NKSNKS--R ExCoolISE
Multiscale Phenomena of Severe Accident

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Experiment-Analysis-Application

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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
Addressing threats to containment integrity during a severe core melt accident

a) **INCO**: Is in-vessel retention achievable with CRGT cooling?

b) **MISTEE**: Are large-scale steam explosions realistic?

c) **EXCO (DEFOR+POMECO)**: 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
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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

- 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

Downward Heat Flux Profiles \((Ra^\prime = 2.93 \times 10^{12})\)

- Analytical
- \(Pr = 0.56\) (CFD)
- \(Pr = 1.91\) (CFD)
- \(Pr = 7.00\) (CFD)

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 \( u \)

\[
U_{up} = \frac{\alpha}{H_{pool}} \times \left( Nu_{up} - \frac{H_{pool}}{H_{up}} \right)
\]

\[
U_{down} = \frac{\alpha}{H_{pool}} \times \left( Nu_{down} - \frac{H_{pool}}{H_{down}} \right)
\]

\[
U_{side} = \frac{\alpha}{H_{pool}} \times \left( Nu_{side} - \frac{2 \times H_{pool}}{W_{pool}} \right)
\]

\( \checkmark \) 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)

Vessel External Surface Temperature

- t = 6.94 h
- t = 6.11 h
- t = 5.0 h
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
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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.
In case of slow dripping of the melt through small opening(s), the mass of the melt available for explosion will be limited.

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

Limiting factors:
- Melt composition
- Melt superheat

Energy Conversion Ratio

Limiting factor:
- Coolant state
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.
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Problem Decomposition in Severe Accident Analysis

Fuel Coolant Interaction (FCI)

Debris Bed Coolability

How?

Data

Gap in knowledge

Data

Problem Decomposition in Severe Accident Analysis

Fuel Coolant Interaction (FCI)

Debris Bed Coolability

How?

Data

Gap in knowledge

Data
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.

Jet fragmentation

Debris formation
- Sizes distribution
- Morphology

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”

Decomposition
- Debris Bed Formation
  - Debris particle formation
  - Particle sedimentation and spreading
  - Debris particle packing

Separate effects study
- DEFOR-HT
- DEFOR-SHARP
- POMECO
- DEFOR-HT
- DEFOR-LT

Simulation
- VAPEX FCI code
  + Models for particle morphology
- DECOSIM code
- WABE code
- DEFORSIM code

Synthesis
- Simulation codes coupling
- Study of feedbacks and sensitivity

Properties of prototypical debris bed
### DEFOR program

#### Research Instruments

<table>
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<th>Research method</th>
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<td>Simulation</td>
<td>DEFOR-E</td>
<td>Obtain first-cut information on integral picture of the debris formation after FCI</td>
<td>Scoping experiments with medium amount (2.5-7 liters) of binary-oxide melts, at 1000-1400 °C</td>
<td>Karbojian et al. (2007, 2009)</td>
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<td>DEFOR-S</td>
<td>Separate effect study of the coolant state and melt composition influence on debris formation and packing</td>
<td>Snapshot experiments with small amount (~1 liter) of heavy, binary-oxide, ceramic-type melts, at ~1000-1400 °C</td>
<td>Kudinov et al. (2007, 2008a, 2009)</td>
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<td>DEFOR-SHARP</td>
<td>Study of the debris particle formation phenomena, melt material and coolant temperature effects</td>
<td>Experiments in SHARP facility on single melt droplet and small jets of heavy, binary-oxide, ceramic-type melts</td>
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<td>DEFOR-LT</td>
<td>Study of coolant flow influence on packing and resulting properties of the debris bed</td>
<td>Low temperature experiments with different shape and size distribution of particles</td>
<td>Budu (2008)</td>
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<td>POMECO</td>
<td>Quantification of drag and heat transfer in the debris bed of prototypical properties</td>
<td>Experiments with prototypical shape, size distribution of particles and porosity of the bed</td>
<td>-</td>
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<td>VAPEX</td>
<td>Development of debris agglomeration mode map. Prediction of pre-deposition state of the debris after FCI.</td>
<td>Solving multi-field equations (water, vapor, melt jet, and debris) in FCIs</td>
<td>Dombrovsky et al. (2008); Davydov &amp; Kudinov (2009)</td>
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<td>WABE</td>
<td>Prediction of the flow, heat transfer, and coolability of the decay heated debris bed</td>
<td>Solving porous media two-fluid equations with different semi-empirical closures for heat and momentum exchange</td>
<td>Ma, Buck, Bürger &amp; Dinh (2007), Ma &amp; Dinh (2007)</td>
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DEFOR-HT (High Temperature) experimental program

Containment: 4x4x4 m, 5 bar max pressure
Debris Bed Formation in FCI
Small particles <1-2 mm

Big particles > 2 mm

Subcooling

Eutectic

Non-eutectic

Low

High

Eutectic

Non-eutectic

Particle size

Internal porosity

Surface micro-roughness

Sphericity

Sharp edges

Convoluted smooth surface

Internal porosity

Convoluted surface

Sharp edges

Particle size
- 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

\[ \varepsilon \approx 0.5-0.7 \text{ in DEFOR} \]

\[
\frac{DHF(\varepsilon = 0.6)}{DHF(\varepsilon = 0.4)} = \frac{2.26}{0.9} = 2.5 \\
\frac{DHF(\varepsilon = 0.7)}{DHF(\varepsilon = 0.4)} = \frac{3.37}{0.9} = 3.7
\]

Increase in coolability due to higher porosity 2-3 times!
Particle Dynamics and Packing
Discrete Element Method (DEM)

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

\[
\begin{align*}
\frac{dx_i}{dt} &= V_i \\
m_i \frac{dV_i}{dt} &= F_i \\
\frac{d\theta_i}{dt} &= w_i \\
I_i \frac{dw_i}{dt} &= T_i
\end{align*}
\]

\[
F_i = F_{i,\text{contact}} + F_{i,\text{gravity}} + F_{i,\text{buoyancy}} + F_{i,\text{drag}}
\]

\[
F_{i,\text{contact}} = \sum_{j=1,j\neq i}^{N} F_{ij} \\
F_{ij} = F_{nji} + F_{tji} \\
F_{ij} = -F_{ji} \\
F_{i,\text{gravity}} = m_i g \\
F_{tji} = k_f |F_{nji}| t_{ji} \\
F_{i,\text{buoyancy}} = -V_i \rho_{\text{fluid}} g \\
T_i = T_{i,\text{contact}} + T_{i,\text{drag}}
\]
Influence of Inter-Particle Forces on Packing and Heap Shape

Low friction and rolling resistance (smooth spheres)

High friction and rolling resistance (irregular shape particles)

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

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

DEM Direct simulation

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

Packing layer

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

Space “tooth” – DEM simulation

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

Time “tooth” – DEM simulation

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

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

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

or 1 hour instead of 1 year
Particle Sedimentation and Spreading

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

Particle trajectories for different diameters are shown on the void fraction field.
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.
Flowfields and debris bed shapes at different stages (debris bed shown by yellow dashed line)
Resolving Feedback Between Scales

- resolvable feedback
- scales
- non-eutectic
- eutectic
- subcooling
- high
- low
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!

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APRI: Accident Phenomena of Risk Importance

SKI: Swedish Nuclear Power Inspectorate

HSK: Swiss Federal Nuclear Safety Inspectorate

NKS: Nordic Nuclear Safety Research

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