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Simulation of transient behavior of corium pool in the lower plenum of RPV using COMPASS

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Introduction

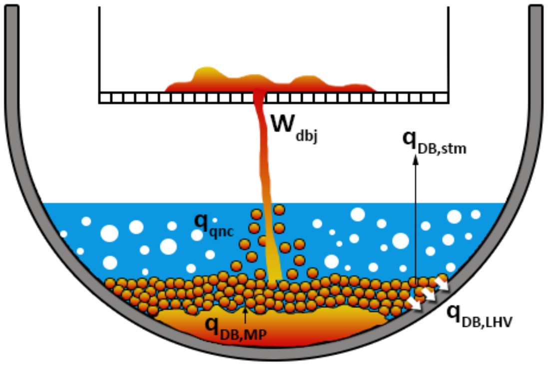
- An integrated severe accident analysis code has been developing by the collaboration of three institutes (KAERI, KHNP, FNC) in Korea.

- KAERI is responsible for developing modules related to the in-vessel phenomena. So, COMPASS (COre Meltdown Progression Accident Simulation Software) is developing for the whole physical phenomena inside the reactor vessel from a core heat-up to a vessel failure.

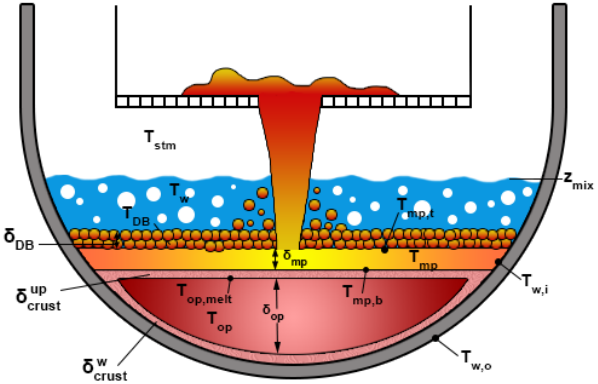
- As a part of the COMPASS development, a numerical module of a SIMPLE (Severe In-vessel Melt Progression in Lower plenum Environment) on the corium behavior in the lower plenum and ablation of the reactor vessel wall has been developed.

- The SIMPLE module calculates thermal hydraulic behavior of particulate debris bed, metallic pool, oxidic pool with crust formation, and vessel wall heat transfer.

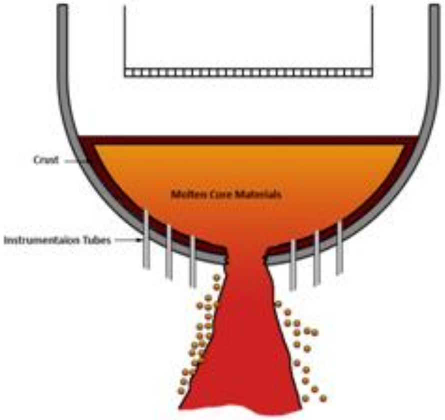
Schematic scenario of SIMPLE



Melt relocation to the lower plenum:
melt-water interaction



Corium pool formation:
two layers formation & heat transfer



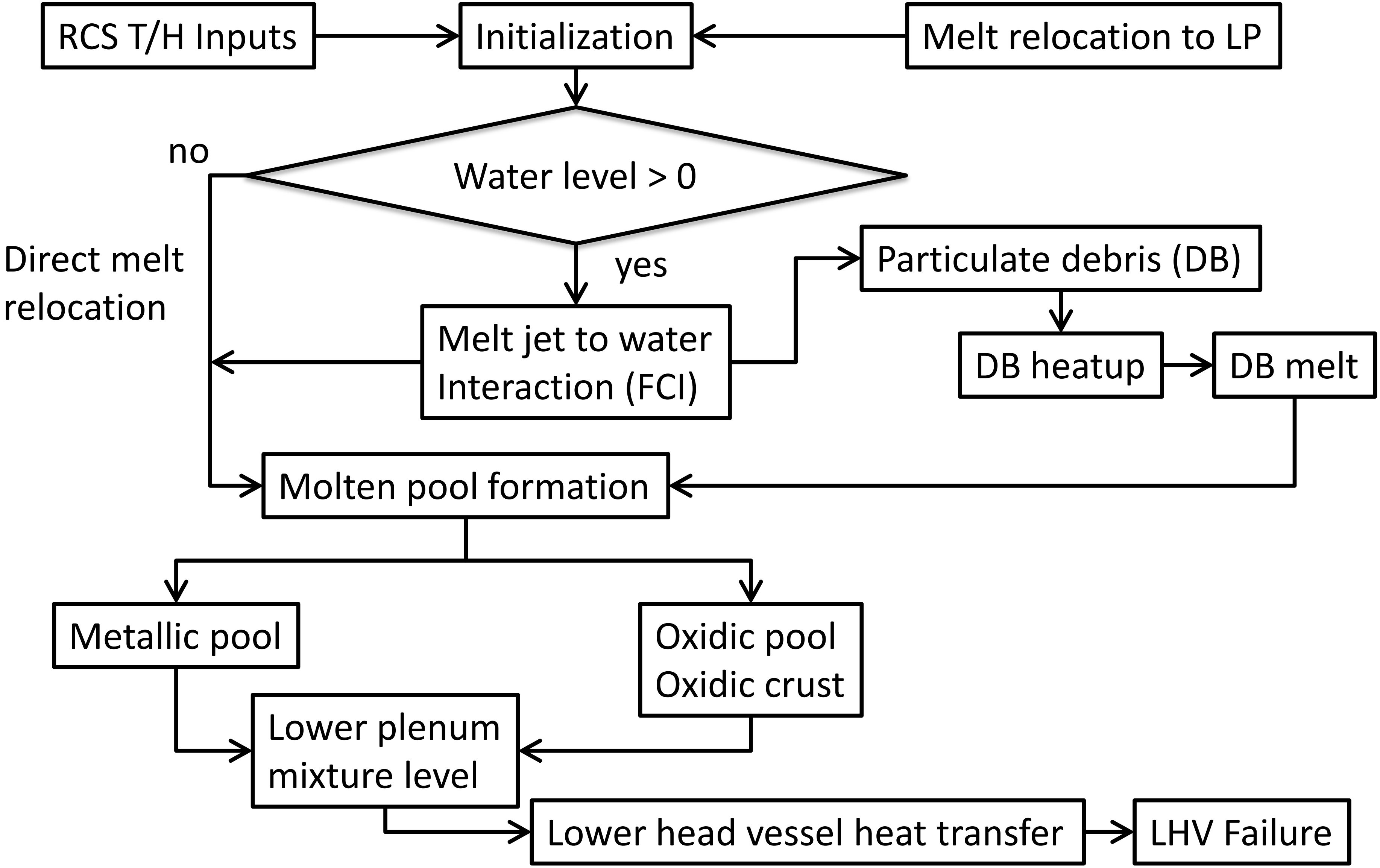
Reactor vessel wall heat transfer & failure: corium relocation to containment

