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MELCOR analyses for Loviisa NPP: Results and effect of steel oxidation

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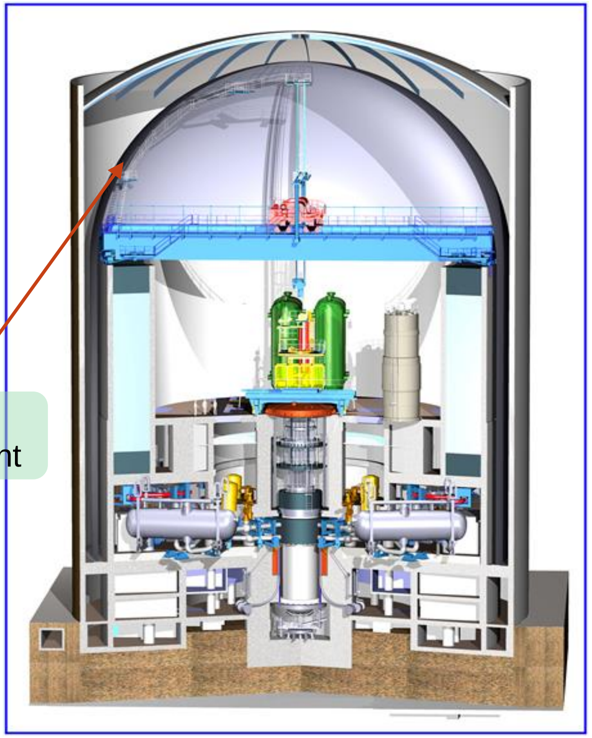
Loviisa Nuclear Power Plant

- Two Soviet-designed VVER-440 PWR reactors (507/502 MWe) taken into operation in 1977/1980 in Loviisa, Finland
- Severe accident systems were installed in 2003 or before
- Relevant systems during severe accident
  - High-pressure injection
  - Low-pressure injection
  - Low-pressure hydro accumulators
  - Containment internal and external sprays
  - Ice condensers
  - Hydrogen recombinators
  - Hydrogen igniters
  - External cooling of RPV



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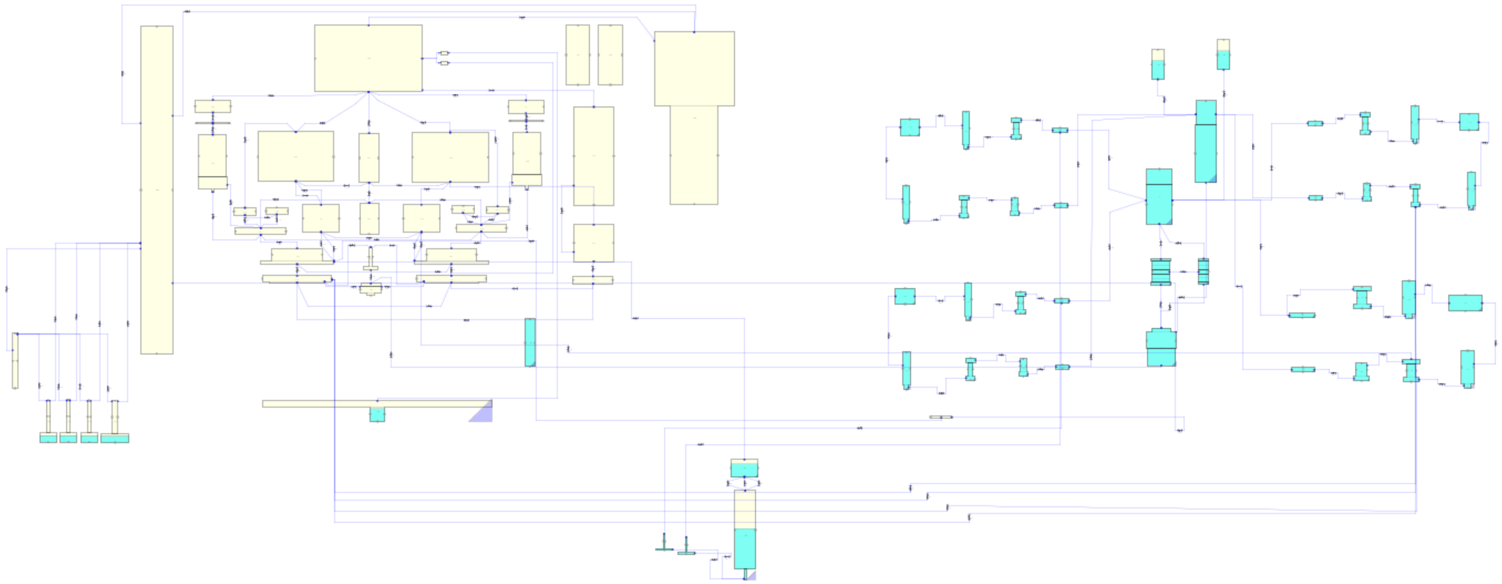
MELCOR nodalization of Loviisa NPP

