# CONFIRMATORY MELCOR ANALYSIS OF SEVERE ACCIDENTS FOR ESBWR

U. S. Nuclear Regulatory Commission Meeting With General Electric Company On ESBWR Severe Accident Sequences and Thermal-Hydraulic Uncertainties

March 8, 2006


by:

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# OUTLINE

- Objective of the NRC MELCOR analyses
- MELCOR Modeling of ESBWR
  - Nodalization
  - Other modeling aspects
  - Status
- Pre-Accident Initialization/Steady-State

# OUTLINE (Cont.)

- Results of Preliminary Calculations
  - Accident Scenario
  - Simulated Cases
    - Case 1: With MCCI
      - Lower Head Sensitivity Calculations
    - Case 2: Without MCCI
- Remaining Data Needs
- List of Plant Calculations

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# OBJECTIVES

- To support the design certification review of severe accident risk by NRC in
  - Independent assessment of severe accident response
  - Confirmatory assessment of representative radiological release estimates
  - Development of uncertainties in the initial and boundary conditions for analysis of selected severe accident issues (e.g., ex-vessel steam explosion)

# MELCOR Model Development

- Developed initial input deck for MELCOR 1.8.6 using GE design data (November 18, 2005)
- This deck subjected to an independent QA and review
- Due to problems with MELCOR 1.8.6, model was converted to MELCOR 1.8.5 and revised based on QA & review comments.
- Plan to perform limited calculations for ESBWR using MELCOR 1.8.6 when the code is ready.

# MELCOR Model Development (Cont)

- Deck conversion to MELCOR 1.8.5:
  - Flat-bottom RPV instead of the new hemispherical LH
  - Minor changes to core nodalization (to enhance running time)
  - Minor changes to the suppression pool (water) nodalization in response to QA & review comments
  - Updated design data based on MFN05-142, 06-003, 06-009, 06-029

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# CORE/RPV NODALIZATION

- The core nodalization:
  - 5 radial rings, 13 axial levels (9 for active fuel, 1 above top of active fuel, 1 between bottom of active fuel & top of the core plate, 2 in the lower plenum).
- Separate Control Volumes (CV) used for each ring, heated channels and the bypass regions
  - 1 CV used for every 3 axial levels of active fuel region, plus another level of CV for regions above the active fuel.
  - As a result, a total of 25 CVs for the core (4 levels x 5 rings for the core channels plus 5 for the bypass).

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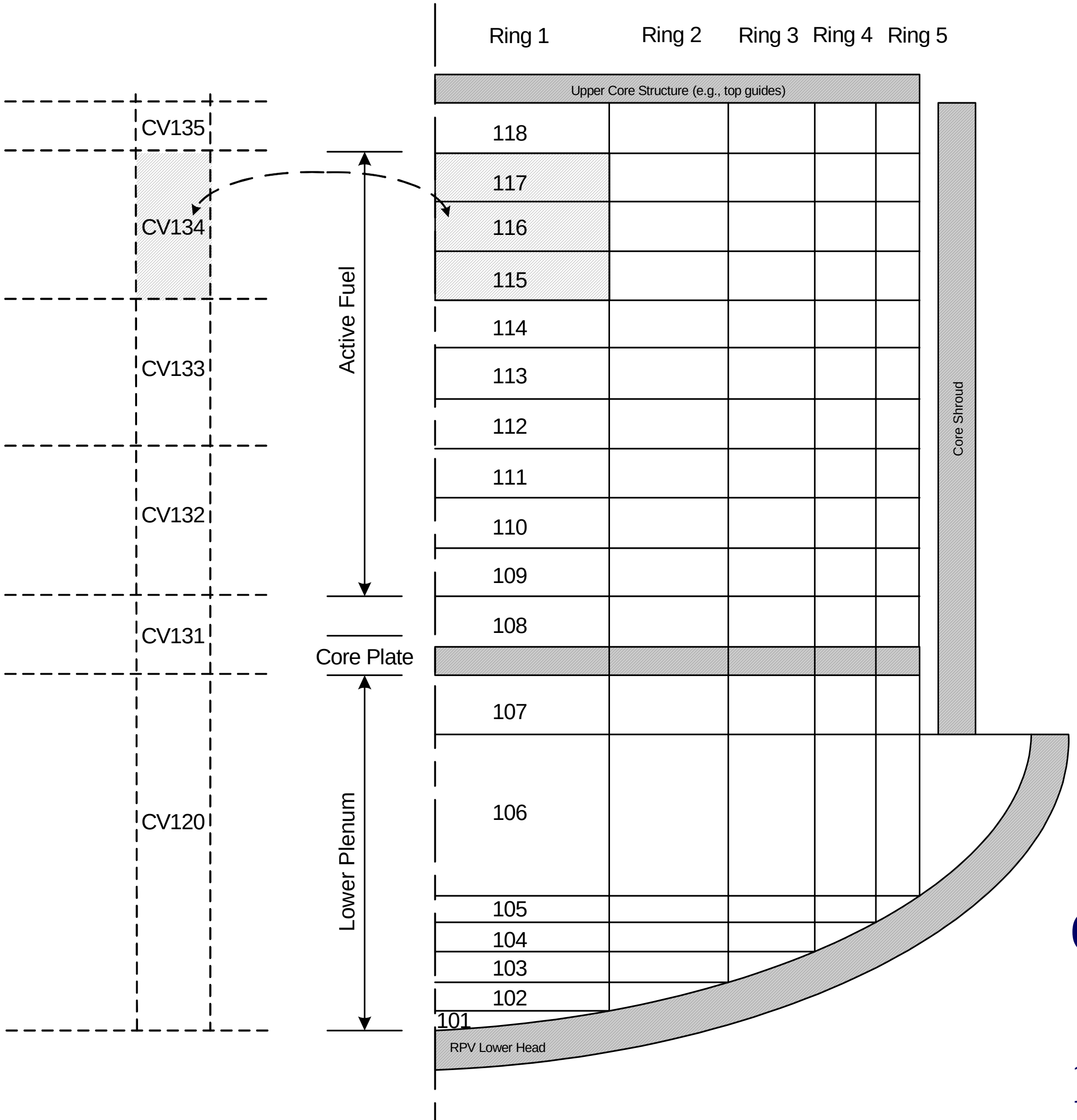


# ORIGINAL MELCOR 1.8.6 Model

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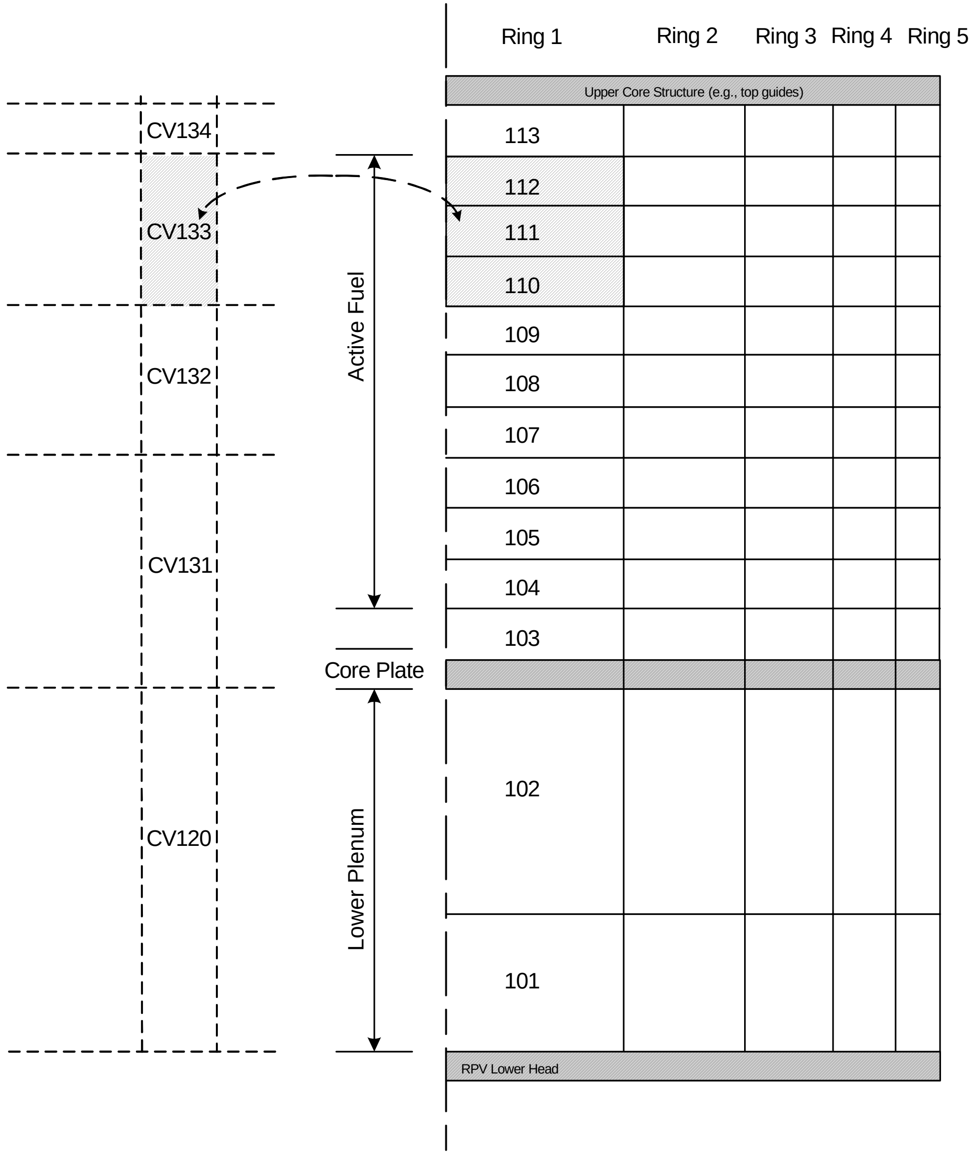


# LATEST MELCOR 1.8.5 Model

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# CORE/RPV NODALIZATION (Cont.)

- Other CVs used inside RPV to represent:
  - Lower plenum;
  - Separators (inside volume of the steam separators) and mixing plenum/partitioned chimney;
  - Dryers and steam dome region;
  - Separator return to upper downcomer, combined with the liquid drain area outside the steam separators; and
  - Lower downcomer.
- 2 CVs used to represent 4 main steam lines (1 CV for one of the lines, and 1 CV combines the remaining 3 lines, allowing simulation of a break in one line).
- Feed water system has been modeled (using external mass and energy sources in the CV package and CFs)

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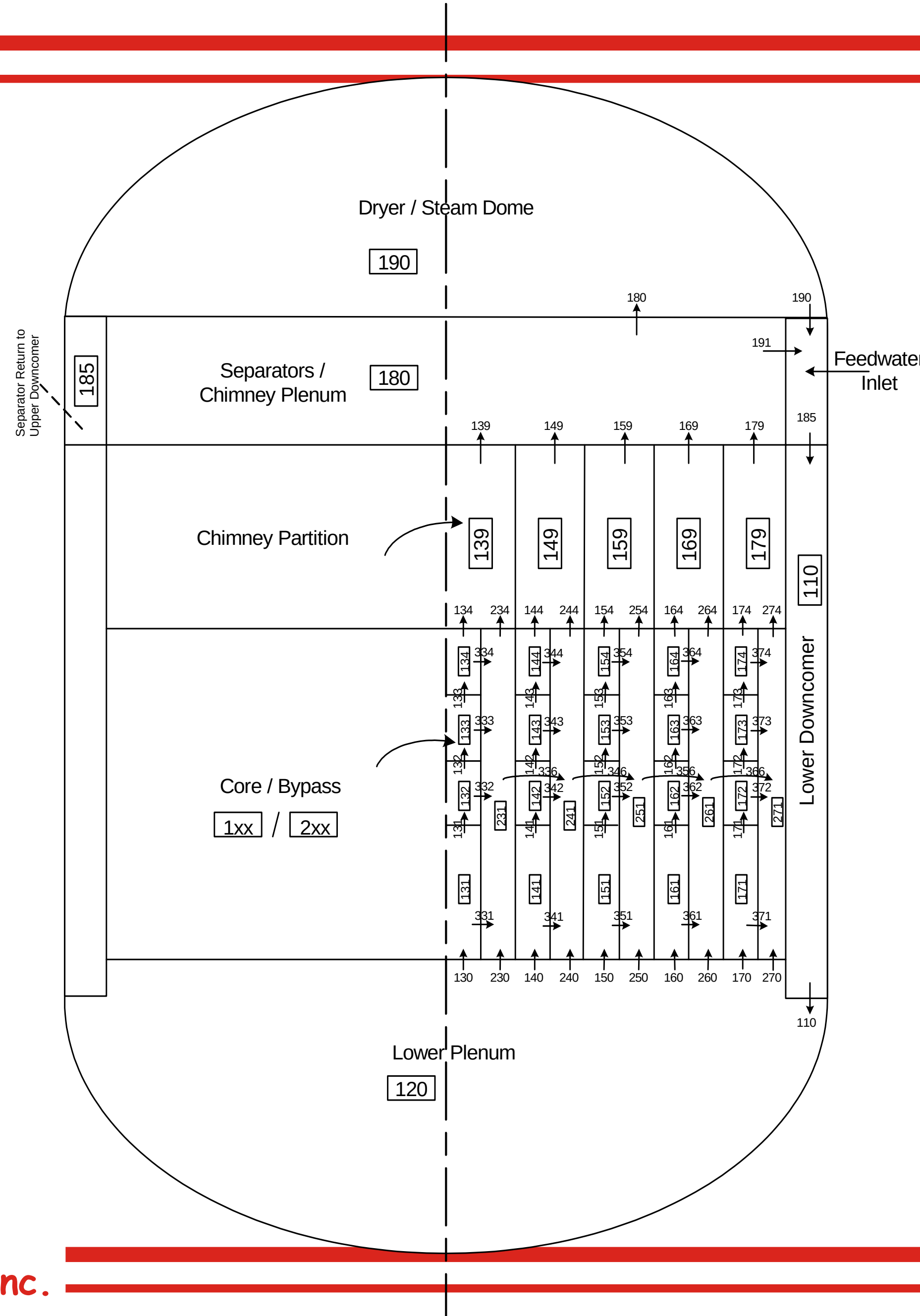


