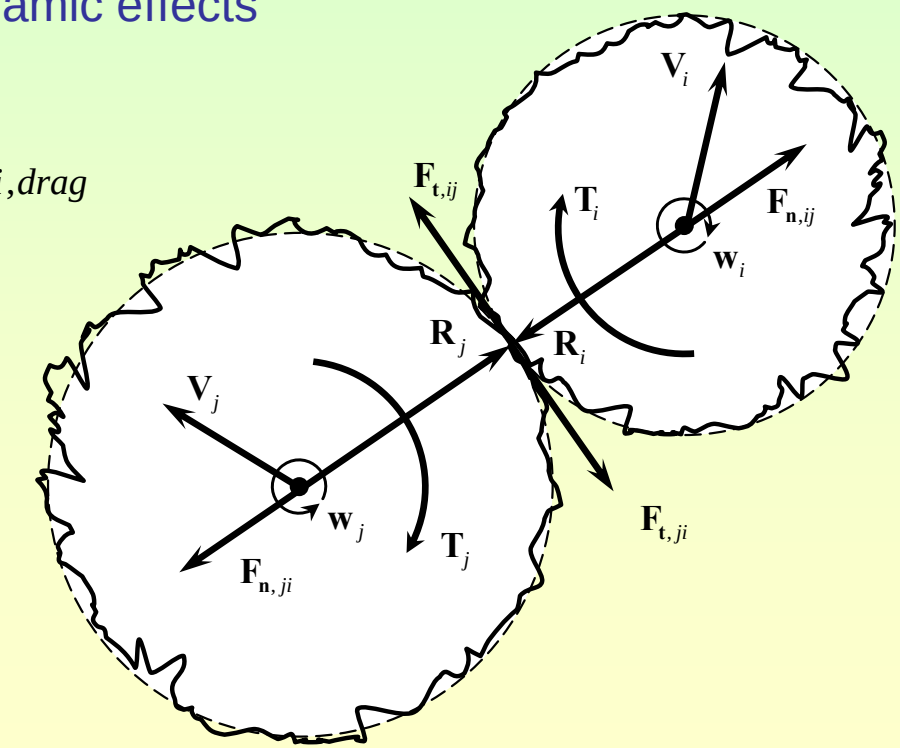
$$\mathbf{F}_{ij} = -\mathbf{F}_{ji}$$

$$\mathbf{F}_{\mathbf{t}ji} = k_f \left|\mathbf{F}_{\mathbf{n}ji}\right| \mathbf{t}_{ji}$$

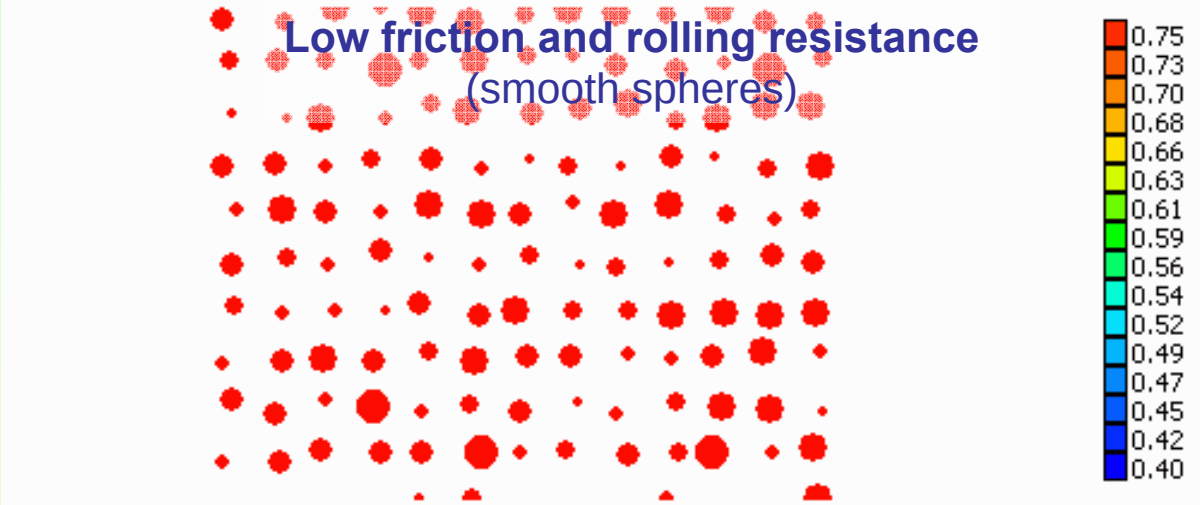
$$\mathbf{F}_{i,gravity} = m_i \mathbf{g}$$

