Assessment of Corium Risk of a Nordic BWR*

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* *With contributions of* KTH-NPS researchers

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- Background
- Experimental studies on severe accident phenomena
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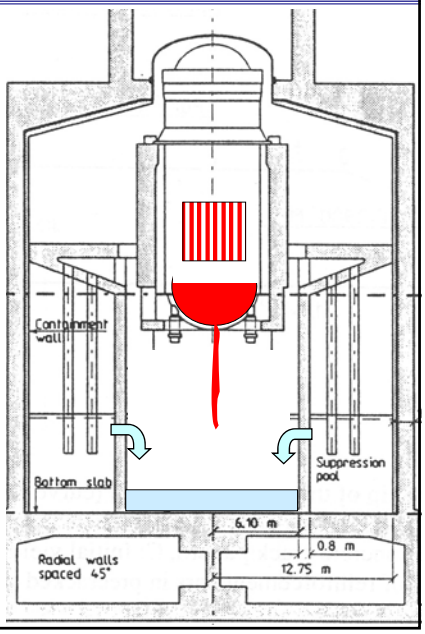
- Concluding remarks

Background (1)

- *SAMS in Nordic BWRs*: Employ the cavity (lower drywell) flooding as a SAM measure to
  - *prevent the basemat penetration;*
  - *promote melt fragmentation and quenching, forming a coolable debris bed on the drywell floor.*



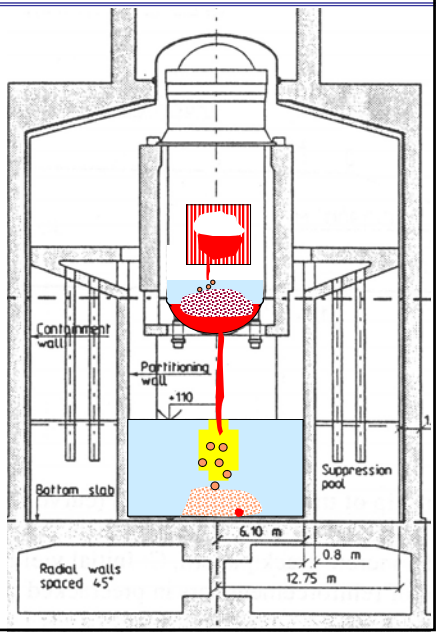
Background (2)

? Efficacy of the SAMS.

i.e. whether the debris bed is coolable and the corium is stabilized in the "wet core catcher".

! Additional Risk of Ex-vessel Steam Explosions.

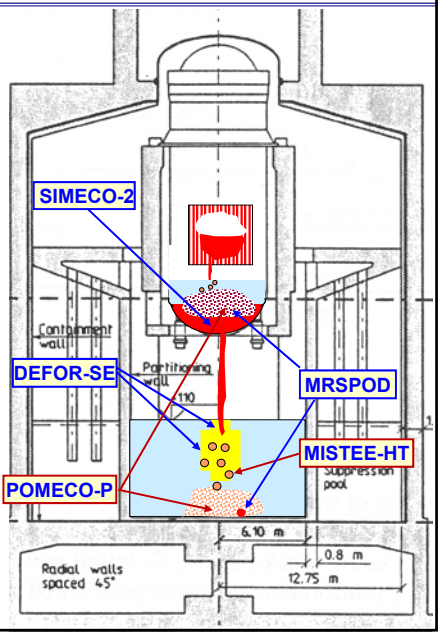
? Influence of Steam Explosions on Debris Coolability.



Experiments at KTH

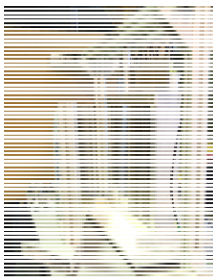
Experimental activities:

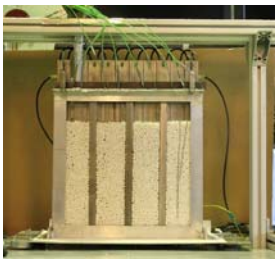
- **MRSPOD**: Study on remelting and relocation of multi-component debris bed
- **SIMECO-2**: Study on heat and mass transfer in stratified melt pool
- **DEFOR-SE**: Study on measures to promote jet fragmentation and to suppress steam explosion (SE) energetics
- **POMECO-P**: Study on post-dryout heat transfer of debris bed
- **MISTEE-HT**: Study on SE mechanisms and oxidation effect on melt fragmentation and SE