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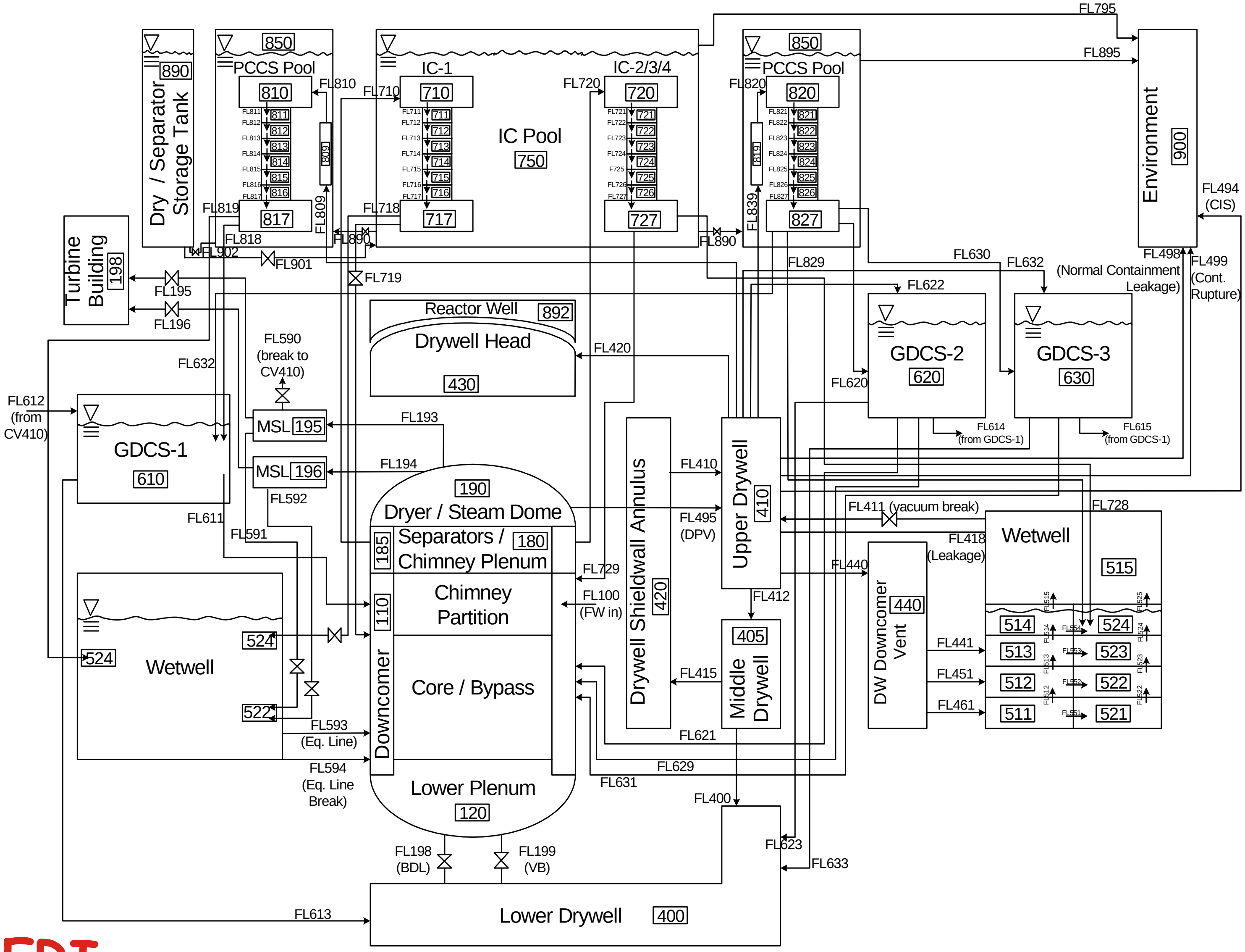
# CONTAINMENT NODALIZATION

- Each of the 4 divisions of the 3 GDCS pools is represented individually (also modeled the 2 divisions existing for GDCS #2). One CV used for each of 3 GDCS pools, along with controlled flow paths for injection, equalization & deluge lines.
- 6 units of PCCS are represented by 2 sets of CVs & FLs. (1 single & 5 combined).
- 4 units of IC are represented by 2 sets of CVs (1 single & 3 combined).

# CONTAINMENT NODALIZATION (Cont)

- PCCS & IC modeled mechanistically
- Condensation and drainage of water inside tubes modeled inside the MELCOR HS package, using a film tracking network.
- PCCS and IC inlet lines modeled as CVs and HSs.
- Heat transfer from drywell (upper head) to the "reactor well" water is included.

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# OTHER MODELING ASPECTS

- Containment spray system and venting system have been included (noting that the missing design data need to be requested from GE).
- Refill of PCC/IC pool is included via a control function to maintain coverage of PCCS tubes.
- BiMAC system has not been explicitly modeled (the intended impact of BiMAC may be investigated through a parametric representation within MELCOR; otherwise, specific design information may be required).

# STATUS

- All aspects of the model, peer review and QA comments have been documented.
- NRC staff have been involved in all aspects of this work (including direct involvement in steady-state calculations).

# STATUS (Cont.)

- A complete 1.8.5 model is available and initial confirmatory calculations are underway.
  - Results of a representative accident scenario with limited comparisons to the GE submittal completed (not yet documented).
  - List of representative scenarios to be analyzed has been prepared and discussed with the NRC staff.
  - Baseline MELCOR calculations should be completed, pending the receipt of requested data from GE.
  - Anticipate completion (MELCOR) within 2-3 months.

# PRE-ACCIDENT INITIALIZATION

- Approach developed in collaboration with NRC.
- Set full power (4500 MW) and the design feedwater flow rate (2451 kg/s) for the duration of simulation.
- Approach to steady-state was relatively smooth
- Iterated with specified loss coefficients to arrive at pressure drop and flow rates (feedwater, recirculation and steam) listed in the DCD:
  - Additional work is needed to resolve the apparent differences with DCD conditions
  - Clarification on the physical locations of the referenced pressure differentials needed from GE
  - Need detailed information on the various form loss coefficients from lower plenum to the chimney region (along the core), the leakage flow paths from the chimney and separators to the downcomer.

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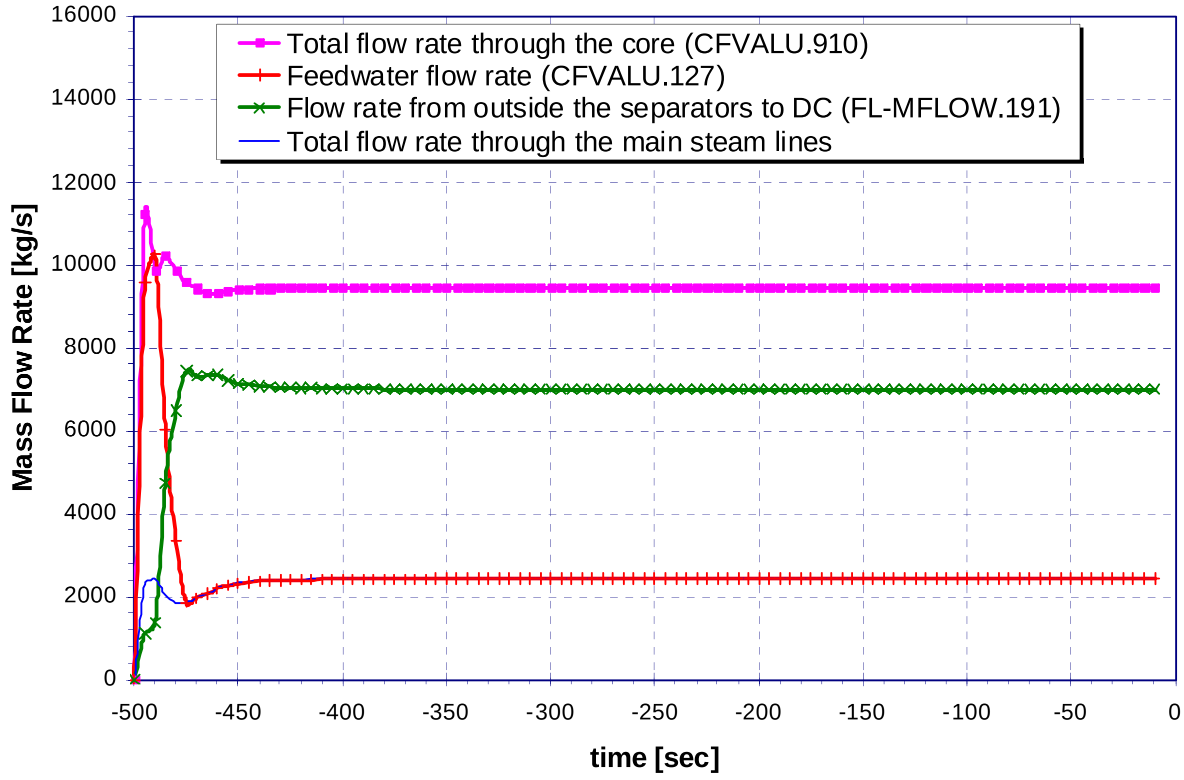
# PRELIMINARY RESULTS (PRE-ACCIDENT INITIALIZATION)

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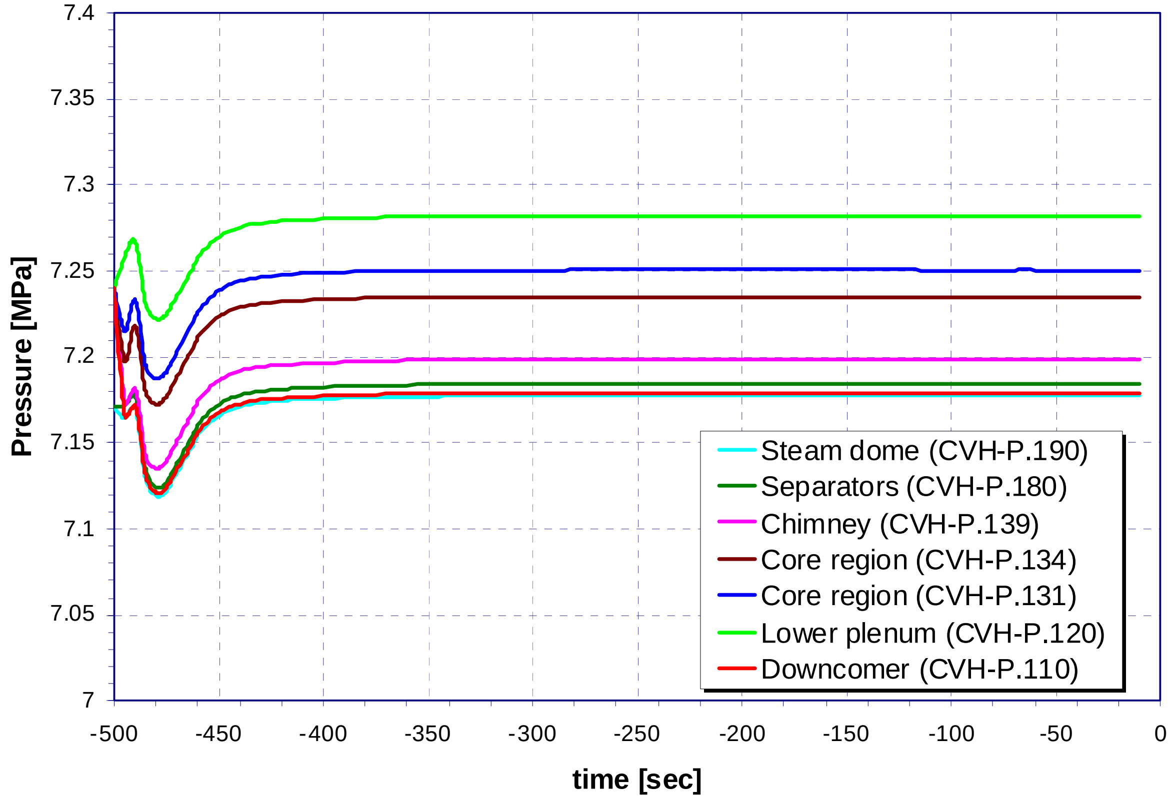
# RPV Pressure