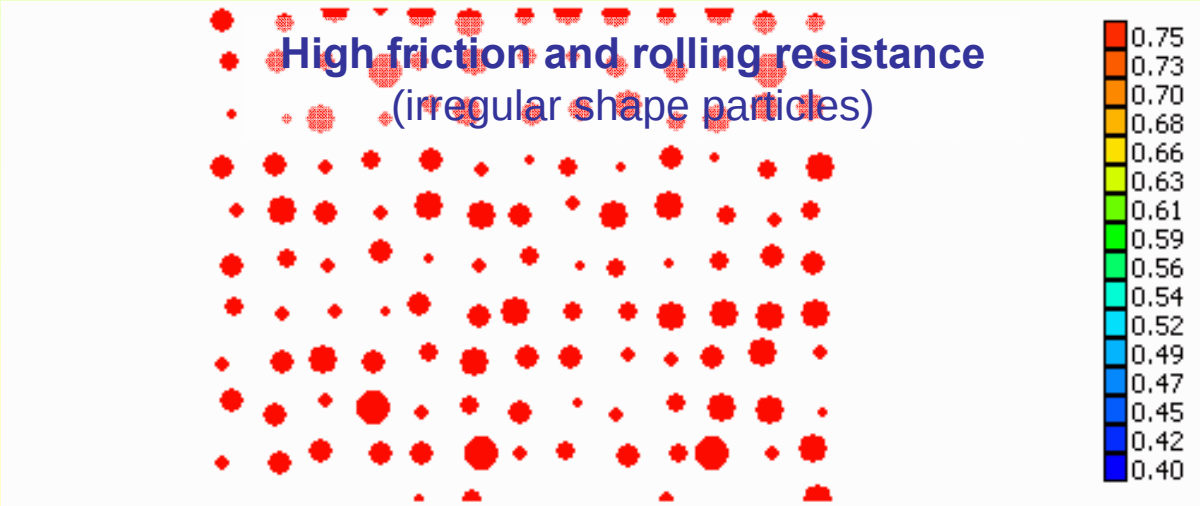
$$\mathbf{F}_{i,buoyancy} = -V_i \rho_{fluid} \mathbf{g}$$

$$\mathbf{T}_i = \mathbf{T}_{i,contact} + \mathbf{T}_{i,drag}$$



Influence of Inter-Particle Forces on Packing and Heap Shape





Higher friction and rolling resistance –

less spreading of the particles on the floor and higher porosity of the bed

Micro-scale phenomena (inter-particle friction) is responsible **for macro-scale** porosity of the debris bed