Overview & Objectives

- Contents of SIMPLE:
  - ✓ Core melt relocation into the lower plenum
  - ✓ Melt jet-water(or vessel) interaction with partial solidification of corium
  - ✓ Water boiling due to corium
  - ✓ Particulate debris bed formation by quenching, heat-up, and melting
  - ✓ Molten pool formation and separation into two layers
  - ✓ Metallic pool behavior with crust formation
  - ✓ Oxidic pool behavior with crust formation
  - ✓ Heat conduction in the reactor pressure vessel
  - ✓ Lower head vessel ablation & failure

- Objectives:
  - ✓ To simulate hypothetical scenario of severe accident of APR1400 by using SIMPLE code
  - ✓ To analyze the results for improvements of the SIMPLE code

Flow chart of SIMPLE


RCS T/H Inputs

Initialization

Melt relocation to LP

Water level > 0

no

Direct melt relocation

yes

Melt jet to water Interaction (FCI)

Particulate debris (DB)

DB heatup

DB melt

Molten pool formation

Metallic pool

Oxidic pool
Oxidic crust

Lower plenum mixture level

Lower head vessel heat transfer

LHV Failure

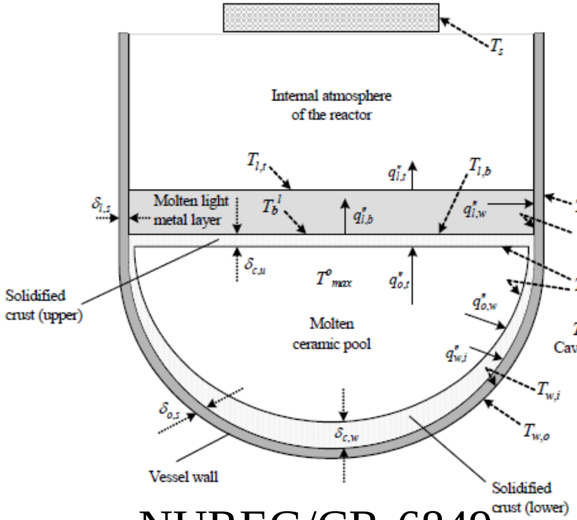
Validation test for steady state IVR analysis

- NUREG/CR-6849 (ERI/NRC 04-201), and KAERI/TR-4281/2011: Analysis of in-vessel retention and ex-vessel fuel coolant interaction for AP1000

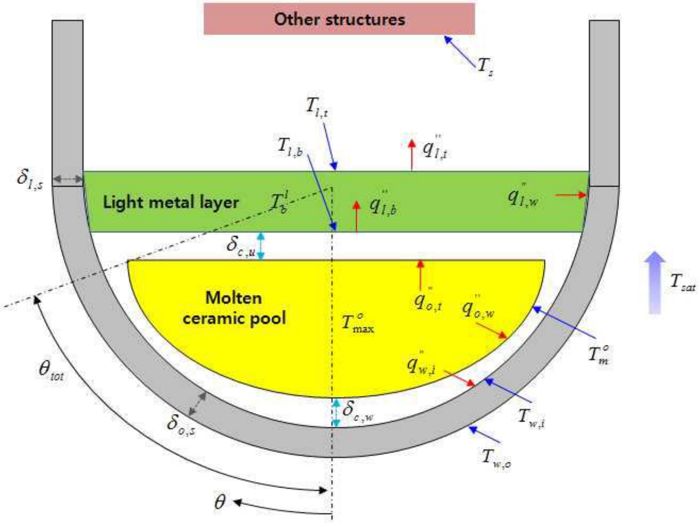
- SIMPLE calculates AP1000 benchmark problem for IVR condition with same geometric and boundary conditions.