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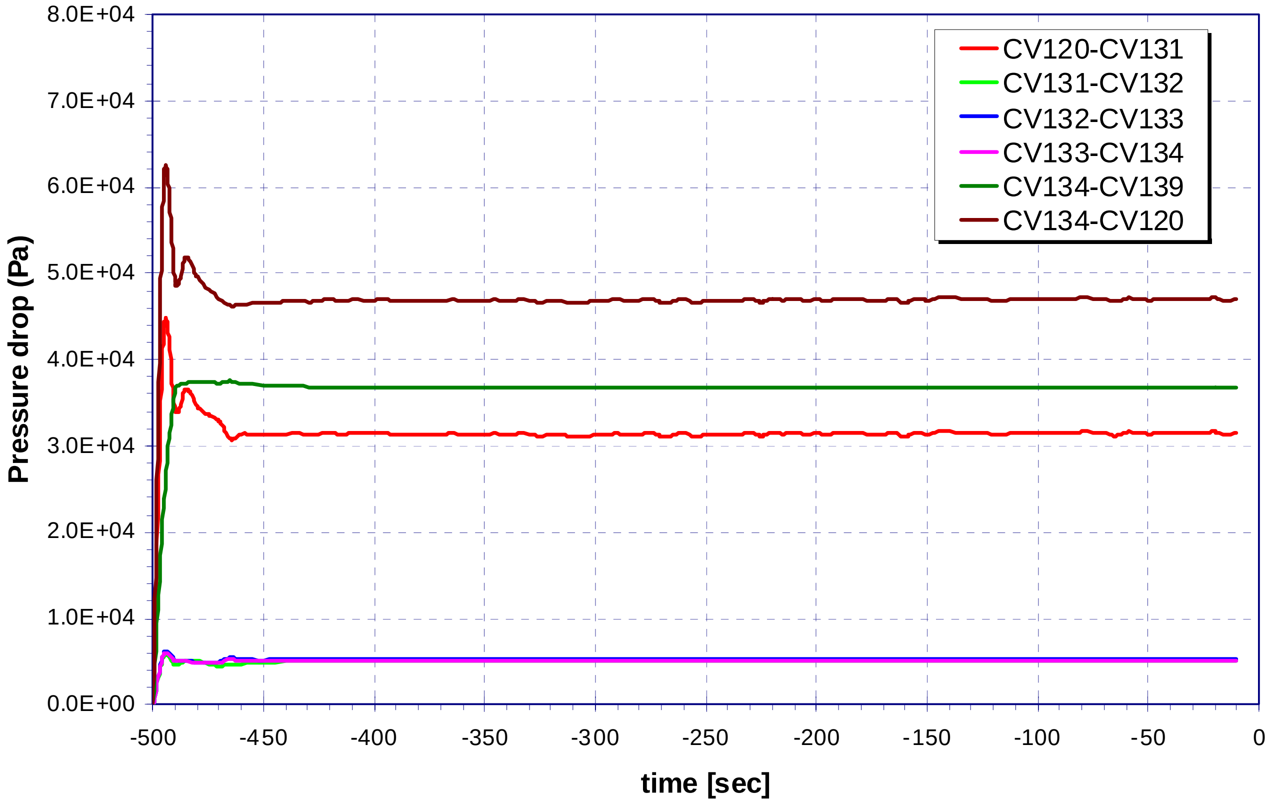
# Pressure Drop Between Various Core Control Volumes

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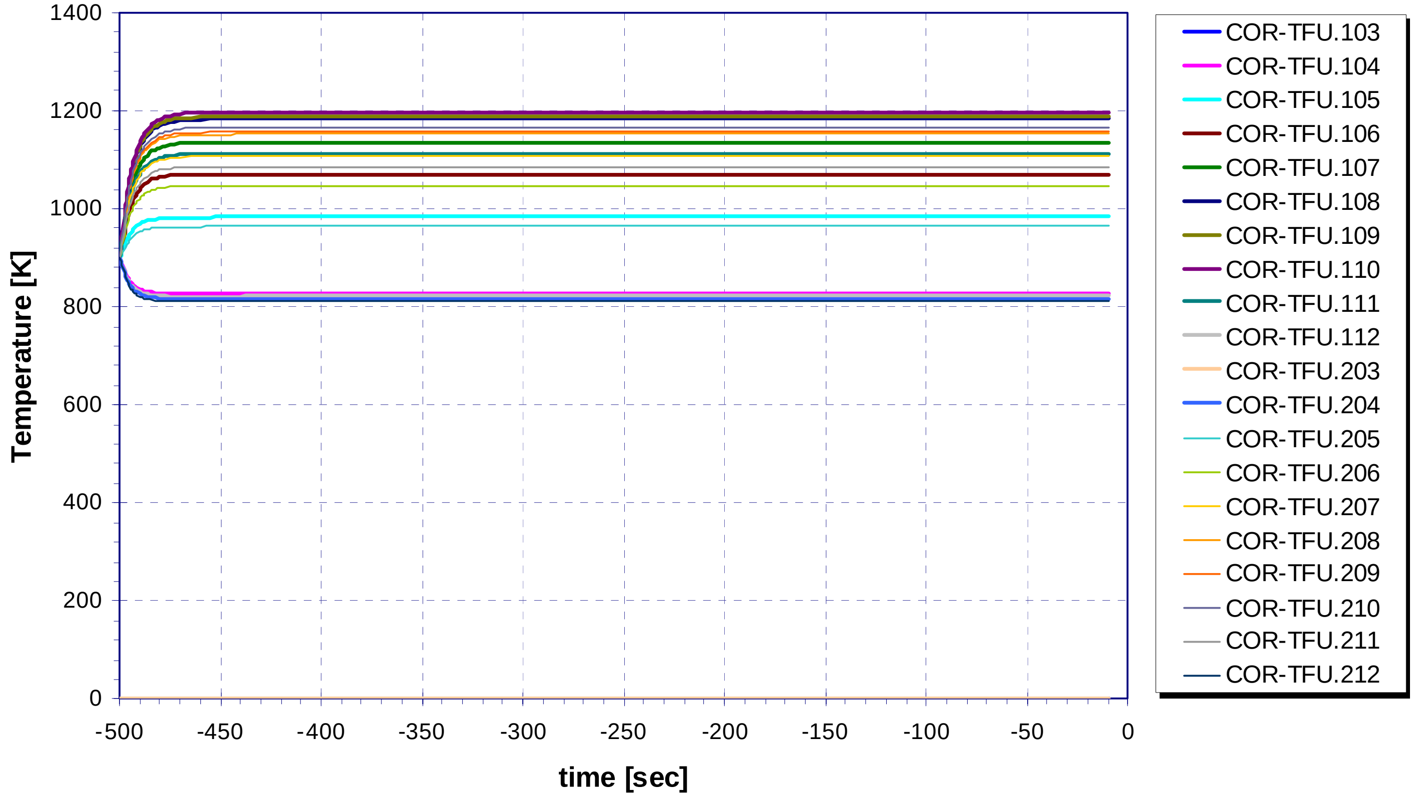
# Fuel Temperature

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# MELCOR Steady-State Results vs. GE DCD Values

| Parameters | Design value | Simulated value |
|---|---|---|
| Steam flow rate (kg/s) | 2433 | 2437 |
| Feedwater flow rate (kg/s) | 2451 | 2439 |
| Core coolant flow rate (kg/s) | 9034-10584 | 9454 |
| System pressure, nominal in steam dome (kPa) | 7171 | 7179 |
| System pressure, nominal core design (kPa) | 7240 | 7243 |
| Core inlet temperature (°C) | 543-545 | 543 |
| Total core pressure drop (from bottom of the core support plate to top of the core) (kPa) | 70.0 | 47.0 |
| Core plate pressure drop (kPa) | 41.3 | 31.5 |
| Core maximum exit void fraction | 0.916 | 0.90 |
| Downcomer liquid level (m) | 17.27 | 17.6 |

# MELCOR-Simulated Accident Scenario

- Transient event initiated by a loss of feedwater (i.e., scenario T_DP_nIN of the ESBWR PRA):
  - Short or long-term coolant injection to RPV not available (i.e., GDCS injection to RPV & wetwell injection through equalization lines not available).
  - ADS is assumed to be actuated if downcomer water level drops below 11 m.
  - Heat removal by ICs not credited.
  - PCC & PCC/IC pool makeup available (thereby allowing long-term containment heat removal).
  - GDCS deluge system is also available for injection onto the lower drywell floor.

# MELCOR-Simulated Accident Scenario (Cont.)

- Two cases considered:
  - Case 1: MCCI allowed to occur (assuming MELCOR standard basaltic concrete composition).
  - Case 2: MCCI suppressed

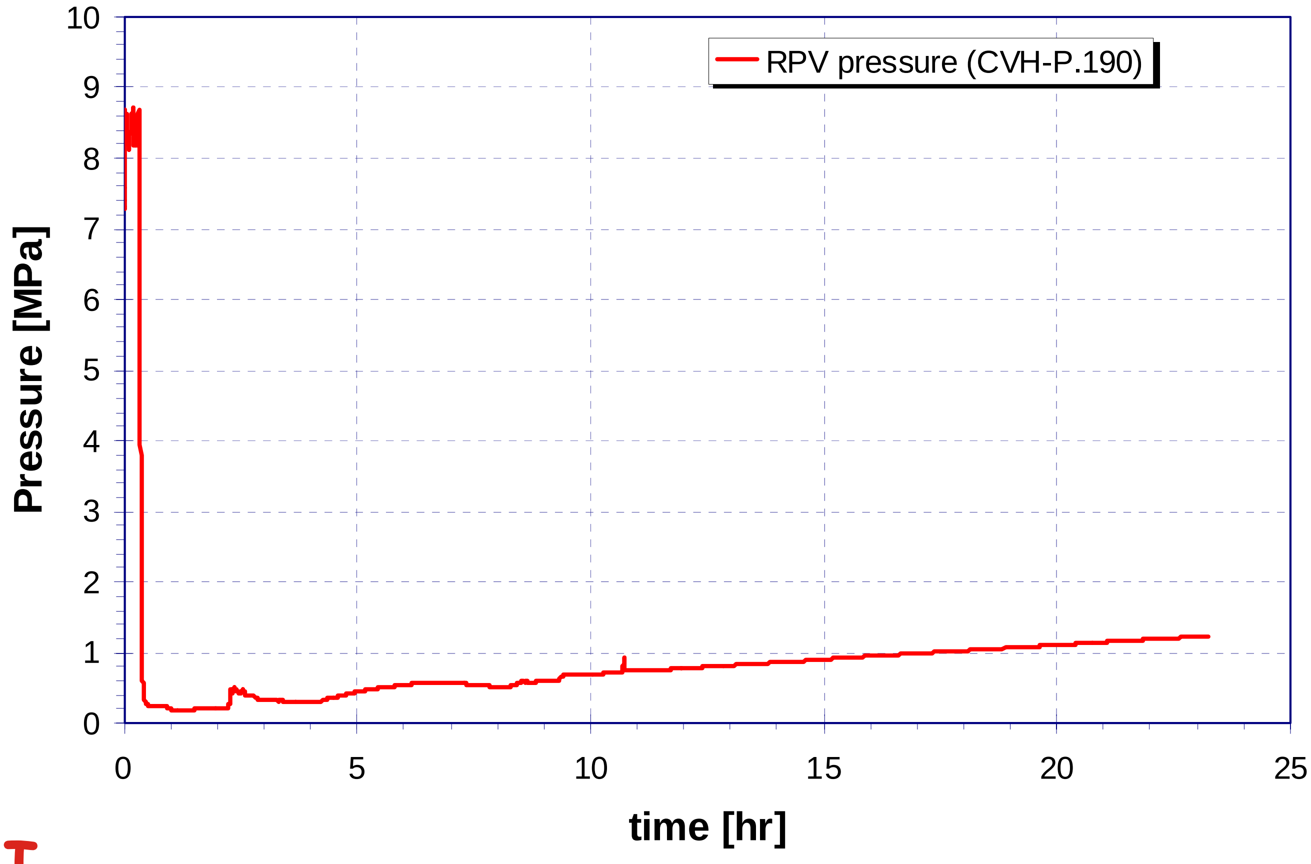
# Preliminary Results (Case 1: With MCCI)

| Event | Value |
|---|---|
| RPV depressurization starts (DPVs open), hour | 0.33 |
| Start of core uncovery, hour | 0.86 |
| Start time of gap release from fuel, hour | 1.08 |
| Range of relocation periods in various core regions (i.e., fuel temperature exceeds 2500 K), hour | 1.69 – 3.82 |
| Local failure of the lower core plate (i.e., T=1273K), hour | 2.26 – 2.52 |
| Gross failure (melting) of the lower core plate (i.e., $T \geq 1700K$), hour | N/A |
| RPV lower head penetration failure, hour | 3.91 |
| Start of MCCI, hour | 4.20 |

# Preliminary Results (Case 1: With MCCI) (Cont.)

| Event | Value |
|---|---|
| Water in reactor cavity reaches saturation, hour | 4.36 |
| Actuation of the cavity deluge system, hour | 7.26 |
| Time of GDCS water depletion, hour | 9.0 |
| Total in-vessel hydrogen generation, kg | 603 |
| Percentage of total core zirconium oxidized prior to vessel breach, % | 18.0 |
| Pressure in upper drywell at 24 hours, bar-abs | 12.5 |
| Maximum atmosphere temperature in upper drywell, K | 801 |
| Water level in drywell at 24 hours (relative to bottom of the RPV), m | 11.5 |
| Total combustible gas generation due to MCCI at 24 hours, kg | 4426 kg of CO<br>3038 kg of $H_2$ |
| Axial concrete erosion at 24 hours, m | 1.42 |