"Gap-tooth" scheme Multi-scale in Time and Space

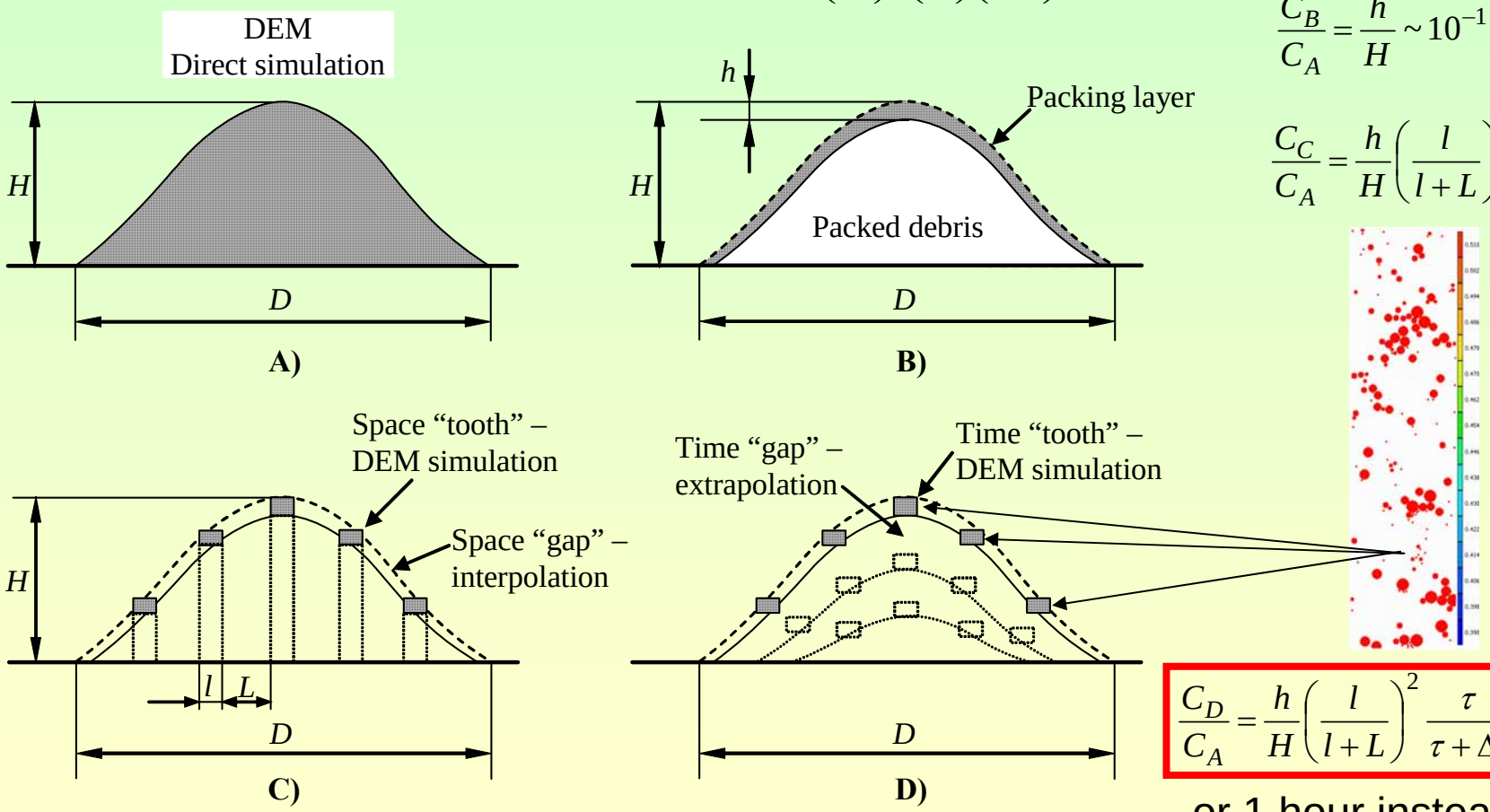
$$C_A \sim \left(\frac{D}{d}\right)^2 \left(\frac{H}{d}\right)\left(\frac{T}{\Delta\tau}\right)$$

$$C_B \sim \left(\frac{D}{d}\right)^2 \left(\frac{h}{d}\right)\left(\frac{T}{\Delta\tau}\right)$$

Computational costs

$$\frac{C_B}{C_A} = \frac{h}{H} \sim 10^{-1} \div 0.5$$

$$\frac{C_C}{C_A} = \frac{h}{H}\left(\frac{l}{l+L}\right)^2 \sim 10^{-3} \div 10^{-1}$$



$$\frac{C_D}{C_A} = \frac{h}{H}\left(\frac{l}{l+L}\right)^2 \frac{\tau}{\tau+\Delta t} \sim 10^{-4} \div 10^{-2}$$