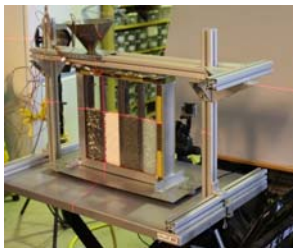


MRSPOD experiment

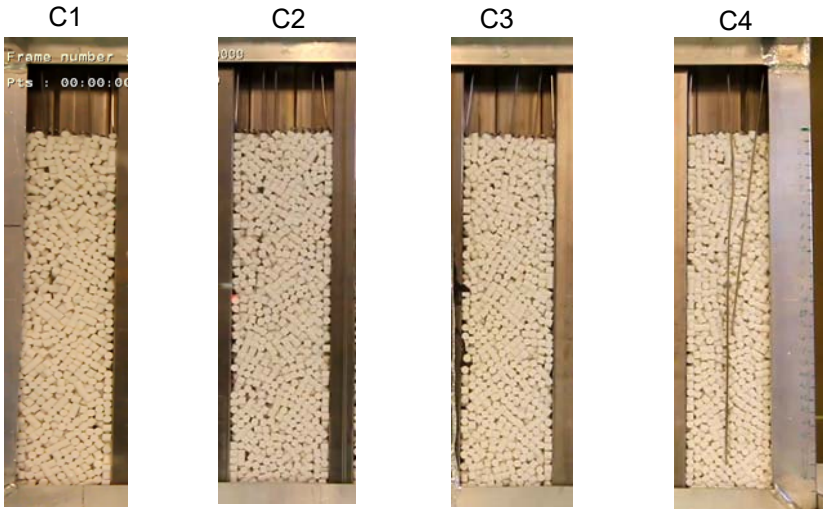
- Objectives: Address remelting phenomena of multi-component debris bed (filtration of molten materials in debris bed, formation of molten pool, etc.)
- Specifications
  - Four compartments with the same debris beds: 319x75x20 mm^3
  - Debris bed preheating with electric strip heaters
  - Removable front platform for preheating and visualization.
  - Supporting plate with 3 force sensors.
  - Funnel and supporting frame for melt supply.
  - Steel nets to hold the debris beds







E08 video recording

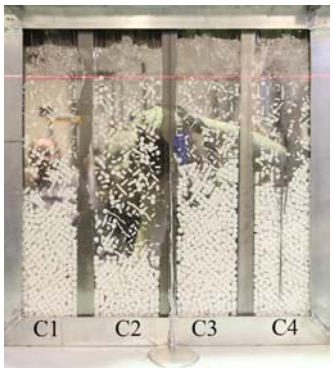


- Recorded videos demonstrate the dynamics of melt propagation which is limited by solidification.
- Different penetration length for each test because of different temperature history.

E08 test conditions

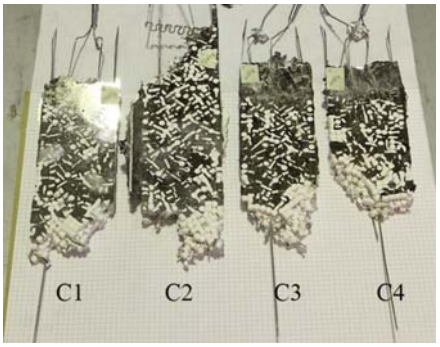
Parameters		C1	C2	C3	C4
Melt					
Material		Sn+Bi (eutectic)			
Melting point	°C	139			
Melt temperature		389	185	178	245
Melt superheat		250	46	39	106
Arrest of melt propagation/time before solidification	s	2.4	4.2	3.24	2.0
Depth of melt penetration	mm	180	220	155	135
Debris bed					
Material		Alumina			
Particle size	mm	6x6 cyl			
Compartment dimensions	mm	70x20			
Porosity		0.32			
Contact angle (wettable if <90)	deg	>90			
Initial debris bed temperature	°C	67;78	84;124;125	79;108	62;76;80
Debris bed temperature difference from melt solidification temperature	°C	-72;-61	-55;-15;-14	-60;-31	-77;-63;-59

Debris bed after dismantling in E08



test	Initial Debris bed temperature difference from melt solidification temperature (°C)	Initial Melt Superheat temperature (°C)	Penetration depth (mm)
C1	-72; -61	250	180
C2	-55; -15; -14	46	220
C3	-60; -31	39	155
C4	-77; -63; -59	106	135

- Deeper melt penetration into the debris along the TCs.
  - This effect is due to increased porosity upon the contact of debris particles with TC



E09 test conditions

Parameters		C1	C2	C3	C4
Melt					
Material		Sn+Bi (eutectic)			
Melting point	ºC	139			
Melt temperature		220	172	204	211
Melt superheat		81	33	65	72
Velocity of melt front propagation (calculated from video)	m/s	0.113	0.147	0.0773	0.156
Average mass flow rate (estimated)	kg/s	0.506	0.757	0.368	0.895
Debris bed					
Material		Alumina	SS		Glass
Particle size	mm	6x6 cyl		3x3 cyl	Ø6 sph
Compartment dimensions	mm	70x20			
Contact angle (wettable if <90)	deg	>> 90	> 90		~ 90
Debris temperature	ºC	151;171;131	182;190;166	189;189;165	152;150;147
Debris bed temperature difference from melt solidification point	ºC	12;32;-8	43;51;27	50;50;26	13;11;8
Porosity		0.39	0.406	0.349	0.456
Debris mass before test	kg	0.8342	1.854	2.0316	0.5506
Debris mass after test	kg	0.8638	1.9532	2.0992	0.6782
Melt mass retained	g	29.6	99.2	67.6	127.6

E09 test video recording

C1
Contact angle >>90

C2
Contact angle >90

C3
Contact angle >90

C4
Contact angle ~ 90

- Recorded videos demonstrate the dynamics of melt front penetration through porous bed.
- No melt was retained above the debris bed.
- Mass flow rate through the debris bed is obtainable by processing mass accumulation rate in the catchers.