- Loviisa model
  - 83 control volumes, 291 control functions, 124 flow paths, 139 heat structures
  - MELCOR 2.2.9541



Model view in SNAP

MELCOR analyses done for FSAR in 2018

- Various accident scenarios starting at full power
- Initial state at time 0 s
  - Reactor scram
  - Loss of emergency AC/DC (SBO), separate SAM diesel generators are working
  - Possible LOCA
- Basic LOCA scenarios
  - Primary pipe break of 4 cm^2 (SLOCA), 22 cm^2 (MLOCA), 220 cm^2 (LLOCA)
  - Systems in operation: Primary system depressurization, passive low-pressure hydro accumulators, ice condensers, hydrogen recombiners and igniters, external cooling of RPV
  - Severe accident systems fullfill single failure criterium (depressurization valves, ice condenser door opening, hydrogen recombiners and igniters)

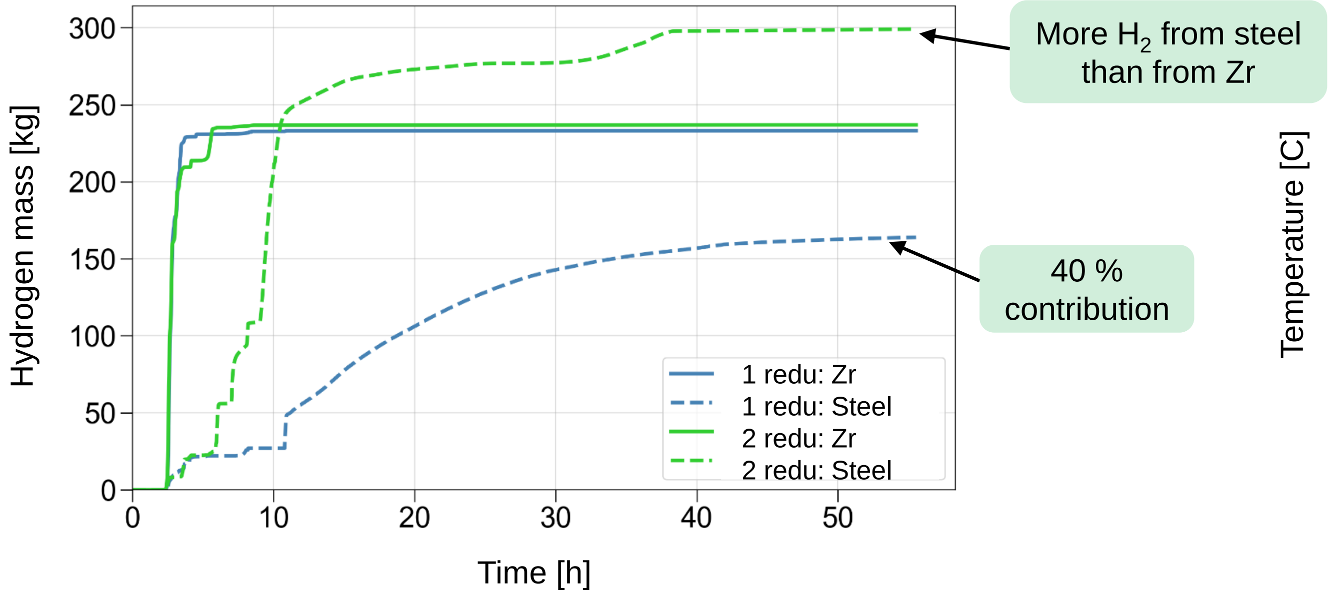
MELCOR analyses done for FSAR in 2018

- Additional variation scenarios
  - Enhanced hydrogen production (required by regulatory authority)
    - MLOCA: Delayed reflooding with high-pressure injection
    - MLOCA: Scaling of of zirconium surface area by a factor of 4 (unphysical)
  - MLOCA: Hydrogen igniters not working
  - SBO: Primary circuit stays intact
  - SLOCA: Both RPV depressurization lines working
  - LLOCA: All ice condenser doors were able to be opened

