Heat Transfer in Homogeneous and Stratified Melt Pools in the Lower Head of a Reactor Pressure Vessel

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In-vessel melt retention by reactor pit flooding. Influencing phenomena

Melt behavior in the RPV

- Heat flux distribution from corium
- Geometry of pool / RPV (elliptic in VVERs)
- Stratified melt pools
  - Focusing effect of metal layer

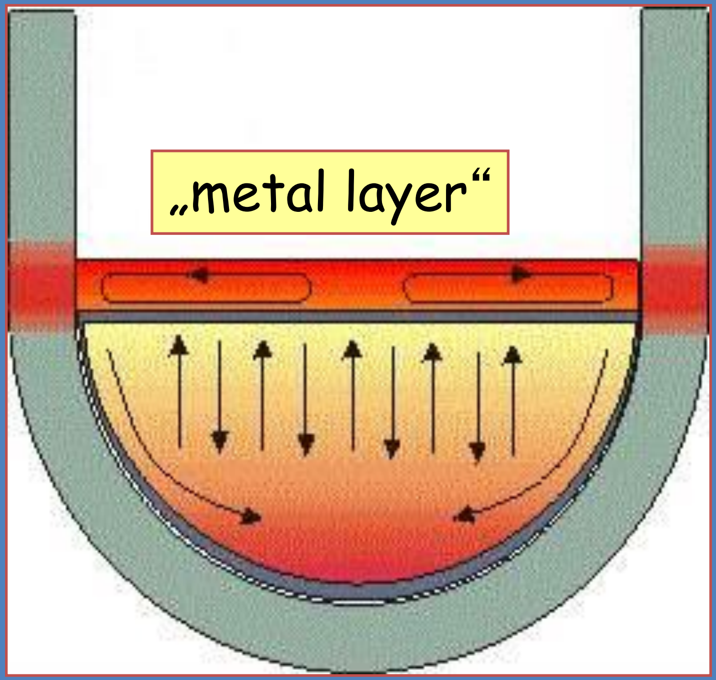
Coolant behavior at the outer RPV wall

- Critical heat flux typical value: 1.2 - 2 MW/m^2

Vessel mechanical behavior

- Can the vessel withstand the loads?

Metal layer on top, focusing effect

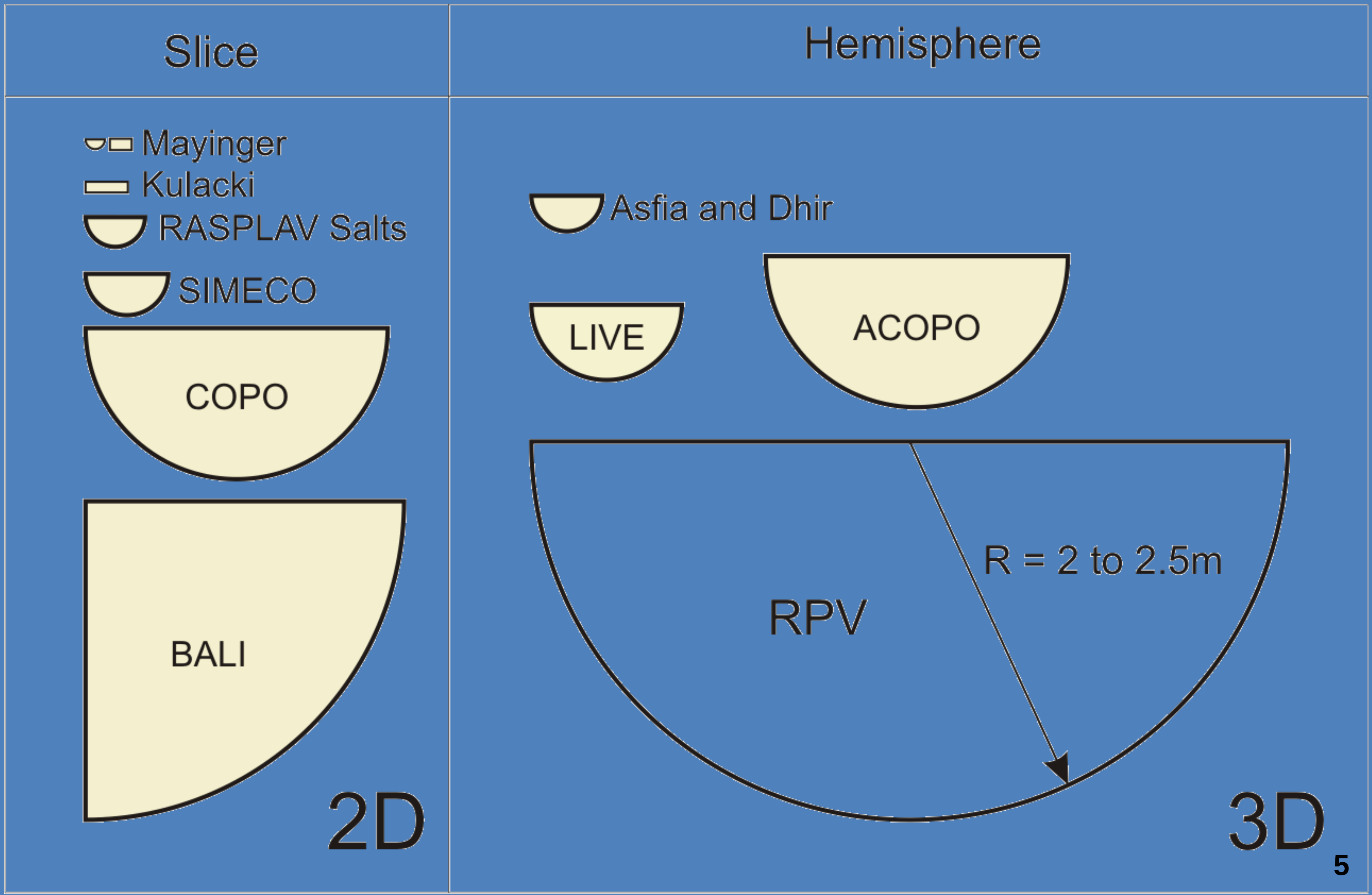


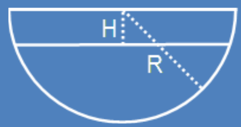
- Since steel and iron are lighter than liquid corium, it was hypothesized that iron should form a metal layer on top of the oxide melt
- This layer is heated from the oxide pool below and lightly cooled on the top by radiation
- At the same time it is in contact with the vessel wall
- ***Focusing effect:*** local thermal loads on the vessel wall at the level of the molten metal layer

Objectives of corium melt pool experiments

- to reduce uncertainties in the understanding of thermophysical phenomena influencing the melt pool configuration, composition and masses/thicknesses of melt layers and interfacial crusts, relative positions of the layers, heat and mass transfer between the layers and heat fluxes to the melt pool boundaries
- to determine the conditions in the melt pool which are critical for the system behavior, such as layer inversion, mixing and focusing of the heat flux
- to develop correlations and validate calculation models for stratified fluid layers
- to predict the heat transfer loadings on the vessel wall for different configurations of the melt pool

