VVER-440 simulations using MELCOR 2.2: degraded core reflood and boric acid transport in the primary

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Input model conversion M1.8.6 $\rightarrow$ M2.2

Using `Reader`: conversion finally successfull with MELCOR version 2.2 (release 02-22-2017)

The last problem identified:

In the MELCOR 1.8.6 input distinction of canister types CN and CB was not done explicitly (split is done by M1.8.6 internaly using sensitivity coefficients 1501).

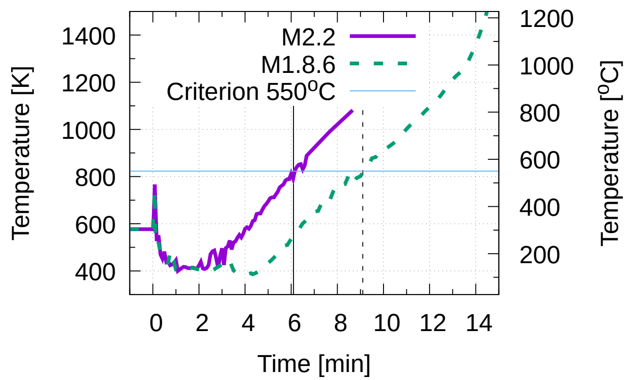
In MELCOR 2.2 mass input for both CN and CB is required. However previous version of MELGEN 2.x failed with converted input model by segmentation fault and it did not indicate where the problem is.

In the current model: xmcnzr = xmcbzr
= xmcnzr/2.0 from 1.8.6., default value of sensitivity coefficients 1501 is 0.5

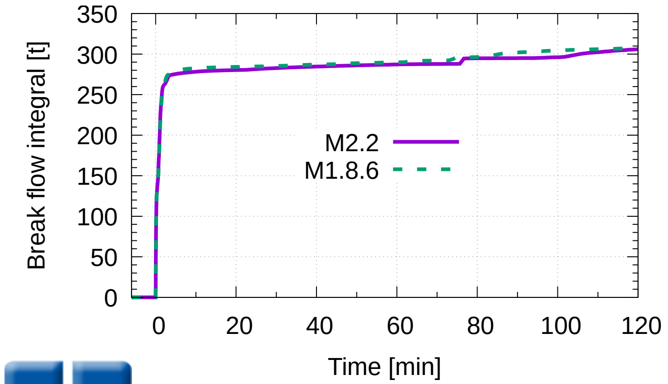
Comparison of M1.8.6 vs. M2.2 with converted input

Large break LOCA scenario:

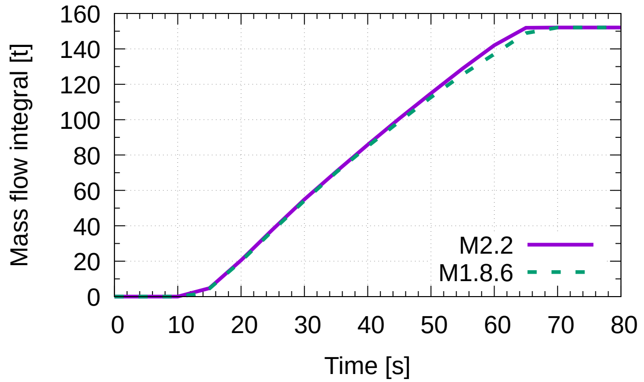
- reasonable agreement for core and RCS
- larger differences in results for containment (MELCOR 2.2 pressure too high)
  - probably due to the Bug 1848 in release 02-22-2017 ?
  - not analysed in detail yet (analyses in 2017 were focused on reflood and boric acid transport)
- problems with occasional CVH (coupled with COR) temperature going to 10000 K (reported Bug 1946)



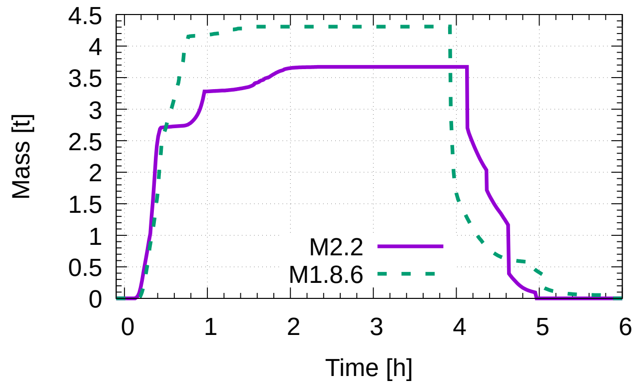
Temperature at the core exit



Integral of the break flow



Integral of flow from HA



Mass of ZrO_2 in the RPV

Boric acid transport model

- transport in liquid coolant — user defined fission product class **BAC** with molar mass 61.8 g/mol, declared as “radioactive”. Initial inventory specified
  - for primary RCS volumes (including hydroaccumulators)
  - and for the volume representing trays of the containment pressure suppression system.
- additional removal processes from the pool:
  - removal from the pool due to oversaturation
  - transport from pool to atmosphere due to intensive boiling

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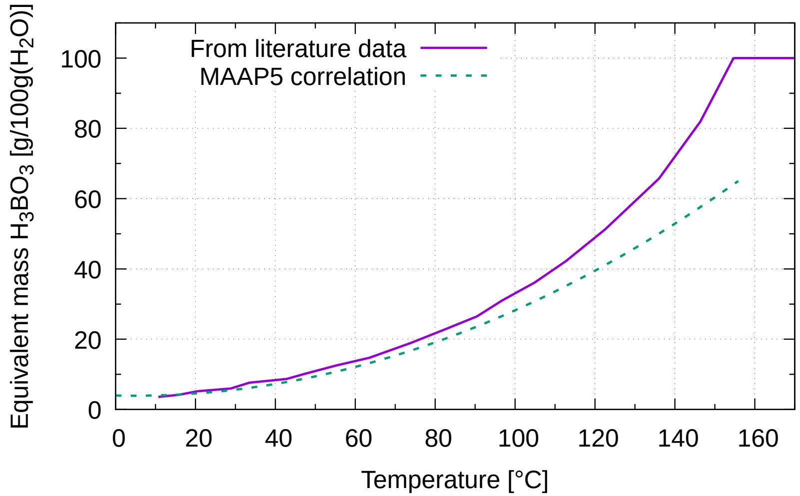
Data on boric acid propertities are based on literature review, mainly on:

- P. Wang, J.J. Kosinski, M.M. Lencka, A. Anderko and R.D. Springer: Thermodynamic modeling of boric acid and selected metal borate systems. Pure Appl. Chem., Vol. 85, No. 11, pp. 2117–2144, 2013. http://dx.doi.org/10.1351/PAC-CON-12-07-09
- A. Bruggeman, J. Braet, F. Smaers and P. De Regge: Separation of Boric Acid from PWR Waste by Volatilization During Evaporation. Separation Science and Technology, 1997 32:1-4, 737-757, http://dx.doi.org/10.1080/01496399708003227

Removal due to oversaturation

Saturation concentration is temperature dependent — lookup table setup based on approximation of literature data (in comparison with correlation used in MAAP5):



$$
\begin{aligned}
\Delta m_{BAC}^{Dep} &= m_{BAC}^{Sat} - m_{BAC} \quad && \text{for } m_{BAC}^{Sat} < m_{BAC} \\
\Delta m_{BAC}^{Dep} &= 0 && \text{for } m_{BAC}^{Sat} \geq m_{BAC}
\end{aligned}
$$

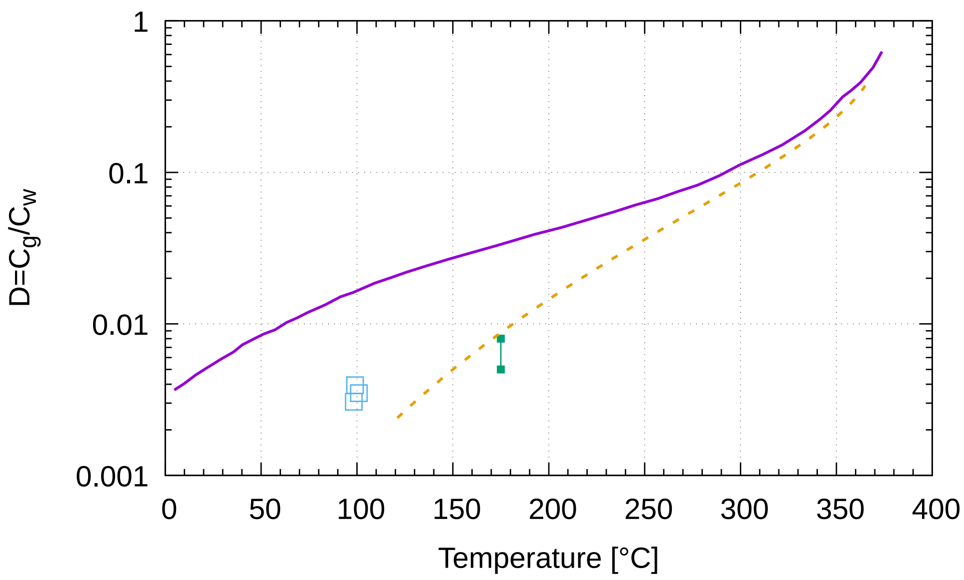
Removal rate calculated using control functions and negative source in selected control volumes.