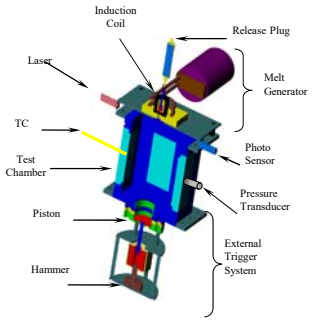
Debris bed with infiltrated melt E09

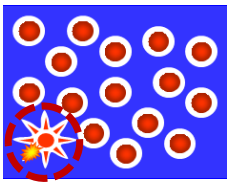
- The largest mass of melt is adsorbed by the glass surface in C4.
- On the other hand, very small mass is adsorbed by C1 (ceramic cylinders).

C1 C2 C3 C4

MISTEE experiment

MISTEE: Micro Interactions in Steam Explosion Experiments

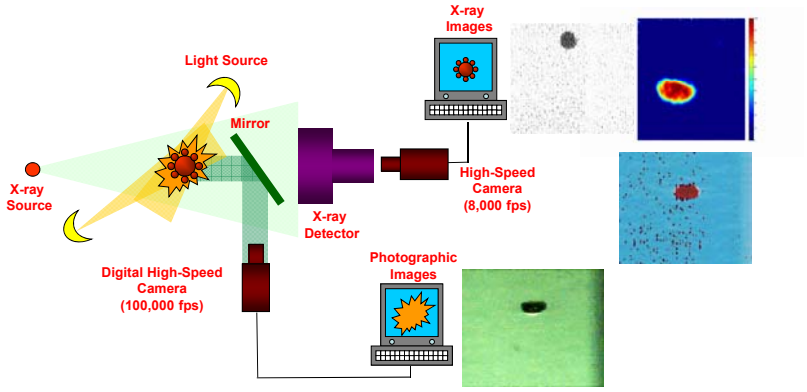




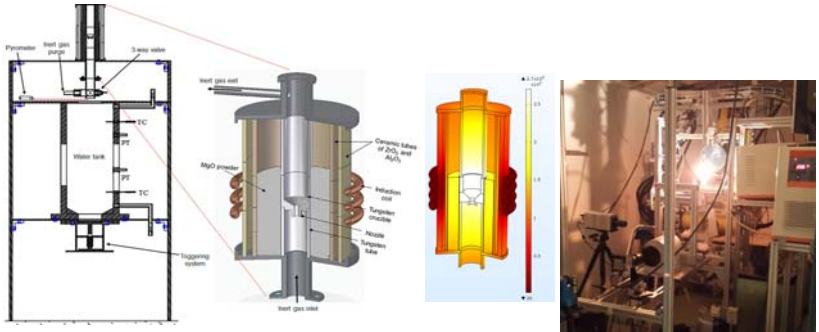
- Corium simulants - metallic (tin) and medium-temperature binary oxide melts (e.g., WO_3-CaO).
- Designed for the visualization of explosion of a single droplet disturbed by a weak pressure wave.

MISTEE visualization

SHARP: Simultaneous High-speed Acquisition of X-ray Radiography and Photography



MISTEE-HT facility



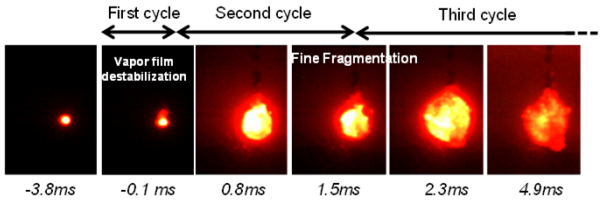
- Induction heating of melt (20 kW, 50 to 250 kHz)
  - Melting and superheating (2000°C or higher)
  - Concentric tubes of advanced ceramics (porous zirconia, alumina and magnesia) to minimize heat losses.
- Aerodynamic plugging of melt
  - 3-way fast acting valve for melt plugging by constant purge of inert gas and rapid delivery.
- Steam explosion triggering
  - Piston set-up driven by the rapid discharge of a capacitor bank (3* capacitors, 400 Vdc and 4700 mF each)
  - A sharp pressure pulse of up to 0.15 MPa with a rising time of 50 μs.

Recent tests on MISTEE-HT

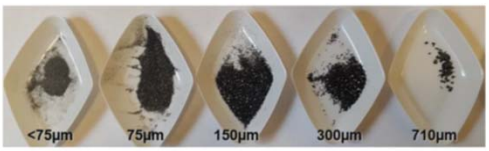
- MISTEE facility is successfully upgraded to study steam explosion with high-temperature melts, for the materials tested so far:
  - Alumina (T_{melt}=**2050**°C) to study material effect on steam explosion energetics
  - Metallic zirconium (T_{melt}=**1870**°C) to study oxidation behavior during FCI
  - CeO_2-ZrO_2 (T_{melt}=**2400**°C) to identify a potential simulant binary oxides for the study of corium phenomenology during FCI
  - A scoping test with ZrO_2 melt (T_{liq}: **2715**°C) has also been attempted
  - *Furnace temperature limit: T≈ 2800°C, which is ready for melting mixture of UO_2/ZrO_2/Zr.*

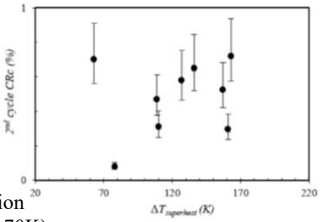
Experiment with alumina (Al_2O_3)