Melt behavior in the RPV. Experiments and scales

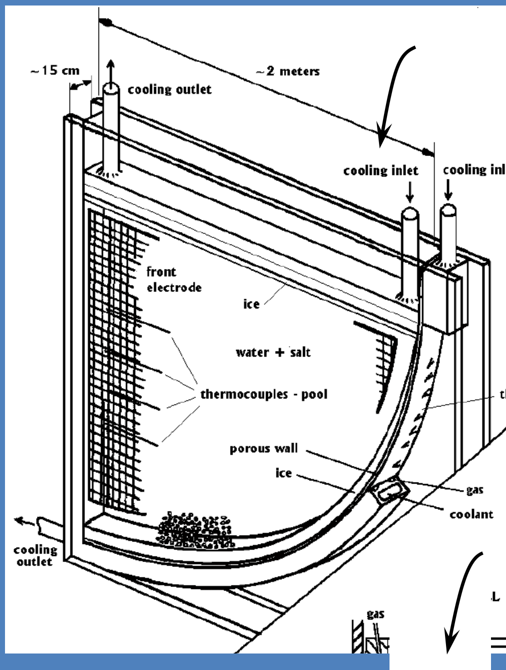




Matrix of the experiments

Data	Aspect ratio	Geometry of top layer	Simulants of corium pool	Input power from bottom layer, W	Average lateral heat flux for the top layer, W/m^2	Ra number for top/bottom layer	Lateral condition	Top condition	CF
BALI *(experiment)*	***0.025***	***Rectangular 2D L=200 cm W=13 cm S=0.26 m²***	**Water**	**5 section 500 W each**	**58650**	**$\approx 3.2\cdot10^{8}$**	**Cooling at 0°C**	**Upward cooling at 0°C with great thermal resistance to simulate heat transfer by radiation**	**6.1**
	0.05				**47115**	**$\approx 1.7\cdot10^{9}$**			**4.9**
	0.1				**41344**	**$\approx 9.8\cdot10^{9}$**			**4.3**
	0.2				**28845**	**$\approx 2.9\cdot10^{10}$**			**3**
SIMECO *(experiment)*	***0.12***	***L=50 cm S=0.045 m²; H=3 cm***	**Cerrobend / ($NaNO_3$-KNO_3)**	**1120**	**51410**	**$\approx 9.7\cdot10^{4}/4\cdot10^{12}$**	**Cooling at 6°C**	**Adiabatic**	**2.1**
	0.24	***H=6 cm***		**1060**	**39500**	**$\approx 1.2\cdot10^{6}/4\cdot10^{12}$**			**1.7**
	0.24	***H=6 cm***		**1386**	**45490**	**$\approx 1.4\cdot10^{6}/6\cdot10^{12}$**			**1.5**
	0.12	***H=3 cm***	**Cerrobend / Glycerol**	**262**	**27500**	**$\approx 1.3\cdot10^{5}/7\cdot10^{12}$**	**Cooling at 77°C**		**4.7**
	0.24	***H=6 cm***		**361**	**30620**	**$\approx 1.2\cdot10^{6}/7\cdot10^{12}$**			**3.8**
	0.12	***H=3 cm***		**262**	**7500**	**$\approx 3.2\cdot10^{4}/7\cdot10^{12}$**		**T_{top}=77 °C**	**0.5**
	0.24	***H=6 cm***		**361**	**6200**	**$\approx 2.4\cdot10^{5}/7\cdot10^{12}$**			**0.4**
SIMECO-2 *(pre-test simulation)*	*0.2*	*L=98 cm H=10 cm S=0.088 m²*	Metal / Salt	8340	328000	Solid/$1.2\cdot10^{14}$	Cooling at 70°C; Radiation heat loss through the front and back (quartz) walls (T_{amb}=25 °C; ε=0.5)	Radiation heat loss (T_{amb}=25 °C; ε=0.15)	3.5
				9620	372000	$9.3\cdot10^{5}/2.3\cdot10^{14}$			3.4
				13470	526000	$3.3\cdot10^{6}/5.9\cdot10^{14}$			3.4
	0.1	*L=99.5 cm H=5 cm S=0.088 m²*		6400	443000	$2.1\cdot10^{5}/1.5\cdot10^{14}$			6.1
				7870	559000	$3.6\cdot10^{5}/2.7\cdot10^{14}$			6.3
				11900	882000	$9.3\cdot10^{5}/5.7\cdot10^{14}$			6.5
LIVE *(experiment)* *L6*	***0.22***	***R=50 cm H=10 cm***	**($NaNO_3$-KNO_3) / ($NaNO_3$-KNO_3)**	**6521**	**11840**	**$8.7\cdot10^{8}/10^{12}$-10^{13}**	**65 °C**	**Adiabatic**	**1.26**
L6				**3605**	**5039**	**$2.8\cdot10^{8}/10^{12}$-10^{13}**	**44 °C**		**0.97**
L6				**2093**	**1840**	**$8.4\cdot10^{7}/10^{12}$-10^{13}**	**29 °C**		**0.61**
LA6				**14135+4500**	**18534**		**81 °C**		**0.91**
LA6				**7701+2500**	**8877**		**52 °C**		**0.80**
LA6				**2658+1250**	**2872**		**31 °C**		**0.75**

BALI experiments

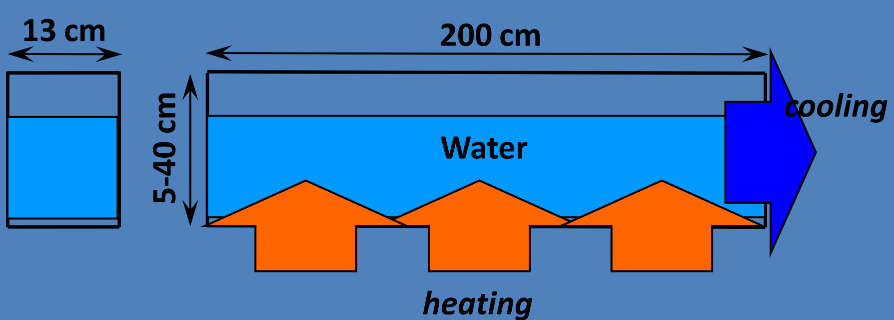


For uniform pool study

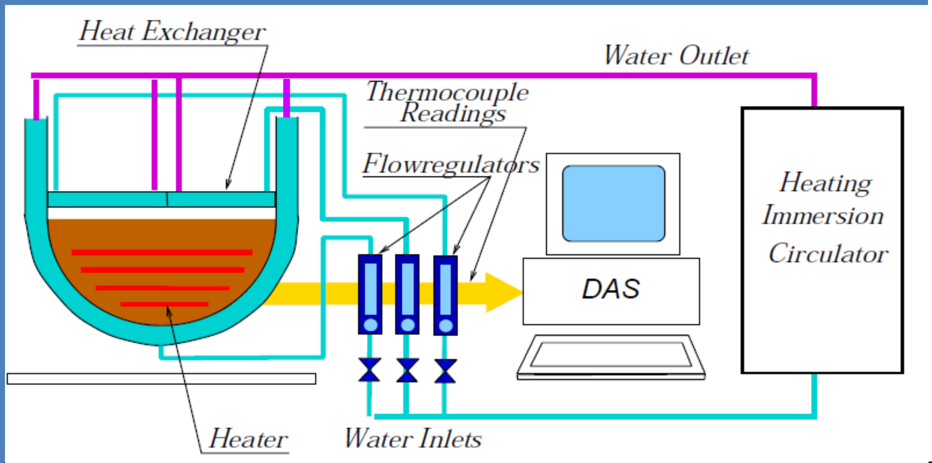
- ✓ Quarter-spherical slice design with rectangular part
- ✓ Radius is 200 cm. Width is 15 cm
- ✓ Water as oxide corium simulant

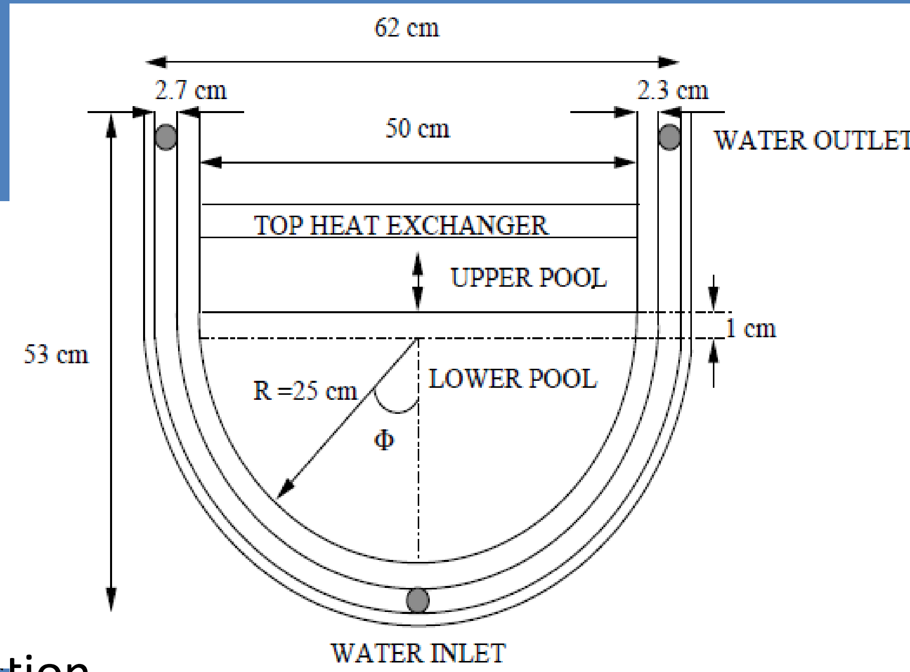
For focusing effect study

- ✓ Special separated rectangular part for focusing effect study. Length, width and height are 200 cm, 13 cm and 5−40 cm respectively
- ✓ Water as corium simulant
- ✓ The water layer was heated from below to simulate heat flux coming from the oxidic pool using direct current heating, cooled on the lateral wall with uniform temperature condition (ice crust formation) and on the upper boundary with a plastic heat exchanger to simulate radiative heat transfer