Removal due to rapid coolant evaporation

$$H_3BO_3(aq) \rightarrow H_3BO_3(g)$$

Transport rate is proportional to the boiling rate with distribution coefficient dependent again on the boiling rate, e.g.:

$$D = \frac{C_g}{C_w} = \left(\frac{\varrho_g}{\varrho_w}\right)^{0.9}$$



Pool→steam distribution coefficient D in boiling conditions.

In the current input model D is taken constant (0.01 or 0.001 for large break LOCA).

Removal due to rapid coolant evaporation (cont.)

Removal rate is calculated using control functions.

Boiling rate has to be calculated from:

- change of pool mass in the control volume
- inlet and outlet of pool through all flow paths

Mass of pool evaporated, Δm_{vap}, in the time interval between t_{i-1} and t_{i-1} can be calculated:

$$\begin{aligned}
\Delta m_{vap} &= \quad m(t_i) - (m(t_{i-1}) + \Delta m_{flow}) \quad && \text{for } m(t_i) < (m(t_{i-1}) + \Delta m_{flow}) \\
\Delta m_{vap} &= \quad 0 && \text{for } m(t_i) \geq (m(t_{i-1}) + \Delta m_{flow})
\end{aligned}$$

where Δm_{flow} is mass of pool entering the volume in this time interval.

$$\Delta m_{BAC}^{VAP} = D \cdot m_{BAC} \cdot \frac{\Delta m_{vap}}{m(t_{i-1})}$$

Removal implementation

Total removal rate is calculated:

$$\dot{m}_{BAC} = \frac{\Delta m_{BAC}^{DEP} + \Delta m_{BAC}^{VAP}}{\text{EXEC-DT}} \qquad (\Rightarrow \ \dot{m}_{BAC} \leq 0)$$

Removal is implemented using fission product source to the pool in the control volume.

Input `RN1_AS`, with **negative** source rate.

Enhancement of `RN1_AS` proposed as a bug 1927.

Testing of the boric acid transport model

Large break LOCA scenario with blackout, variants:

00 — converted 1.8.6 input model

01 — BAC class added

02 — like **01** but removal from pool due to oversaturation

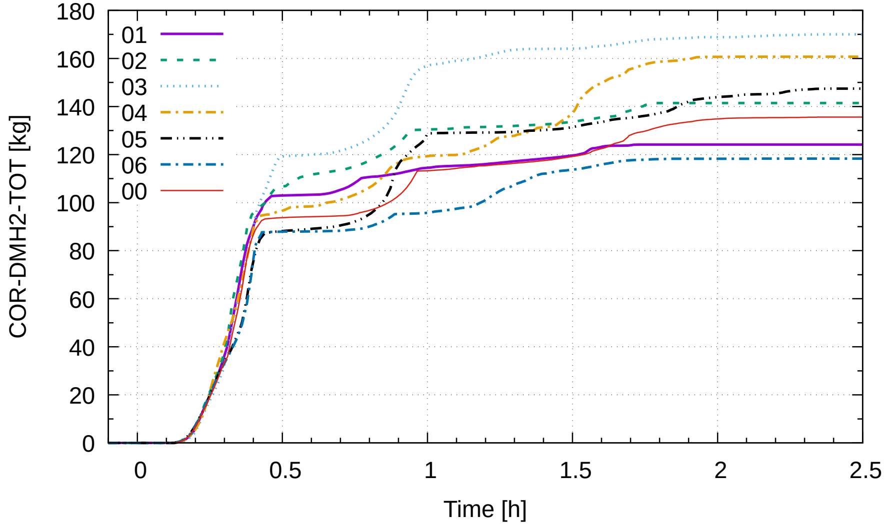
03 — like **01** but removal from pool with steam $D = 0.001$

04 — like **03** but $D = 0.01$

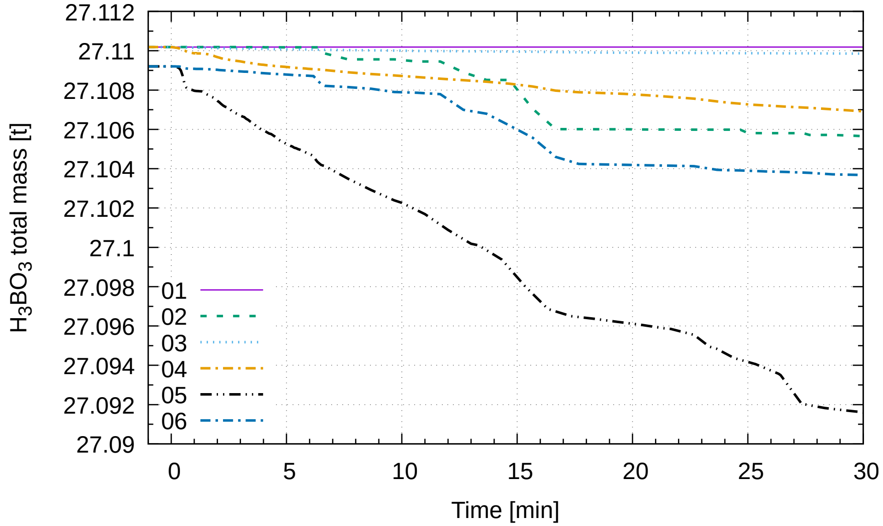
05 — both removal processes, $D = 0.01$

06 — both removal processes, $D = 0.001$

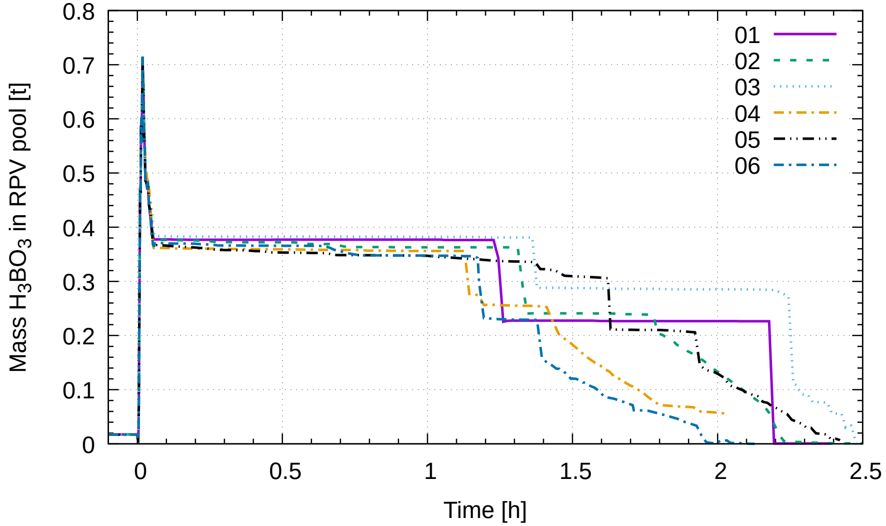
Testing of the boric acid transport model



