Recent VVER-440 severe accident analyses with MELCOR 1.8.6

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Overview

- Base case model, pre-processing for specific nodalization
- First simulations of a shutdown accident scenario
- First simulations of IVR strategy
- Conclusions
- Linux/Unix issues — code portability, post-processing

VVER-440 Base Case Input Model for MELCOR 1.8.6

- already presented in detail at MCAP 2009:
  - mixed BWR (for the core) and PWR (primary&sec. circ.) input model
  - crossflow from the VVER-440 fuel follower channel to the bypass at the main core region
- it uses minimalistic approach in order to:
  - allow fast running simulations
  - demonstrate the capability of the code and the input model to simulate severe accident of a VVER-440
  - allow regular testing on various accident scenarios including station blackout, LOCAs, . . .

Pre-processing for specific nodalization

Objective: to keep consistency of input models with different nodalization

- Core input models are pre-processed in Python
- Other parts of the input deck are split into small blocks:
  - generic — common parts to all input models
  - parts specific to particular nodalization

- Everything is joined together using R*I*F command

First simulations of a shutdown accident scenario — Overdraining

Scenario: "Overdraining during the preparation to remove the reactor lid" was selected from the existing PSA-1 according to criteria:

- large relative frequency
- preliminary estimation of the source term: large but not catastrophic

Initial plant state:

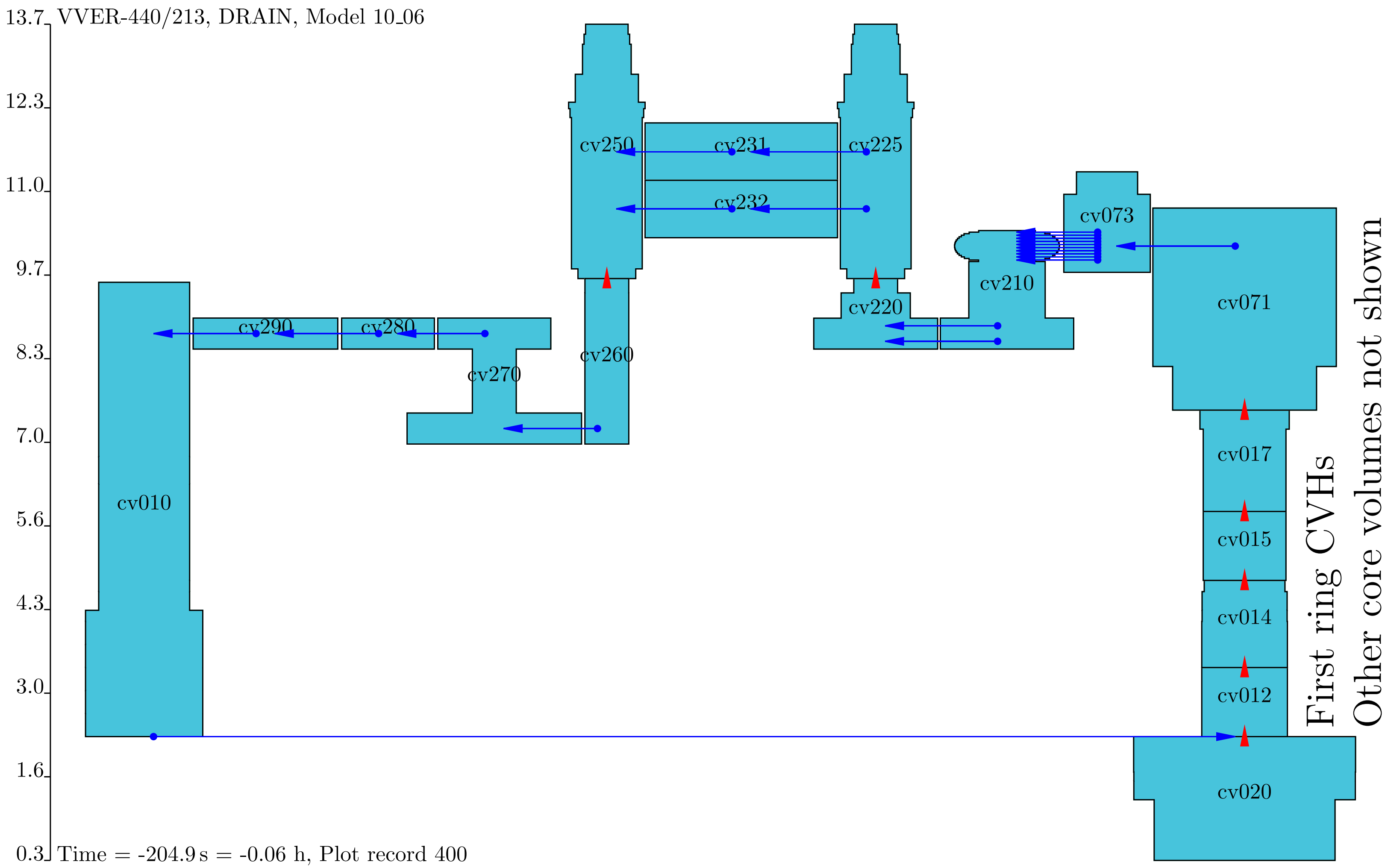
- about 5 days after shutdown; reactor is at atmospheric pressure, cooled by natural circulation in two primary loops and secondary heat removal in "water-water" mode; control rod drivers are being dismantled