SIMECO experiments





✓ Slice: diameter and height of the test section are, respectively, 50.0 cm and 26.0. Slice thickness is 9.0 cm

✓Cartridge heaters, 14 K-type TCs in the pool and 40 K-type TCs in the vessel. Top heat exchanger

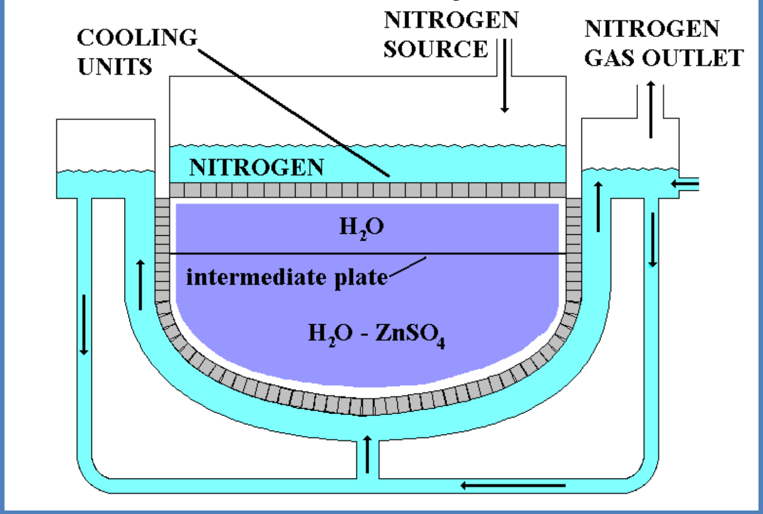
✓Simulants:

- *Water/Paraffin oil;*
- *Benzyl benzoate/Paraffin oil;*
- *Chlorobenzene/Water/Paraffin oil;*
- *Glycerol/Cerrobend;*
- *$NaNO_3$-KNO_3/Cerrobend.*

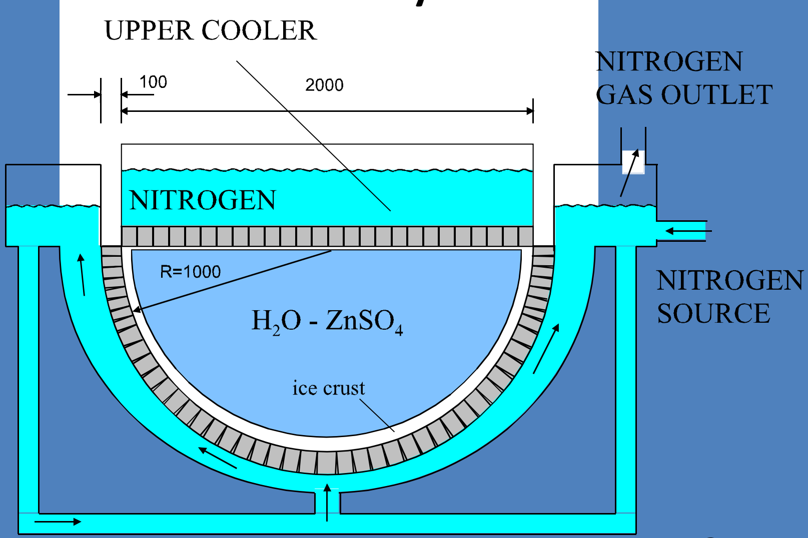
COPO experimental study of 2-layer pool

- ✓**Elliptically** (Lo) and **hemispherical** (AP) shaped lower head
- ✓ Radius of lower head is **1.0 m**
- ✓Corium pool is modelled by 2-D slice (thickness 9.4 cm)
- ✓1:2 linear scale, **Ra'_{max} ~ $5 \cdot 10^{15}$**
- ✓Corium simulated by **($ZnSO_4$ - H_2O)/H_2O system**
- ✓Cooled by liquid nitrogen on the outside of the pool boundaries
- ✓Heat flux obtained through temperature gradient in the Al wall
- ✓Heating by AC passing through the solution using Cu electrodes

COPO II-Lo facility



COPO II-AP facility

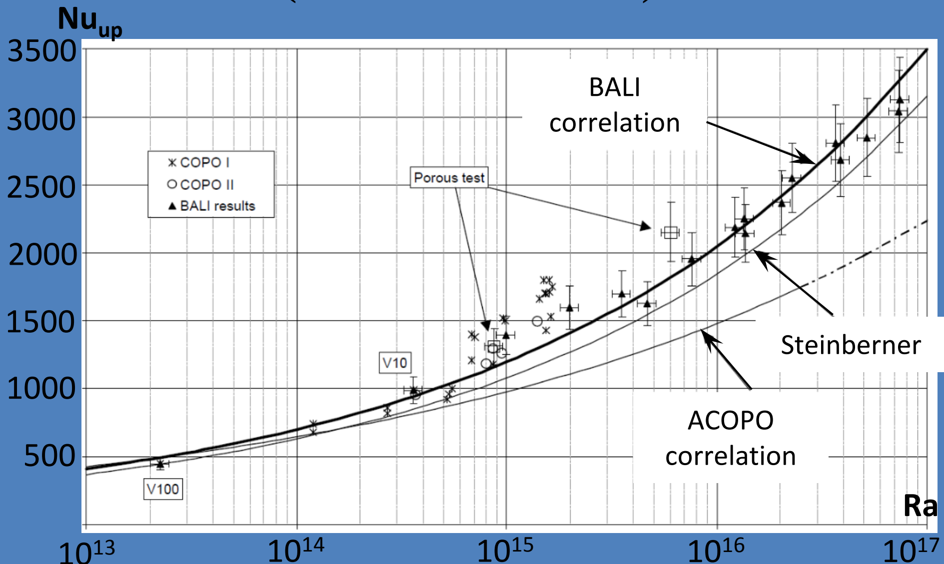


Correlations for natural convection in volumetrically heated pools

ACOPO correlation

$$Nu_{up} = 1.95 \cdot Ra^{0.18}; Nu_{dn} = 0.3 \cdot Ra^{0.22}$$

$$(10^{13} \leq Ra \leq 10^{17})$$



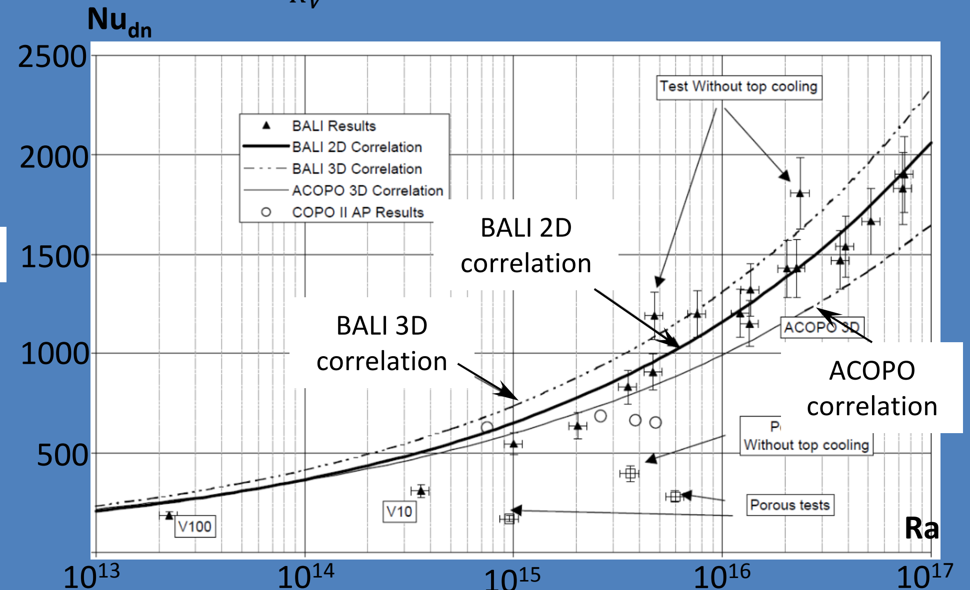
Average upward Nu numbers in COPO and BALI compared to the BALI, ACOPO and to Steinberner correlation