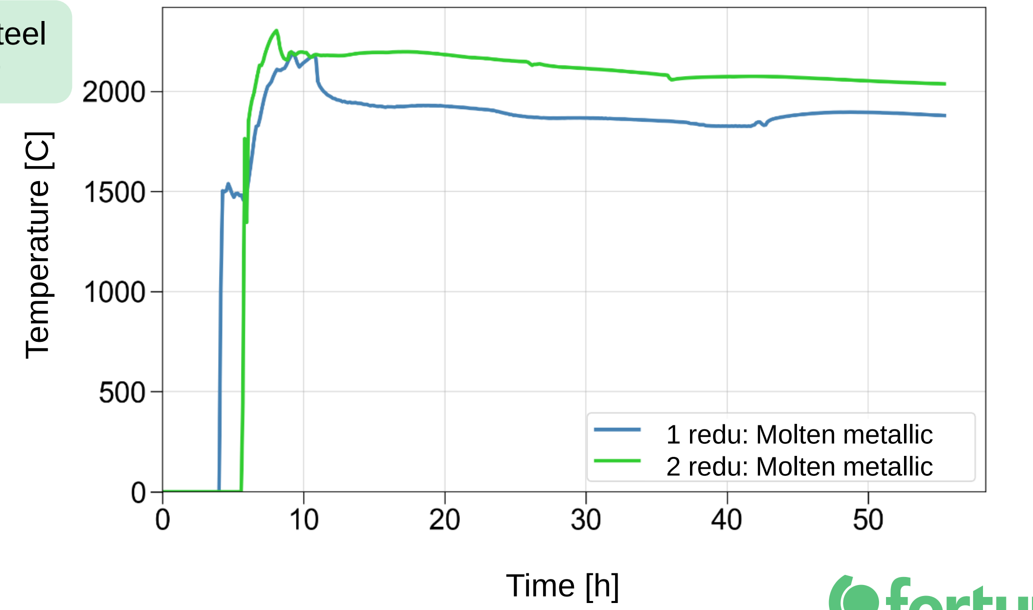
Analysis results:
Effect of opening ice condenser doors (1/2)

- As a severe accident measure the ice condenser doors are opened to mix the containment atmosphere. The openining system has two redundancies.
- Using two redundancies instead of one the oxidation of steel almost doubled in MLOCA
- Practically no change in oxidation of zircaloy
- Loviisa NPP: Amount of steel relatively high

Produced hydrogen in RPV (MLOCA)



Lower head molten pool temperature (MLOCA)



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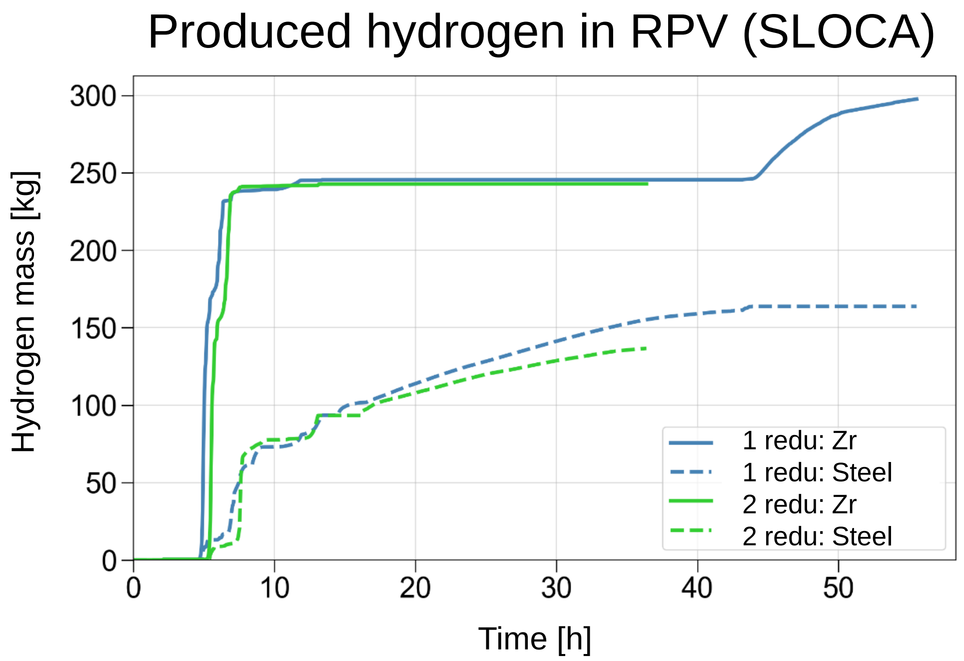
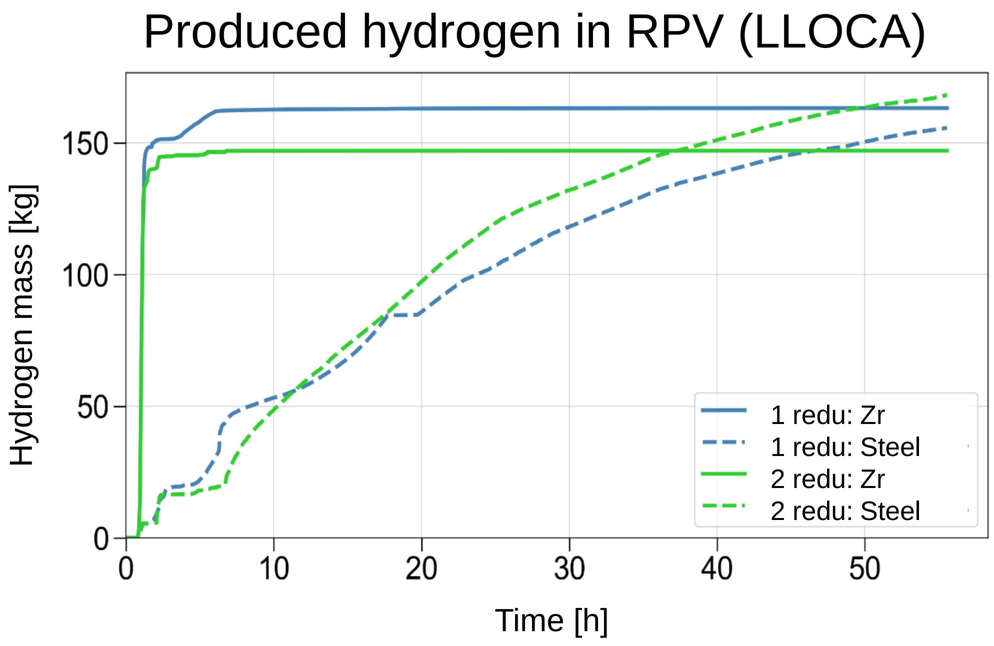
Analysis results:
Effect of opening ice condenser doors (2/2)