# RPV Pressure (Case 1: With MCCI)

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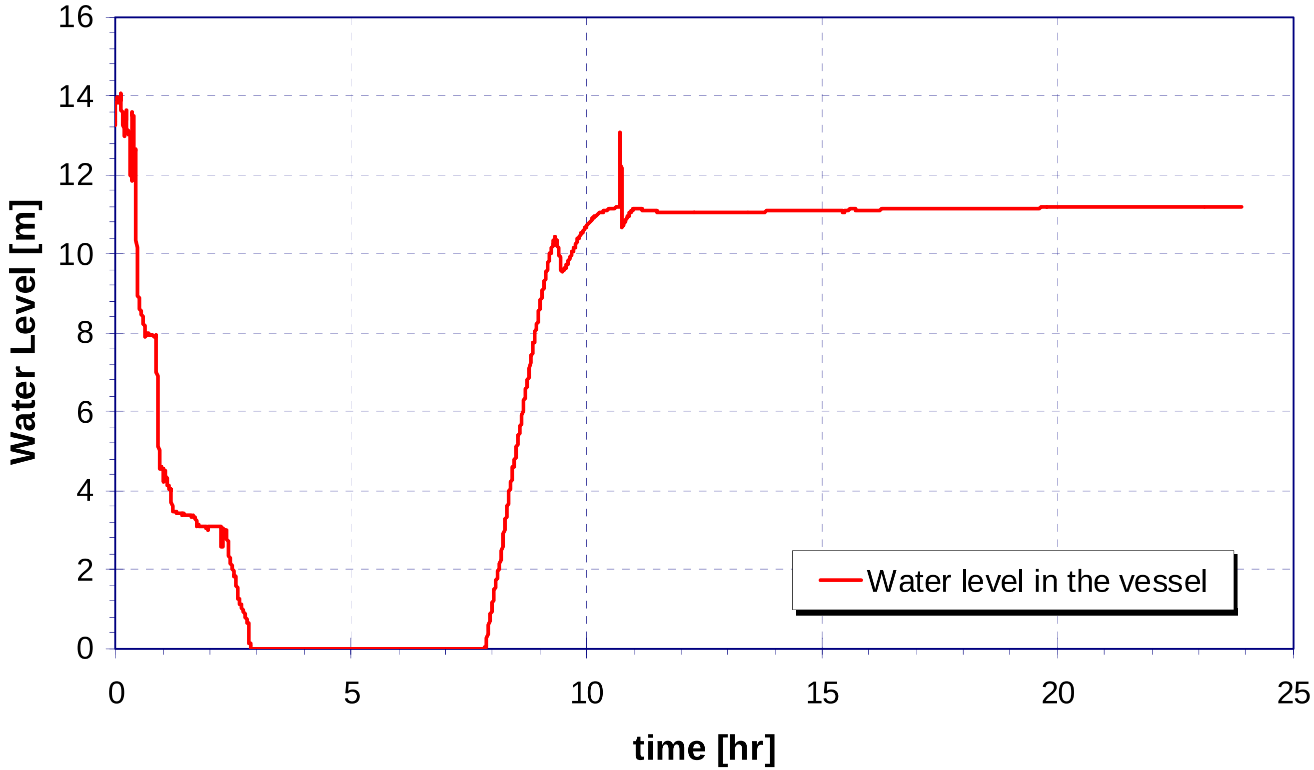
# RPV Water Level (Case 1: with MCCI)

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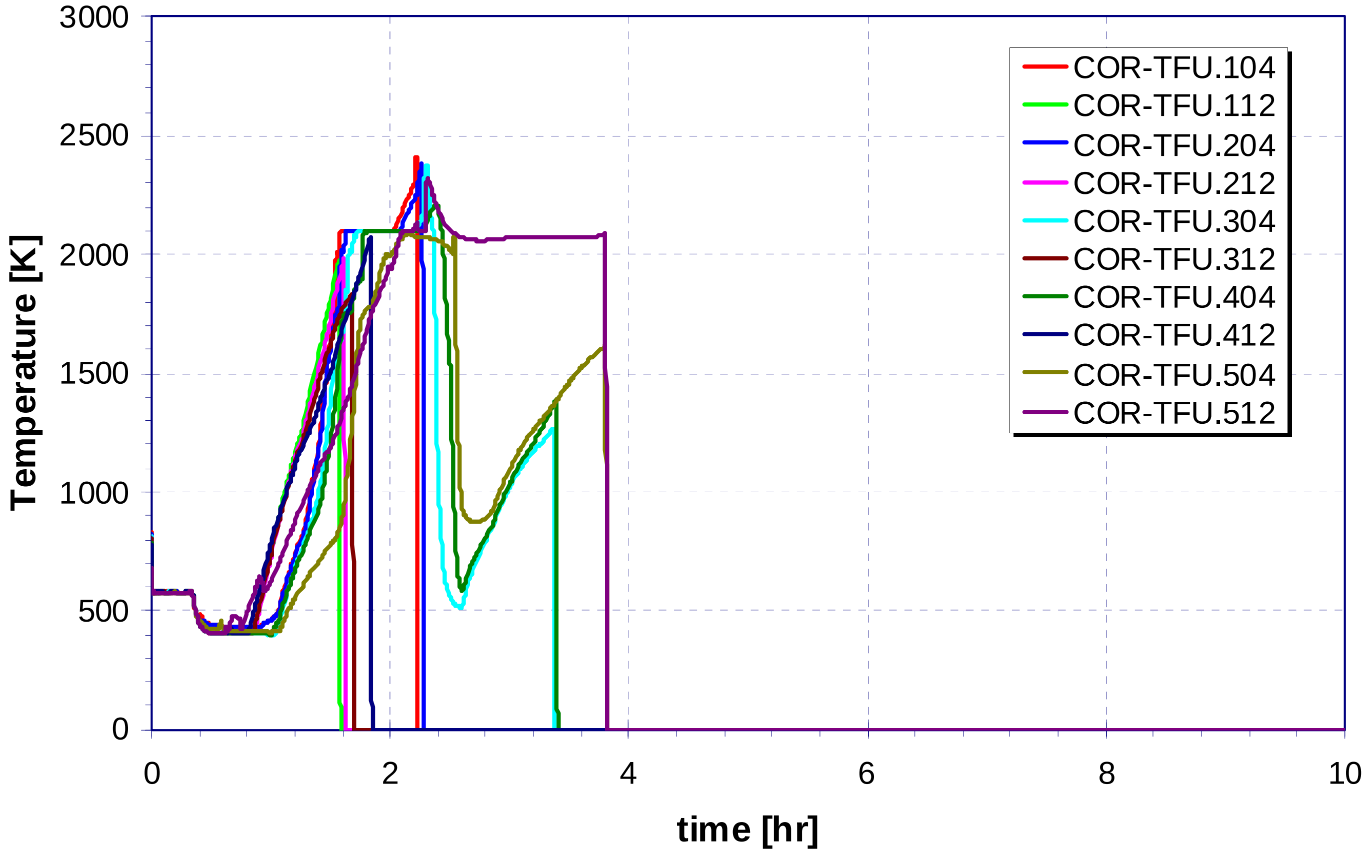
# Fuel Temperature

# (Case 1: with MCCI)

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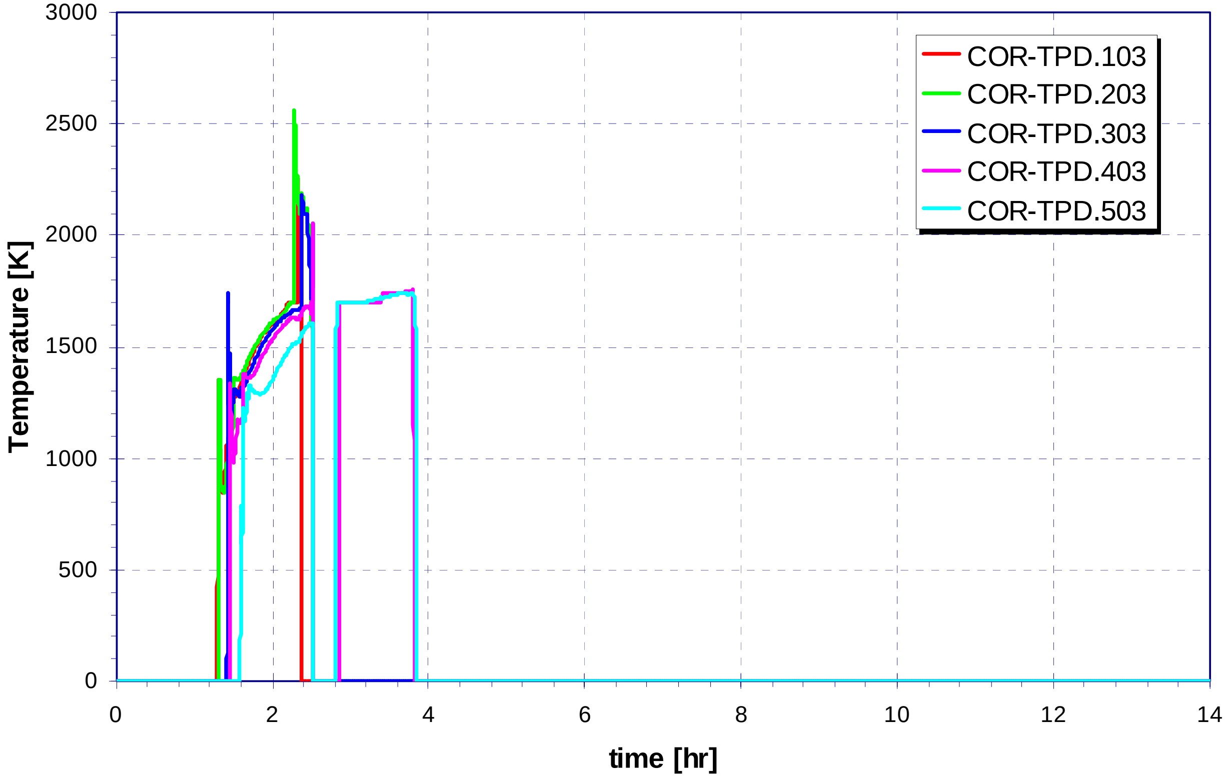
# Temperature of Debris on the Core Plate (Case 1: with MCCI)

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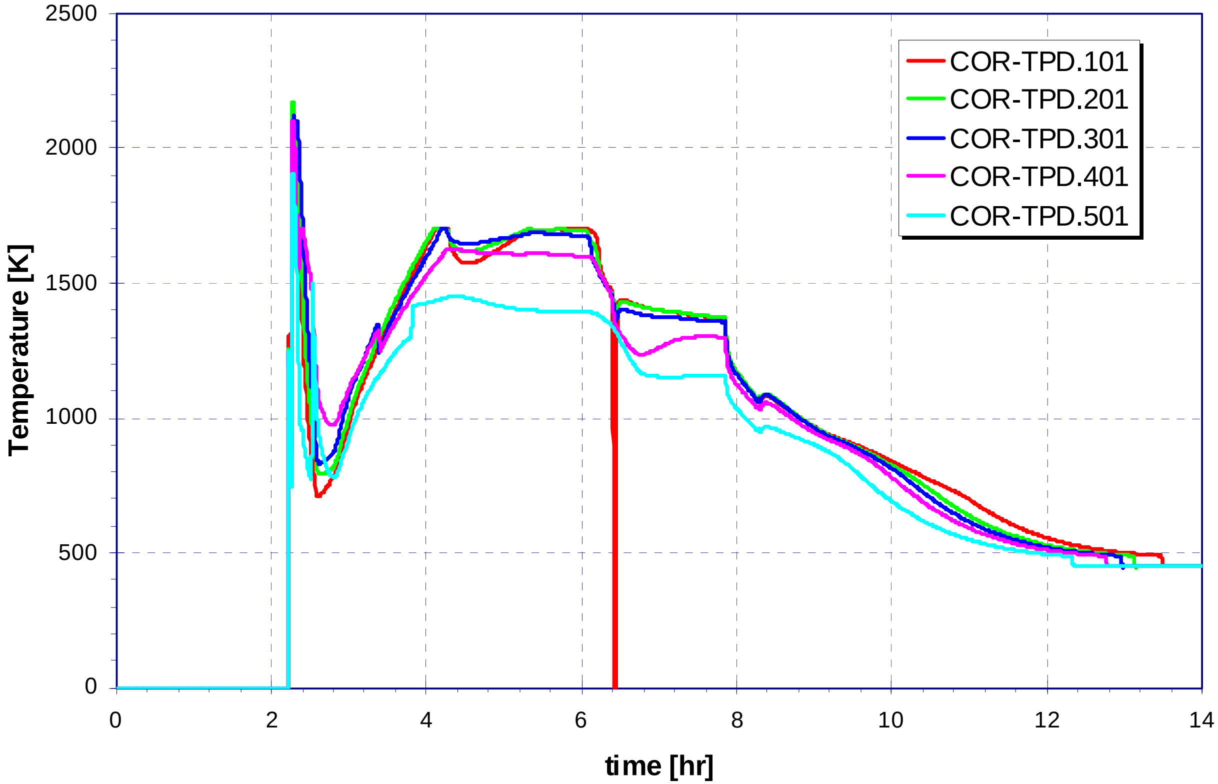
# Debris Temperature in the Lower Plenum (Case 1: with MCCI)