- To obtain settled results, 10000 sec. of transient time was calculated.

- SIMPLE shows similar heat balance as compare to the references, resulting in reasonable similarity of crust thickness, pool temperature, RPV wall thickness etc.



NUREG/CR-6849



KAERI/TR-4281/2011

Validation test for steady state IVR analysis

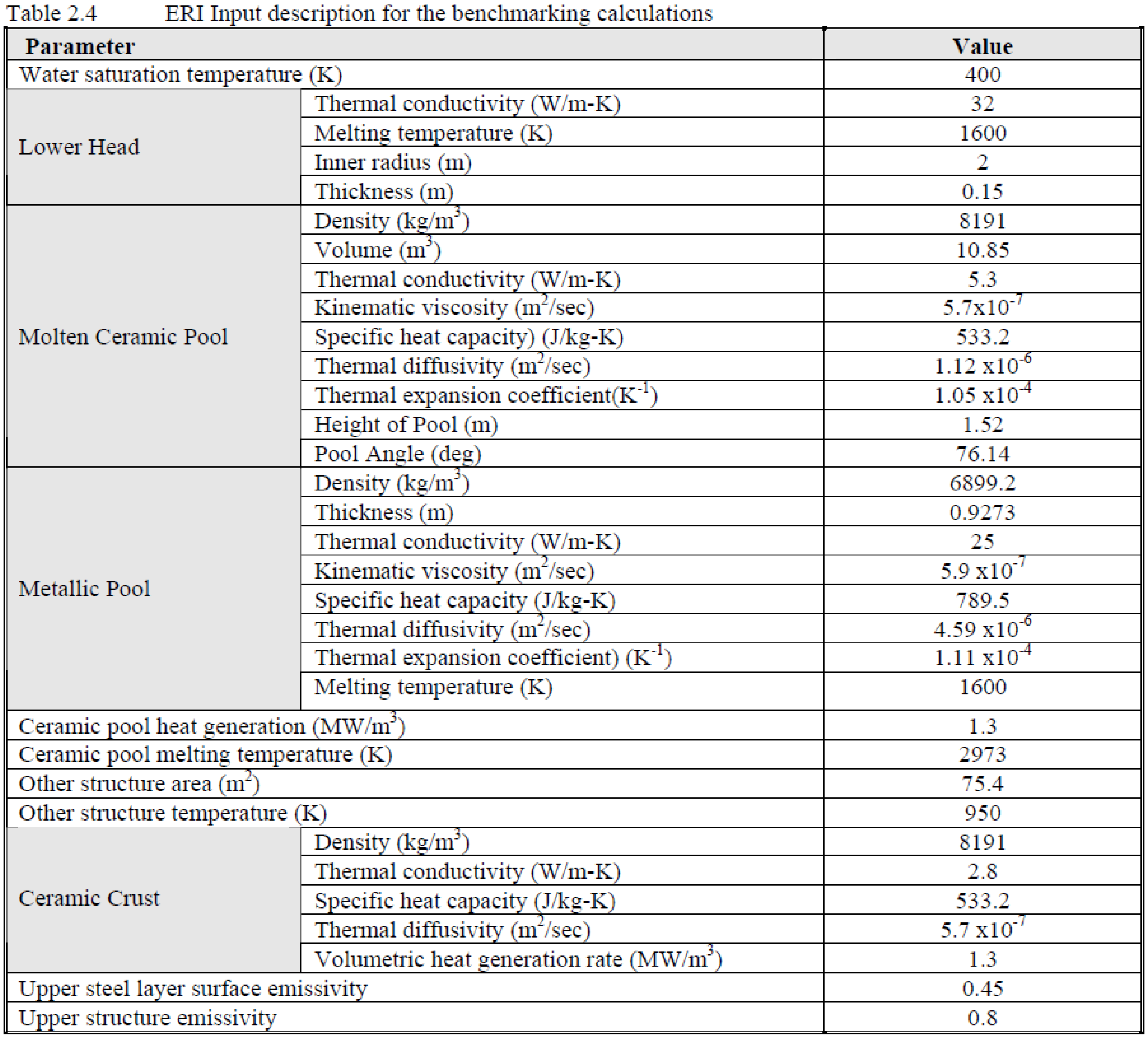


Table 2.4 ERI Input description for the benchmarking calculations

Parameter		Value
Water saturation temperature (K)		400
Lower Head	Thermal conductivity (W/m-K)	32
	Melting temperature (K)	1600
	Inner radius (m)	2
	Thickness (m)	0.15
Molten Ceramic Pool	Density (kg/m^3)	8191
	Volume (m^3)	10.85
	Thermal conductivity (W/m-K)	5.3
	Kinematic viscosity (m^2/sec)	$5.7 x 10^{-7}$
	Specific heat capacity) (J/kg-K)	533.2
	Thermal diffusivity (m^2/sec)	$1.12 x 10^{-6}$
	Thermal expansion coefficient(K^{-1})	$1.05 x 10^{-4}$
	Height of Pool (m)	1.52
	Pool Angle (deg)	76.14
Metallic Pool	Density (kg/m^3)	6899.2
	Thickness (m)	0.9273
	Thermal conductivity (W/m-K)	25
	Kinematic viscosity (m^2/sec)	$5.9 x 10^{-7}$
	Specific heat capacity (J/kg-K)	789.5
	Thermal diffusivity (m^2/sec)	$4.59 x 10^{-6}$
	Thermal expansion coefficient) (K^{-1})	$1.11 x 10^{-4}$
	Melting temperature (K)	1600
Ceramic pool heat generation (MW/m^3)		1.3
Ceramic pool melting temperature (K)		2973
Other structure area (m^2)		75.4
Other structure temperature (K)		950
Ceramic Crust	Density (kg/m^3)	8191
	Thermal conductivity (W/m-K)	2.8
	Specific heat capacity (J/kg-K)	533.2
	Thermal diffusivity (m^2/sec)	$5.7 x 10^{-7}$
	Volumetric heat generation rate (MW/m^3)	1.3
Upper steel layer surface emissivity		0.45
Upper structure emissivity		0.8