Accident initiating event:

- at postulated time "zero" of the scenario, a draining pump is started to decrease water level in the RPV below the reactor lid separation elevation to allow the lid removal
- it is assumed that due to the wrong RPV water level measurement, the water level in RPV drops below the hot leg nozzles, it leads to the loss of natural circulation in the primary and to the loss of the heat transfer to secondary (though secondary heat exchangers are still operable); then the draining pump is stopped and draining pipes closed

Overdraining: Model adaptation

- Core input models from the "Base Case" without any change
- Three loop primary model :
  - triple loop isolated from secondary and closed by the main isolation valves at cold legs
  - double loop on natural circulation
  - single loop with pressuriser, it is connected to a coolant sink representing the draining pump (coolant removal flow rate was set to maximum allowed according to the operator guidance)
  - pressuriser is open through the drained quench tank to SG boxes
  - additional flow path through the reactor lid simulates the dismantled control rod drives
- The secondary circuit input model is limited to heat exchanger connected to the double primary loop on natural circulation
- Containment and Reactor Hall input models are the same as in the Base Case
- Modified initial conditions and the decay heat for shutdown conditions



- the hot leg nozzle is simulated by 10 small flow paths stacked vertically - to allow smooth flow rate decrease with decrease of water level in RPV — very important nodalization change
- the hot leg loop seal simulated by two flowpath to allow the counter-current flow

Overdraining: Simulation results

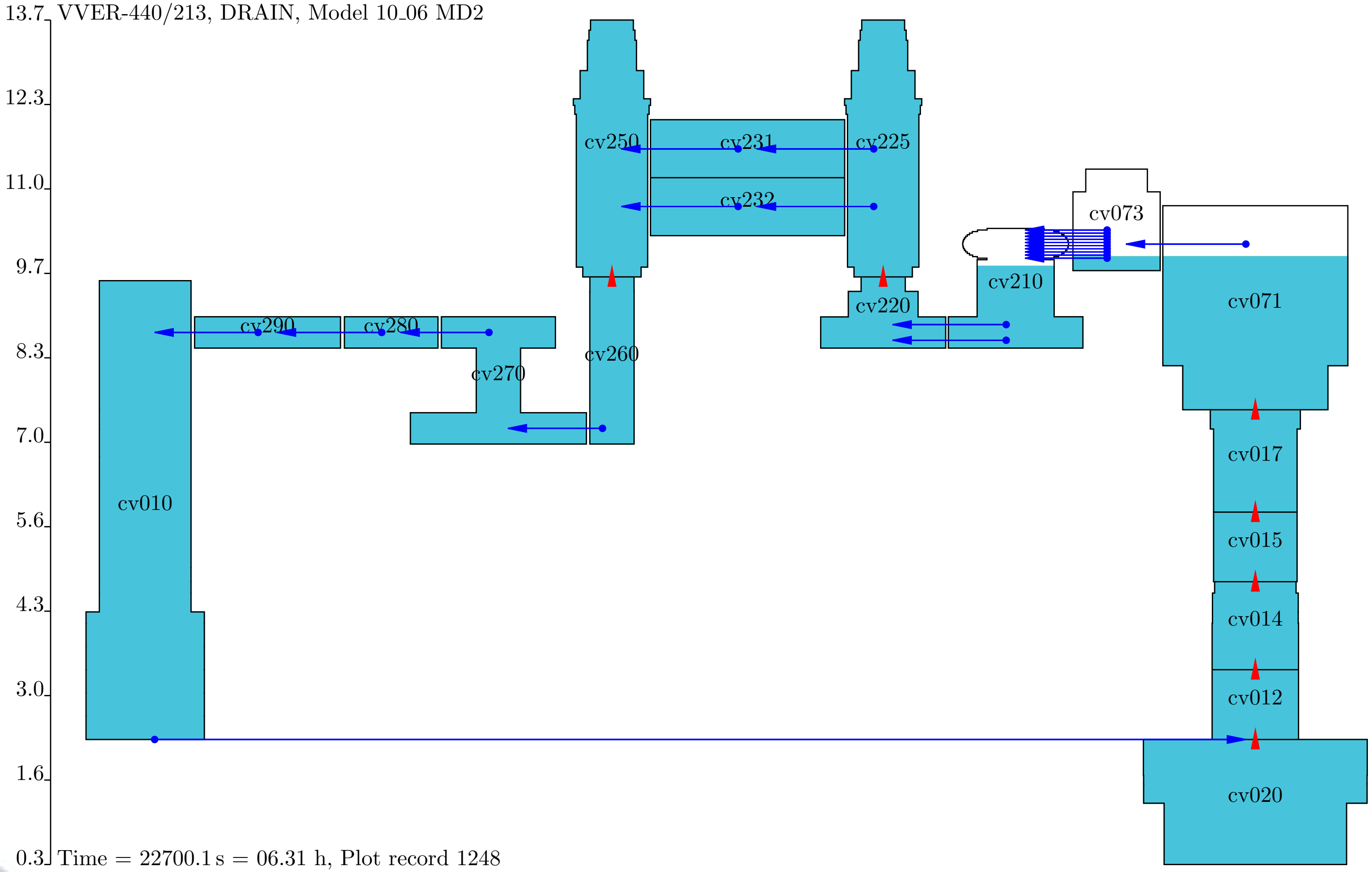
- the RPV water level at the hot leg nozzle elevation: ∼1.1 h top, ∼1.6 h bottom
- the coolant in RVP starts to heat-up (∼1.4 h) and then it starts to boil (∼2.2 h)
- the increase of coolant temperature causes the coolant volume increase and the partial water level recovery in RPV
- **boiling in RPV causes recovery of natural circulation in the double loop**, it is two phase circulation and it is sufficient to remove residual power from the core (it is assumed that secondary coolant is kept at constant temperature by a heat exchanger)
- the loss of coolant from primary through openings is negligible — boiling is not intensive and in some calculations (sensitivity studies) temperature in RPV even decreased few degrees below saturation (this occurs at ∼6 h)
- **sensitivity study indicates that the complete loss of natural circulation occurs only when the draining pump is left operating for almost one hour after the start of the boiling in RPV** — this is very unlikely situation — the core damage is predicted at ∼17 h