- Triggered SE ($\Delta T_{superheat} \approx 167K$, $\Delta T_{subcooling} \approx 82K$)



- Distinct cycles of explosion similar to those of low temperature simulant materials
- Mass median fragment size: up to 100 µm

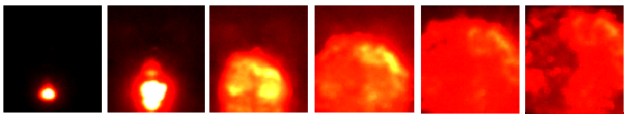




- The superheat was always enough to initiate an explosion
- No specific differences for the given superheat (up to170K)

Experiment with alumina (Al_2O_3)

- Spontaneous SE ($\Delta T_{superheat} \approx 205K$, $\Delta T_{subcooling} \approx 81K$)



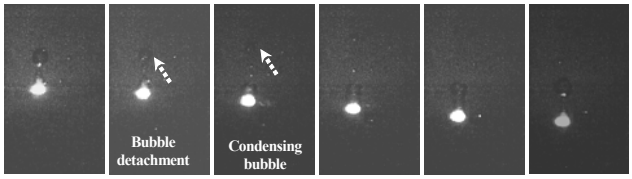
- Spontaneous SE at a combination of high melt superheat and high subcooling.
  - Sensibly more energetic explosion than the triggered SE (damage to test section)

Effect of melt superheat

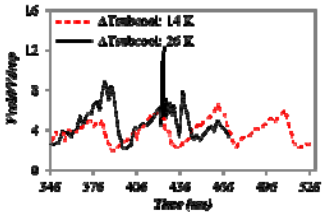
Experiment with alumina (Al_2O_3)

- SE suppression at low water subcooling
  - Stable vapor film
    - Relatively increased vapor production at low subcooling conditions

$\Delta T_{superheat} \approx 116K$, $\Delta T_{subcooling} \approx 14K$



- Volume of void ≈ 6 times volume of the droplet
- Pressure wave not strong enough to establish direct melt-water contact

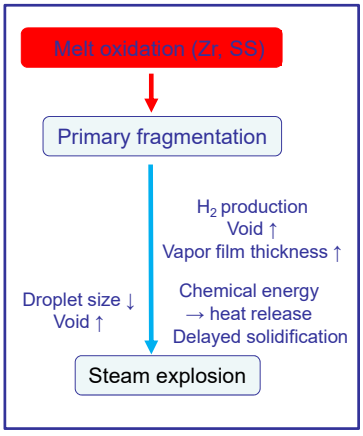


Effect of water subcooling

Experiment with Zr oxidation

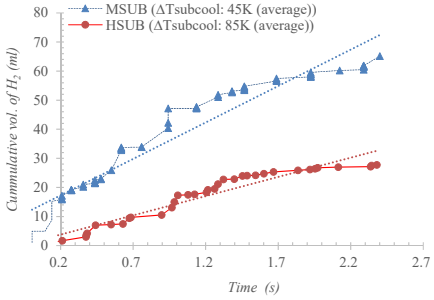
- Zirconium oxidizes in water vapor according to the following reaction, during which heat is released and hydrogen is formed:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + energy\ (\approx 6.5\ MJ/kg\ Zr)$$



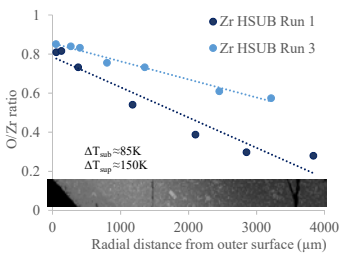
Visualizaton with Zr oxidation

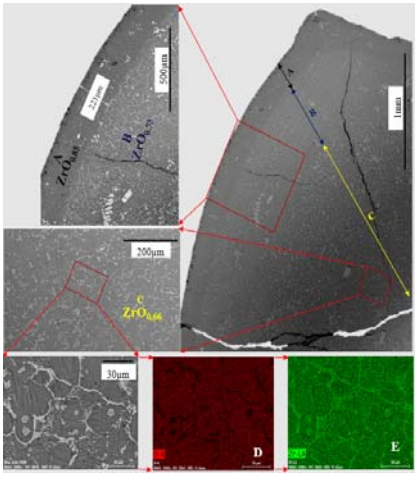
- Major observations
  - A cyclic process of bubble growth and detachment. The bubbles do not seem to condense even at high subcooling
  - Spontaneous triggering of steam explosion is not observed



Debris composition with Zr oxidation

- Oxygen concentration decreases from the surface to the bulk
- An oxygen rich outer layer to be of almost constant thickness along the surface is visible
- The degree of oxidation reduces in a linear trend further towards the core of the droplet
- The nature of the layer can be connected with surface quenching