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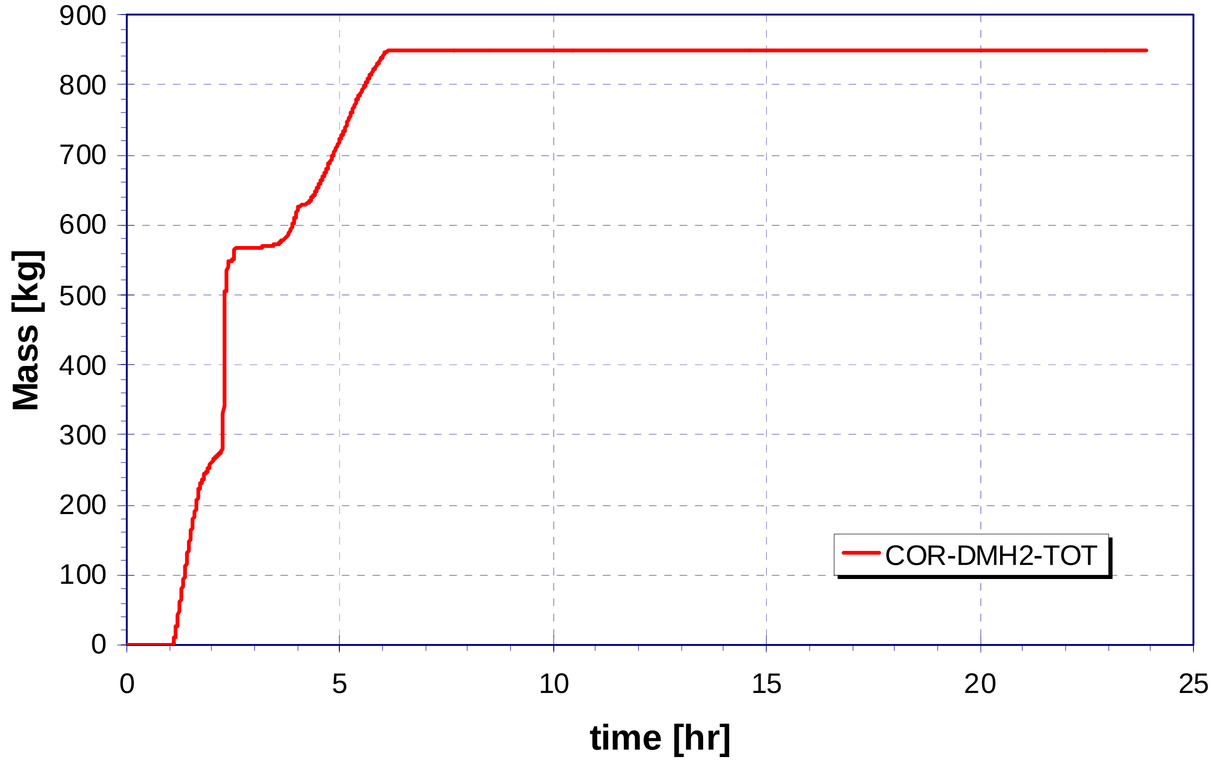
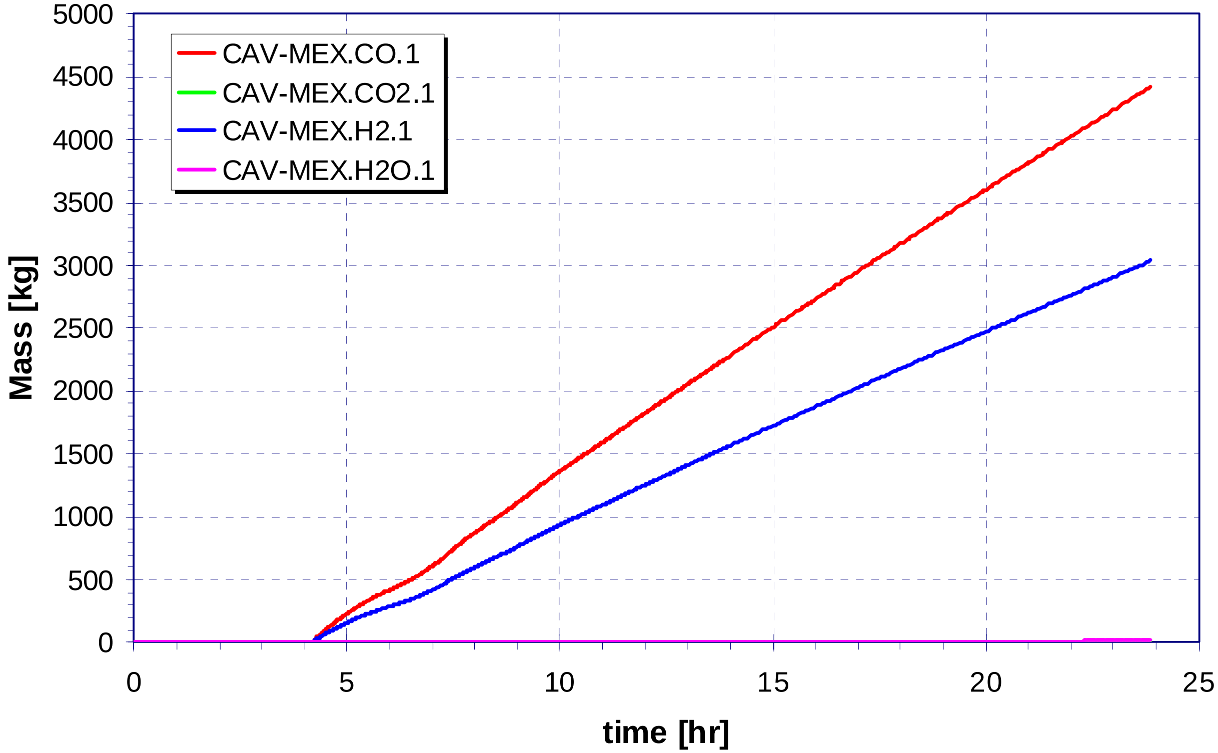
# Total In-Vessel Hydrogen Generation (Case 1: with MCCI)



# Total Gas Generation Due to Core-Concrete Interaction (Case 1: with MCCI)

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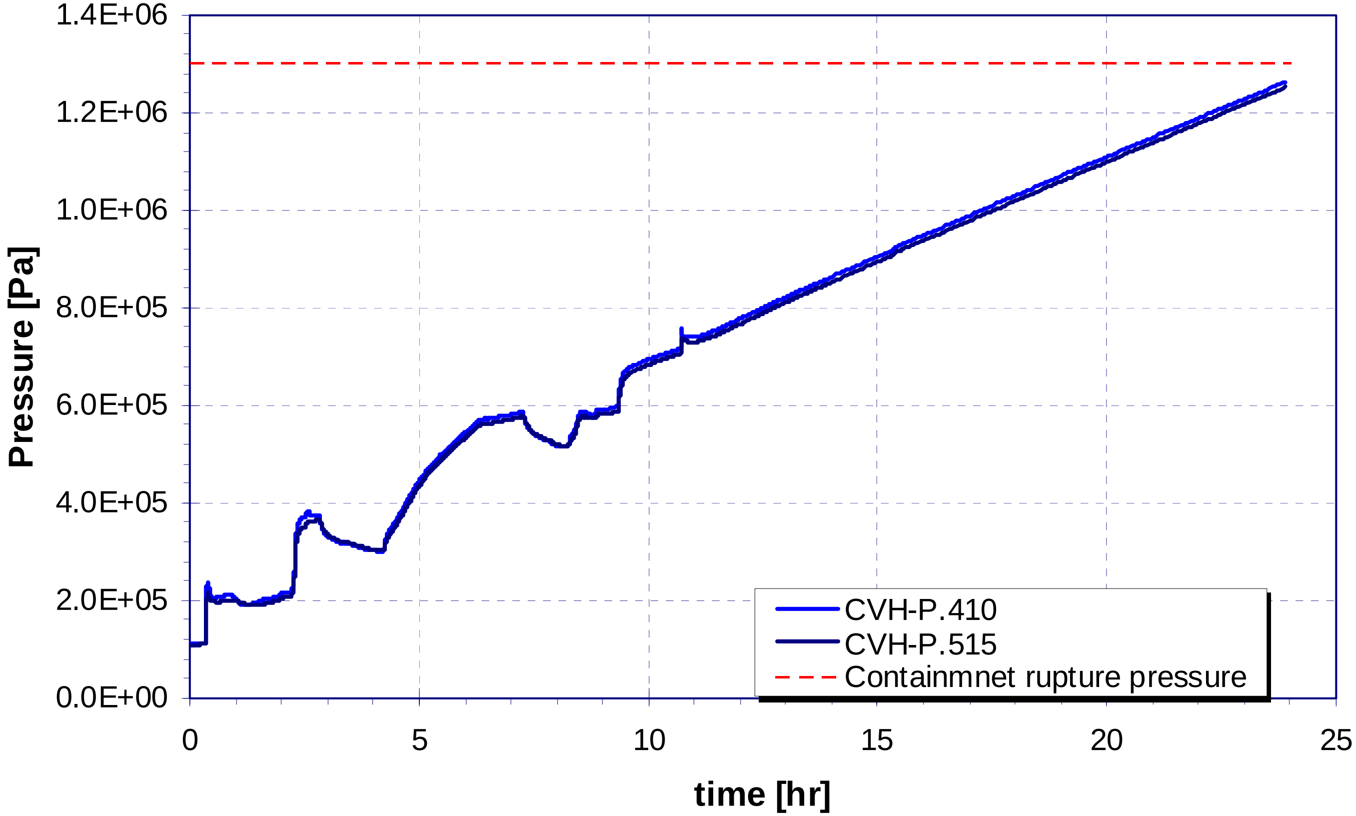
# Upper Drywell and Wetwell Pressure (Case 1: with MCCI)

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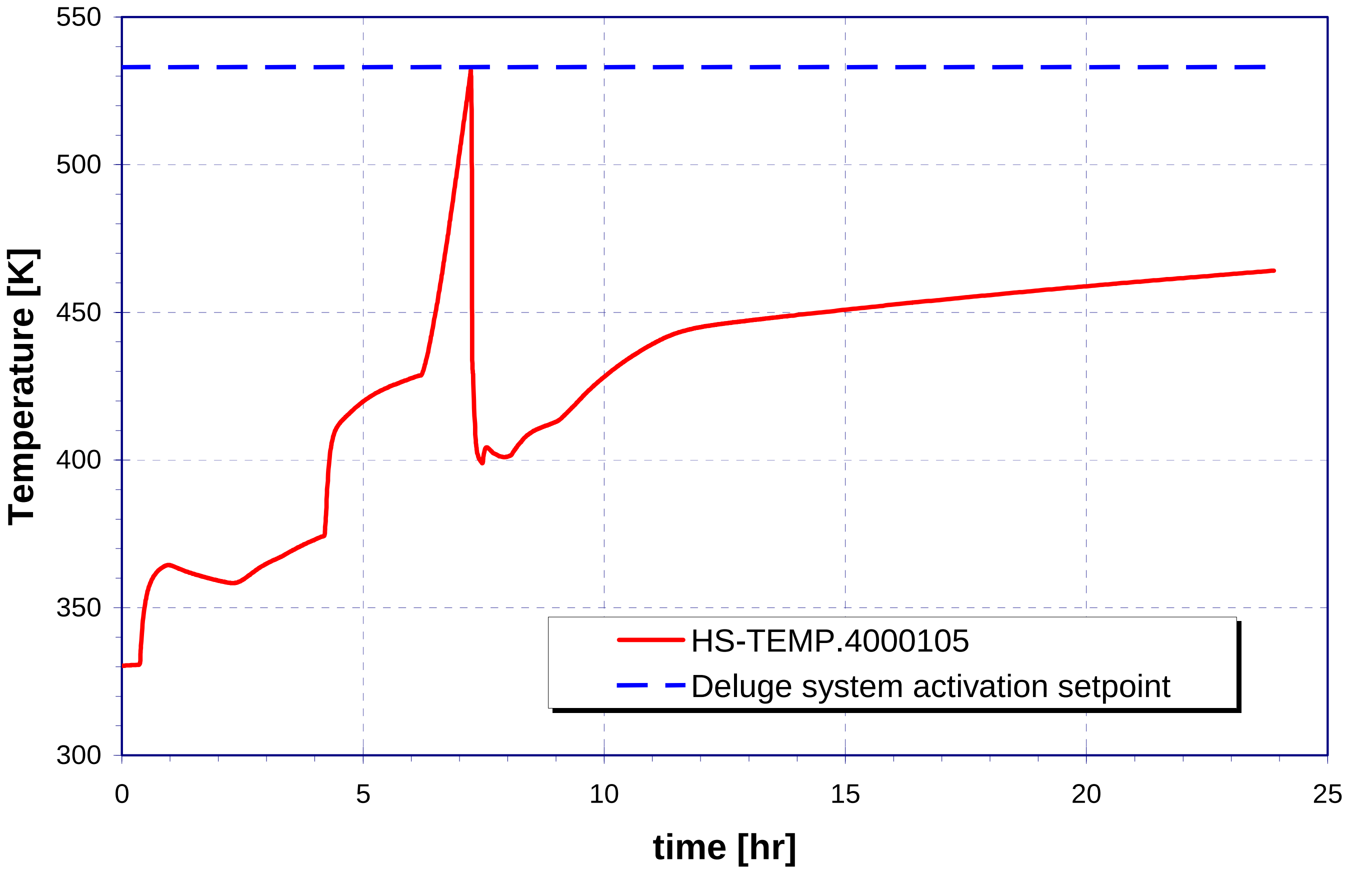
# Containment Concrete Floor Temperature (Case 1: with MCCI)