NUREG/CR-6849
ERI/NRC-04-201

Validation test for steady state IVR analysis

	Reference (Kaeri/TR-4281/2011)	present SIMPLE
Oxidic pool heat transfers (kW/m^2)	upward: 1020 sideward: 570	upward: 924 sideward: 640
Metallic pool heat transfers (kW/m^2)	upward: 214 sideward: 1709 downward: 1027	upward: 230 sideward: 1512 downward: 924
Pool temperatures (K)	T_{op}: 3214 $T_{mp,b}$: 1952 T_{mp}: 1787 $T_{mp,top}$: 1752	T_{op}: 3140 $T_{mp,b}$: 1912 T_{mp}: 1838 $T_{mp,top}$: 1820
Oxidic pool crust thickness (cm)	Top: 0.321 $\theta = 9.7$: 3.20 $\theta = 25$: 1.9 $\theta = 38$: 0.8 $\theta = 59$: 0.5	Top: 0.324 $\theta = 9.7$: 4.60 $\theta = 25$: 2.13 $\theta = 38$: 0.77 $\theta = 59$: 0.43
Remaining thickness of RPV (cm)	Metallic: 2.0 $\theta = 9.7$: 16.5 $\theta = 25$: 16.5 $\theta = 38$: 7.5 $\theta = 59$: 4.5	Metallic: 2.54 $\theta = 9.7$: 16.5 $\theta = 25$: 16.5 $\theta = 38$: 7.37 $\theta = 59$: 3.82

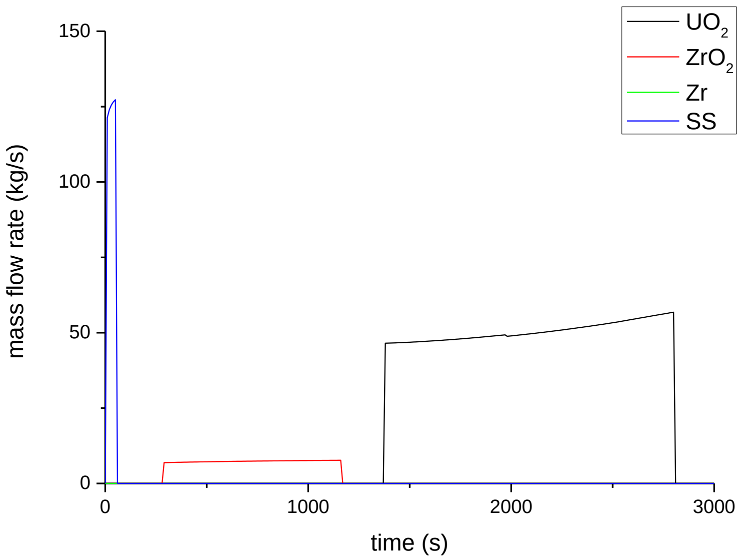
Inputs of SIMPLE for transient calculation

- The following information is needed as input:
  - ✓ Molten corium delivery from the core support plate (temperature, mass, and composition, see a table below)
  - ✓ Core and lower plenum pressure
  - ✓ Inlet coolant flow from the downcomer (temperature and corresponding enthalpy)
  - ✓ Initial coolant level and temperature in the lower plenum: 1.8 m
  - ✓ Core structures: their temperature, heat transfer area, etc. to calculate radiation heat transfer
  - ✓ Outer boundary condition (heat flux or temperature to the lower head vessel outer wall, in the present, $T_{out} = 350$ K)

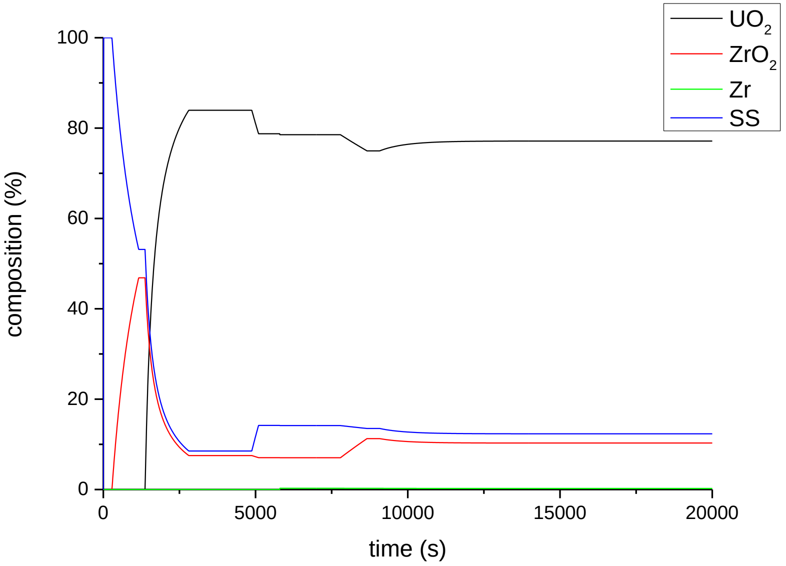
Start (sec)	**End (sec)**	**Temp. (K)**	**UO_2 (kg/s)**	**ZrO_2 (kg/s)**	**Zr (kg/s)**	**SS (kg/s)**
0	59	1700	0	0.076	4.3	220.7
283	1162	2973	0	12.36	0	0
1372	2807	3113	67	0	0	0