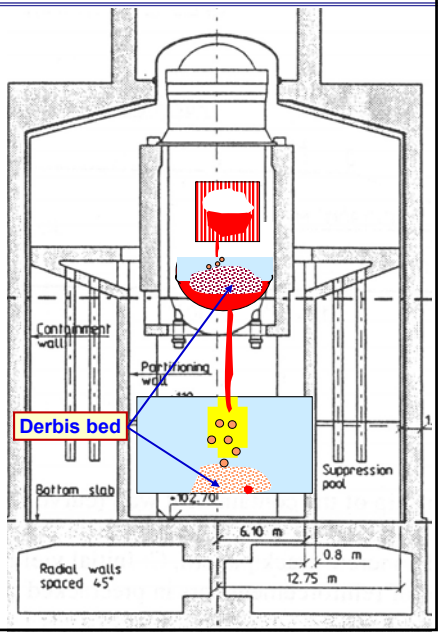


Assessment of corium risk

- Motivation
- Simulation tool: MEWA code
- Validation of MEWA code
- Quench of in-vessel debris bed
- Quench of the ex-vessel debris bed

Motivation

- Previous studies: mainly focused on the long-term coolability of debris beds.
- Realistic situation: Molten corium first need go through a quenching process, which is the prerequisite for the long-term cooling.
- Characteristics of quenching problem:
  - Thermal non-equilibrium (large temperature difference);
  - Multi-phase flow through porous media coupled with boiling heat transfer
  - Chemical interaction (oxidation of metallic components)



MEWA code

- Flow through porous media
  - Friction force is evaluated by using Ergun equation.
  - Various models were proposed to predict the parameters in Ergun equation (e.g. Lipinski, Reed).

Momentum equations:

$$-\nabla p_g = \rho_g \vec{g} + \frac{\vec{F}_{pg}}{\varepsilon\alpha} + \frac{\vec{F}_i}{\varepsilon\alpha}$$

$$-\nabla p_l = \rho_l \vec{g} + \frac{\vec{F}_{pl}}{\varepsilon(1-\alpha)} - \frac{\vec{F}_i}{\varepsilon(1-\alpha)}$$

Ergun equation:

$$\vec{F}_{pg} = \varepsilon\alpha\left(\frac{\mu_g}{KK_{rg}}\vec{j}_g + \frac{\rho_g}{\eta\eta_{rg}}|\vec{j}_g|\vec{j}_g\right)$$

$$\vec{F}_{pl} = \varepsilon(1-\alpha)\left(\frac{\mu_l}{KK_{rl}}\vec{j}_l + \frac{\rho_l}{\eta\eta_{rl}}|\vec{j}_l|\vec{j}_l\right)$$

K: permeability ε: porousity
η: passability J: superfical velocity

MEWA code (*contd.*)

- Boiling heat transfer
  - Nucleate boiling region (*Rhosenow*)

$$\frac{c_L(T_w - T_{sat})}{H_{fg}} = C_{sf}\left[\frac{q}{\mu_L H_{fg}}\sqrt{\frac{g_c\sigma}{g(\rho_L - \rho_g)}}\right]^{0.33}\left(\frac{c_L\mu_L}{k_L}\right)^{1.7}$$

  - Film boiling region (Lienhard)

$$Nu = 0.67\left[\frac{g(\rho_L - \rho_g)H_{fg}D^3}{\nu_g k_g(T_w - T_{sat})}\right]^{0.25}$$

  - Transition region
    - Interpolation with respect to the solid temperature

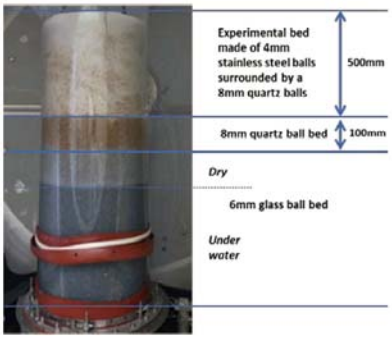
MEWA code (*contd.*)

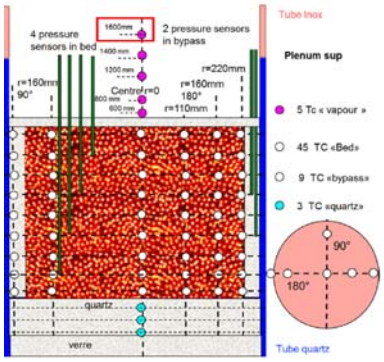
- Oxidation of Zr
  - Reaction rate

Parabolic kinetic law: $\frac{dX^2}{dt} = K$

Arrhenius formulation: $K = A \cdot exp\left(-\frac{B}{RT}\right)$

MEWA validation against PEARL test



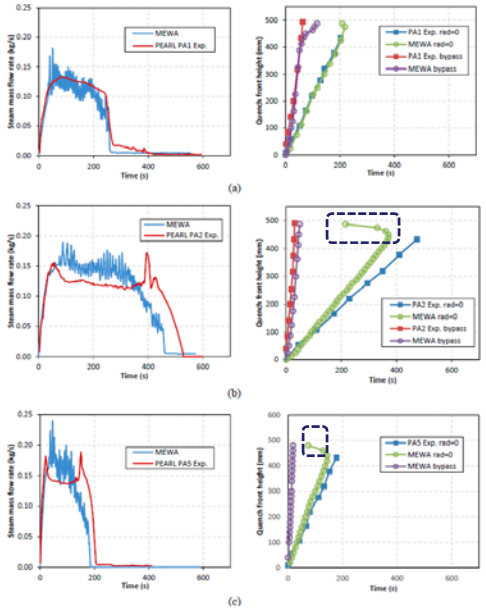


- Φ=450mm, h=500mm;
- W=150W/kg
- Initial bed temp.: 150~700℃
- Cooling water: 60℃, 5~10m/h

MEWA validation against PEARL test (*contd.*)

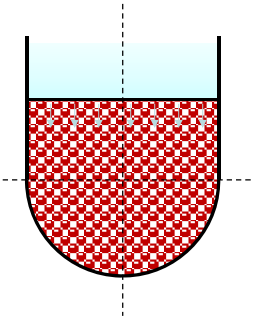
- ❑ Left: steam production flow rate;
- ❑ Right: propagation of quench front.