- SLOCA and LLOCA do not show notable change in steel oxidation





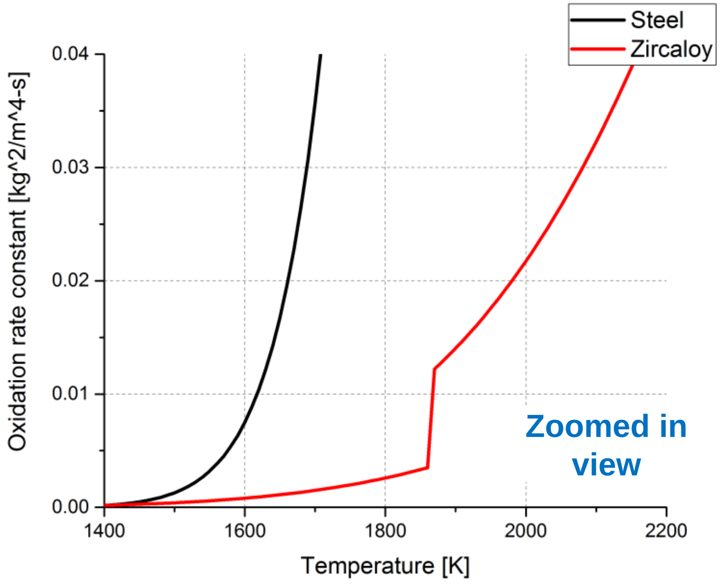
Oxidation processes in MELCOR

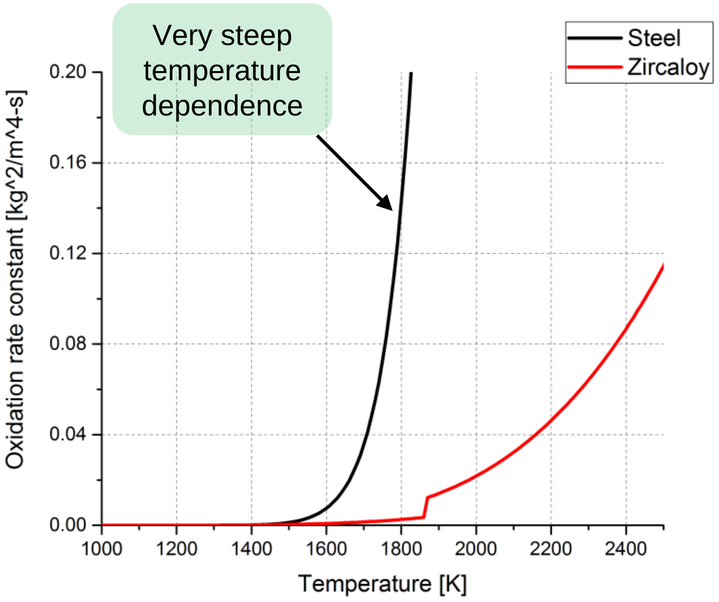
- Report: L. Baker, Jr., Hydrogen-generating reactions in LWR severe accidents
  – *”White’s parabolic rate law appears to describe the observed reaction well at 1400 °C but gives high predictions at 1600 °C”*
- Oxidation of steel seems to be very sensitive to temperature in RPV
- SC1002: Steel oxidation constant coefficients