COPO-BALI correlation

$$Nu_{up} = 0.383 \cdot Ra^{0.233}$$

$$Nu_{dn} = 0.116 \cdot \left(\frac{H}{R_V}\right)^{0.32} \cdot Ra^{0.25} \; (10^{13} \leq Ra \leq 10^{17}) \; (2D)$$

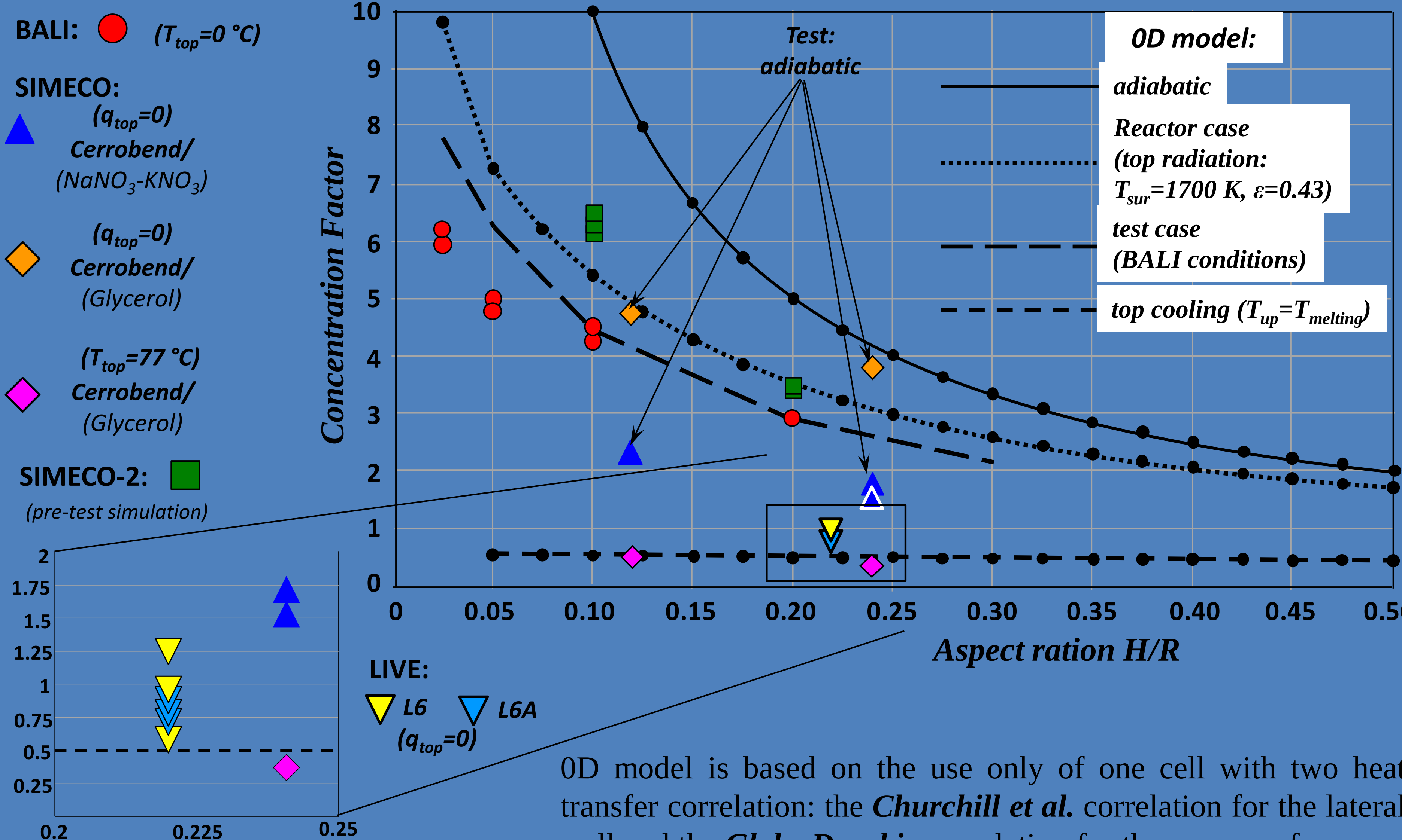
$$Nu_{dn} = 0.131 \cdot \left(\frac{H}{R_V}\right)^{0.19} \cdot Ra^{0.25} \; (10^{13} \leq Ra \leq 10^{17}) \; (3D)$$



Average downward Nu numbers in COPO and BALI compared to the BALI, ACOPO correlation

Discrepancy between BALI and ACOPO correlations increases at higher Ra number

Concentration factor of heat focusing by the top layer



0D model is based on the use only of one cell with two heat transfer correlation: the ***Churchill et al.*** correlation for the lateral wall and the ***Globe Dropkin*** correlation for the upper surface.

Transient behavior: melt relocation in debris bed
LIVE L8A and L8B test design:

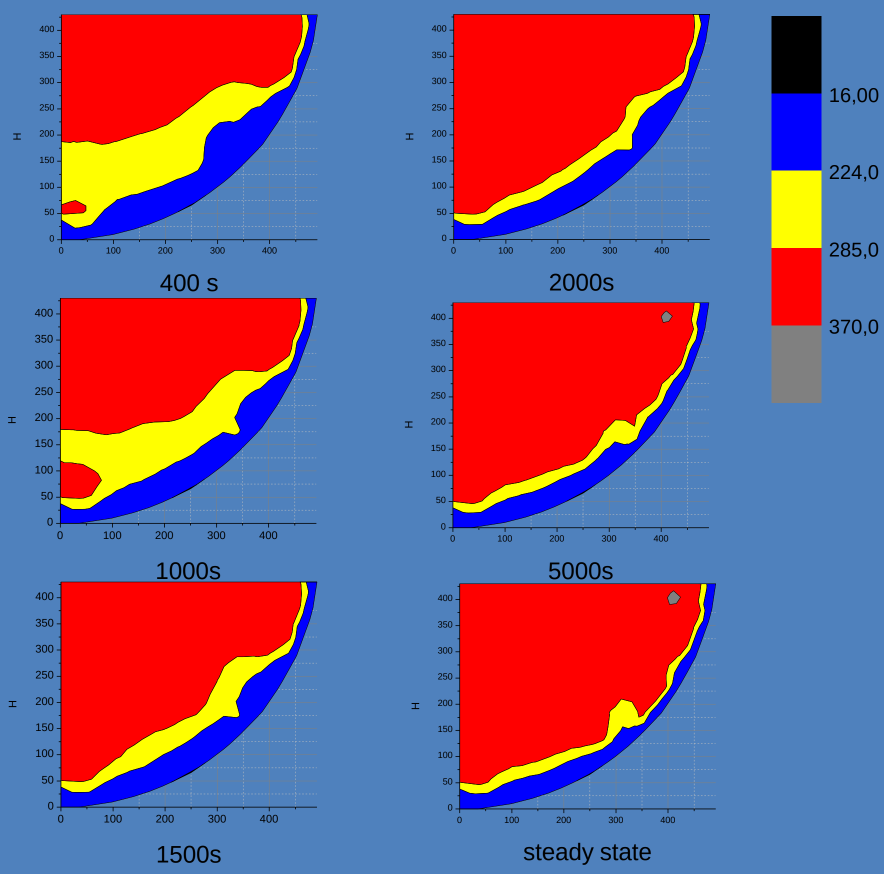
- L8A test: 70 vol % total mass as liquid relocated
- L8B test: 50 vol % total mass as liquid relocated
  - Formation and progression of melt pool during debris melting
  - melt temperature and heat flux distribution

- Debris
  - 20 mol% $NaNO_3$ - 80 mol% KNO_3
  - Diameter: 3-16 mm
- Liquid melt
  - 20 mol% $NaNO_3$ - 80 mol% KNO_3
  - temperature 350°
- Debris is preheated
- Heating with 21 KW and external cooling started immediately after melt relocation