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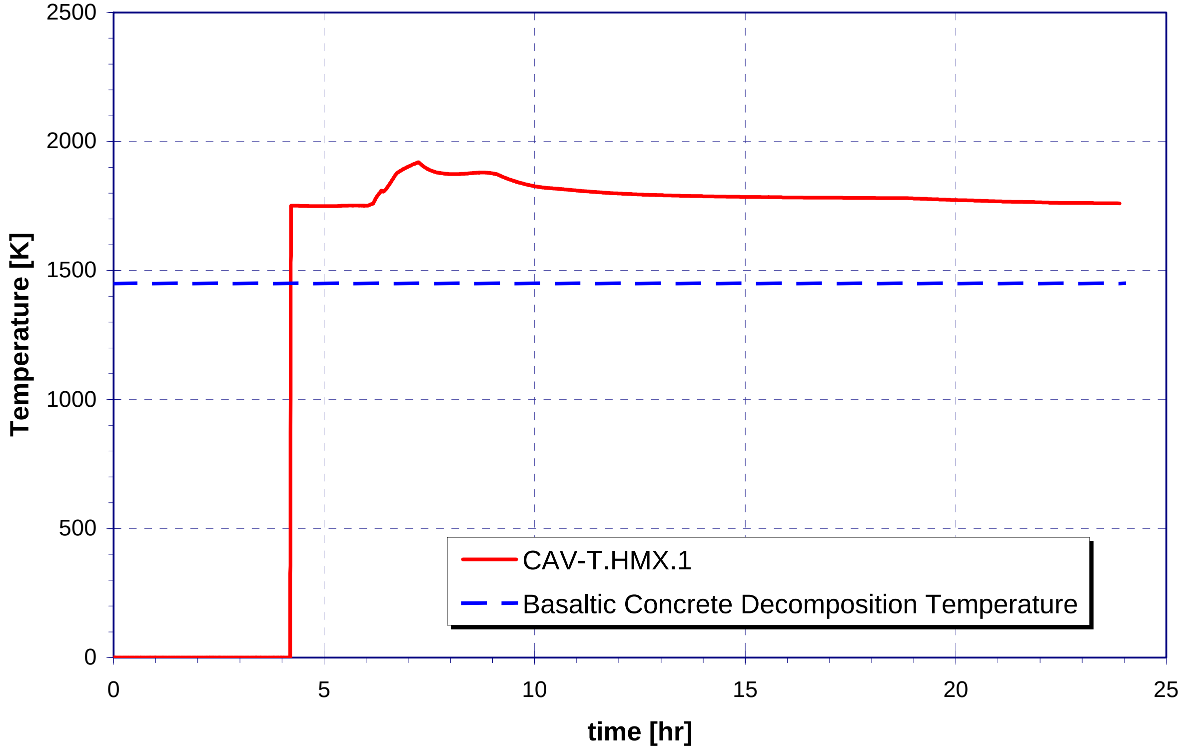
# Debris Pool Temperature in the Lower Drywell (Case 1: with MCCI)

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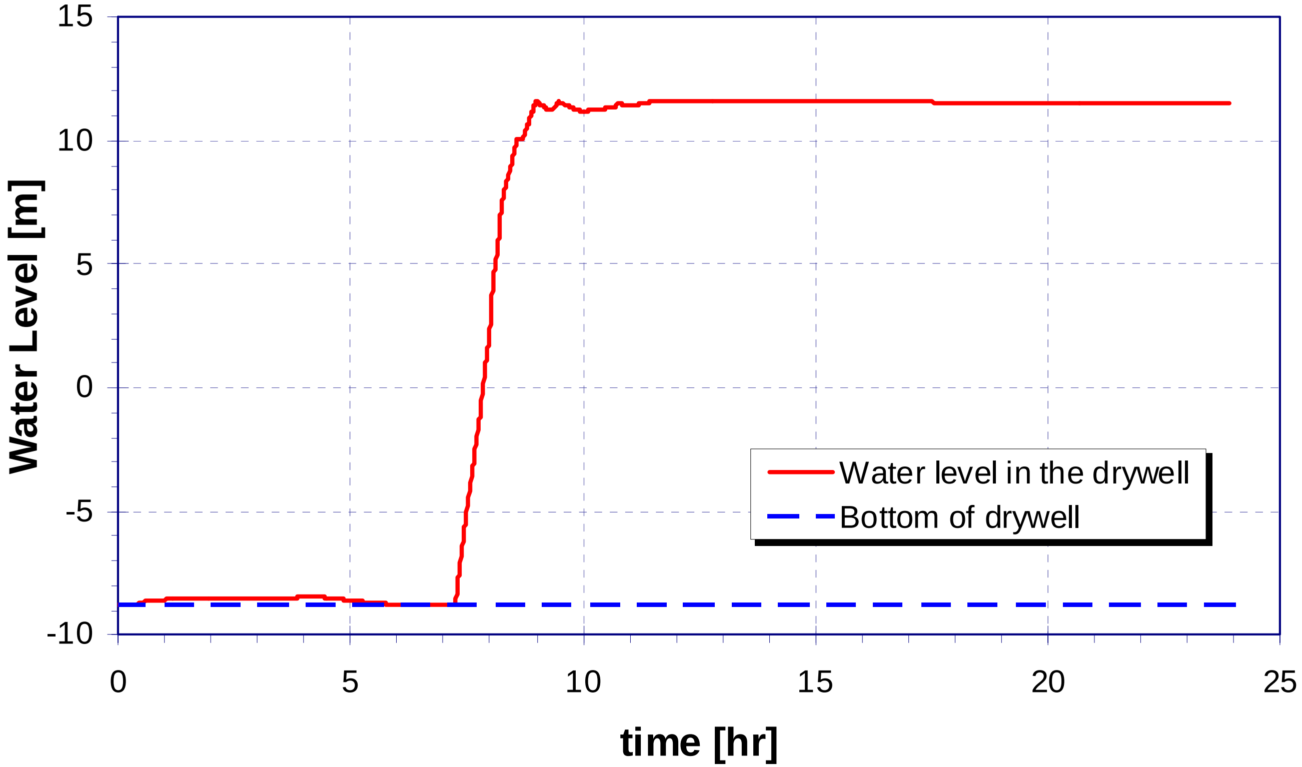
# Water Level on the Containment Floor (Drywell) (Case 1: with MCCI)

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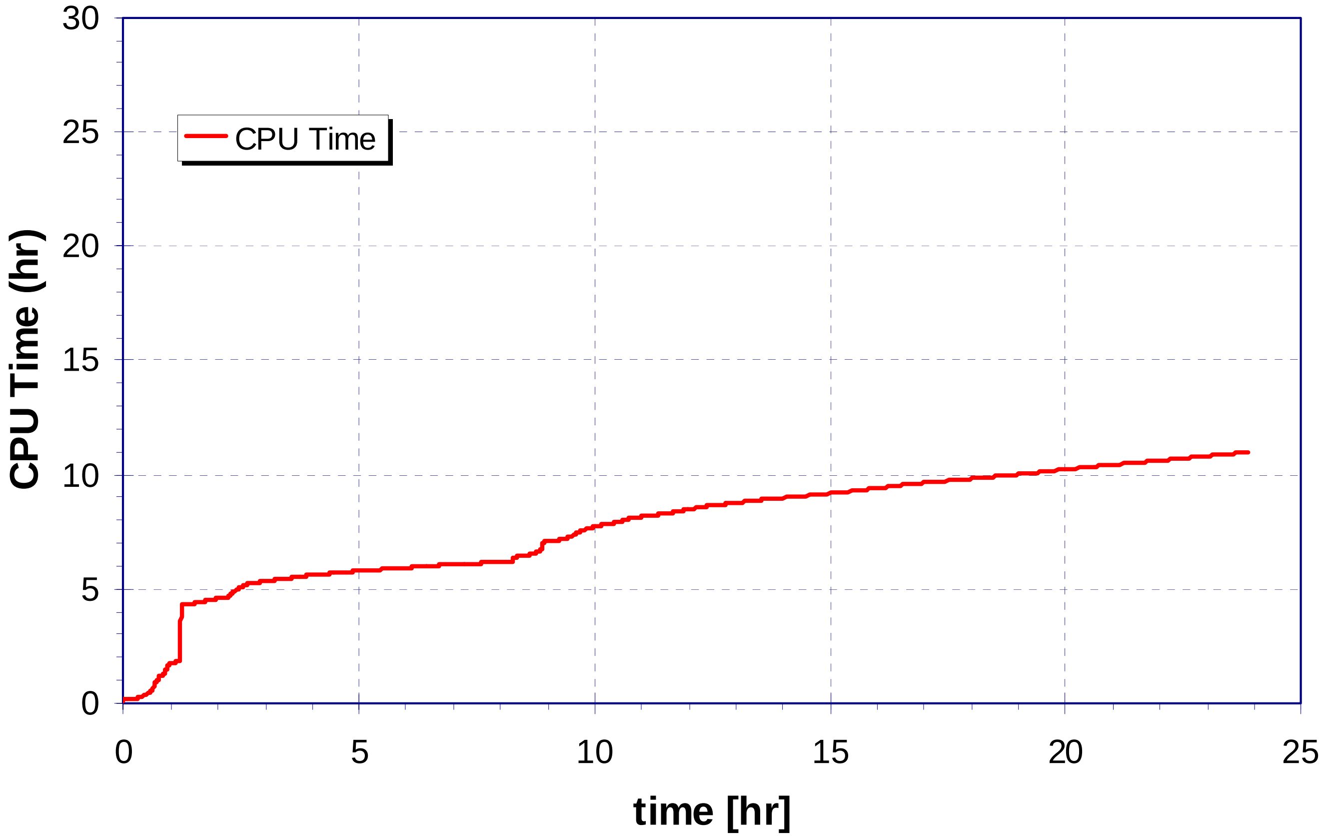
# MELCOR 1.8.5 CPU Time

# (Case 1: with MCCI)

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# Sensitivity to MELCOR Lower Head Model Parameters

| Cases | HTC (debris-LH) (W/m²K) | Debris quenching HTC (W/m²K) | Debris dryout HTC (W/m²K) | Debris fall velocity (m/s) | Particulate debris size (m) | Porosity of particulate debris | Conduction enhancement for molten components | Radiation exchange factor | Candling HTC (W/m²K) |
|---|---|---|---|---|---|---|---|---|---|
| Case 1 | 1000 (def.) | 100 (def.) | ~11 (def. C1242) | 1.0 (def) | 0.001 | 0.3 | 3200K/0.01 (def) | 0.25 (def) | 1000 (def) |
| Case 2 | 100 | | | | | | | | |
| Case 3 | | 10000 | | | | | | | |
| Case 4 | | | | | | 0.5 | | | |
| Case 5 | 20(2) | 220 | | | 0.025 | 0.4 | | FCELR and FCELA=0.1 others=0.25 | 7500 for UO2, Zr, ZrO2 others=2500 |
| Case 6 Best Estimate | 200 | 1300 | | | 0.025 | 0.5 | | FCELR and FCELA=0.1 others=0.25 | 7500 for UO2, Zr, ZrO2 others=2500 |

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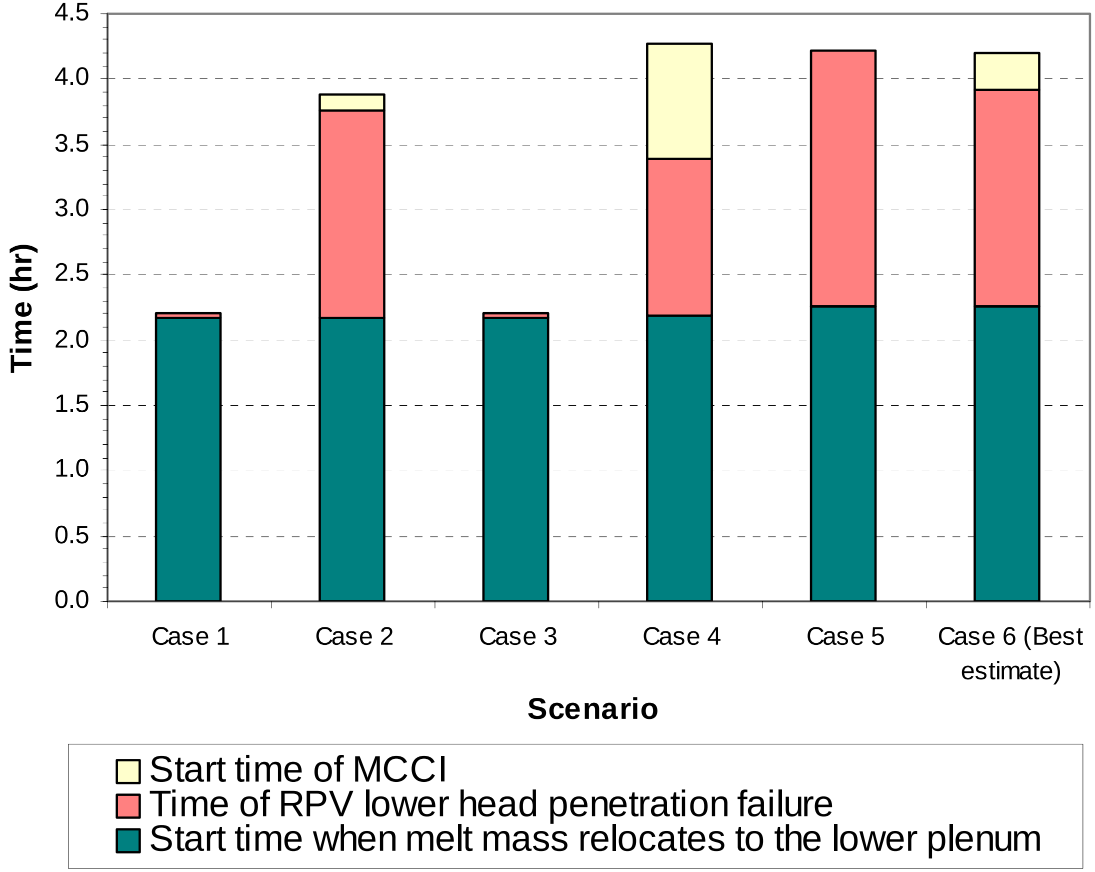
# Sensitivity to MELCOR Lower Head Model Parameters (Cont.)