Overdraining: Simulation results

Sensitivity study MD2: draining for 2 h, increased pressure drop on MCP

Stabilization of flow pattern in the double primary loop occurs after 6 h.

Coolant temperature in RPV is below saturation. Liquid coolant just overflows the hot leg nozzle bottom. Decay heat is completely removed from the core to the secondary.



Overdraining: Uncertainties of simulation results

- the residual heat removal exchanger on secondary side: how will it behave after loss and recovery of natural circulation in the primary loops?
- flow friction coefficients on loops with natural circulation; mainly on MCPs, loop seals, SG tubes ...

  sensitivity study did not change the conclusions about the natural circulation recovery
- should the primary side of SGs be drained? when?

  start of the water level decrease in the hot collector of the drained loop ∼1.66 h, in the cold collector of the drained loop ∼1.7 h

  water level at the top of SG tubes in the drained loop ∼1.75 h, at the bottom of SG tubes ∼2.68 h (if the drainage continued at this time)

  start of the water level decrease in the hot collector of the double loop ∼2.91 h (if drainage continued at this time)
- the size of release path in the reactor lid has negligible influence on results — the loss of coolant is related only to the boiling rate

⇒ **uncertainties are large**; recovery of natural circulation should be confirmed by a detailed TH code simulation

IVR: Development of VVER-440 input model

Assumption: the VVER-440/213 cavity can be modified for IVR without any restriction

Objective: develop MELCOR input model for the IVR strategy (it is not intended to verify whether IVR is successful or not)

Base case input modification steps:

1. (input model 10_02)
   changes to allow draining of the bubble tower to the reactor cavity
   RPV thermal isolation removed
   modified cavity CVH model to cool RPV efficiently (two volumes)
2. (input model 10_05)
   modification of the lower plenum COR nodalization
   (two CVH volumes in the cavity)
3. (input model 10_07)
   modification of the lower plenum CVH nodalization - not successful
   three CVH volumes in the cavity

1. IVR with the base case model

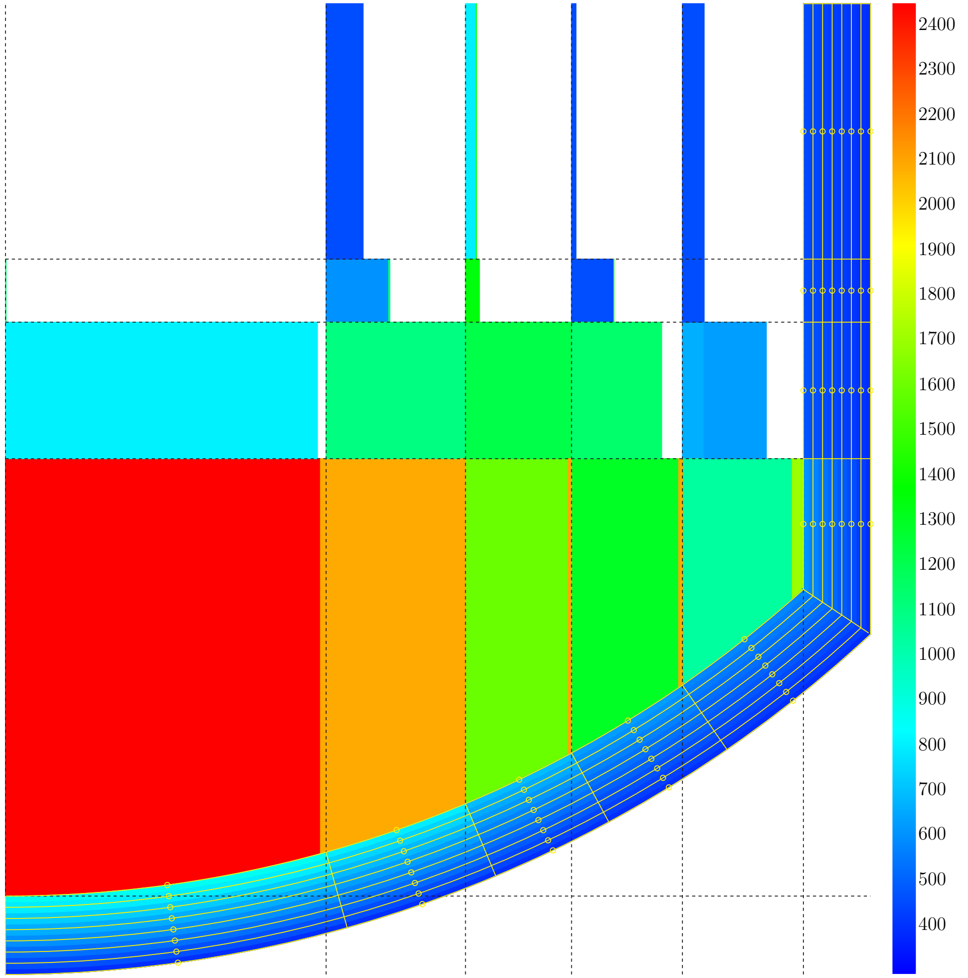
- reference scenario: station blackout with the RCS depressurisation:
  BRU-A opened at 10 min,
  OVKO and PORV-1 at 2 h.
  Coolant mass in LP (cv020) <1 t at ~9.2 h,
  RPV fails at ~9.5 h.