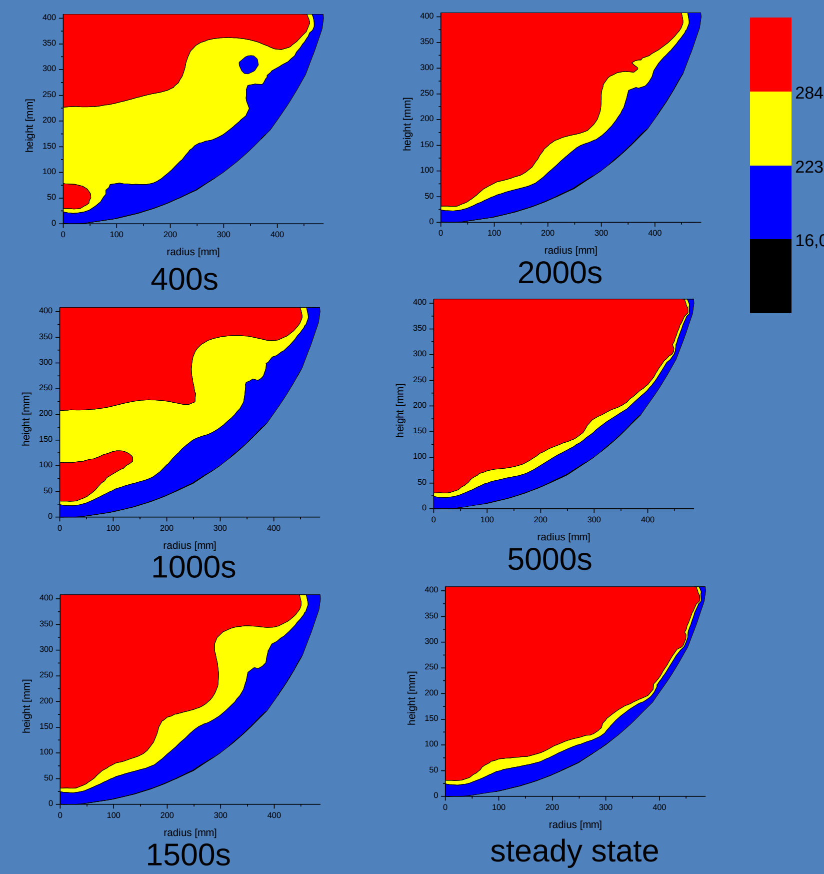
Transient behavior: melt relocation in debris bed

Melt pool progression in LIVE L8A and L8B test

L8A: 70% as relocated melt



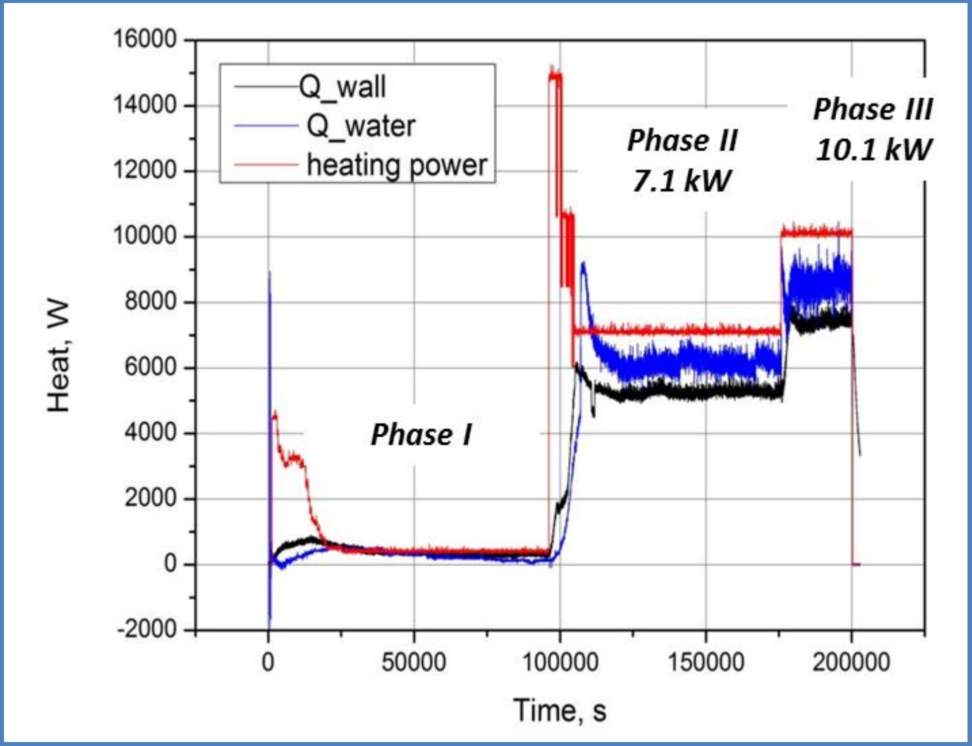
L8B: 50% as relocated melt



Transient behavior: two-component debris bed

LIVE-L8C test design

- Simulant materials
  - 50 vol. % non-eutectic nitrate debris , T_{liq}=224 °C
  - 50 vol. % granite
  - Debris size 3-6 mm
- 3 heating phases
- External cooling



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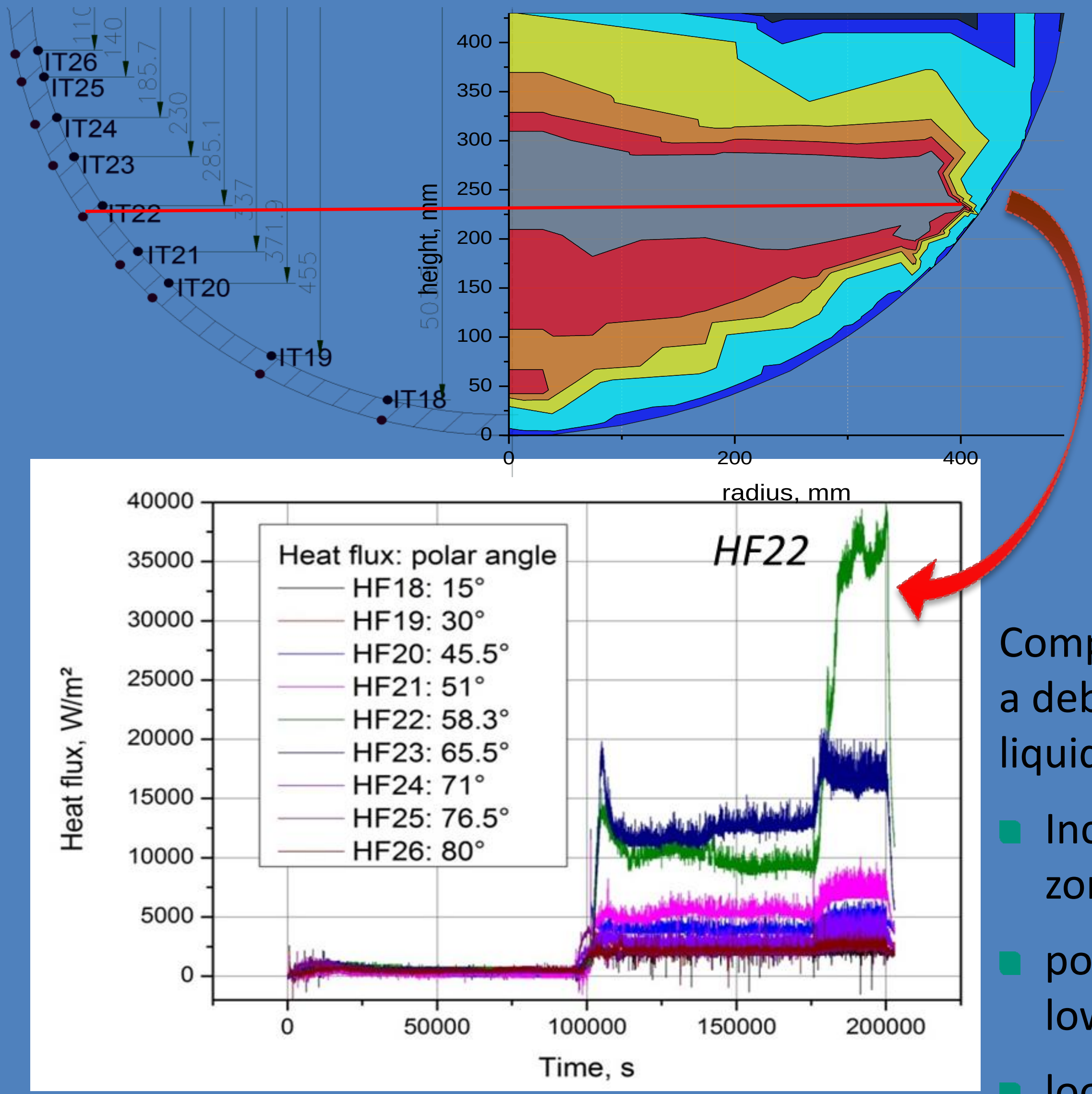
Transient behavior: two-component debris bed