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# Comparison With MAAP Results (Case 2: Without MCCI)

| Event | MAAP* | MELCOR |
|---|---|---|
| RPV depressurization starts (DPVs open), hour | $8.6\times10^{-3}$ | 0.33 |
| Start of core uncovery, hour | 0.36 | 0.86 |
| Onset of core damage (i.e., fuel temperature exceeds 2500 K), hour | 0.97 | 1.69 |
| RPV lower head penetration failure, hour | 6.3 | 3.91 |
| Deluge system actuated, hour | 6.3 | 7.9 |
| Containment (upper drywell) pressure at 24 hours, bar-abs | 5.0 | 4.8 |
| Containment (lower drywell) temperature at 24 hours, K | 425 | 427 |
| Containment fail/vent, hour | N/A | N/A |
| PCCS heat removal at 24 hours, MW | 18.5 | 22.7 |
| Water level in drywell at 24 hours (relative to bottom of the RPV), m | 13.1 | 12.5 |
| Axial concrete erosion in 24 hours, m | 0.07 | 0.0 |
| Mass fraction of noble gases released to environment | $9.0\times10^{-4}$ | $8.7\times10^{-4}$ |
| Mass fraction of CsI released to environment | $7.4\times10^{-5}$ | $1.8\times10^{-5}$ |

*MAAP results taken from NEDC-33201P (Rev 0)

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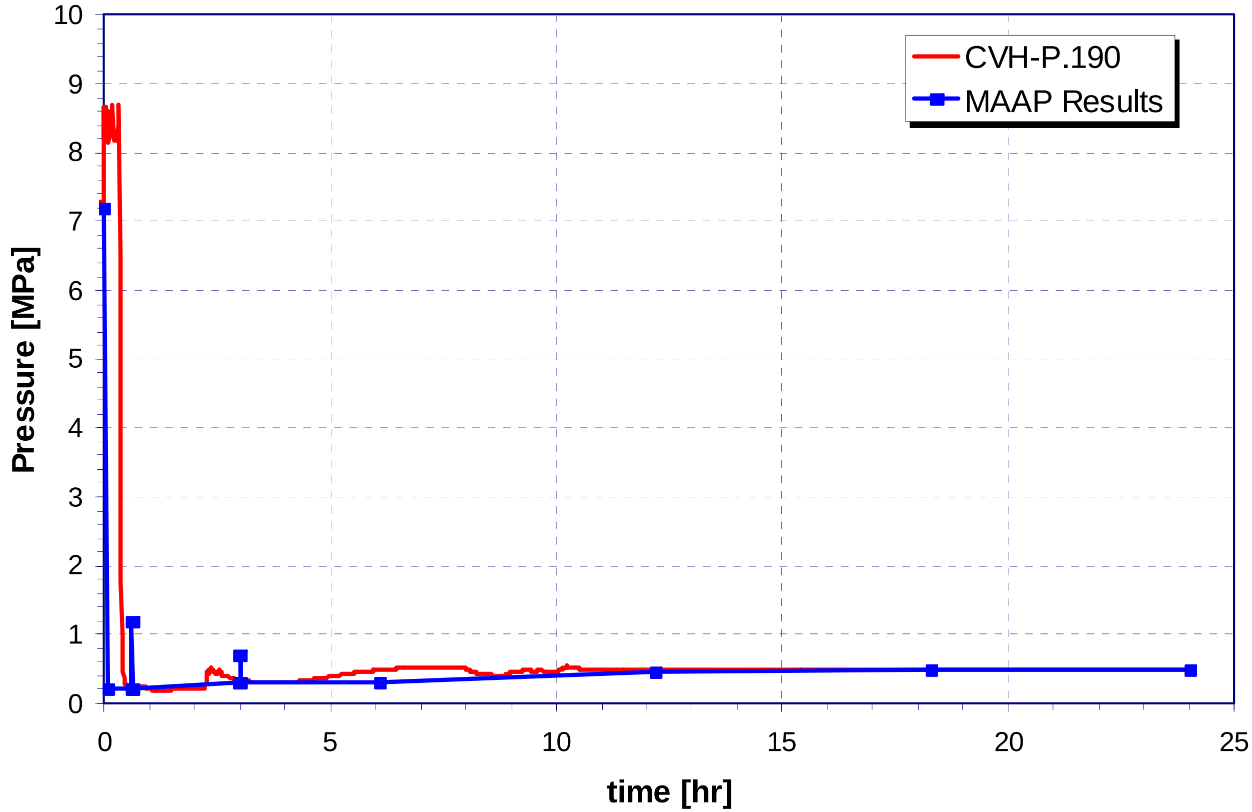
# RPV Pressure (Case 2: Without MCCI)




MAAP results taken from NEDC-33201P (Rev 0)

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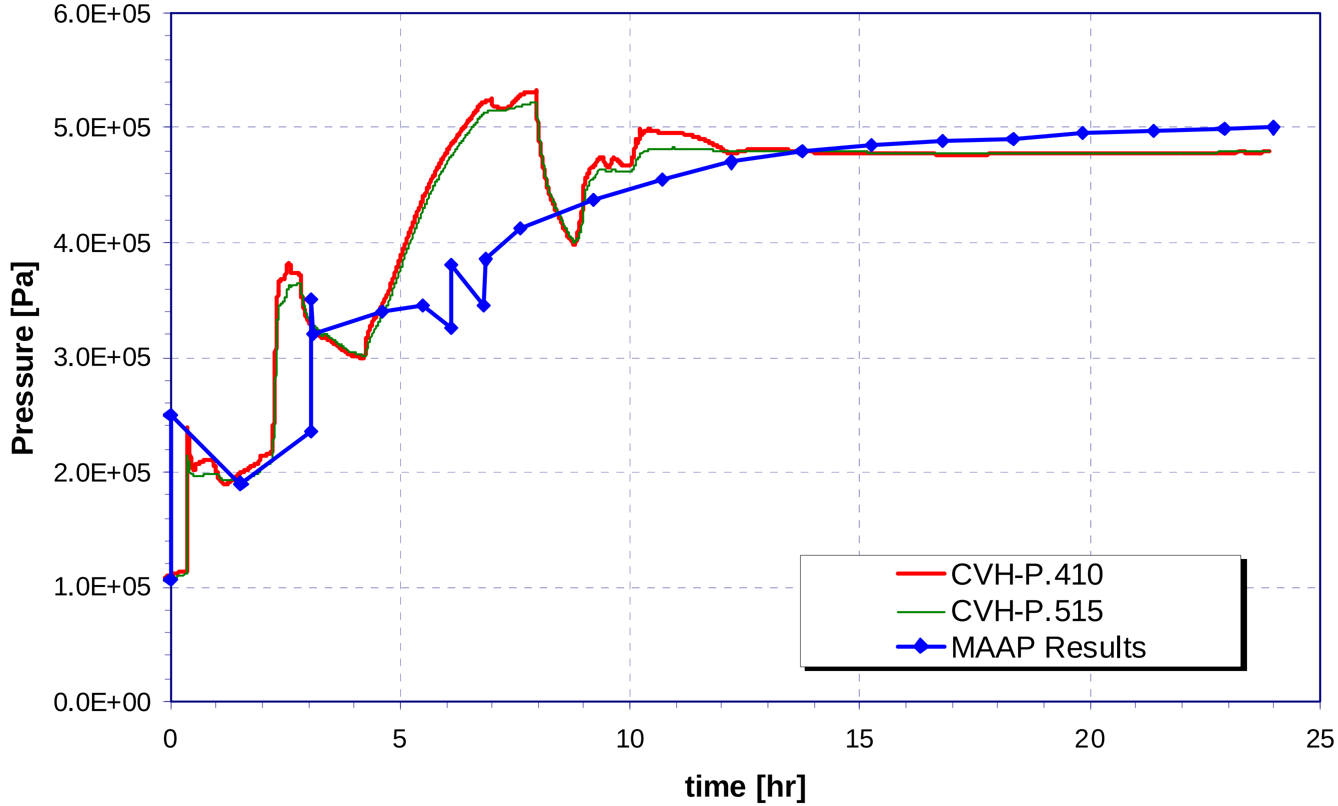
# Upper Drywell and Wetwell Pressure

# (Case 2: Without MCCI)




MAAP results taken from NEDC-33201P (Rev 0)

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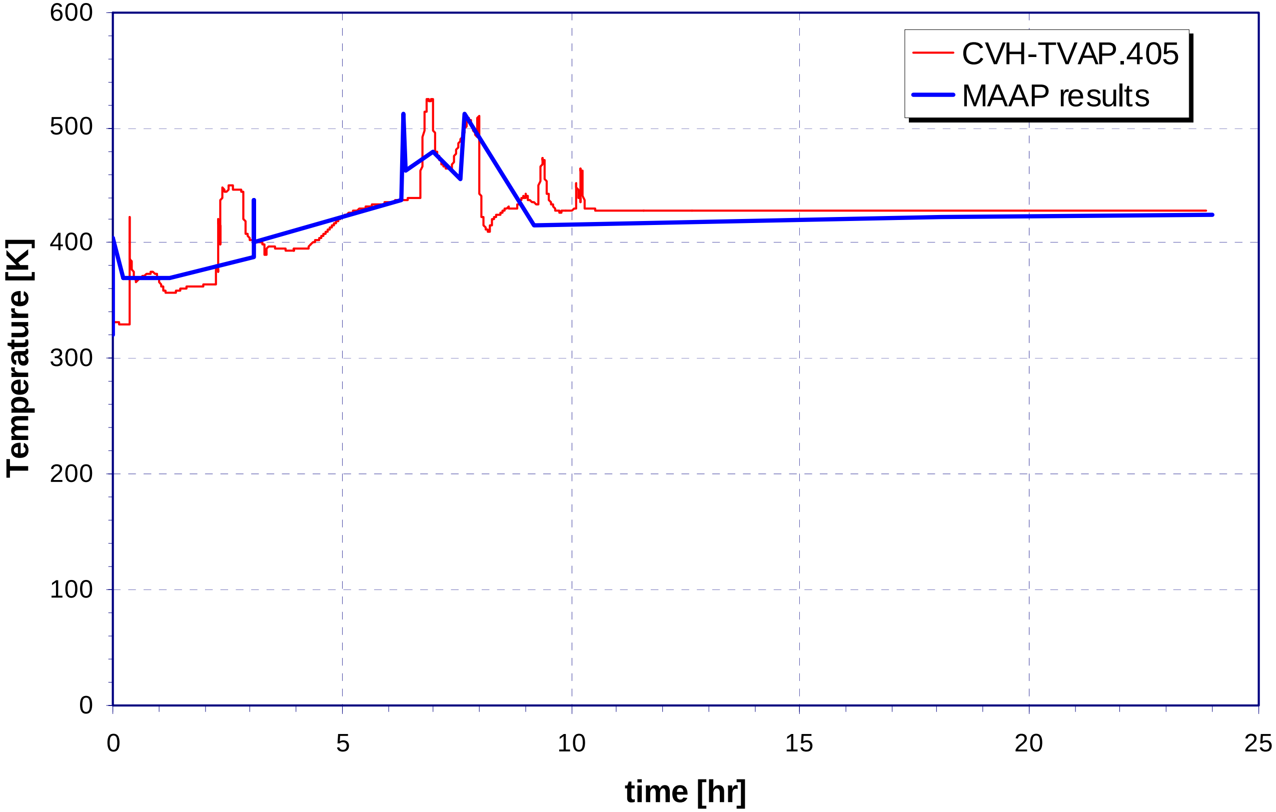
# Lower Drywell Temperature

# (Case 2: Without MCCI)




MAAP results taken from NEDC-33201P (Rev 0)

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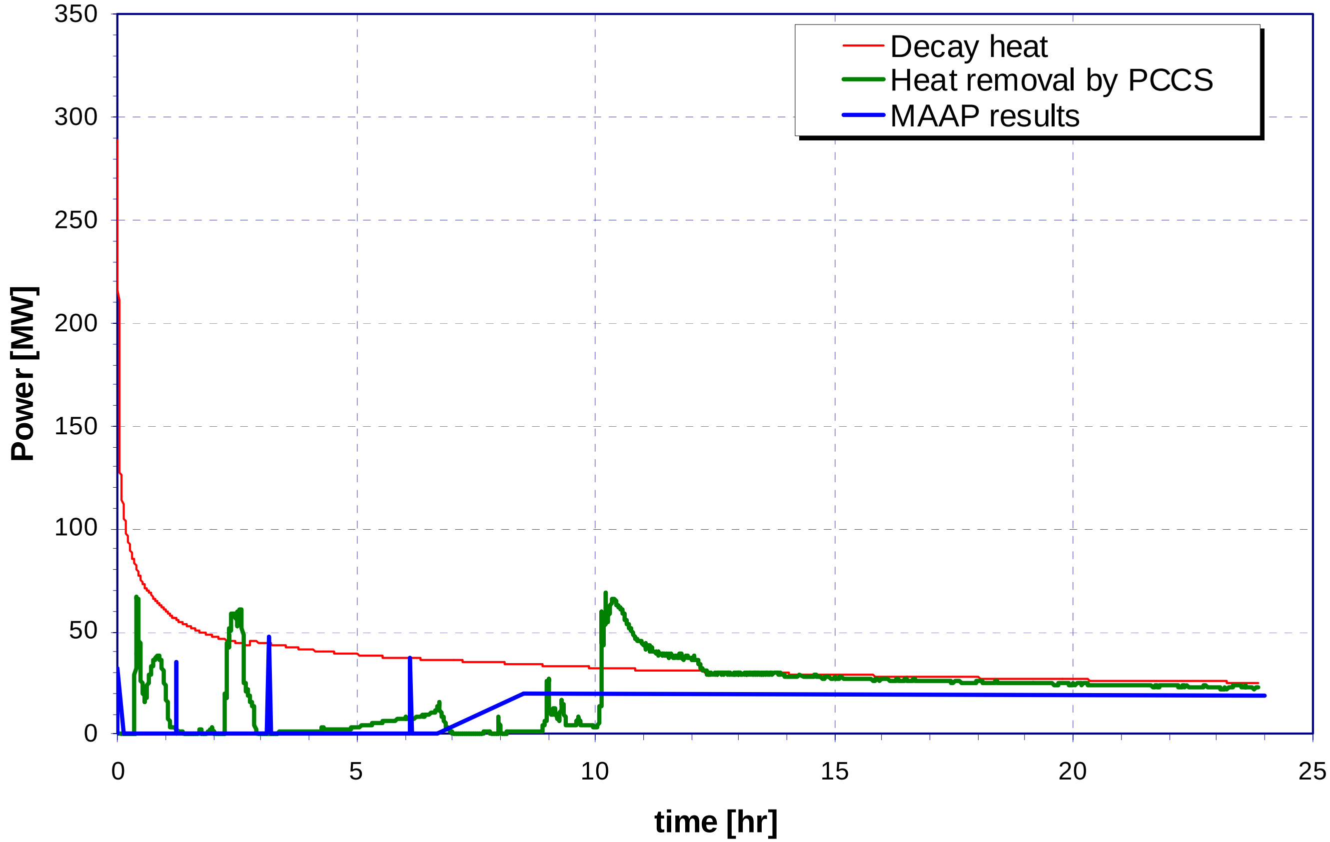
# Decay Heat Generation and Heat Removal by PCCS (Case 2: Without MCCI)