White’s rate equation for steel oxidation (MELCOR Reference Manual):

$$K(T) = 2.42 \cdot 10^{9} \exp\left(\frac{-42400.0}{T}\right)$$

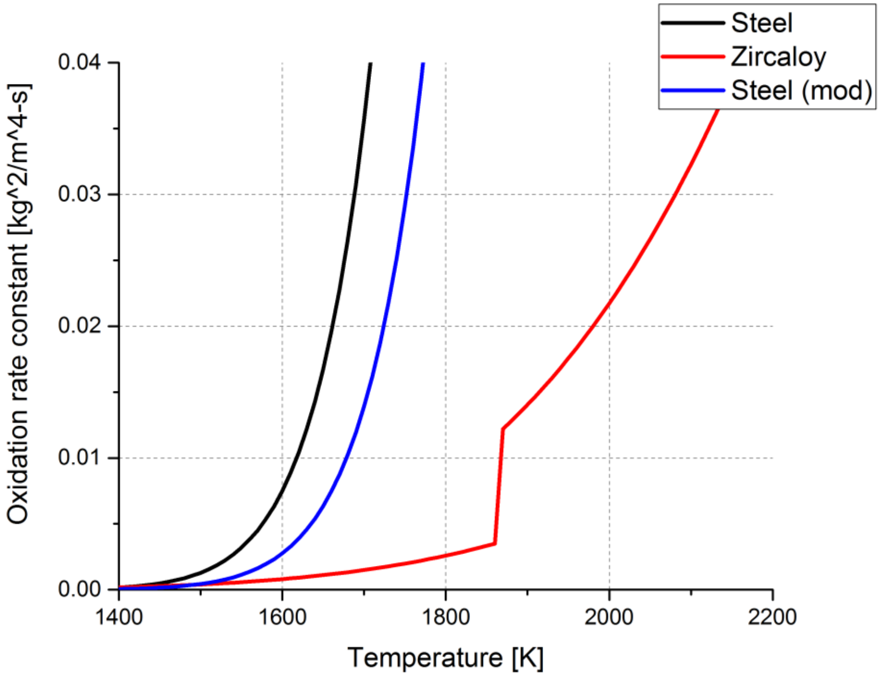
Oxidation rate constant

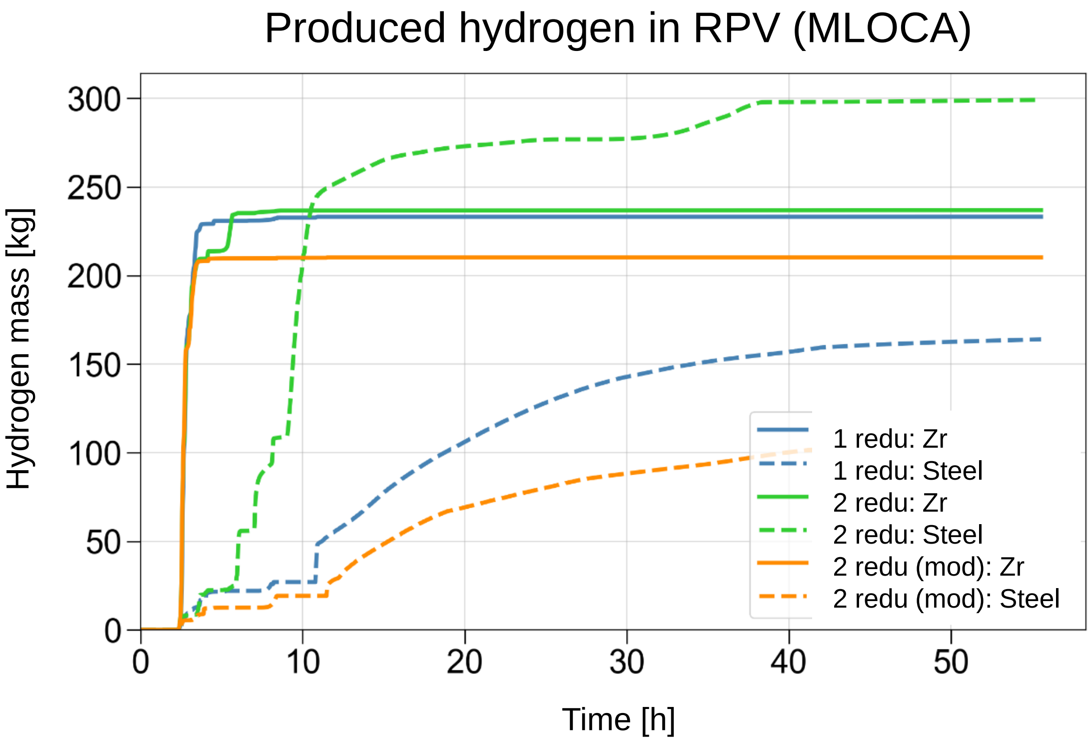




Test with modified steel oxidation

- By adjusting equation parameters possible to tame steel oxidation efficiently
- Modified sensitivity coefficient in testing: SC1002(2,1) = 4.4e4 (default: 4.24e4)





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External cooling of RPV