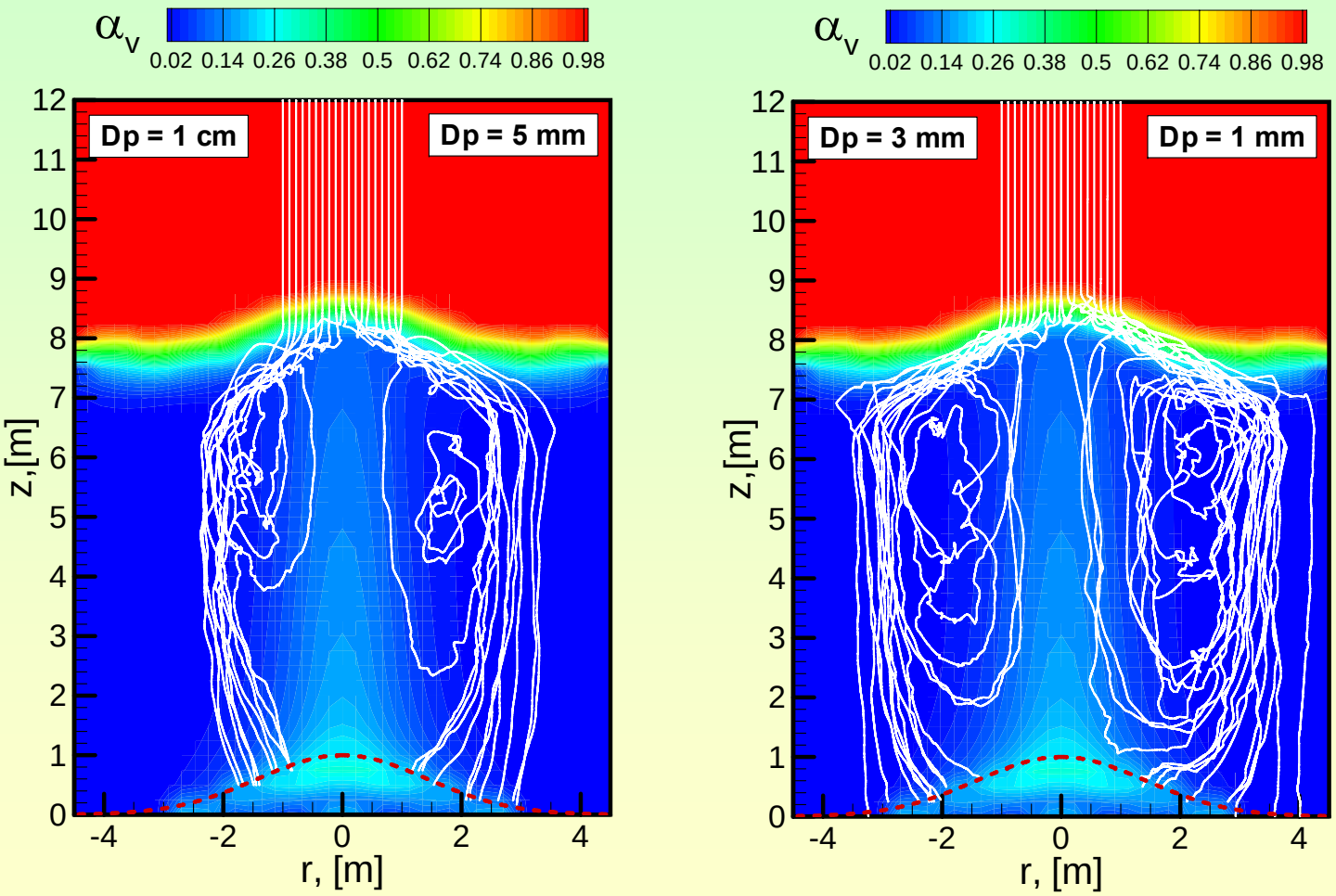
or 1 hour instead of 1 year

$$C_C \sim \left(\frac{l}{d}\right)^2 \left(\frac{D}{l+L}\right)^2 \left(\frac{h}{d}\right)\left(\frac{T}{\Delta\tau}\right)$$

$$C_D \sim \left(\frac{l}{d}\right)^2 \left(\frac{D}{l+L}\right)^2 \left(\frac{h}{d}\right)\left(\frac{\tau}{\Delta\tau}\right)\left(\frac{T}{\tau+\Delta t}\right)$$