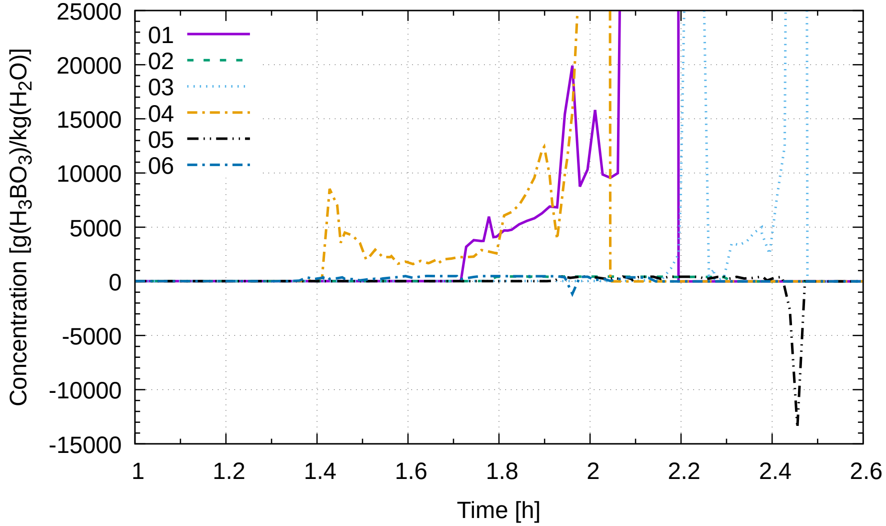
Hydrogen produced



Total mass of H_3BO_3



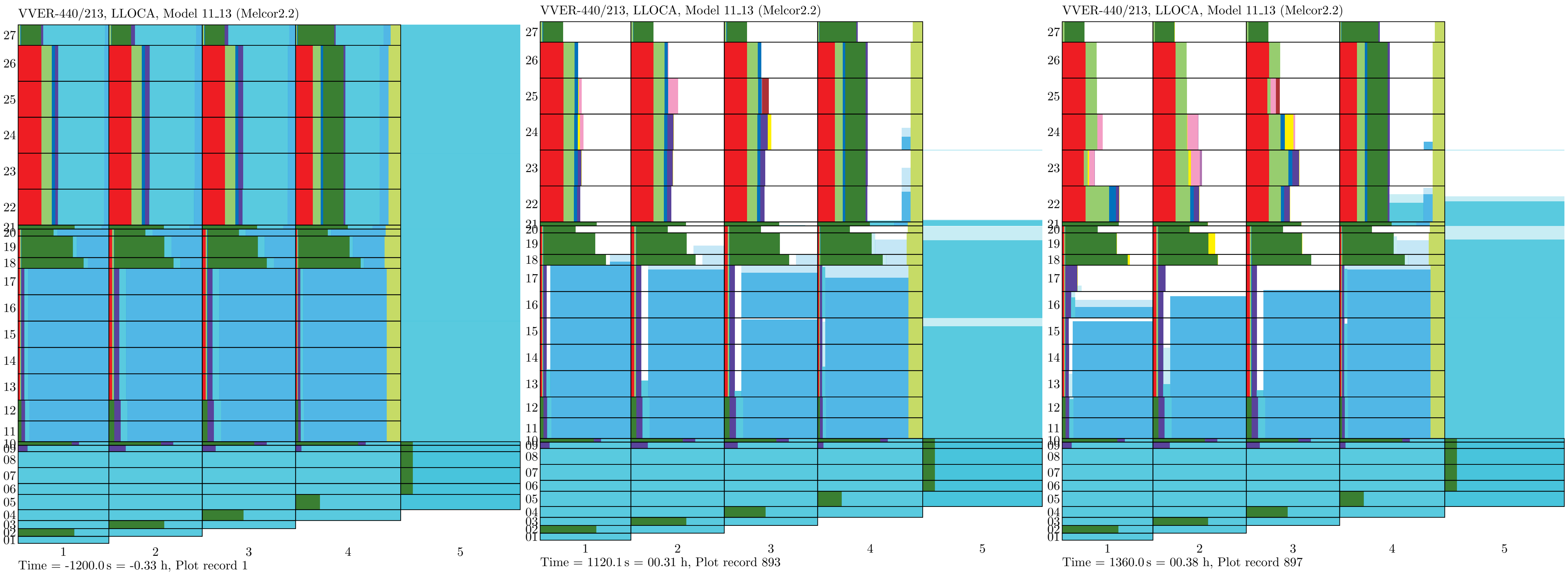
Mass of H_3BO_3 in RPV pool



Concentration of H_3BO_3 in lower plenum

VVER-440 simulations using MELCOR 2.2

Degradation of borated steel from control elements



Initial state | Melting of borated steel | Just before fuel geometry collapse

Why does NS melt to MB1 instead of MB2?

What does it held molten steel in the bypass after canister failure? Reported as a bug 1957.

Should I put control elements into separate ring(s)?

Reflood calculations

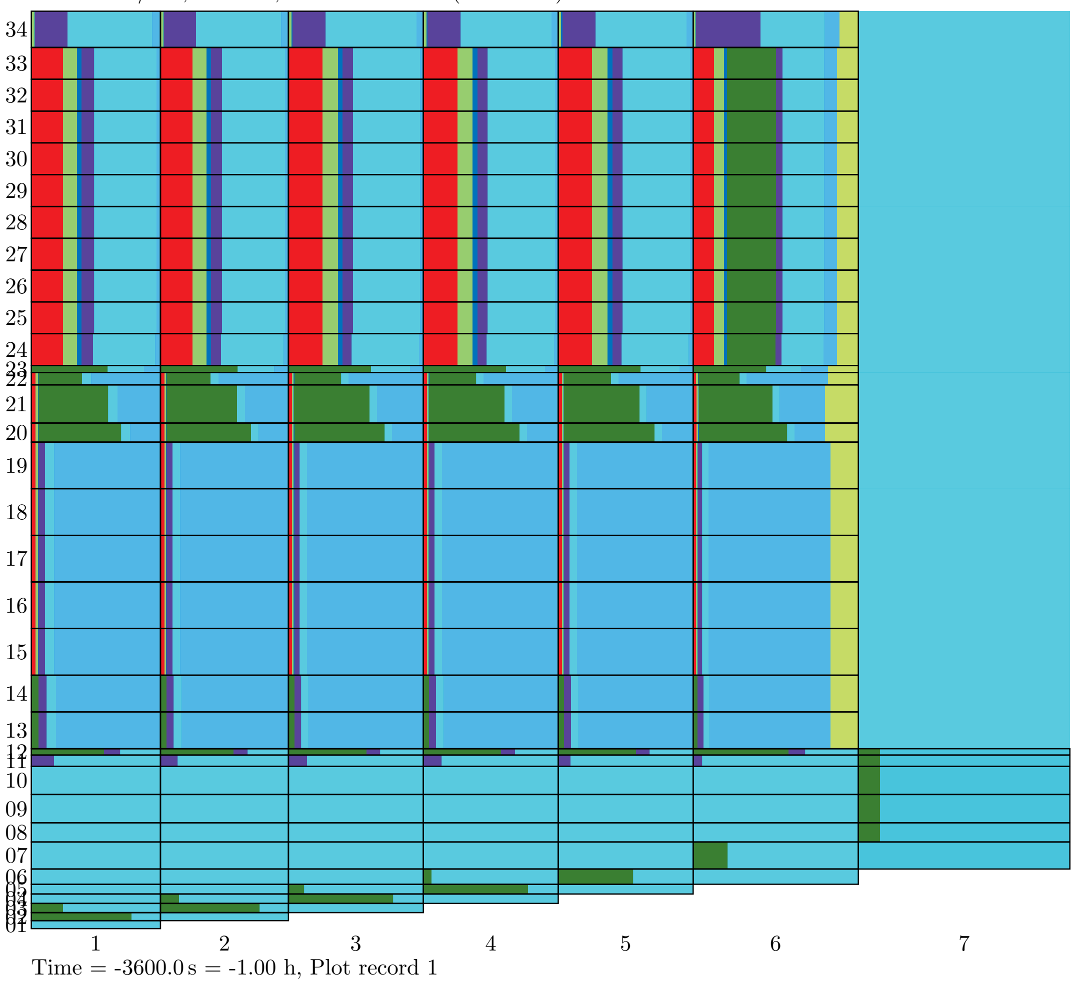
Reflood calculations with converted model were not successfull — quenching of the core not efficient even in cases when it should be (early reflood with large injection rate) $\Rightarrow$ review of the input model:

- opening height of channel$\leftrightarrow$bypass radial cross flow flowpaths (blockage option `channel-box`) — increased for the whole height of connected volumes
- channel$\leftrightarrow$channel radial cross flow flowpaths in the upper core added. Each flowpath is opened by control function on canister failure.
- refined COR axial nodalization in the upper core: 5 $\rightarrow$ 10 axial levels in the fuel region. CVH/FL nodalization kept the same.
- refined COR radial nodalization: 4 $\rightarrow$ 5 or 6 rings including CVH/FL for each ring.