- ▪ Agreement is satisfactory.
- ▪ Top quenching is predicted but not observed in the experiment.

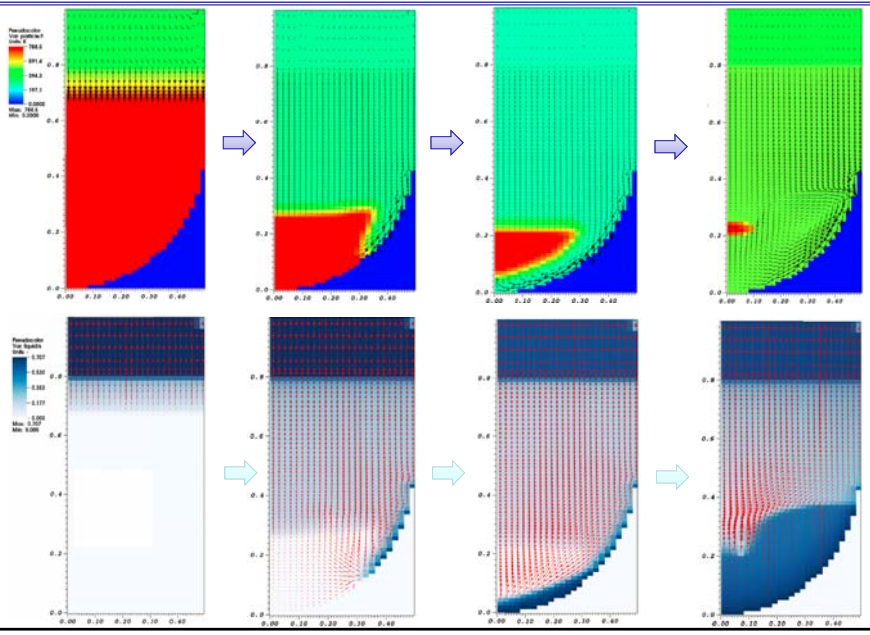


Quench of the in-vessel debris bed

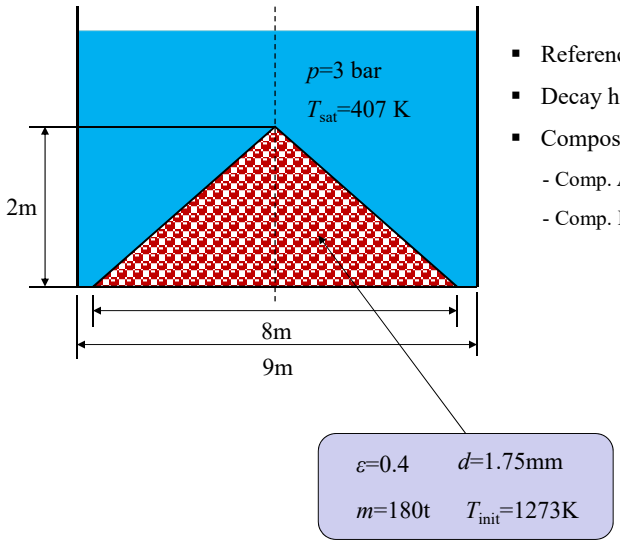
- ▪ Decay heat: W = 150 W/kg
- ▪ T_{init} = 500 °C