Particle Sedimentation and Spreading

Q_{tot} = 1.17 MW (R=2 m, W=100 kW/m^3)

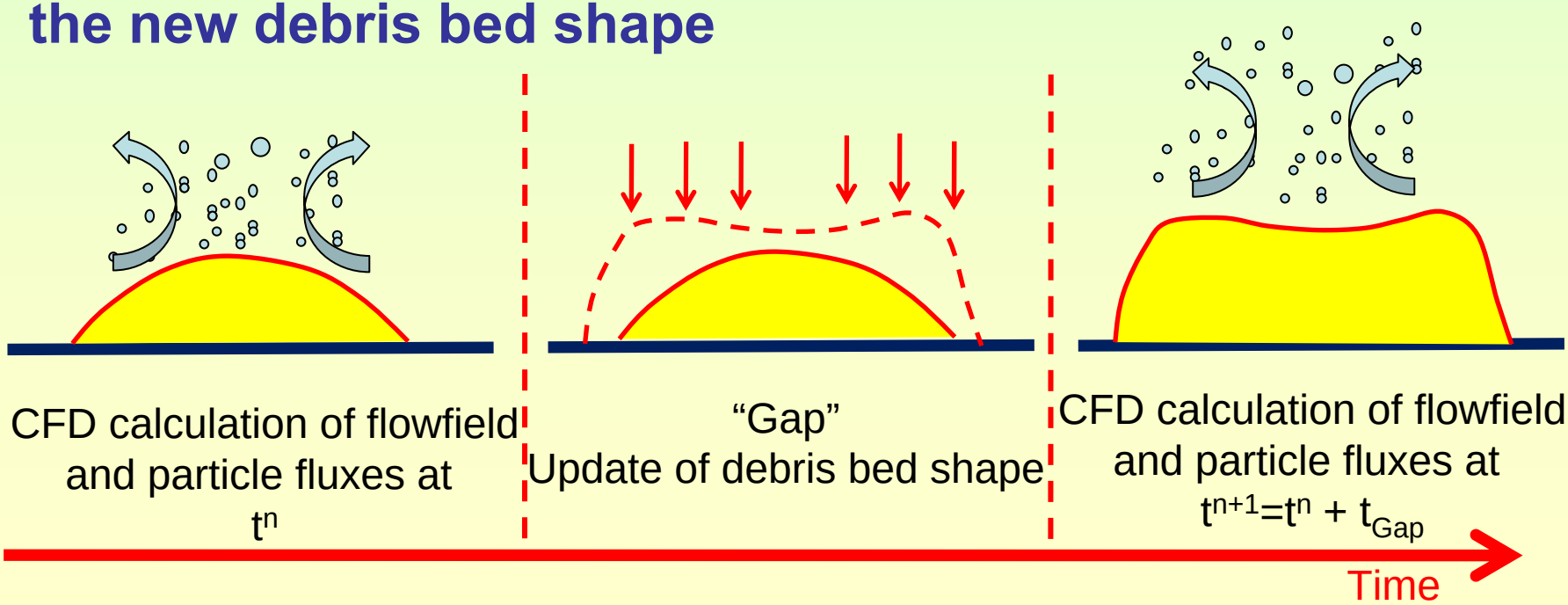


Particle trajectories for different diameters are shown on the void fraction field