Heat flux

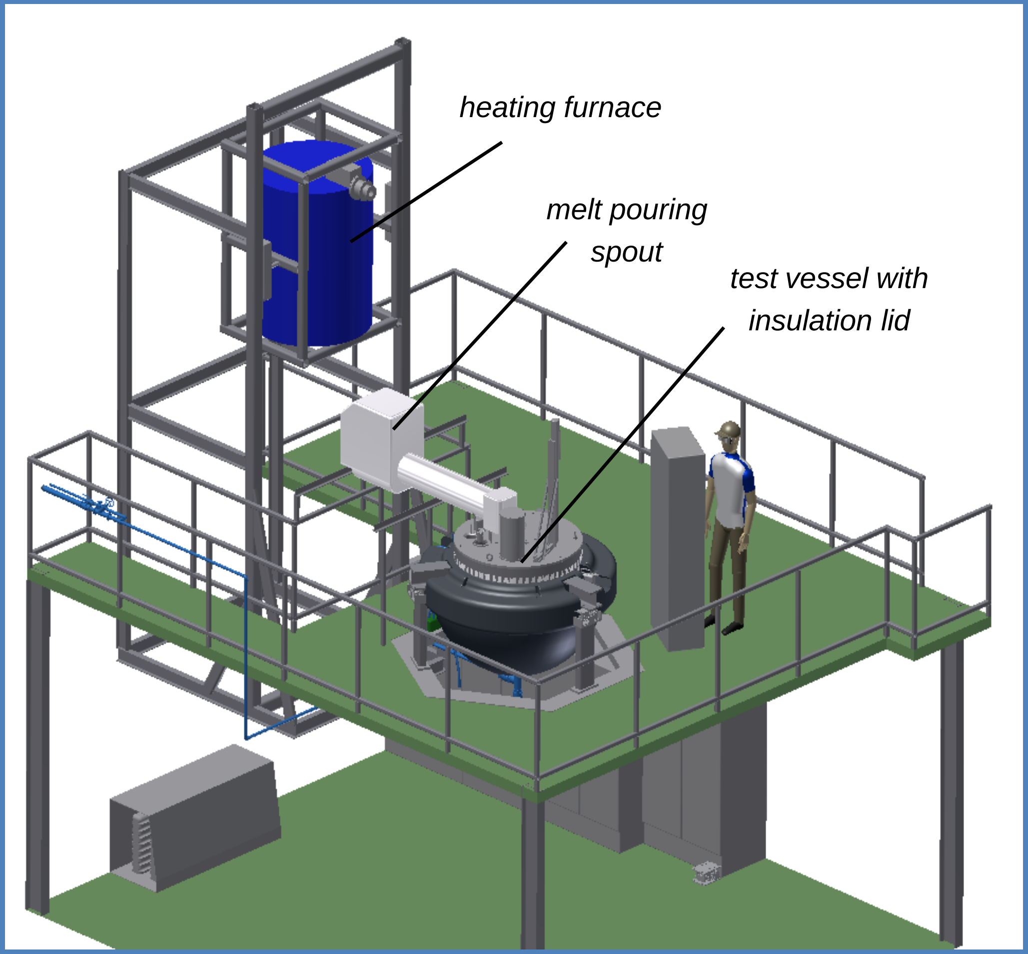


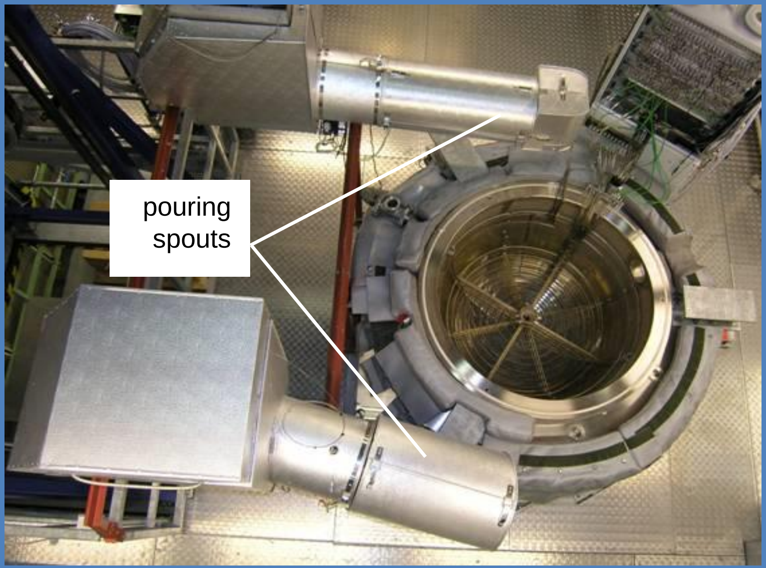
Loose debris at vessel bottom

Compared to a homogeneous melt pool, a debris bed with co-existing solid and liquid phases shows

- Increase of heat flux at the upper zone
- poor downward heat transfer at the lower zone
- loose debris at the bottom of the vessel

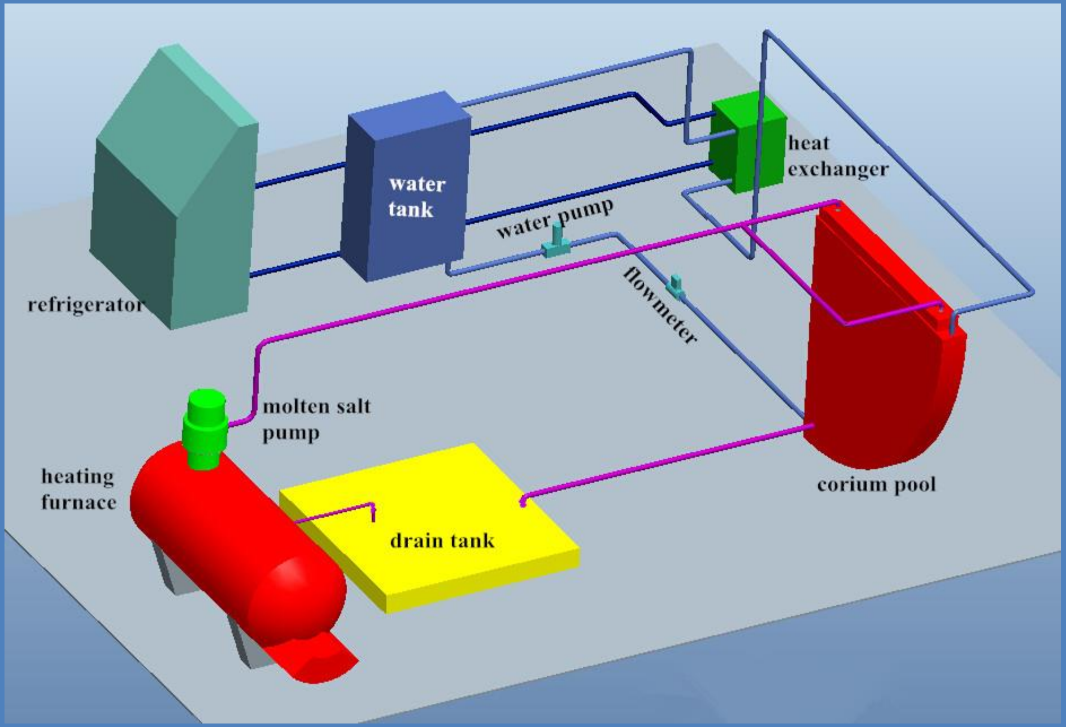
LIVE 3D test facility at KIT





- diameter 1 m, 1:5 scaled hemispheric PWR reactor lower head
- different melt pouring positions
- heating system: resistance wires
- external water cooling system

COPRA facility at XJTU



- diameter 2.2 m, 1:1 scaled 1/4 circular slice PWR reactor lower head
- different melt pouring positions
- heating system: resistance wires
- external water cooling system

Comparison of LIVE and COPRA

Similarities

- Simulant materials: non-eutectic binary nitrate salt
- Heating method: resistance wires
- Similar vessel wall material and thickness
- Melt pour: central and lateral position
- External cooling: water
- Crust formation can be realized with salt simulants