Quench of the in-vessel debris bed

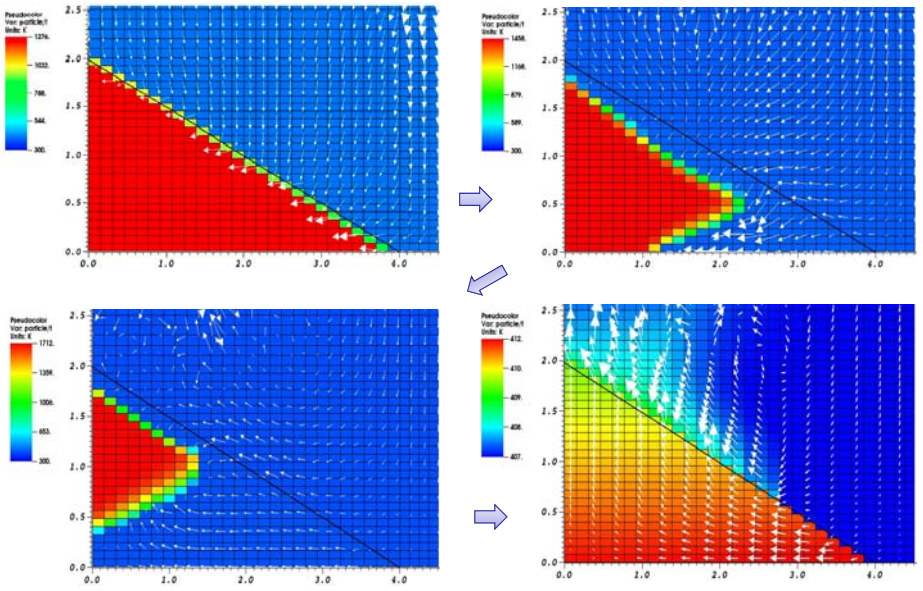


Quench of the ex-vessel debris bed

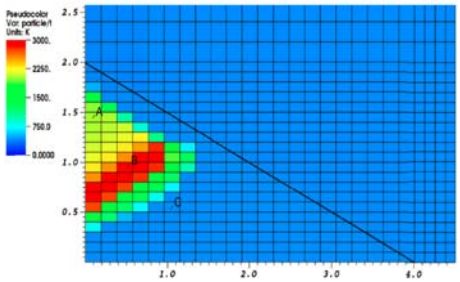


- Reference BWR power: 2100 MWth
- Decay heat power: 109W/(kgUO_2)
- Compositions of corium:
  - Comp. A: 75% UO_2 + 25% ZrO_2
  - Comp. B: 75% UO_2 + 15% ZrO_2 + 10% Zr

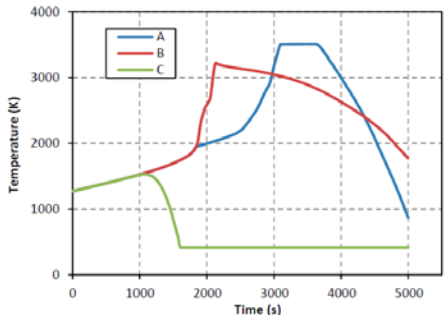
Quench of ex-vessel debris bed (Comp. A)



Quench of ex-vessel debris bed (Comp. B)

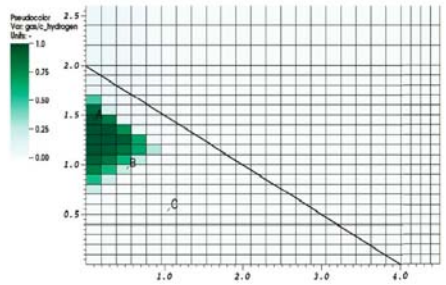


(a) Temperature distribution at 2090 s

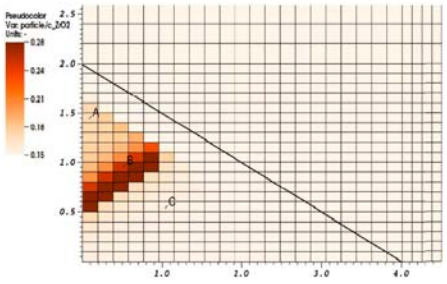


(b) Temperature evolution at 3 locations

Quench of ex-vessel debris bed (Comp. B)

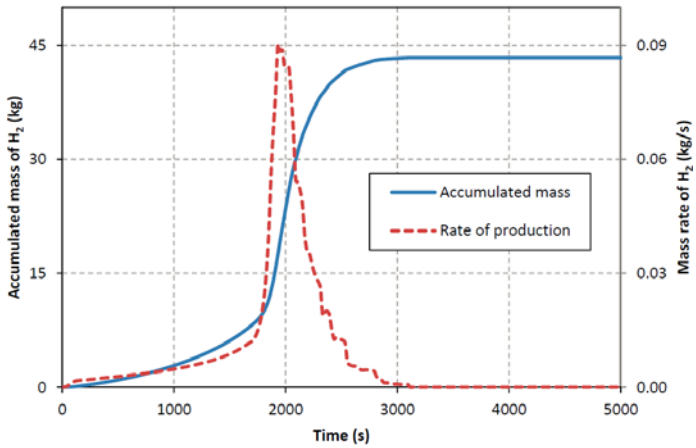


(a) H_2 mass fraction



(b) ZrO_2 mass fraction

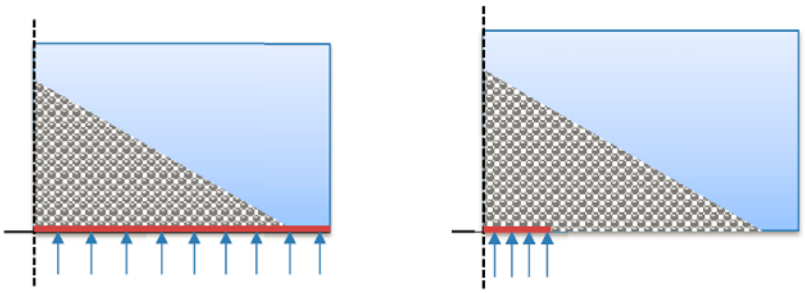
Quench of ex-vessel debris bed (Comp. B)



Accumulated mass and production rate of H_2

Quench of ex-vessel debris bed (Comp. B)