- Loviisa NPP: During severe accident lower part of the containment (reactor cavity, lower compartment) is flooded to provide external cooling
  - keeps the pressure vessel intact and cools down corium
- MELCOR: Sometimes the lower head fails in spite of external cooling
  - Does not reflect our best understanding

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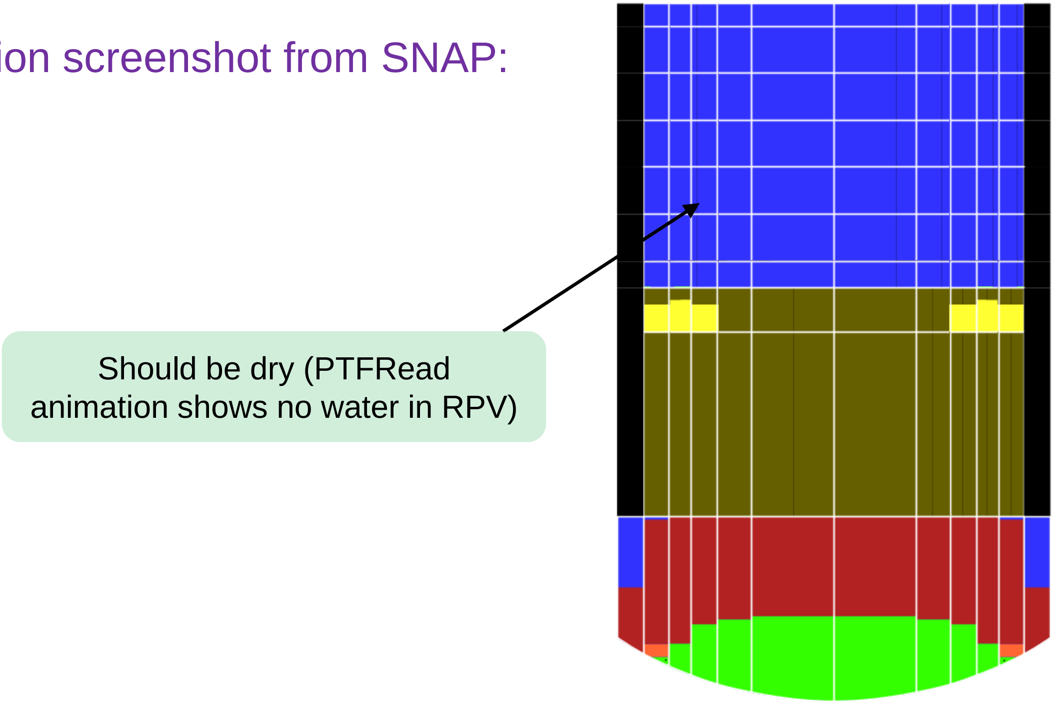
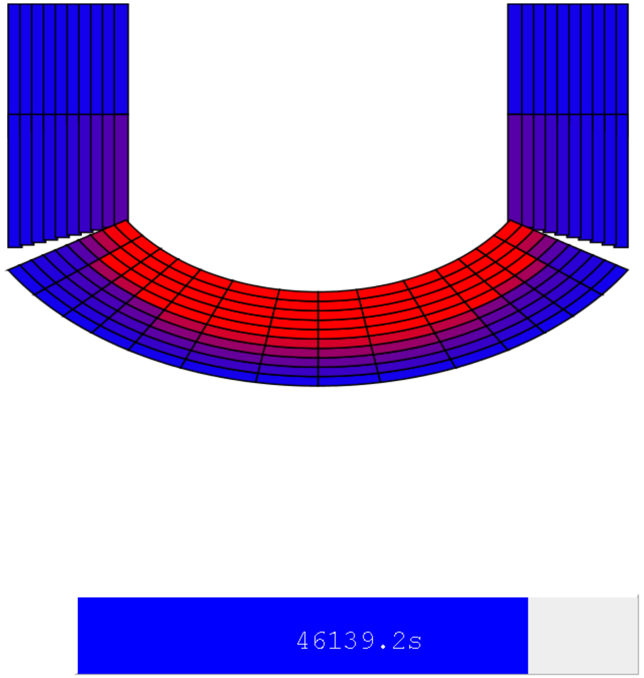
Lower head failure