  (warp=0.23, min(warp)=0.16; high pressure SBO min(warp)=1.29)

- IVR scenario:
  the bubble tower is drained at 2.22 h,
  at ~3.2 h water level in the cavity is above the elliptical LH.
  Coolant mass in LP (cv020) <1 t at ~9.7 h,
  RPV fails at ~12 h.

  (warp=0.25, min(warp)=0.19)

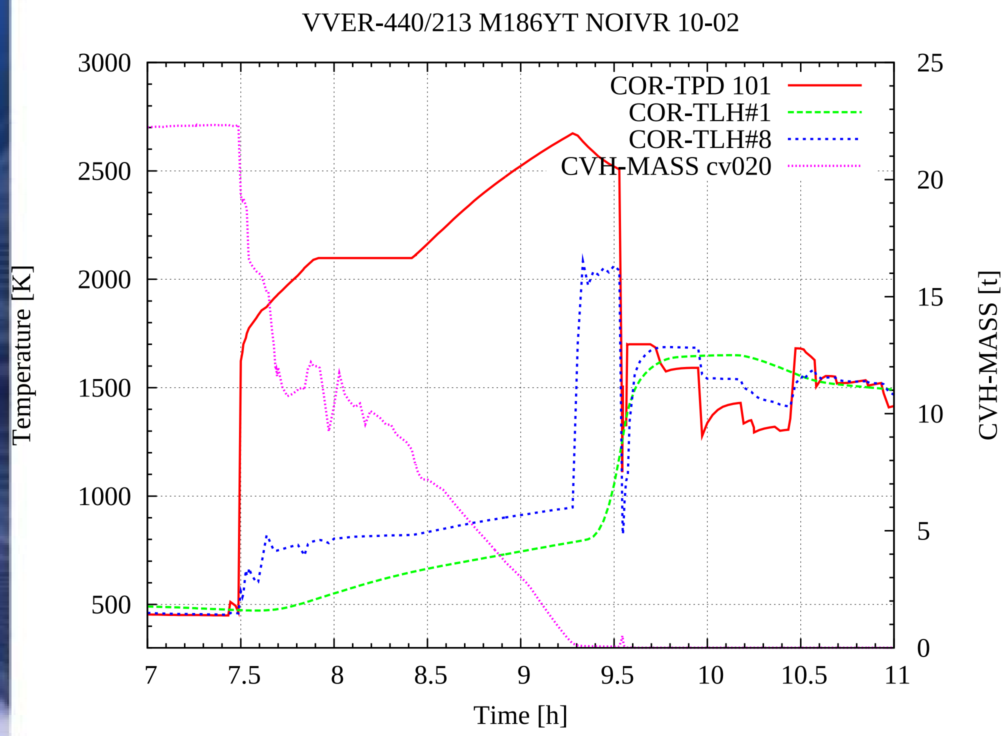
VVER-440/213, IVR, Model 10_02



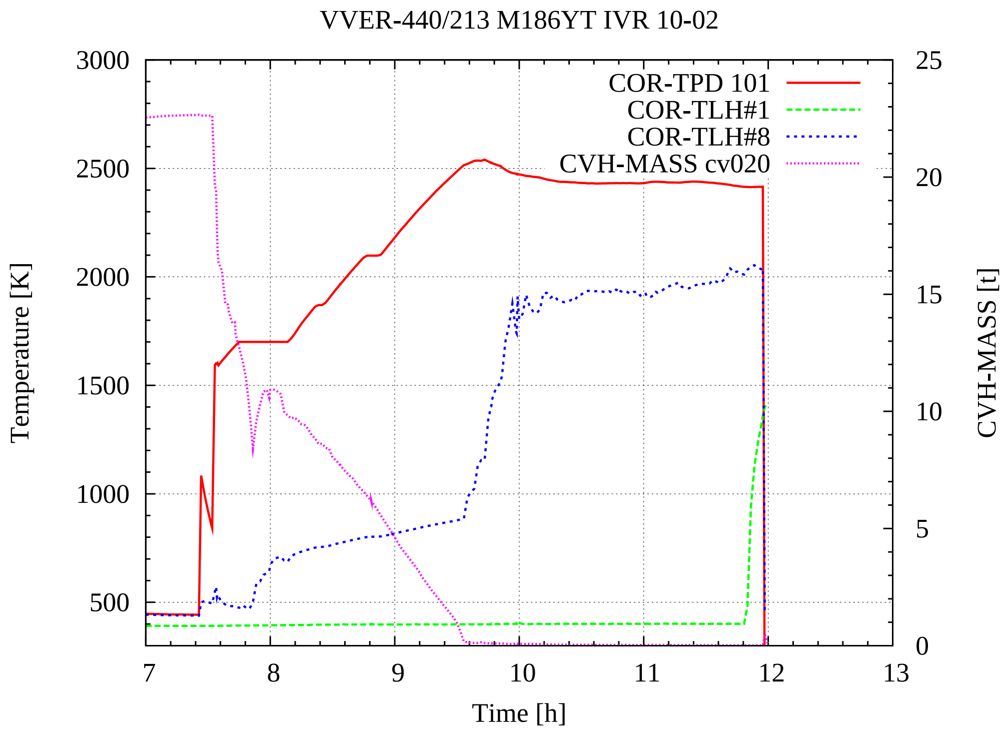
Time = 34000.2 s = 09.44 h, Plot record 505

1. IVR with the base case model

Comparison of temperature of particulate debris in the node 101 with temperature of the RPV wall in the central ring. Temperature difference depends on amount of coolant in the lower plenum (`cv020`).