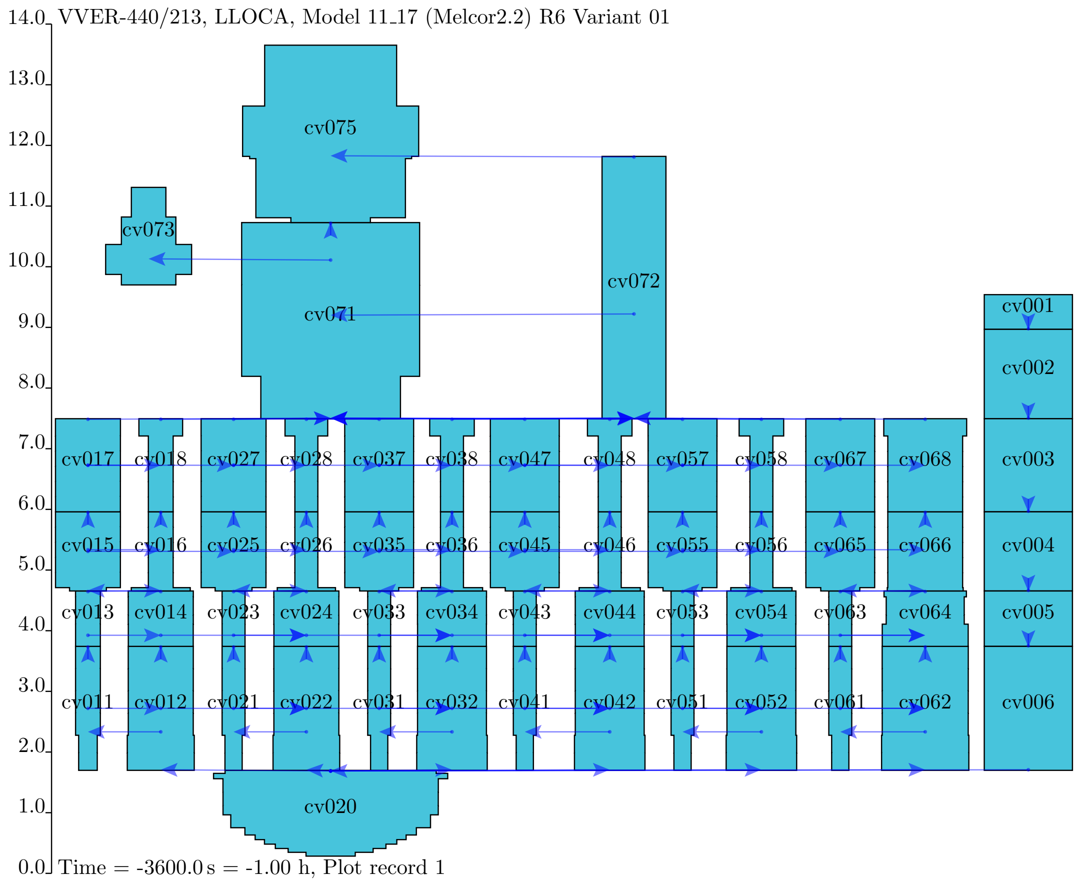
$\Rightarrow$ results looks better

(anyway validation on QUENCH11 is planned to be done in 2018 to gain more confidence)

Reflood calculations — refined nodalization



Six ring core nodalization



CVH in RPV nodalization

Reflood calculations

Scenario:

- large break LOCA on a cold leg, blackout
- alternative core cooling recovery at certain time

Reflood with the flow rate $0.3\,m^3/s$ of clean water at 55 ℃ was assumed. The coolant is distributed by equal portion both below and above the core. For 312 fuel assemblies in the upper part of the core and 126 rods in the assembly it corresponds to about 8 g/(s·rod) (4 g/(s·rod) from above the core — coolant injected below the core is lost to the break).

Variants with different time of injection start:

11 — at 400 s (6.7 min), i.e.: shortly after the criterion 550 ℃ on the core exit is met.

21 — at 600 s (10 min), shortly before the onset of rapid cladding oxidation.

31 — at 800 s (13.3 min), shortly before the onset of steel components melting.

41 — at 1100 s (18.3 min), during the melting of steel components.

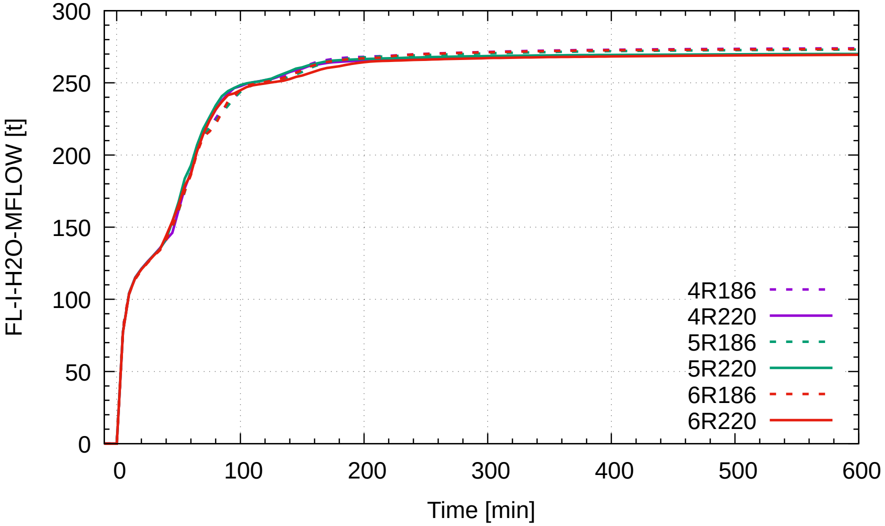
51 — at 1300 s (21.7 min), shortly before the first loss of fuel rods geometry.

61 — at 1400 s (23.3 min), after fuel relocation in the limited part of the core.

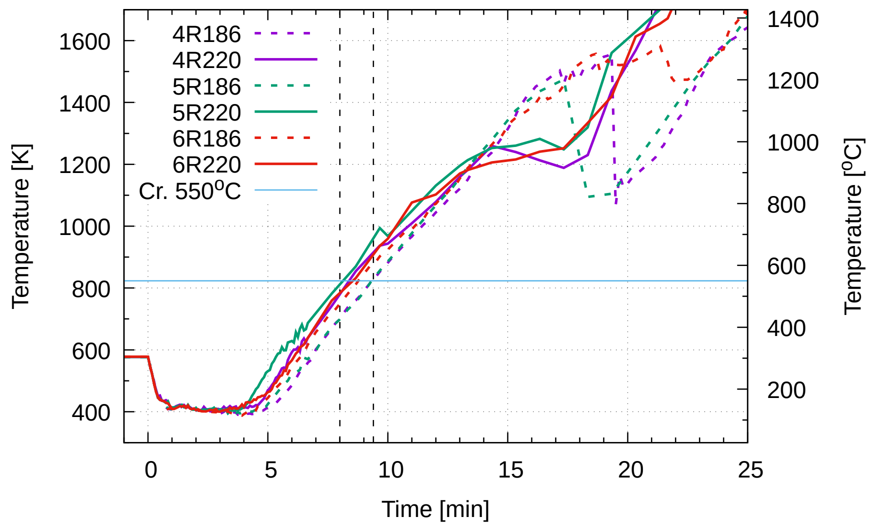
(based on timing of the calculation with the converted input)

VVER-440 simulations using MELCOR 2.2

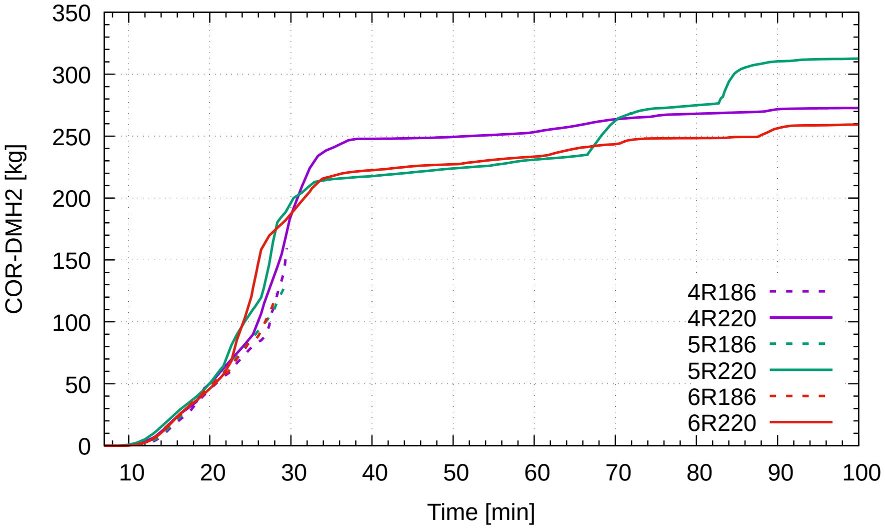
Reflood calculations — base case without reflood