- Change in Loviisa model to prevent from LH failure: Heat flux correlation term SC1245-1 from 0.034 to 0.2
  - Does not always work, difficult to find a realistic set of parameters
- Relatively small liquid oxide pool

Animation screenshot from SNAP:

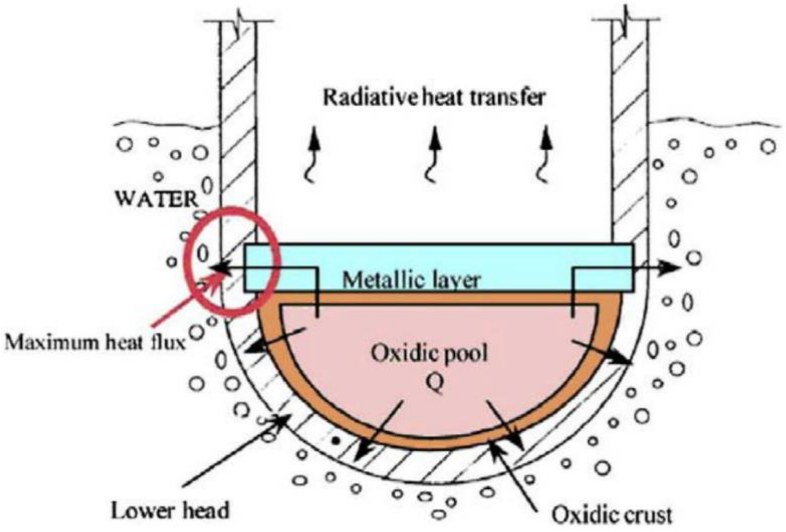


Before failure of LH



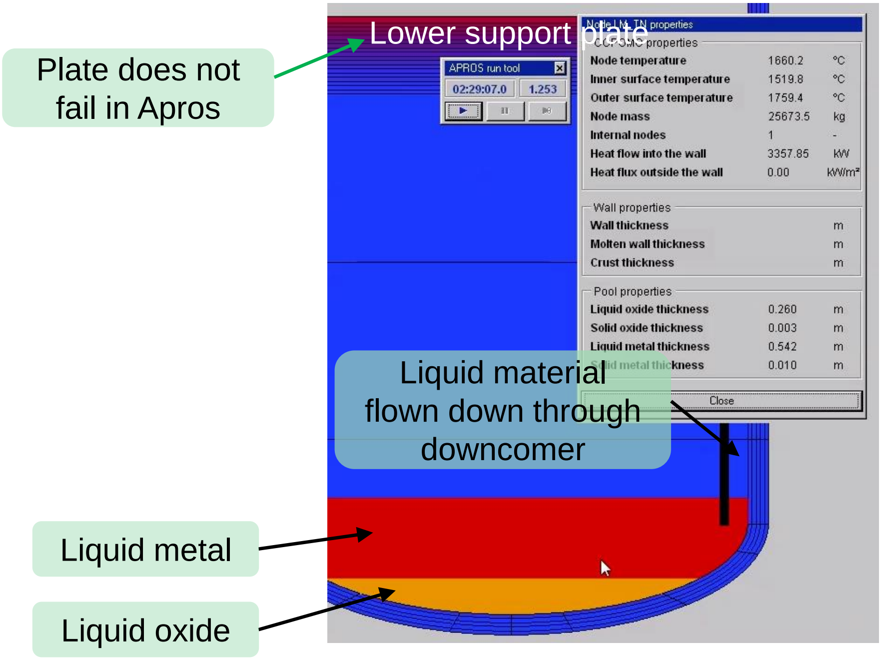
Modelling of corium structure

- What we would expect
  - Formation of crust on the lower head
  - Large oxidic and metallic pools, highest heat transfer to the side walls
- Based on currently ongoing ”In-vessel melt retention” project MELCOR has significantly different modelling approach than many other codes



Courtesy: Sehgal, Nuclear Safety in Light Water Reactors – Severe Accident Phenomenology, 2012