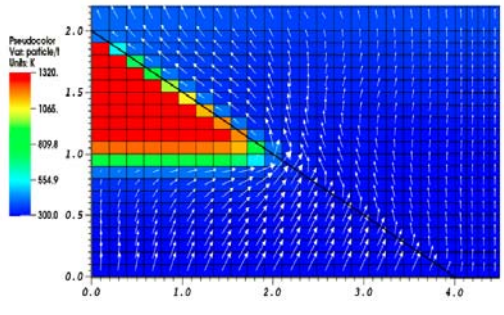
- Mitigation strategy 1: bottom injection



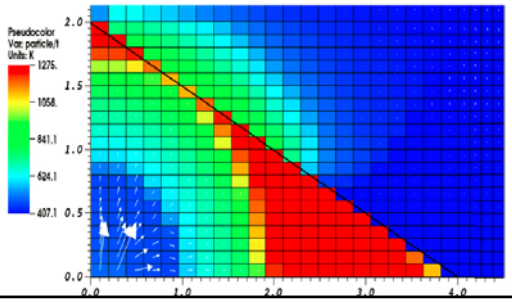
(a) Full bottom-flooding

(b) Partial bottom-flooding

Quench of ex-vessel debris bed (Comp. B)

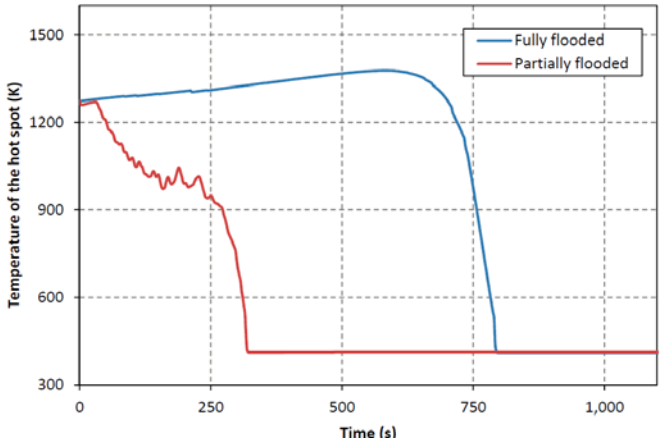


(a) Full bottom-flooding



(b) Partial bottom-flooding

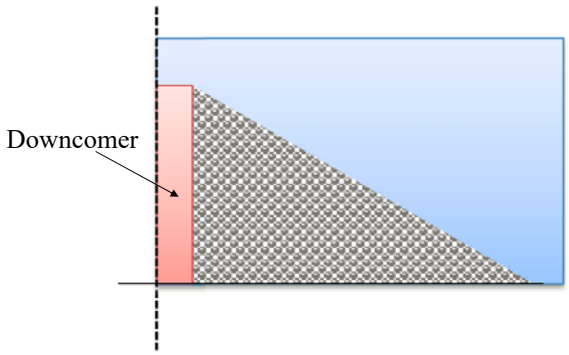
Quench of ex-vessel debris bed (Comp. B)



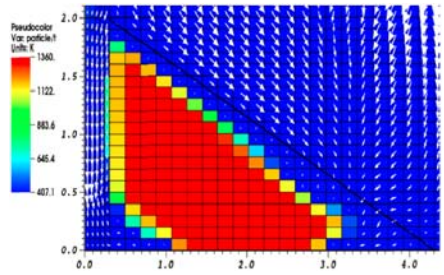
Temperature of the hot spot for both injection schemes

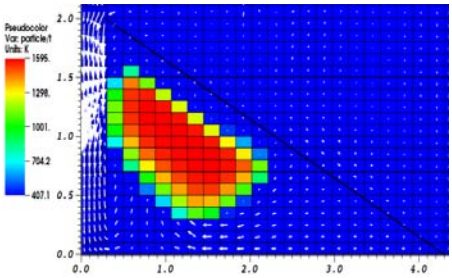
Quench of ex-vessel debris bed (Comp. B)

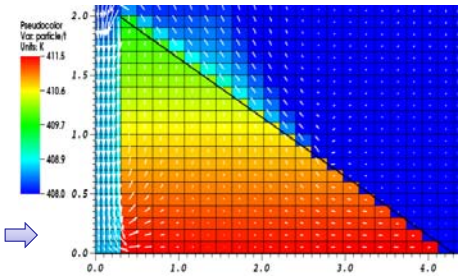
- Mitigation strategy 2: Embedding a downcomer



Quench of ex-vessel debris bed (Comp. B)







- Effect of the bypass:
  - Provide a preferential exit path for vapor to avoid accumulation;
  - Induce extra ingression of water.

Concluding remarks

- Motivated to resolve the severe accident issues of debris coolability and steam explosion in Nordic BWRs, both experimental and analytical studies on relevant phenomena are performed at KTH.
- Experimental data on melt penetration in particulate beds as functions of melt superheat and bed's temperature were obtained.
- Experimental study on single alumina droplet steam explosion and Zr droplet oxidation in a water pool were carried out.
- MEWA simulations of the quench process of both in-vessel and ex-vessel debris beds of a Nordic BWR indicated that the beds were quenched in a multi-dimensional manner.
- The oxidation of the residual Zr in the corium has a great impact on the coolability of the debris bed due to reaction heat and release of H_2.
- Two mitigation measures, namely bottom ejection and downcomer, are predicted to have significant impacts on the quenching process and final state of coolability.