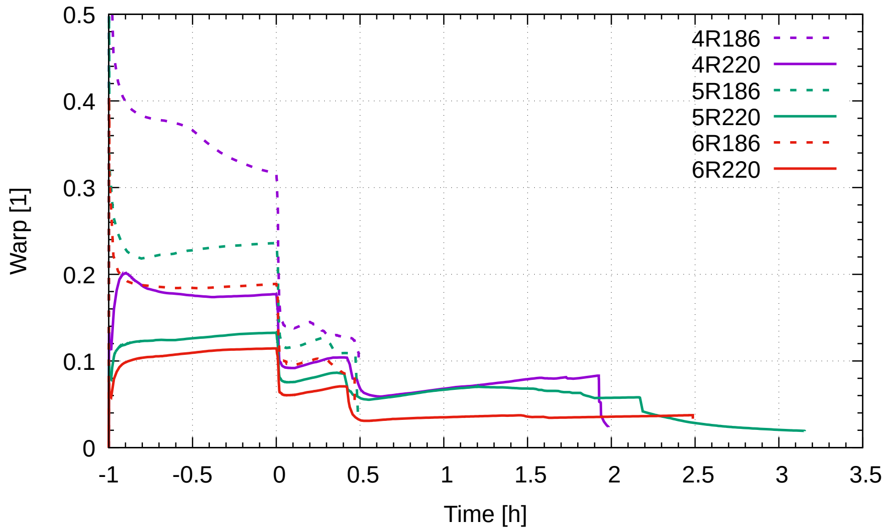
Integral of the break outflow



Core outlet temperature



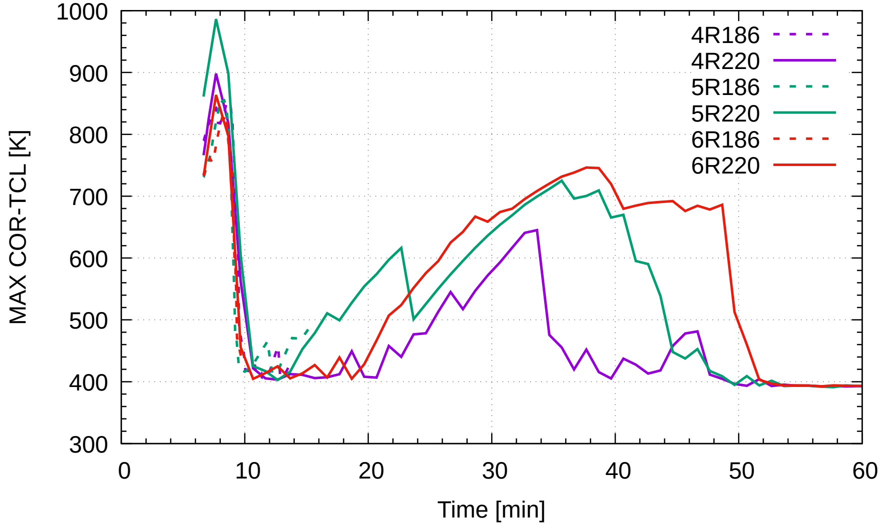
Hydrogen production



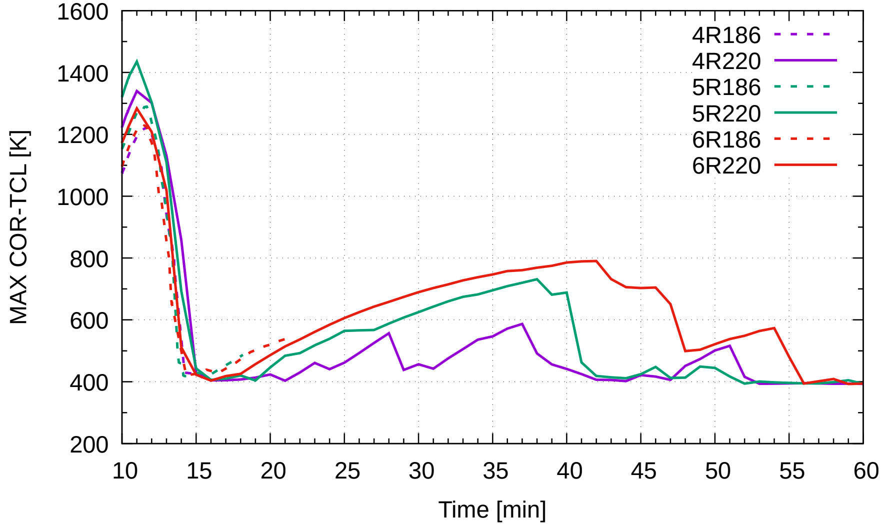
CPU demand

Reflood calculations — maximum clading temperature

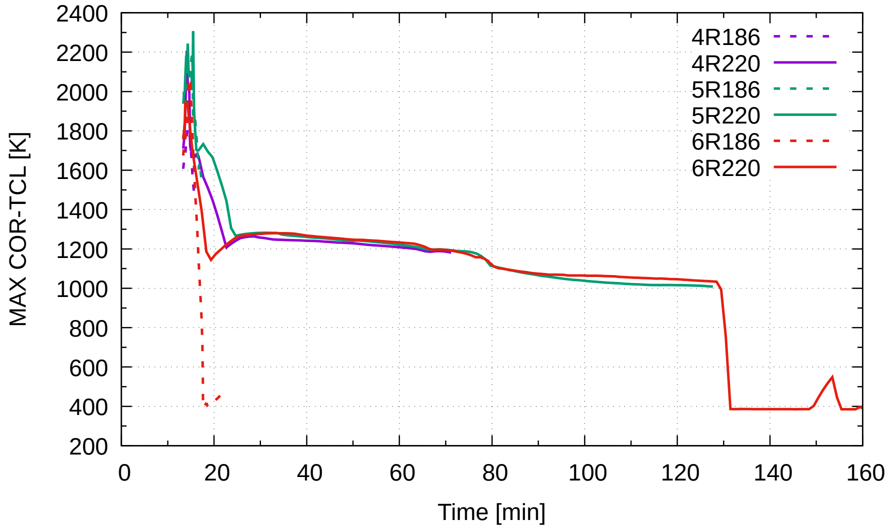
11,21: Temperature increase after reflood at the top fuel node in the peripheral ring



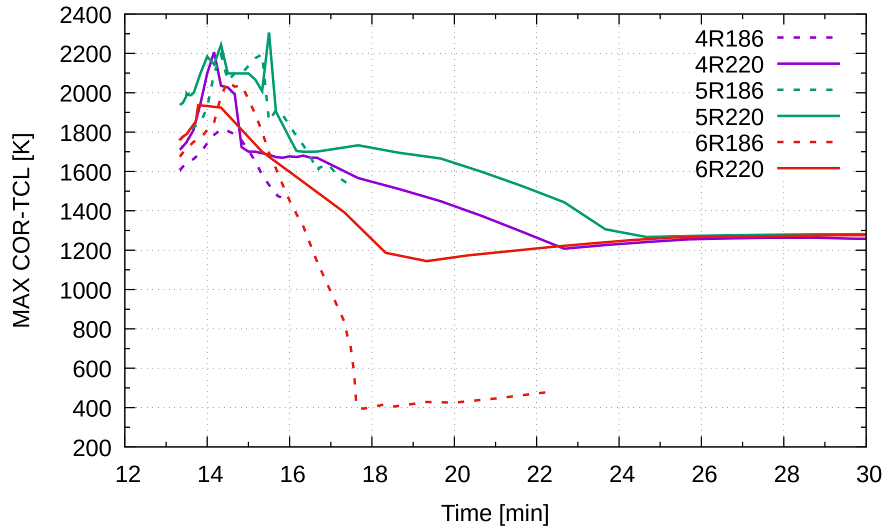
11 (reflood at 400 s)



21 (reflood at 600 s)