Mass flowrates and composition of the pool

Mass flowrate to the pools



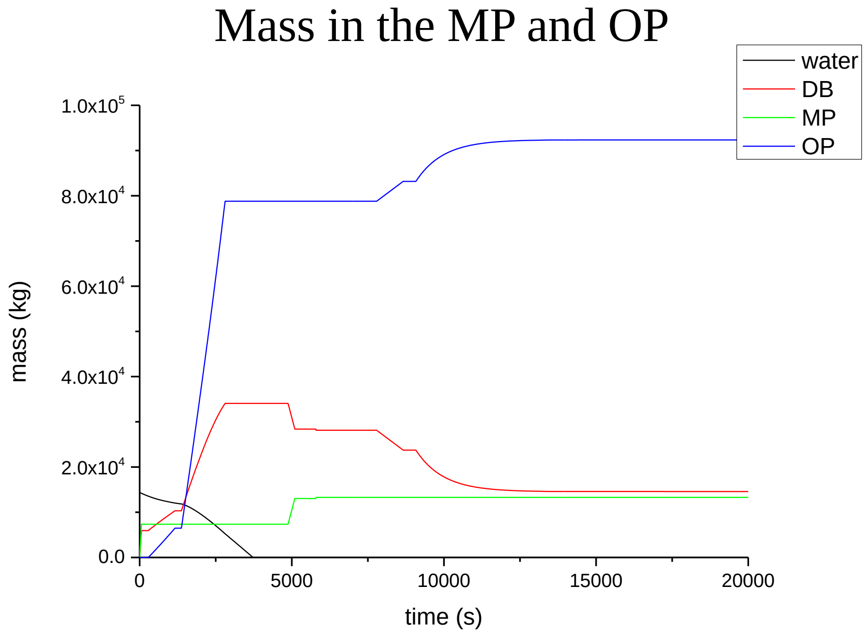
Mass composition in the molten pools

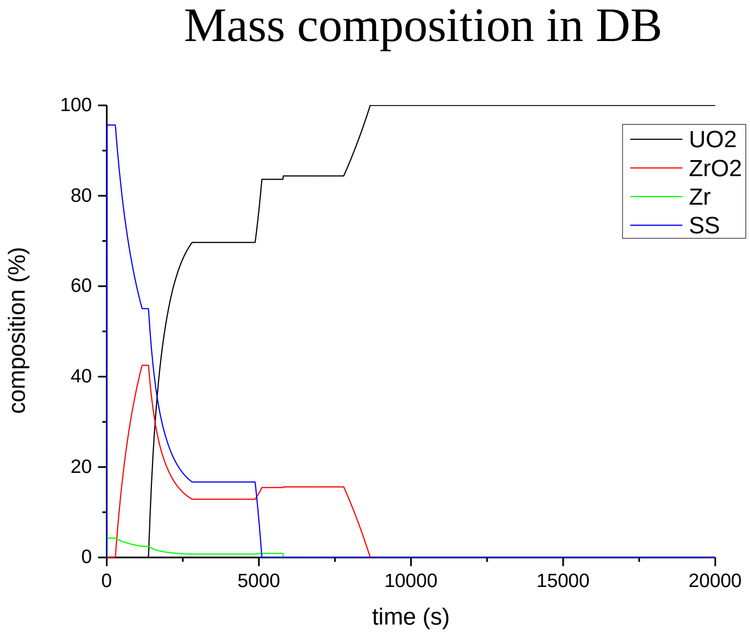


- 0 ~ 59 sec: SS relocation (~140 kg/s) to the MP, remaining (~80 kg/s) to the DB
- 283 ~ 1162 sec: ZrO2 relocation (~7 kg/s) to the MP, remaining (~5 kg/s) to the DB
- 1372 ~ 2807 sec: UO2 relocation (~50 kg/s) to the MP, remaining (~17 kg/s) to the DB

- Mass composition of the pools (MP and OP) change in time.
- At the early stage of calculation, there is only SS.
- After then, composition of ZrO_2 and UO_2 increase by the relocation and melting from DB.