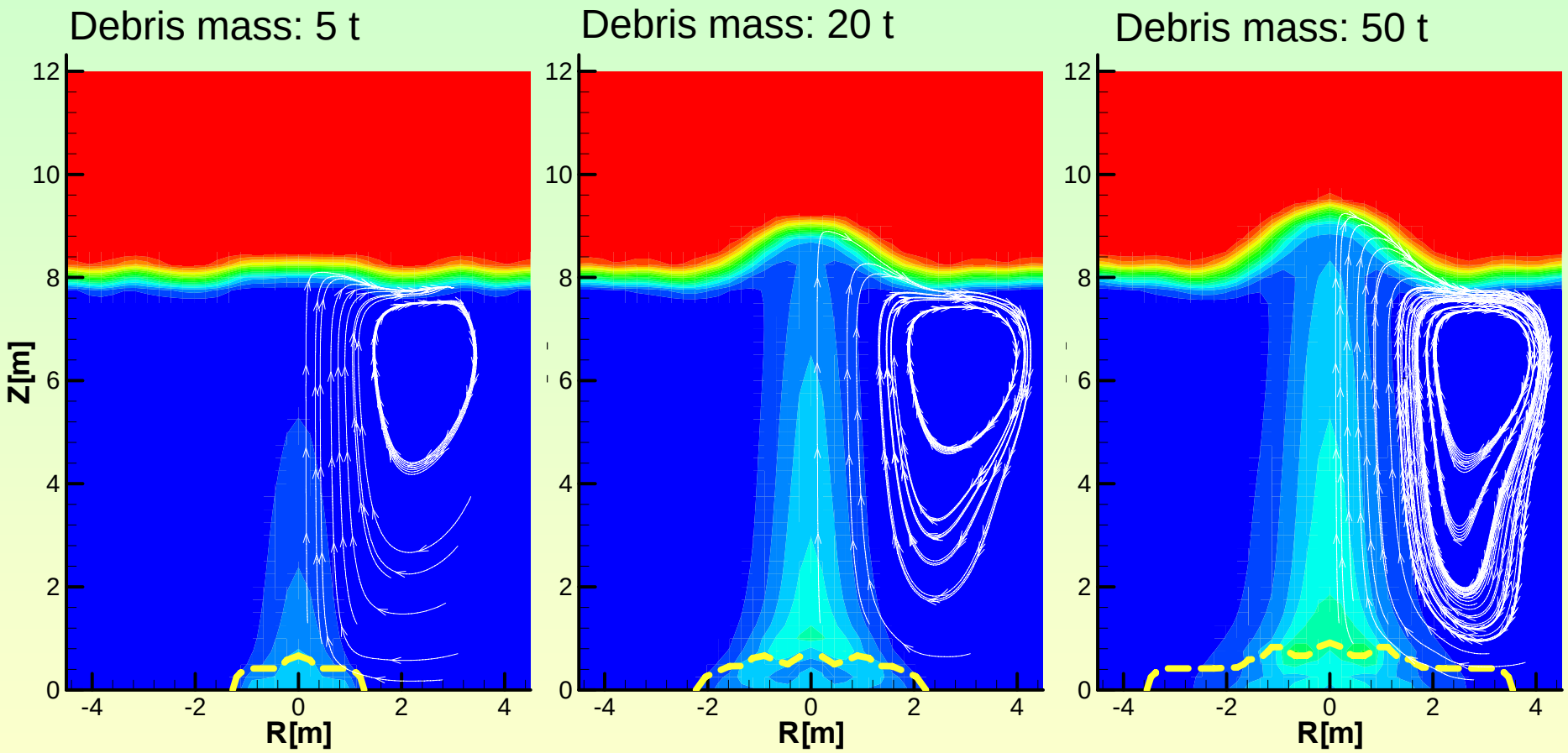
Multiscale "Gap-Tooth" Approach for the Growing Bed

- At each snapshot instant, the debris bed is first grown using the particle mass flux from the previous "global" time step