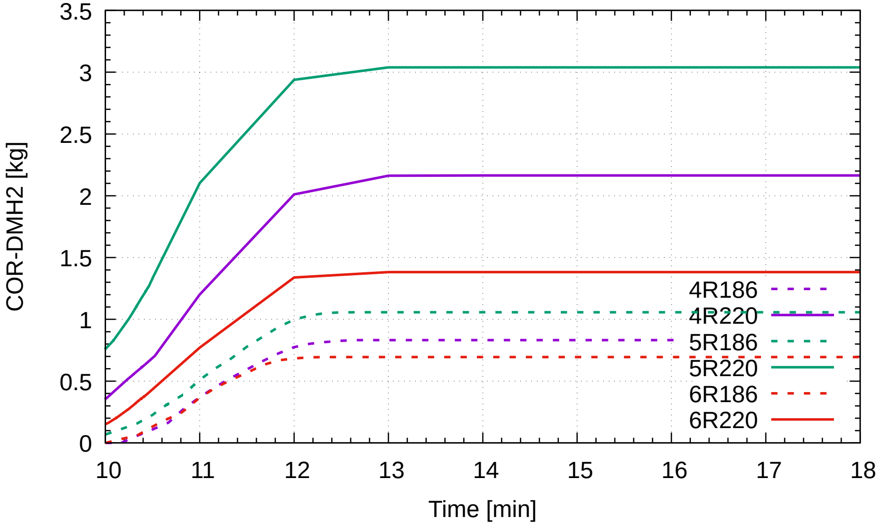
31 (reflood at 800 s)



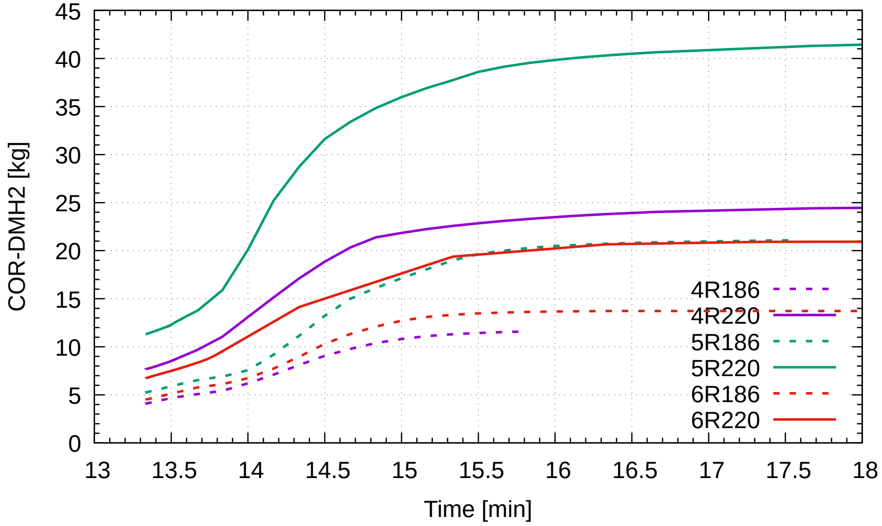
31 zoom

VVER-440 simulations using MELCOR 2.2

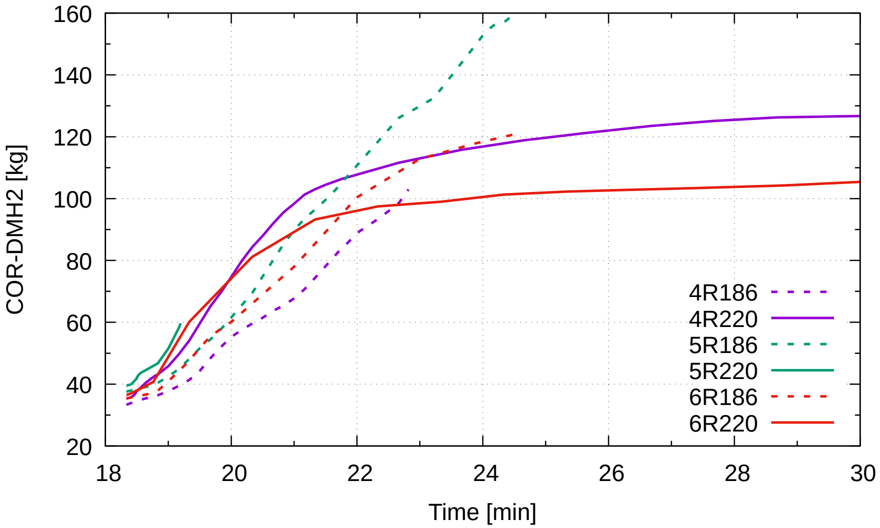
Reflood calculations — hydrogen production



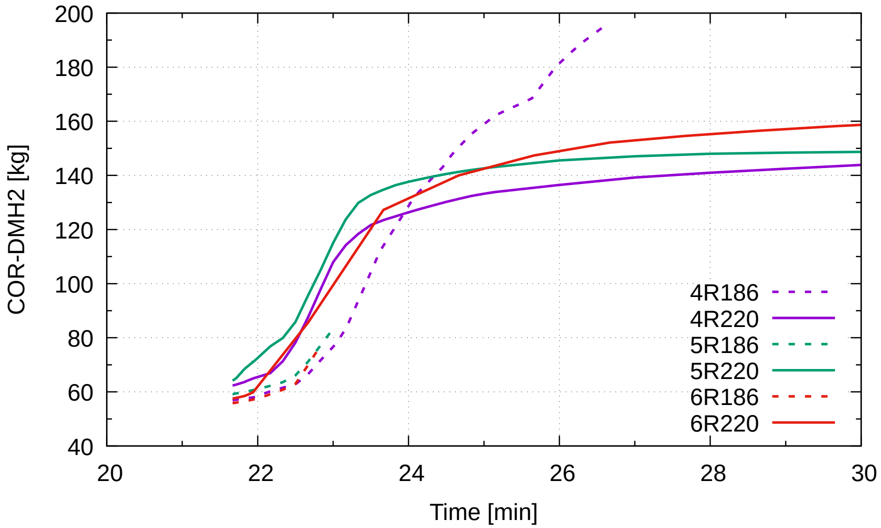
21 (reflood at 600 s)



31 (reflood at 800 s)

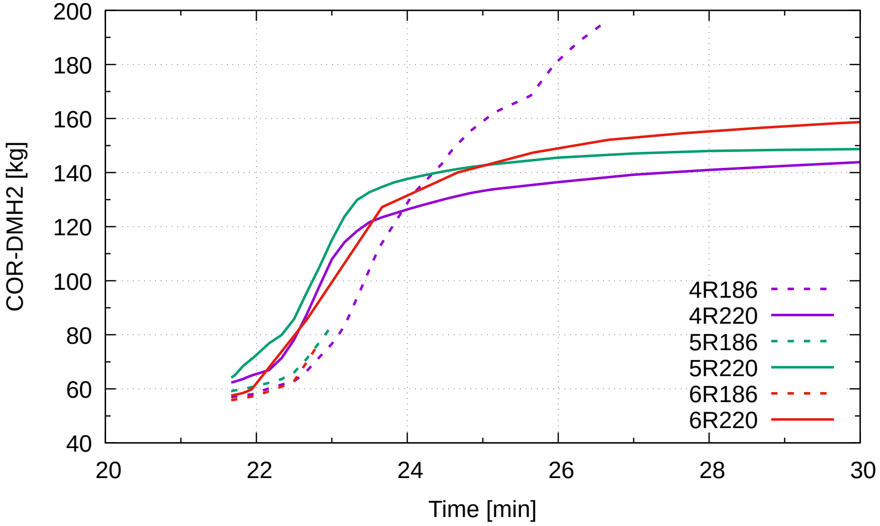


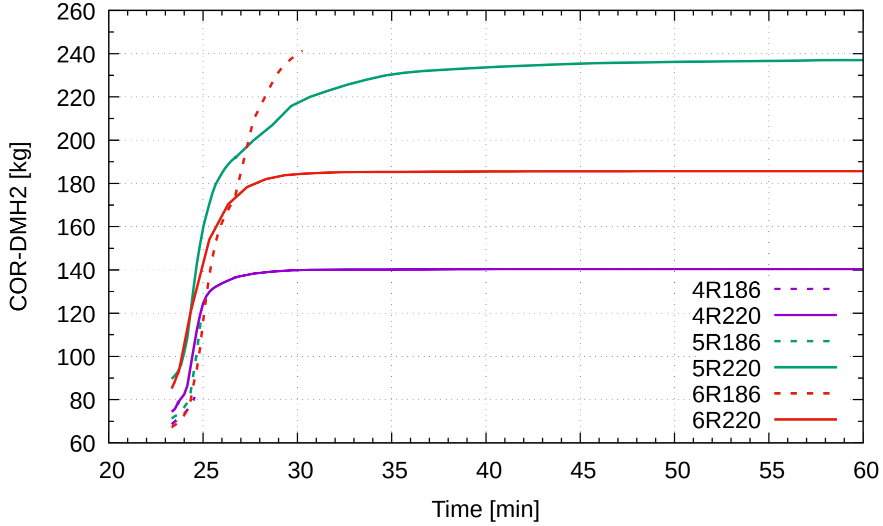
41 (reflood at 1100 s)