Difference

	LIVE	**COPRA**
Dimension	3D, 2D	2D
Ra_{in} number	10^{14}	10^{16}

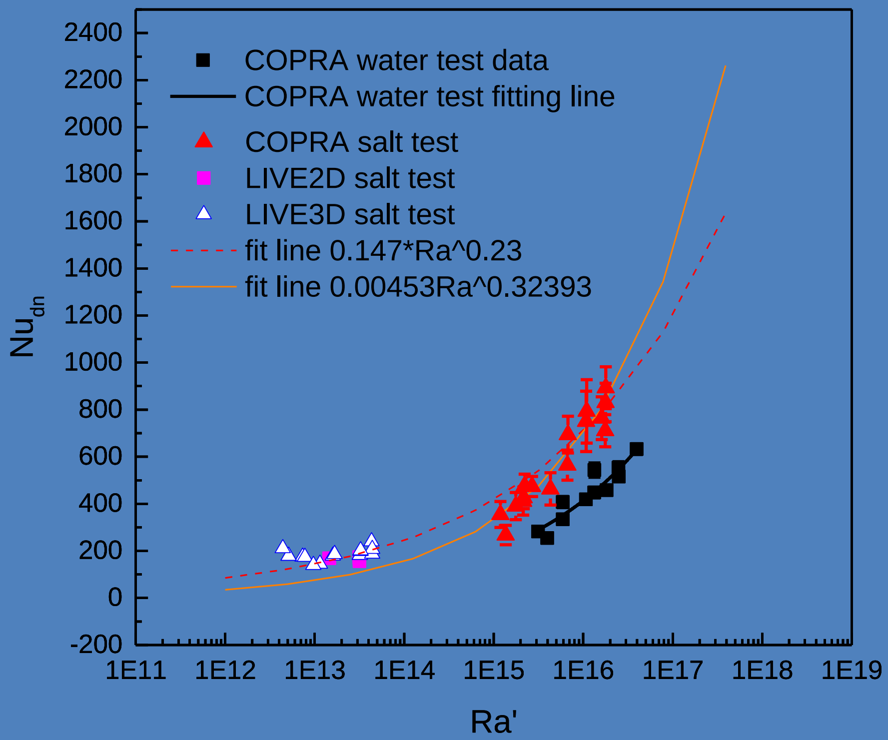
Phenomena

- Melt/debris transient behavior
- Influence of dimension
- Influence of crust formation
- Influence of Ra number

TH steady-state behavior:

downward heat transfer Ra_i~Nu_{dn}

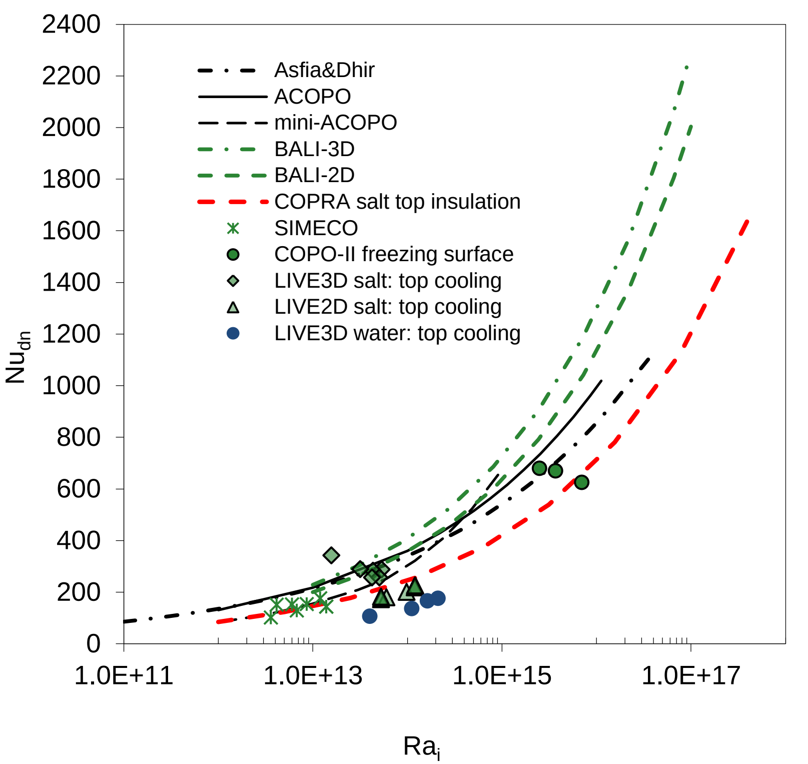
Downward Nu in



$$Nu_{dn} = 0.00453 Ra'^{0.32393}$$

$$Nu_{dn} = 0.14707 Ra'^{0.23205} \left(\frac{H}{R}\right)^{0.39542}$$

Downward Nu in



- Higher Nu_{dn} in top cooling condition
- Higher Nu_{dn} in 3D geometry

Transient behaviour

- Lateral melt relocation - significantly higher heat flux at pouring area
- Vessel flooding
  - Quenching of hot wall
  - Low crust growth rate after melt pour leads to higher crust conductivity and thicker crust layer
- Melt pour in the debris bed
  - Partially freezing of poured melt in the lower part of debris
  - Followed by molten pool downward extension and recovery of melt temperature
  - A thin layer of loose debris exists on the lower part of the vessel bottom
- Melting of debris bed with different melt temperature
  - Void formation and collapse inside the debris bed
  - Increase of the heat flux at the position of melt layer atop of solid debris
  - Hotspot on the vessel wall as consequence of horizontal progression of molten melt
  - Smaller downward heat transfer

TH steady-state behaviour

- Cooling vs. insulation of melt upper surface
  - Higher Nu_{up} number during upper surface cooling
  - Homogeneous melt temperature and lower local heat flux in the upper part of the pool during upper surface cooling
- Nucleate boiling vs. subcooling on external boundary
  - Similar melt pool temperature in the whole pool
  - Higher heat flux at the upper part of vessel wall during nucleate boiling
- 3D vs. 2D geometry
  - Higher downward heat flux and melt temperature in the upper part in 2D
- Crust vs. crust-free boundary
  - Uniform boundary temperature in the presence of crusts
  - Higher upward heat transfer coefficient
  - Different downward heat flux distribution

Some conclusions from previous tests

- Large discrepancy exists between the experimental data and correlations used for heat generating layers for high Ra numbers typical for reactor condition (10^{15}-10^{16})

- Poor data for side heat flux of top layer externally heated from below

- No correlations exist for a heat transfer in a three-layer pool

- First confirmation of focusing of surface liquid layer atop of solid debris filled by the melt in LIVE experiment

- Large discrepancy exists in the modeling of the heat flux in the two-layer melt pool and experimental data due to excessively simplified assumptions in models

New data required

- Need of experimental data for 2 and 3 layer pools under following conditions:
  - higher Ra numbers
  - interfacial crust between top and bottom layer
  - top cooling (transient heat flux evolution) and thermal insulation
  - layer mixing/inversion
  - high thermal conductivity of top layer
- Such experiments are planned in the IVMR EU project

New tests on heat transfer within stratified molten pool at steady-state and transient conditions

Thermal impact of molten pool stratification and possible transient evolutions of pool configuration.

Experimental programs address the following phenomena:

Heat transfer between a heat generating layer and an immiscible layer on top or at the bottom (including a 3-layer configuration) under different boundary conditions. Effects of relative molten layer positions and of the top layer thickness on the heat partitioning and focusing

Inversion of layers caused by their density evolution and evaluation of corresponding transient heat fluxes, e.g. during formation of a new top layer

Influence of **turbulence** on the mixing and heat transfer between two layers having different densities

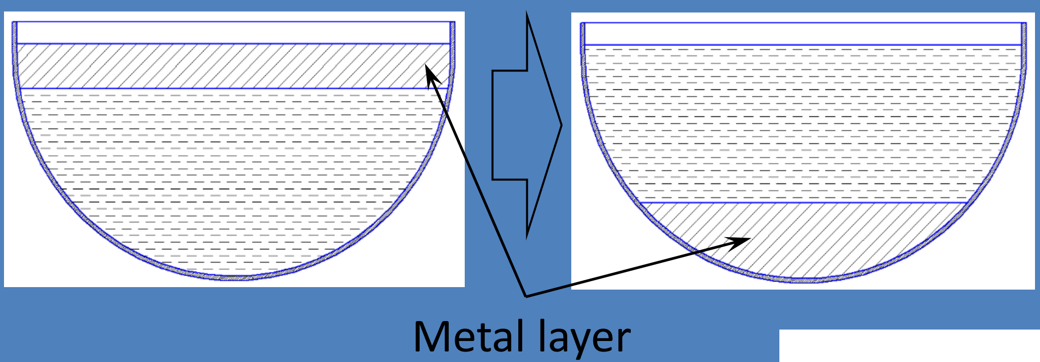
Influence of **interfacial crust and partially solidified crust** on the heat transfer between the heat generating layer and the layer atop of it.