SA in Loviisa NPP:
Example of Apros calculation



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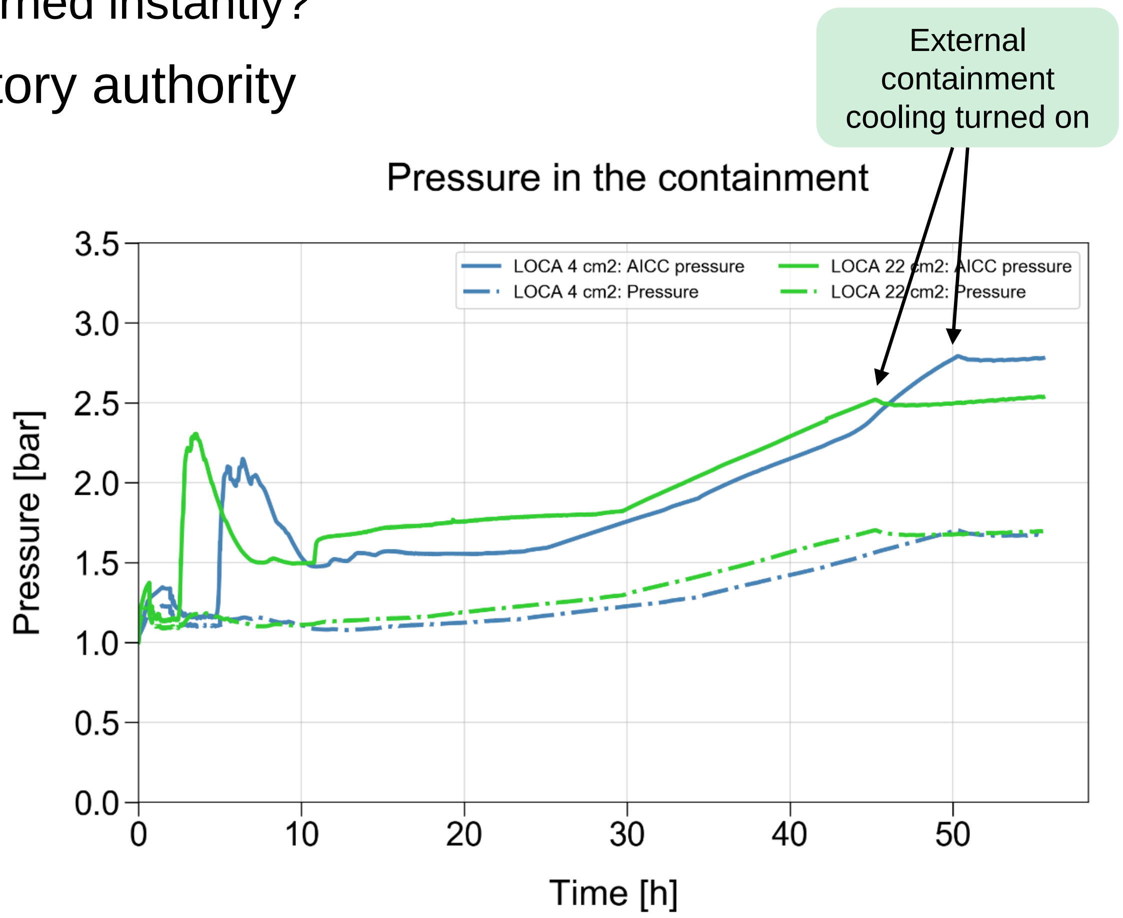
Calculation of AICC pressure

- AICC: Adiabatic Isochoric Complete Combustion
  - What would containment pressure be if all hydrogen burned instantly?
- Calculation of AICC pressure required by the regulatory authority in Finland
  - Additional 50 % margin for overpressure
  - Loviisa NPP: dynamic pressure safety limit 3.2 bar
- AICC is calculated during postprocessing of data
  - Requires various information of several nodes



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MELCOR analyses to be done for FSAR in 2019

- Various accident scenarios occuring during plant outage
- Things still to be added to the model
  - Removal of RPV lid
  - Cooling down primary coolant
  - Removal part of primary coolant
  - Opening of various doors and hatches
  - Addition of spent fuel pool (located in the containment) as a heat/steam source
  - Etc.

Summary

- Produced hydrogen from oxidation of steel very sensitive to conditions in RPV
  - Sometimes even more hydrogen than that from oxidation of zircaloy
- Corium on top of lower head
  - Unrealistically RPV may fail in spite of external cooling
- MELCOR provides realistic behaviour of progression of severe accidents in Loviisa NPP
  - Used for FSAR and PRA analyses
  - Provides useful input for various kind of analyses (e.g. transportation of radioactive nuclides in the containment, radiation dose rate calculation using MCNP and doses in the environment)

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