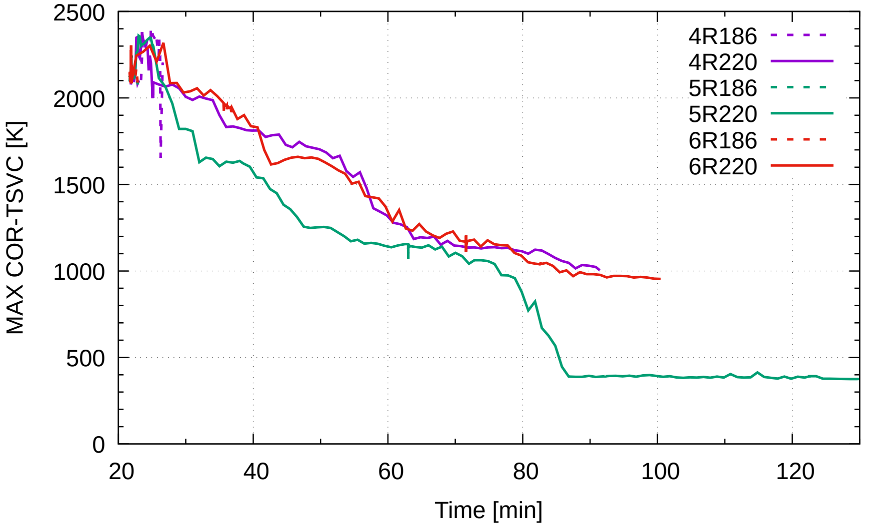
51 (reflood at 1300 s)

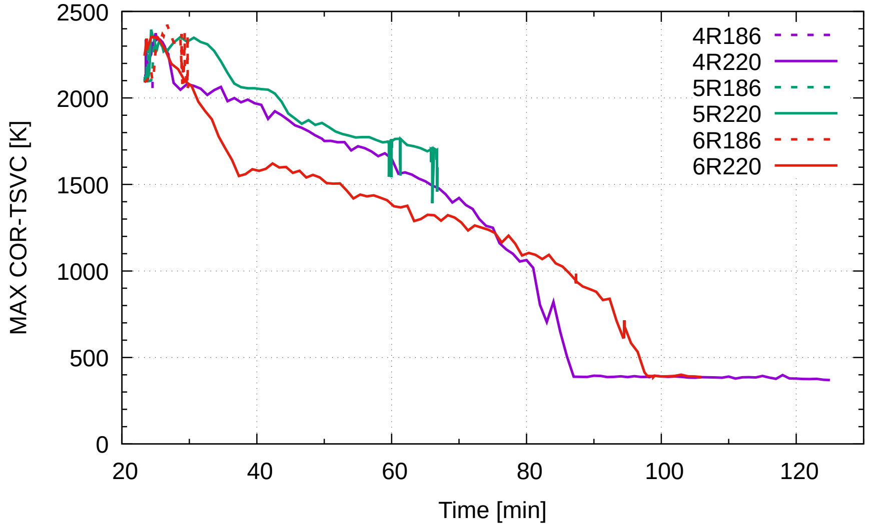
51 vs 61 — Hydrogen production





51 vs 61 — Max COR-TSCV

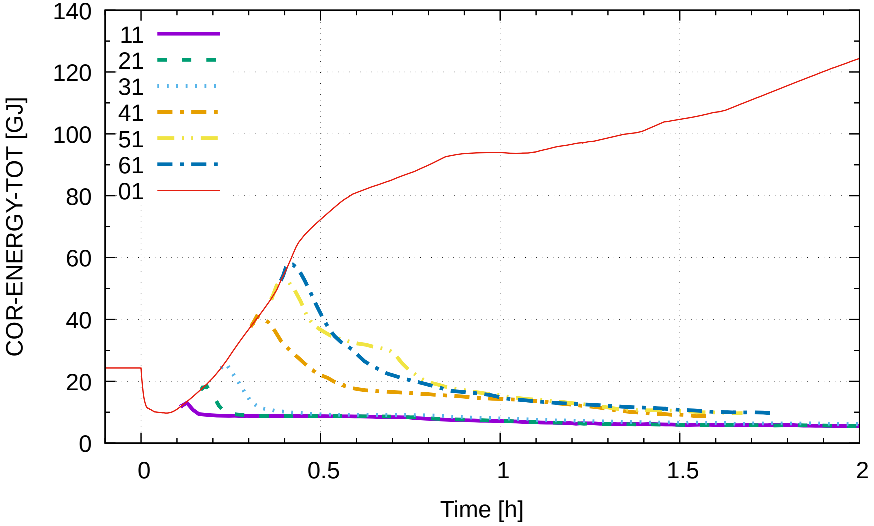




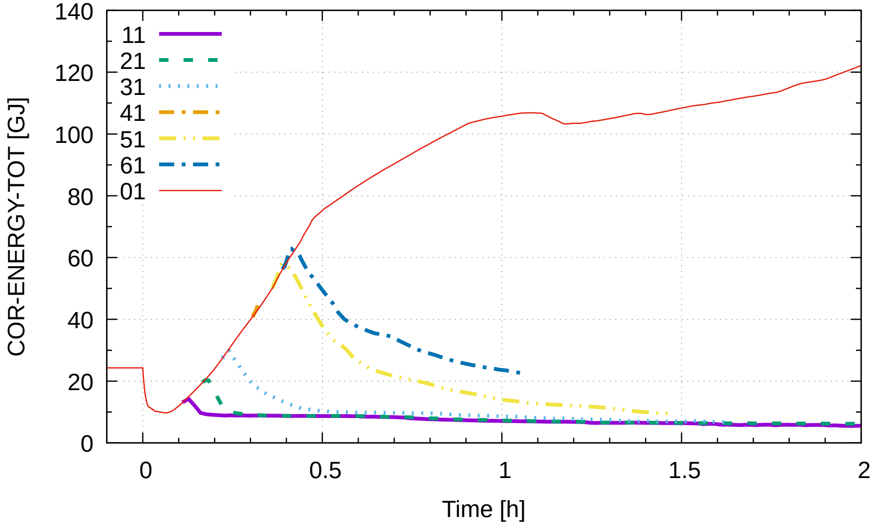
51 (reflood at 1300 s)

61 (reflood at 1400 s)