- Then, a new quasi-steady flowfield is calculated for the new debris bed shape

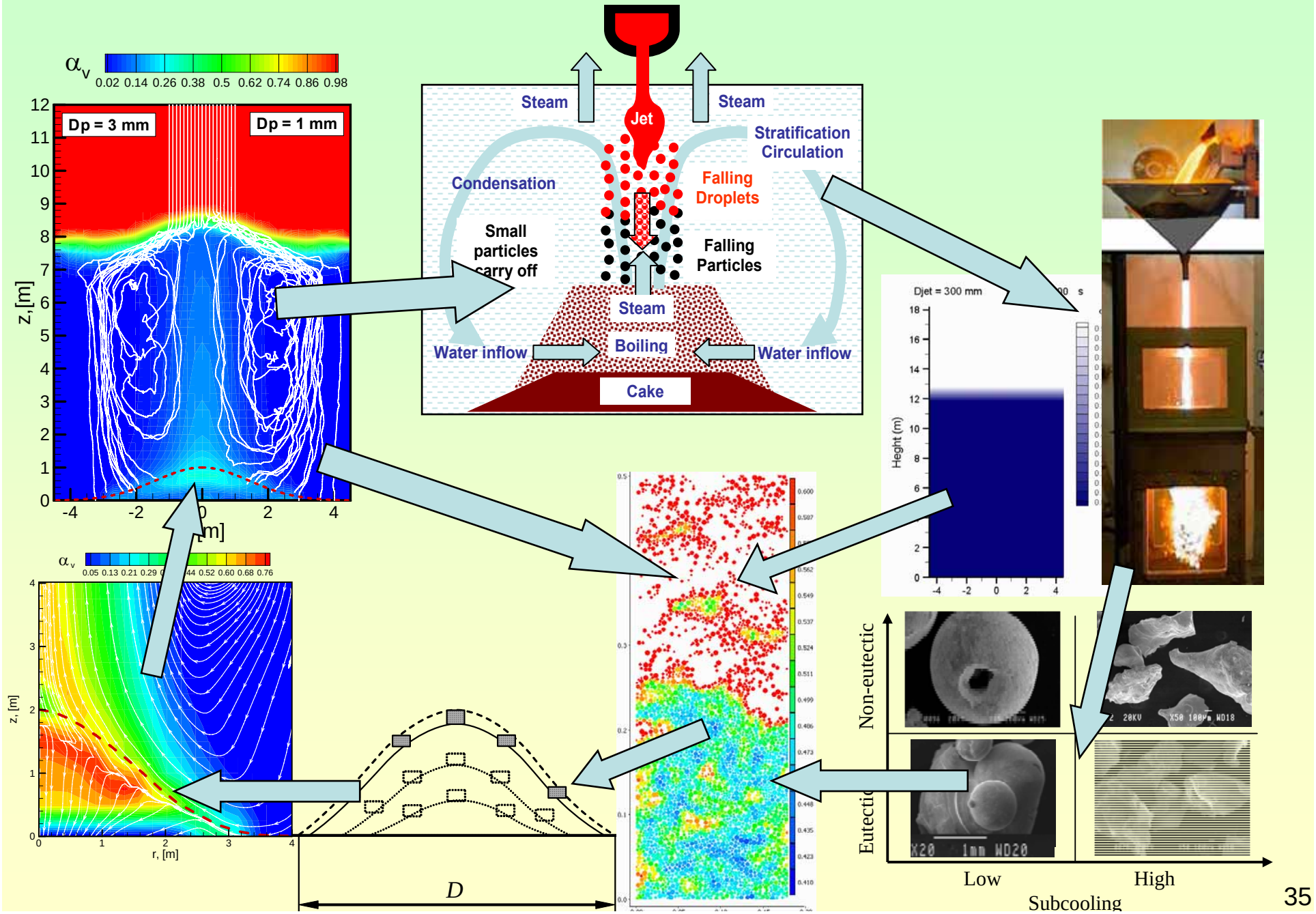


Self Organization in Debris Bed Formation



Flowfields and debris bed shapes at different stages (debris bed shown by yellow dashed line)

Resolving Feedback Between Scales



Severe Accident Multiscale Phenomena

- Severe accident is **complex multi-physics and multiscale** problem.

- In the analytical-experimental program and multiscale simulation tools were developed which helped to identify:
  - ✓ complex non-linear **feedbacks** between different scales and phenomena which
  - ✓ **limiting physical mechanisms** which lead to reduction of uncertainty in safety analysis

- ✓ Results achieved so far helps to make a step toward severe accident issues resolution is Swedish and Finnish BWRs.

Thank you!

The work is sponsored by:

APRI-SKI, HSK, NKS, and SARNET

APRI: Accident Phenomena of Risk Importance
SKI: Swedish Nuclear Power Inspectorate

Swiss Federal Nuclear Safety Inspectorate

Nordic Nuclear Safety Research

Network of Excellence for a Sustainable Integration of European Research on Severe Accident Phenomenology