Experiments with stratified molten pool

Heat transfer between a heat generating layer and an immiscible layer on top or at the bottom (including a 3-layer configuration) under different boundary conditions

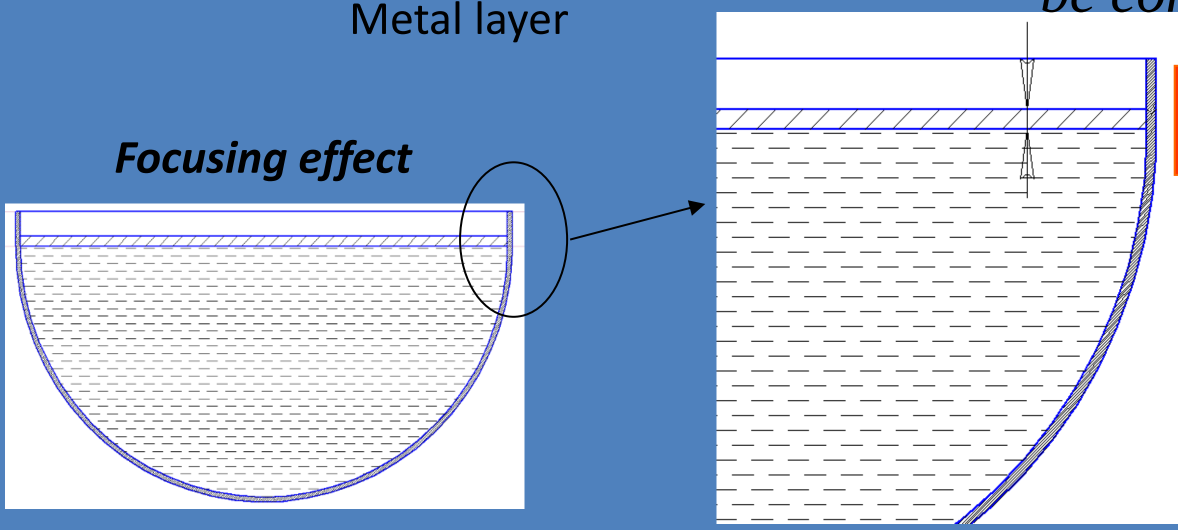
Experiments with two layers

Layers inversion



Effects of relative molten layer positions and the top layer thickness on the heat partitioning and focusing will be considered

Focusing effect



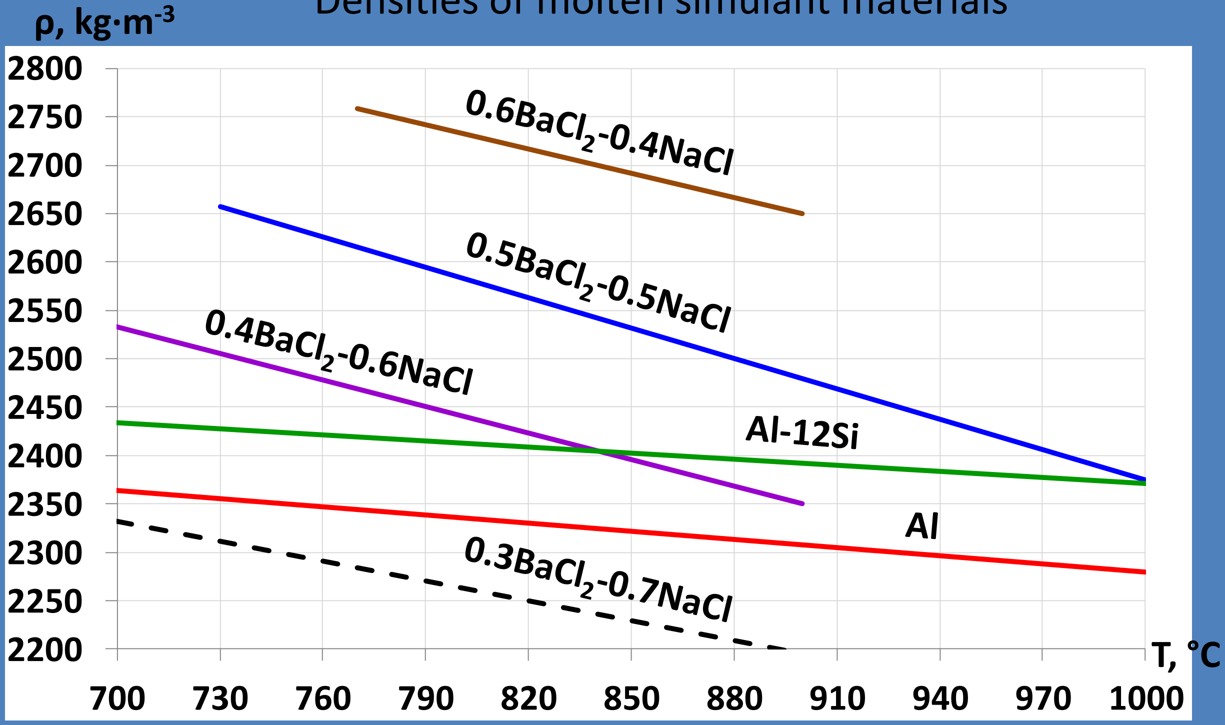
Influence of top metal layer thickness on the local heat flux through the metal wall

Simulant materials

<u>Metal layer simulant</u>: **Aluminum or its alloys**

Stratified pool at 800 °C

Densities of molten simulant materials



Al

($\rho = 2328\ kg \cdot m^{-3}$)

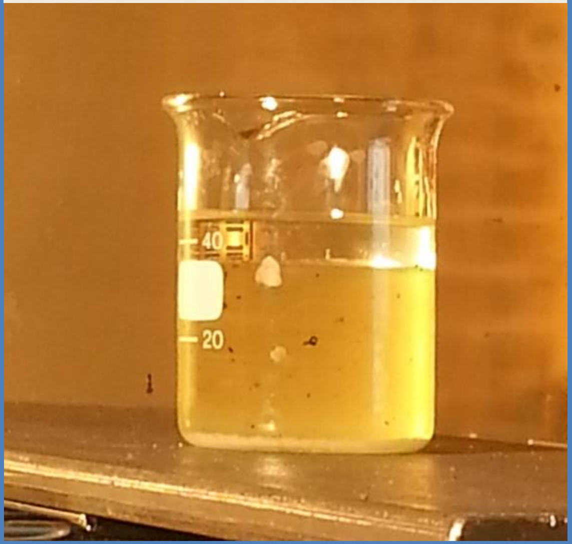
$0.5BaCl_2$ – 0.5NaCl

($\rho = 2542\ kg \cdot m^{-3}$)

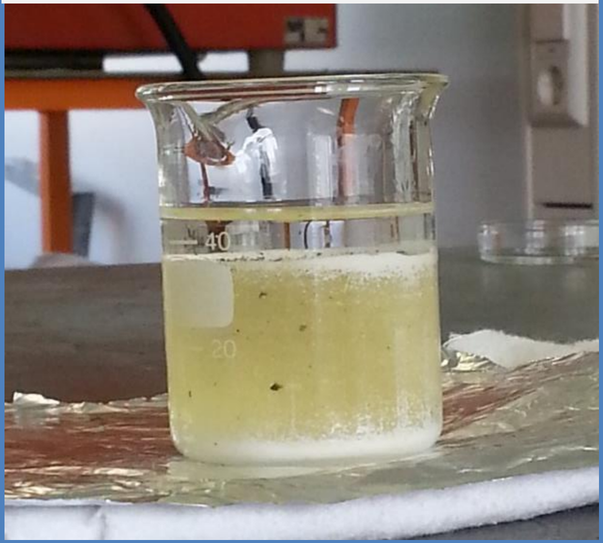
Laboratory scale tests addressing material compatibility

- Nitrate-oil mixture is tested in laboratory tests from 240 °C – 280 °C in air.
- There is no chemical and physical changes in both materials up to 260 °C.
- Above 260°C oil begins to evaporate, nitrate salt remains stable.
- The laboratory tests at higher temperatures are planed in the near future.
- Both materials have no interaction with insulation material.

During exposure in furnace at 250°C



Short after exposure



Visualization of melt behaviour in LIVE 2D

Transparent sidewall in LIVE 2D

- **Important phenomena during the transient state:**
  - mixing and segregation of immiscible layers
  - crust formation between layers
  - gap formation between the crust and the vessel wall
  - heat transfer in the gap

- **Continuous process of**
  - crust thickness profiles at the boundary and layer interface
  - eventually flow patterns in the liquid pools

Thank you for your attention!