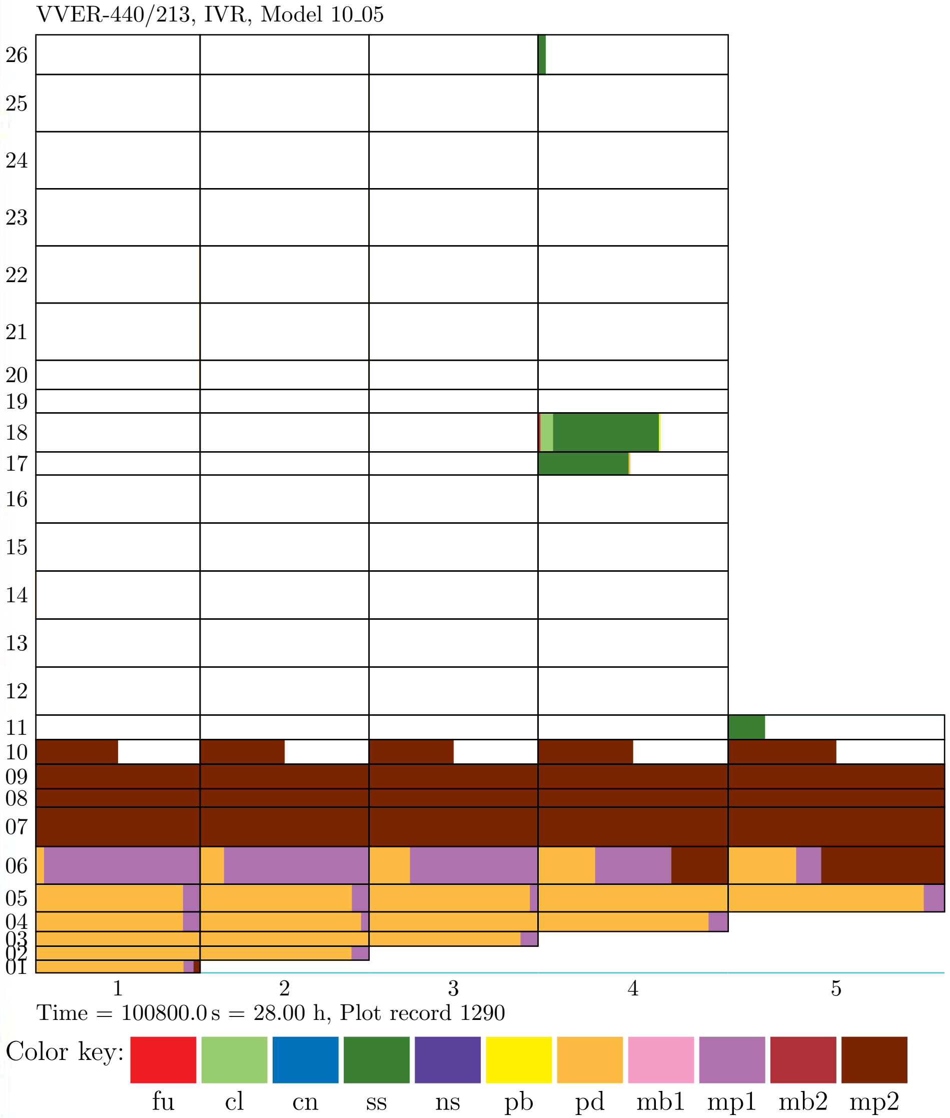


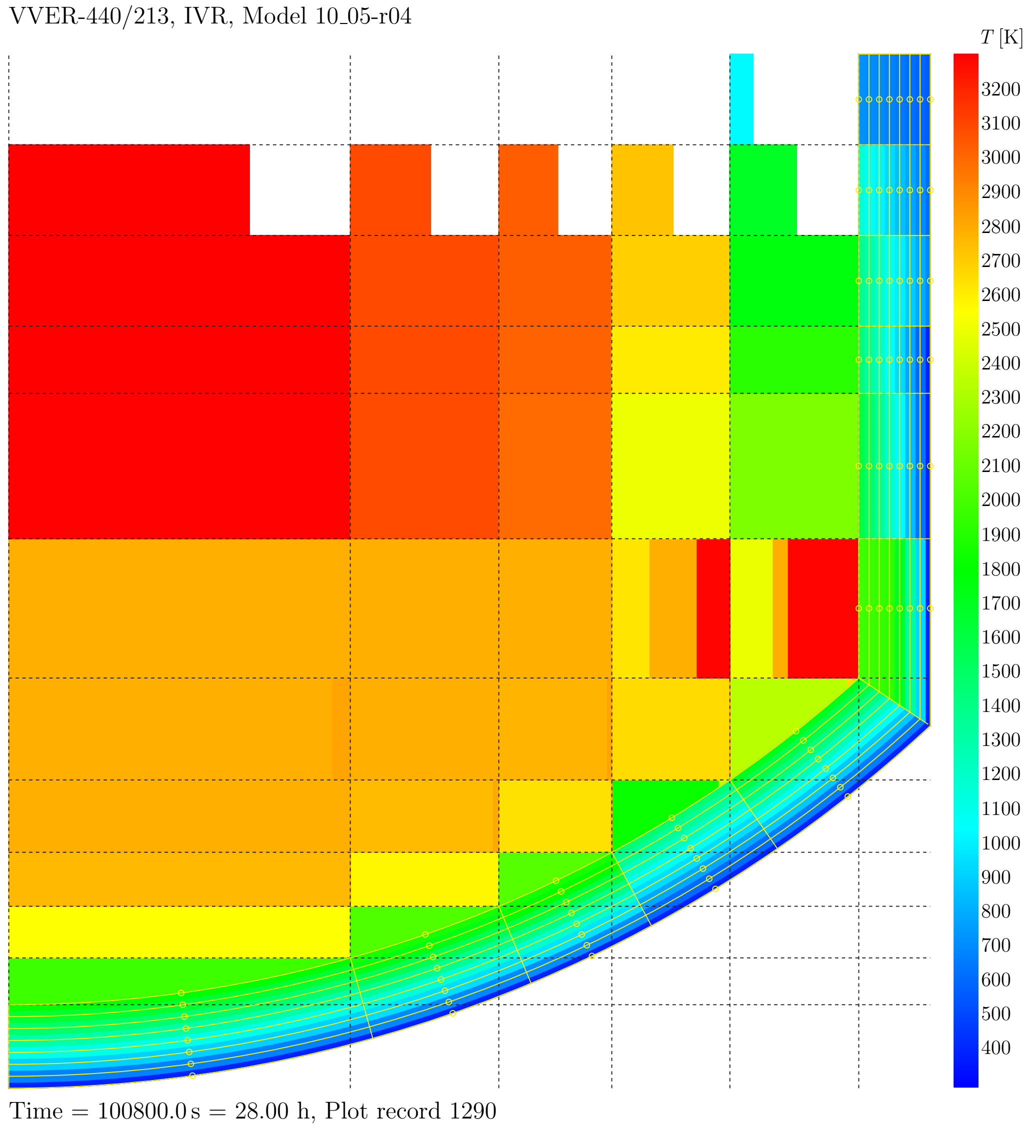
Scenario without the cavity flooding



Scenario with IVR

2. IVR: Improved COR nodalization in the lower plenum





Core state | Core and RPV wall temperatures

Simulation normal end at 28 h (110 h CPU, warp=0.25, min(warp)=0.1)