Mass of the components in the LP and composition in the DB



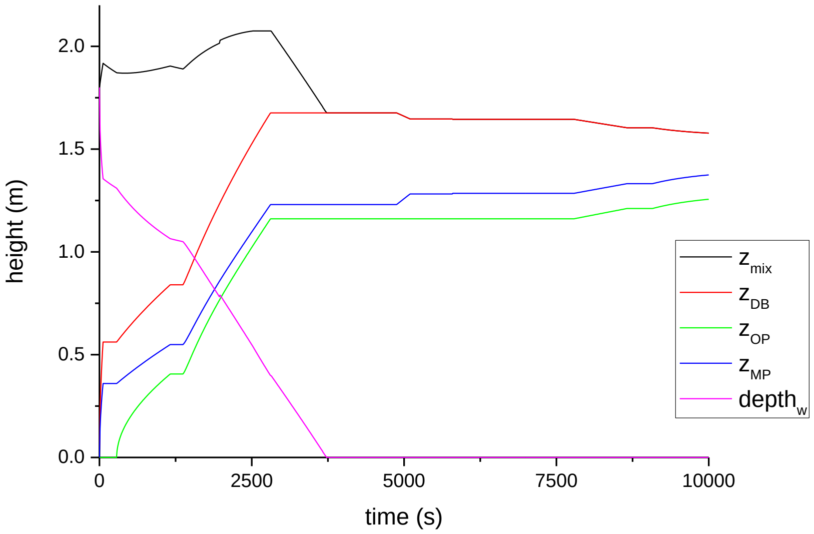


- Water is dried out at t = 3720 s.
- Melting of the SS in the DB starts at t = 4870 to 5100 s.
- Mass of the MP, OP are changed in time by melting of DB, or freezing to the crusts.

- At the early stage of calculation, there is only SS.
- After then, composition of SS, Zr, and ZrO_2 decrease by melting of DB.

Level and depth of the pools and water

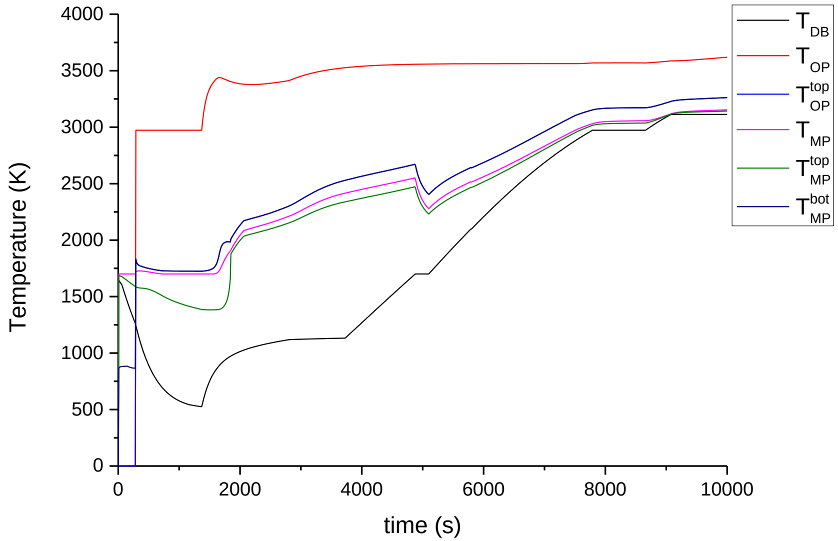
Level of the pools



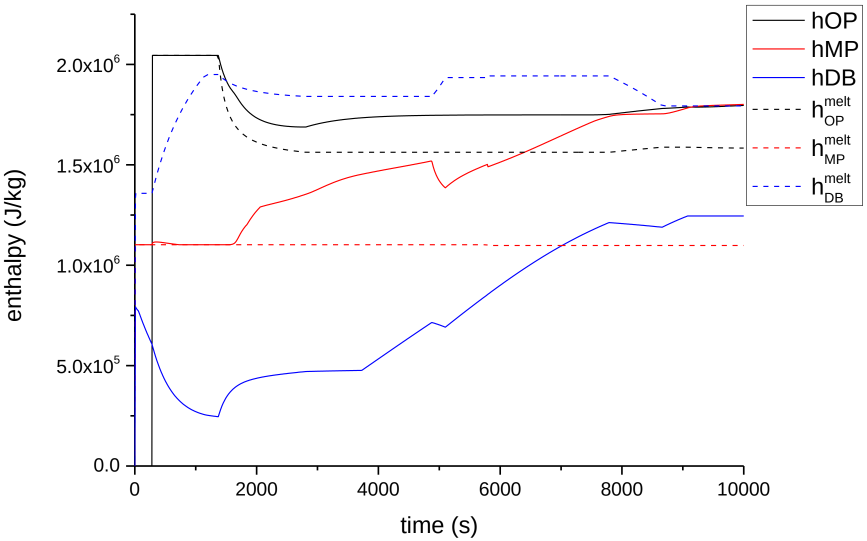
- Depth of the water decreases to zero (dry out) in 3720 s.
- Thin MP is formed after UO_2 relocation.
- Because of rapid relocation of the UO_2, mixture level (pools + water) temporally increases from 1400 s to 2800 s.
- Level of MP and OP changes in time by the melting of DB.