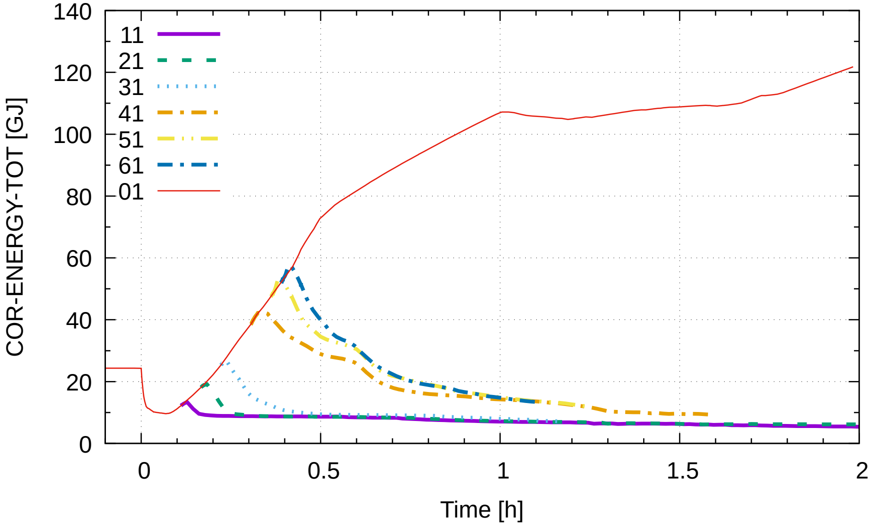
M22 Total core energy



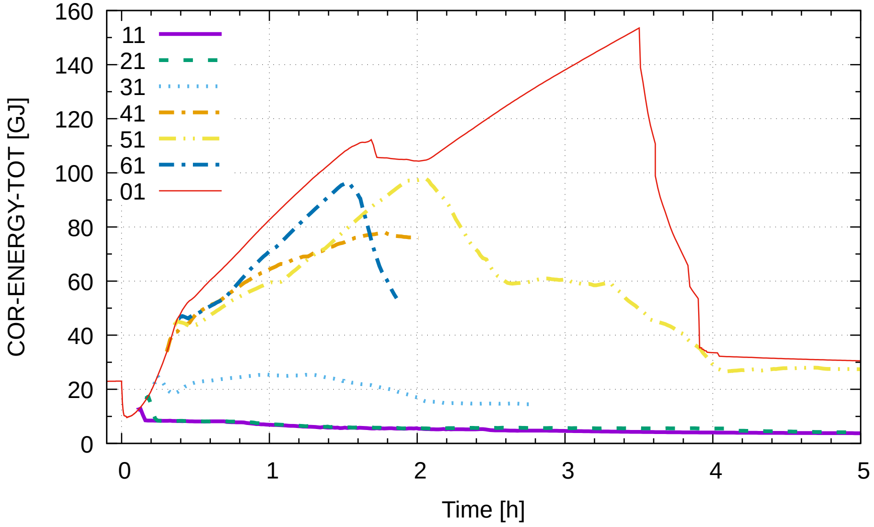
6 ring model



5 ring model



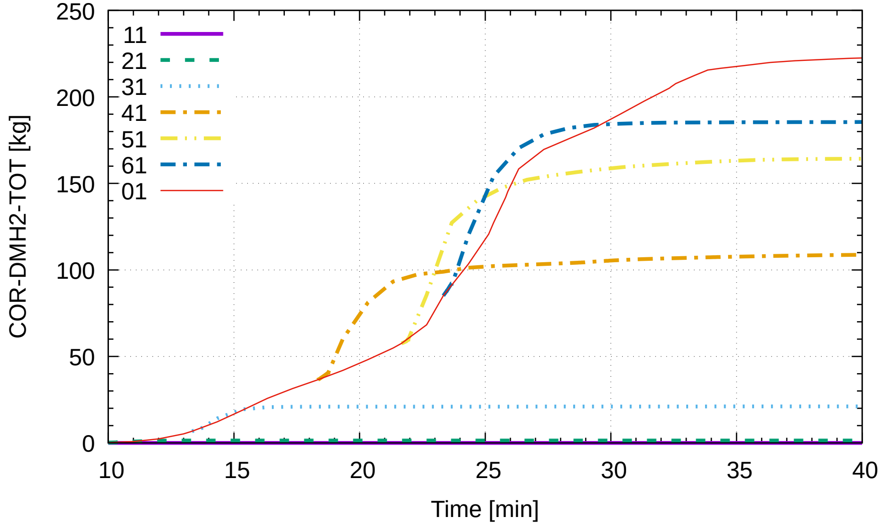
4 ring model



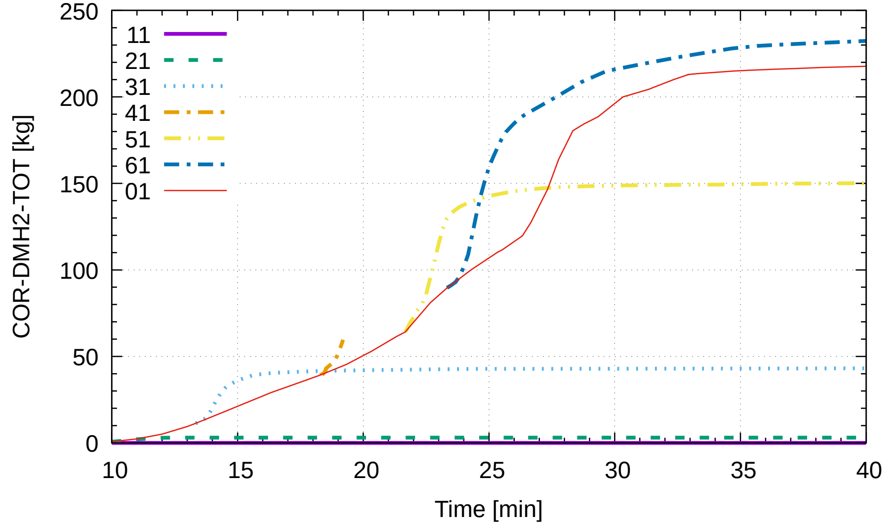
4 ring, the first converted model

VVER-440 simulations using MELCOR 2.2

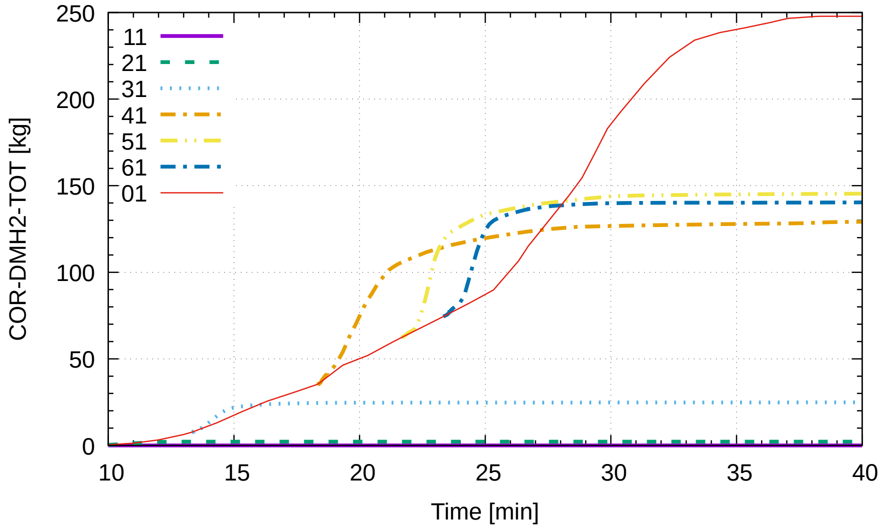
M22 hydrogen production



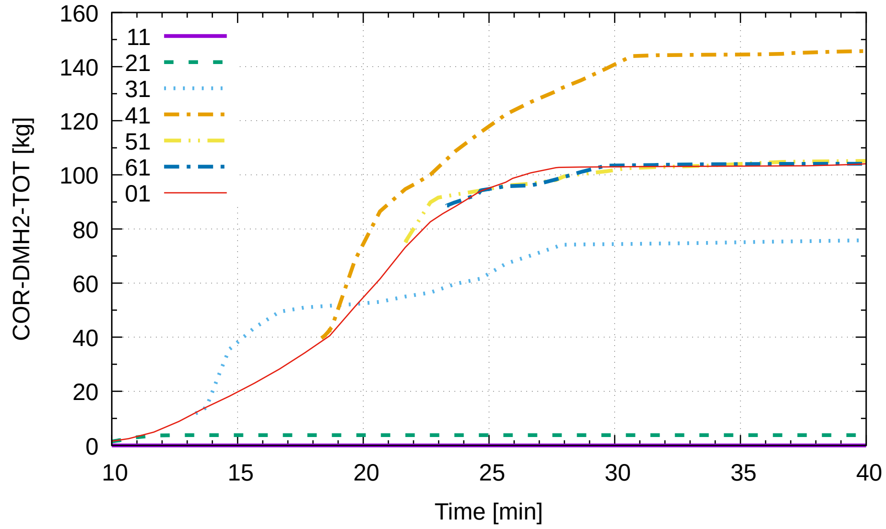
6 ring model



5 ring model



4 ring model



4 ring, the first converted model

Conclusions

- input model successfuly converted M1.8.6→M2.2
- results:
  - comparable for core and RCS
  - overestimated pressure in the containment in M2.2 (waiting for updated MELCOR release)
- simulations of core reflood more successfull with M2.2 (M1.8.6 too slow)
- boric acid transport model implemented using user defined FP class and lot of CFs — not numerically stable and reliable
  ⇒ **enhacement of MELCOR code requested**
- **non-physical behaviour of molten steel from control elements observed** ⇒ ?