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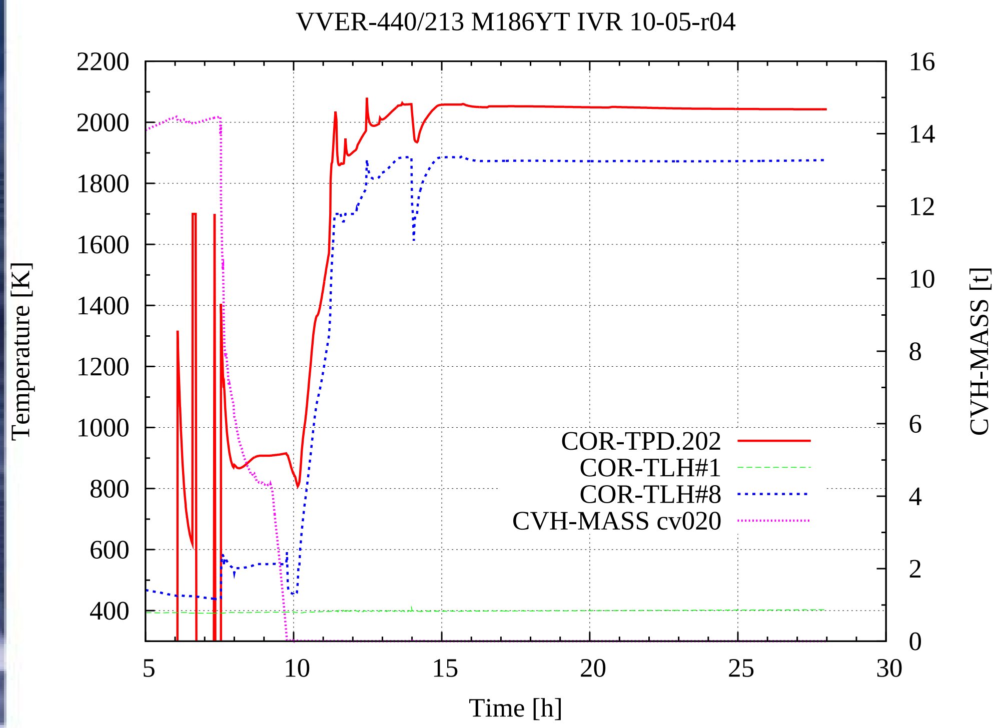
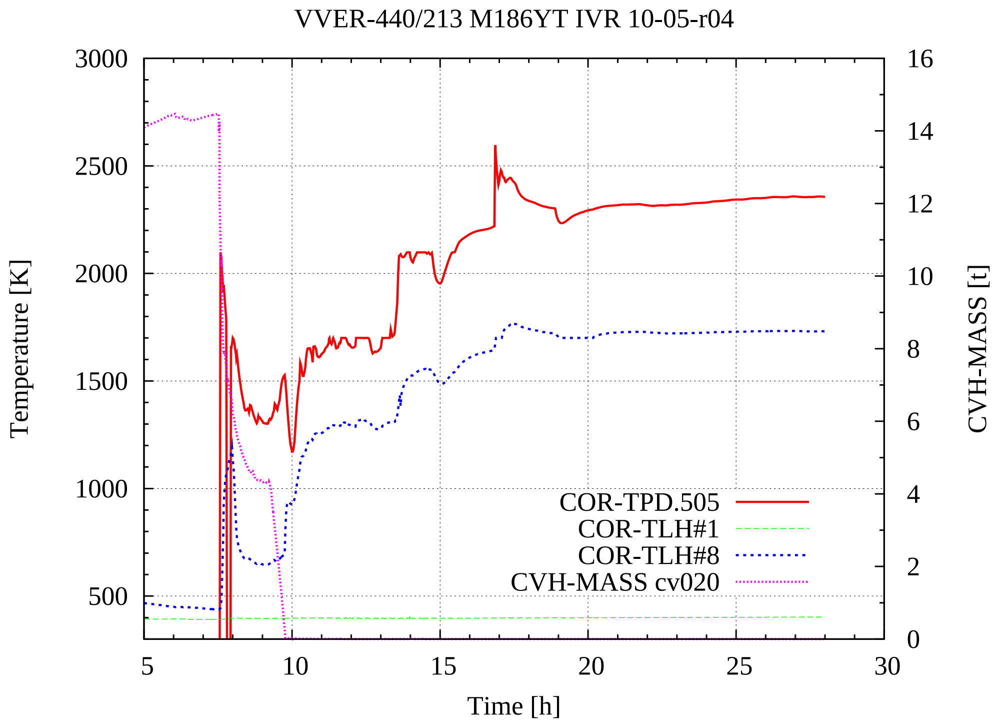
2. IVR: Improved COR nodalization in the lower plenum

The whole lower plenum (below the original followers fuel bottom) is still in one CVH node (`cv020`).

Coolant in `cv020` still influences heat transfer between the debris and the RPV wall. It is just not so clearly visible as compared to the simple (base case) COR nodalization.