Enthalpy and temperature change in time

Temperature of the pools



Enthalpy of the pools

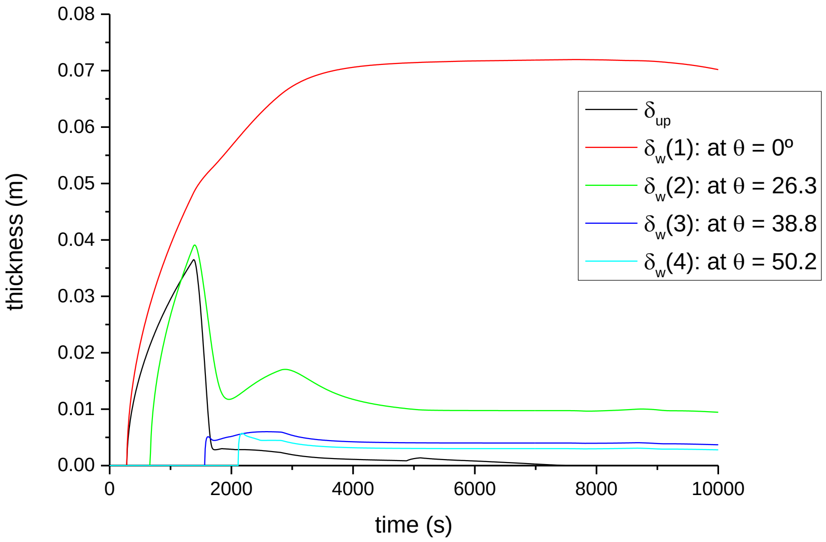


- T_{OP} is the ZrO_2 melting temperature before UO2 relocation.
- T_{DB} is the SS melting temperature while the SS in the DB melts.
- T_{MP} decreases during the SS melting.

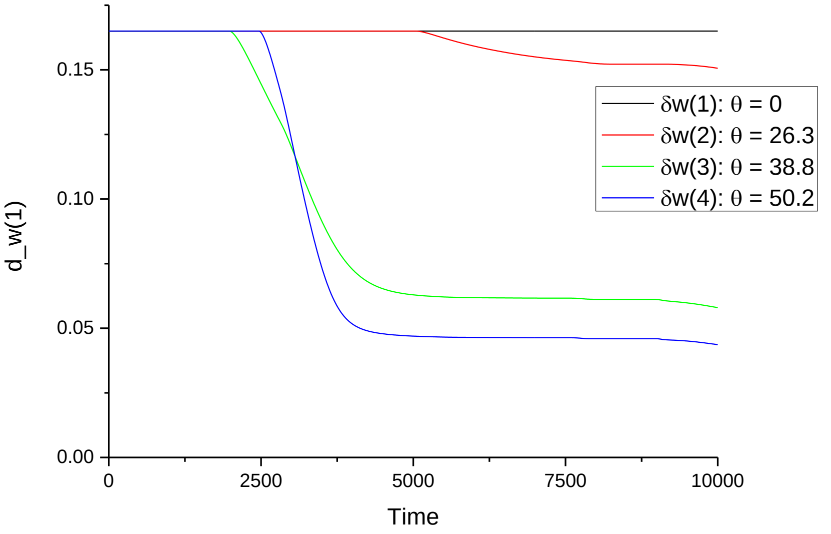
- h_{DB} and h_{MP} increases after UO_2 relocation.
- Melting enthalpy of OP decreases after UO_2 relocation
- h_{MP} decreases when the molten SS from the DB is added.

Crust and vessel wall thickness

Crust thickness



Vessel wall thickness

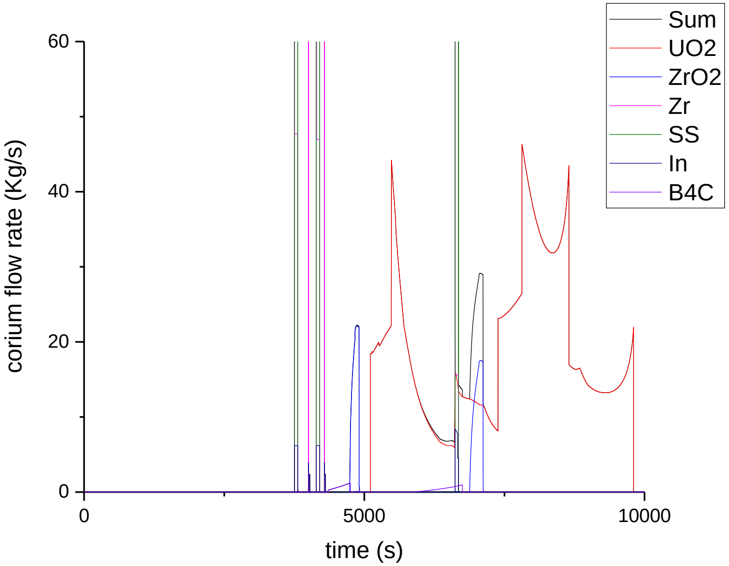


- Starting of crust formation in time is different at each θ.
- Upper crust thickness of the OP decreases when the UO_2 is relocated.
- Crust thickness of OP is different by changing θ.