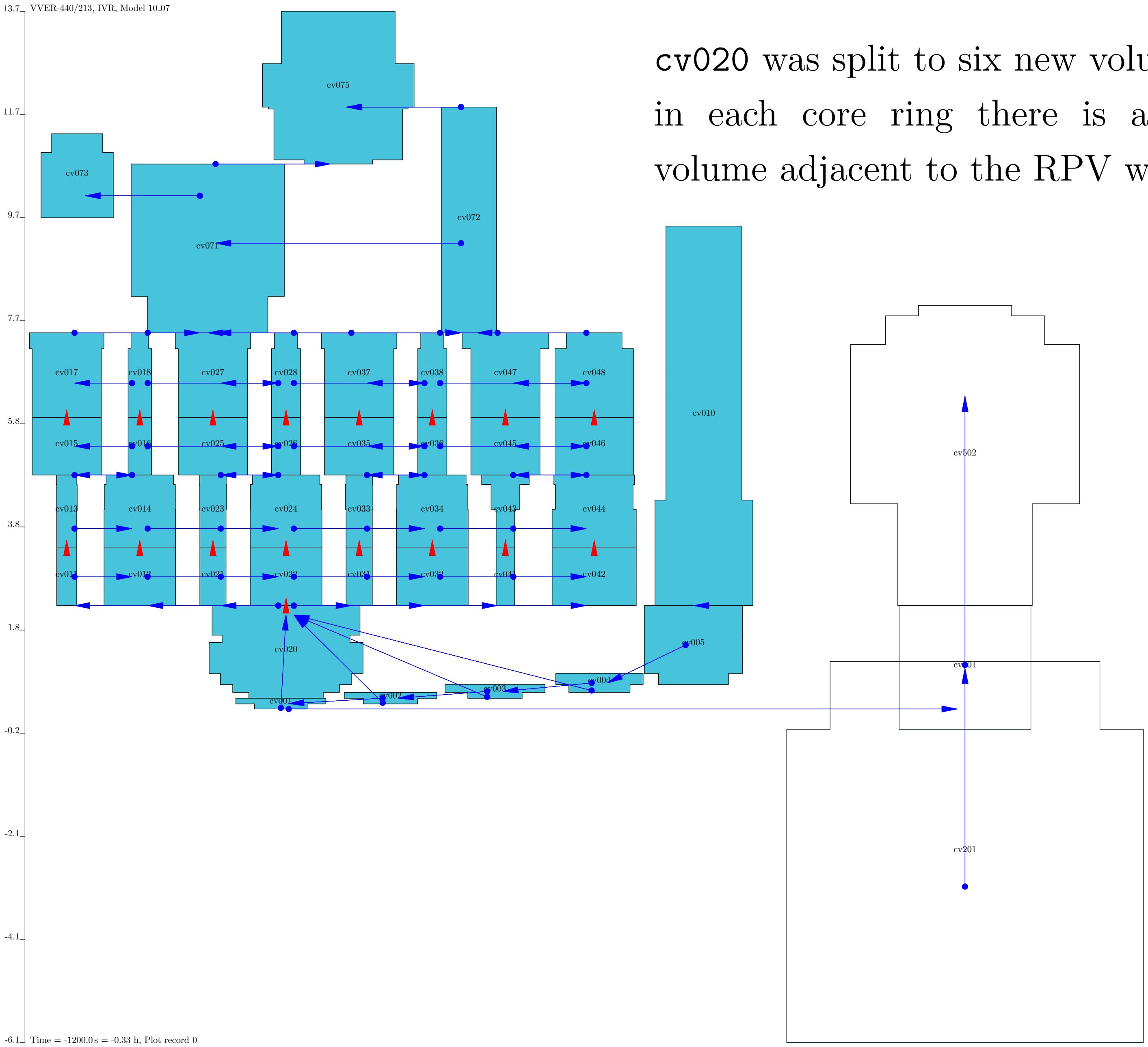


Ring 2



Ring 5

3. IVR: Improved CVH nodalization in the lower plenum



`cv020` was split to six new volumes:

in each core ring there is a small cvh volume adjacent to the RPV wall

3. IVR: Improved CVH nodalization in the lower plenum

- Coolant from the small CVH volumes is forced away on debris/melt arrival (some 2-3 kg of liquid coolant remains).

  It seems that temperature difference between RPV wall and debris is not influenced by the remaining coolant in `cv020`.

- Calculations failed at ∼10 h due to a sudden temperature increase of vapour in new small CVH volumes. This event is connected to the removal of the remaining liquid coolant from the volume.

- Calculations with the more detailed CVH nodalization were very slow (∼10 h of scenario consumed almost 7 days of CPU on Core 2 Duo@2.4 GHz, warp=0.06)

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Conclusions

(for both IVR and shutdown scenarios)

- prediction of vessel failure with the input model containing just one CVH volume for the whole LP is not correct
- attempts to split LP to more CVH volumes failed:
  - simulations are too slow
  - simulations always fail — some problem with coolant remaining in small CVH volumes filled with melt and debris
- coolant boiling at low pressure slows down the simulations

Implementation of MELCOR on UNIX based workstations

- presented VVER-440 simulations were calculated and evaluated on Linux (64bit kernel) with optimised (-O1) MELCOR 1.8.6.YT executable compiled with Intel FORTRAN 10.0:
  - no problems with optimised executable experienced
  - only -O0 (no optimisation) recommended by SNL (why?)
- post-processing tools developed in FORTRAN, Python (PyGTK, PyX), GNUPlot
- compile script converted to Makefile (without dependencies of include files)
- alternative platform tested: Mac Mini with Mac OS X 10.6
  - it allows to run the same GNU tools as on Linux
  - MELCOR plotfile is binary compatible on Linux, Mac, Windows
    ⇒ the same pre/post-processing tools can be used on Mac and Linux
  - However Intel FORTRAN for Mac costs $700. Is it worth to buy this compiler just to make -O0 executable?

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Thank you for your attention