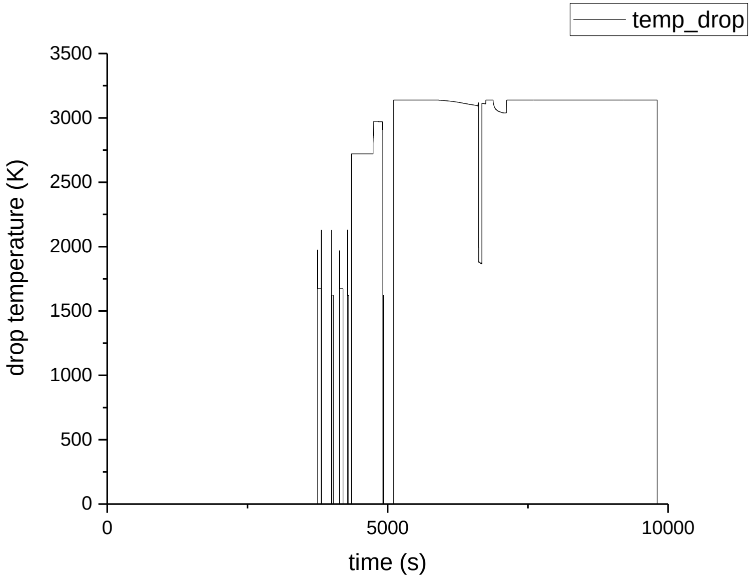
- At the bottom position of vessel, LHV is not melted.
- Melting of LHV starts at t = 2000 s, at the 3rd ring of lower plenum (θ = 38.8º)
- Minimum thickness of the LHV is 4.36 cm, at the 4th ring of lower plenum (θ = 50.2º)

Combined COMPASS & SIMPLE

Mass flowrate to the LP



Drop temperature

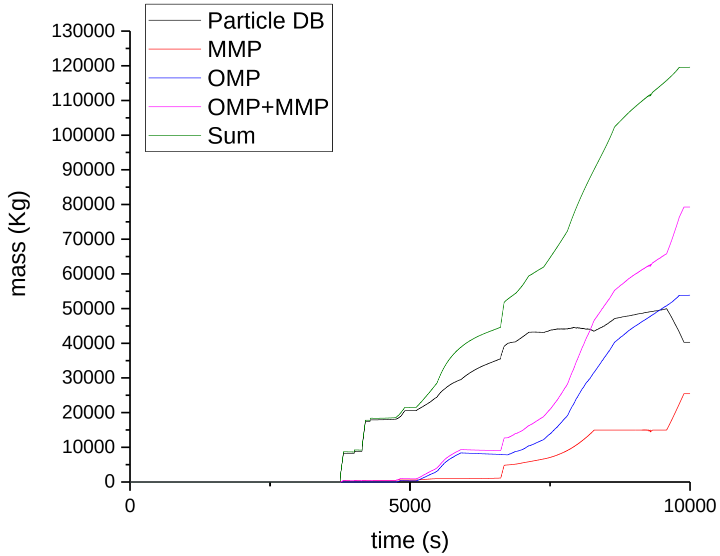


- 3750 sec: relocation starts (SS, Zr, In)
- Melt relocation takes place intermittently
- 4750 sec: ZrO2 relocation
- 5100 sec: UO2 relocation

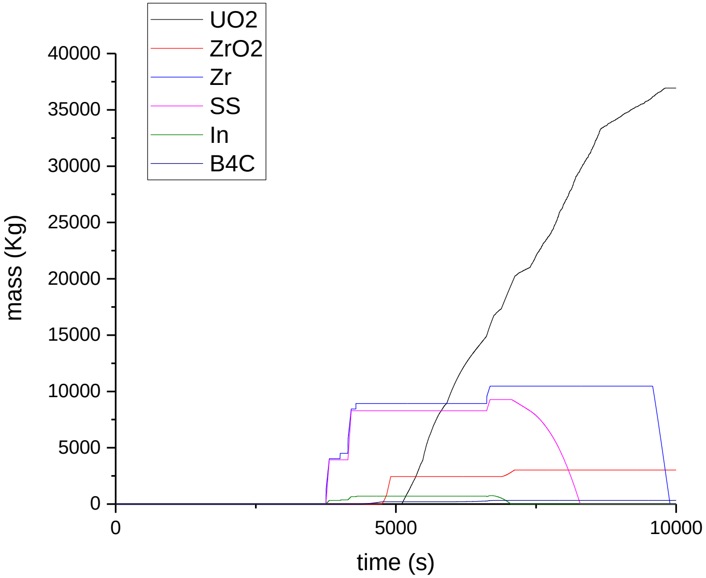
- Drop temperature of corium varies in time by the core status and quenching heat transfer during the relocation

Combined COMPASS & SIMPLE

Mass in the LP



Mass in the particle DB



- 3750 ~ 4800 sec.: most of corium is in the particle DB
- OMP forms after molten UO2 relocation

- MMP mass increases by melting of In (6600 ~ 7000 sec.), SS (7100 ~ 8300 sec.), and Zr (9600 ~ 9900 sec.)
- After Zr melting (at 10000 sec.), particle DB is composed with UO2, ZrO2, and B4C

Summary

- The SIMPLE (Severe In-vessel Melt Progression in Lower plenum Environment) module was developed to analyze molten pool behavior in the lower plenum of the reactor vessel.
- We formulated the mass and energy equations of particulate debris bed, metallic molten pool, oxidic molten pool, and coolants.
- The results showed temporal behavior of variables, and we briefly discussed about it.
- Toward more reliable simulation results, further analysis efforts with different initial and boundary conditions were needed.

Future works

- Model updates
  - Layer inversion, three layer formation & its heat transfer
  - Reactor vessel failure by penetration failure (on going)
  - Boiling heat transfer and CHF on the outer vessel wall for ERVC evaluation

- Verification & Validation
  - Using of LIVE, LHF, penetration failure experiments at KAERI