MAAP results taken from NEDC-33201P (Rev 0)

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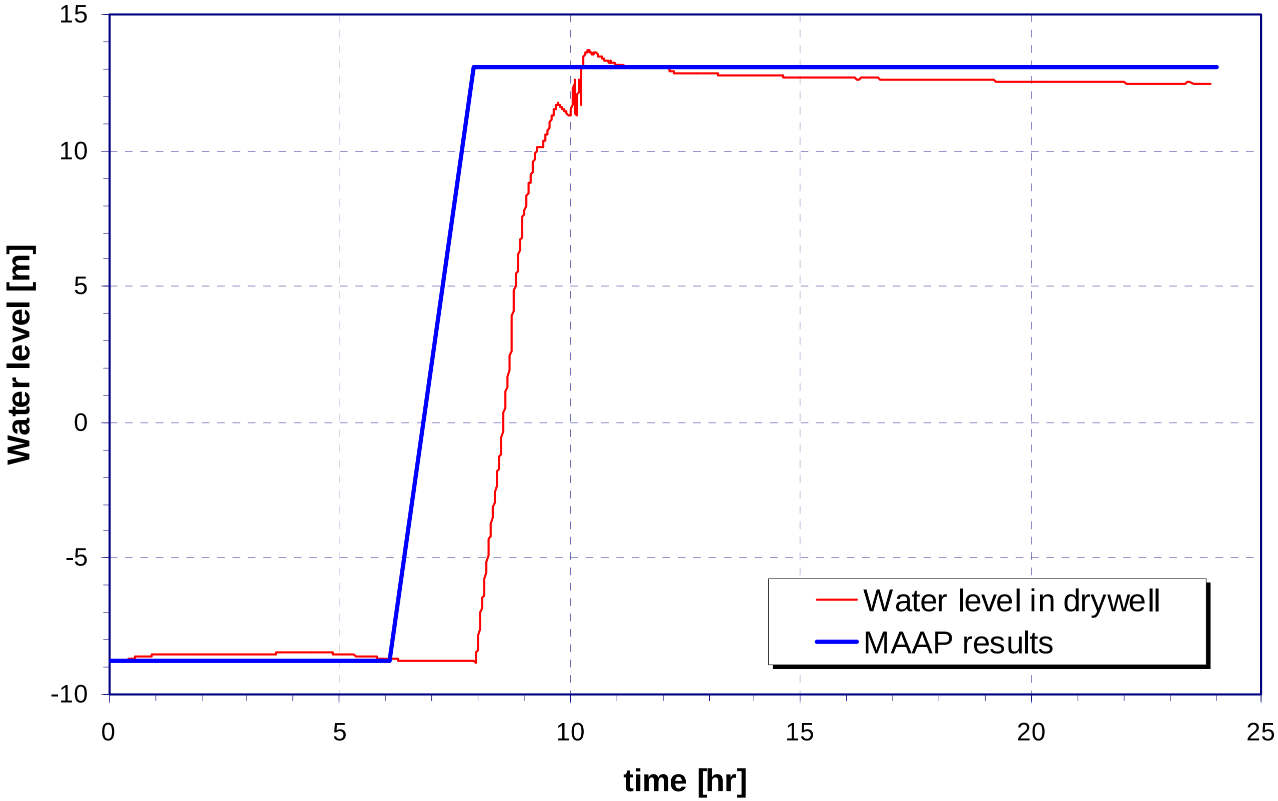
# Water Level in the Drywell

# (Case 2: Without MCCI)




MAAP results taken from NEDC-33201P (Rev 0)

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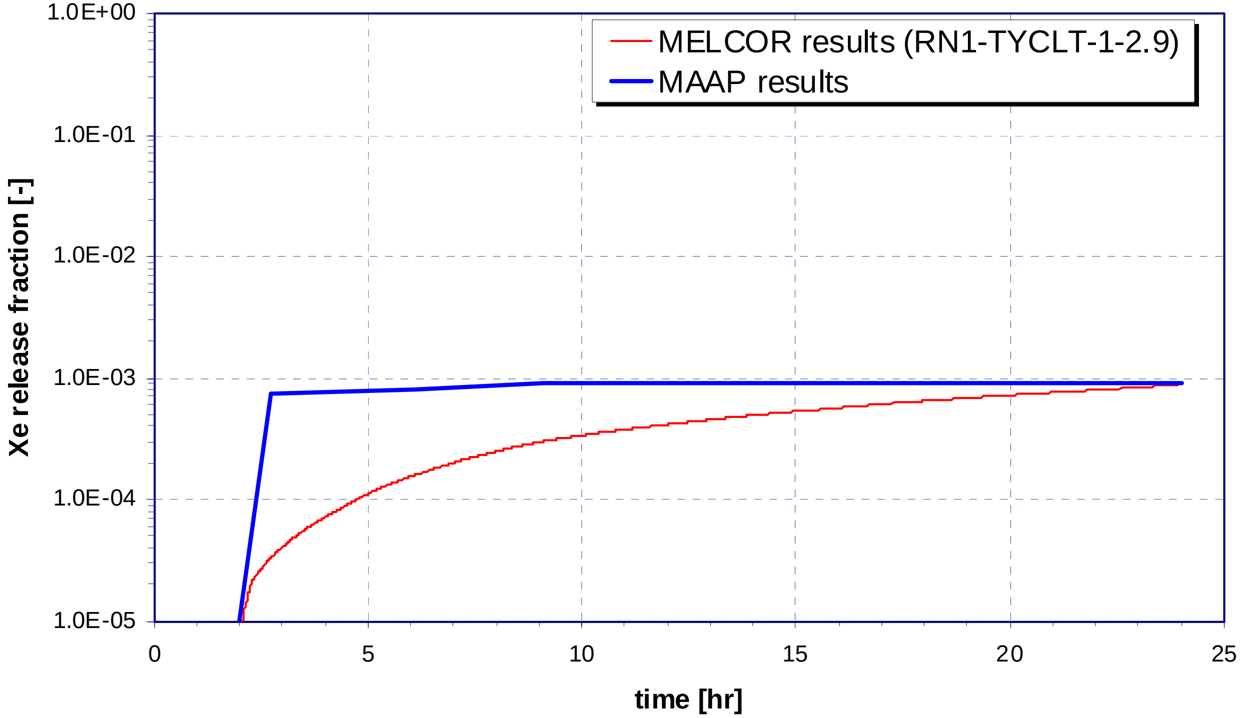
# Release of Noble Gases to the Environment

# (Case 2: Without MCCI)




MAAP results taken from NEDC-33201P (Rev 0)

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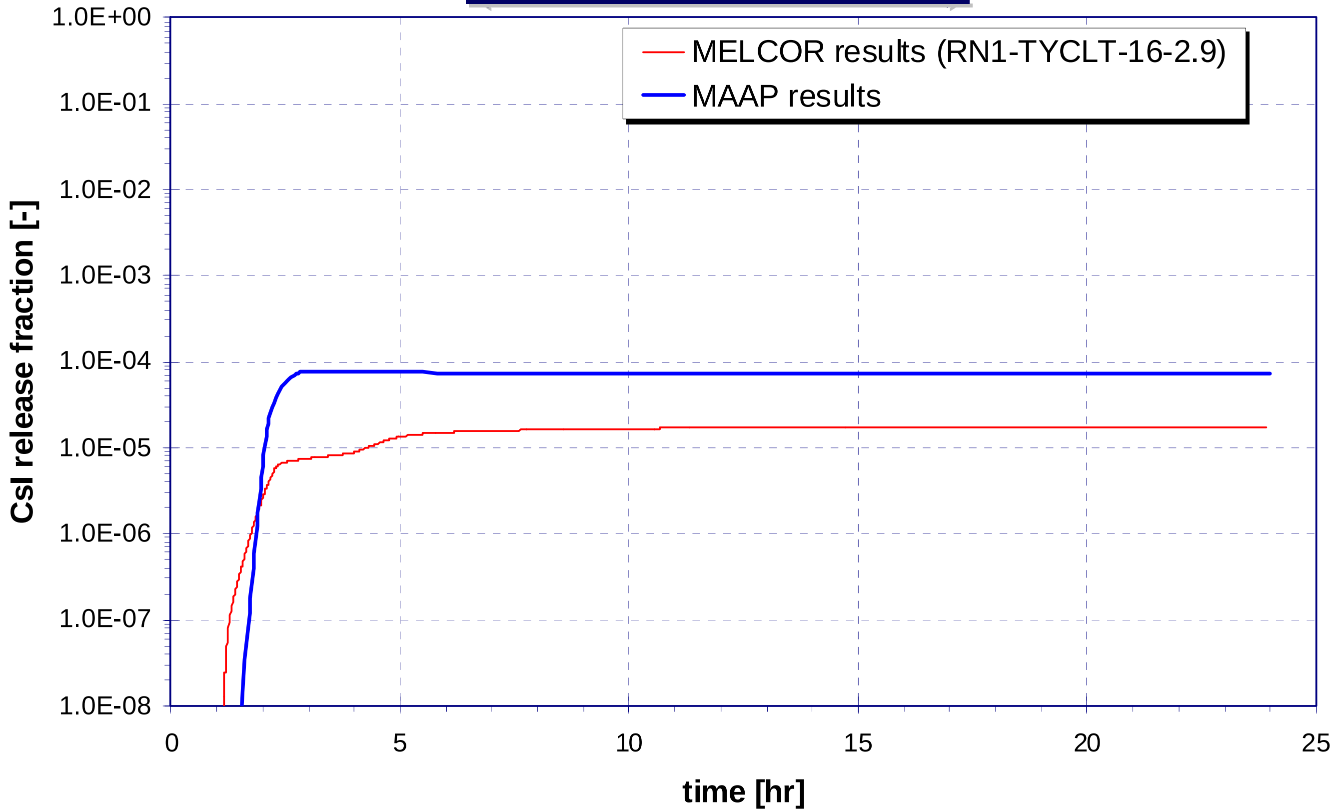
# Release of CsI to the Environment (Without MCCI)




MAAP results taken from NEDC-33201P (Rev 0)

MELCOR calculations use the CORSOR-BOOTH option for in-vessel releases

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# SUMMARY

- Generally, MELCOR and MAAP results are in reasonable agreement
- Desirable to have a discussion of MAAP modeling/parametric assumptions to better resolve some of the observed differences, e.g.,
  - Debris/water/LH interactions
- Comparison of calculated source term

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# REMAINING DATA NEEDS

- Containment spray system
  - The elevation of the containment spray header inside the drywell;
  - Spray water temperature; and
  - Spray mean droplet diameter.
- Containment venting system
  - Elevations of containment venting system in both the suction and the discharge sides; and
  - Length of various pipe sections in the vent lines.

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# REMAINING DATA NEEDS (Cont.)

- PCCS and IC system
  - The pipe wall thickness of the PCCS and IC inlet lines.
  - The inlet pipe location relative to PCCS/IC pool and if it is insulated
- Additional BiMAC system design data may become necessary, after the DCD information is more carefully examined.

# Planned Calculations

- Rationale for selection of scenarios:
  - To provide initial & boundary conditions for NRC confirmatory analyses (e.g., FCI, DCH, BiMAC, etc.)
  - To enable limited comparison to MAAP predictions
  - To assess sensitivity to design/operational aspects (e.g., sprays)
  - To support other NRC objectives
- "Frequency-dominant", "risk-dominant" and "consequence-dominant" scenarios will be examined, together with influence of various assumptions and sensitivity cases

| Case | MELCOR SCENARIO | ACC. CLASS | COMMENTS | EXPLORATORY OR CONFIRMATORY | SENSITIVITIES |
|---|---|---|---|---|---|
| 1 | T_DP_nIN | I | High CDF, Representative of low pressure sequences | Confirm | BiMAC availability, PCCS damage/failure after core damage |
| 2a | T_IRV_DP_nIN_nD | I | Highest societal risk & 3rd highest societal consequences & individual risk | Confirm | Concrete types, overlaying water pool |
| 2b | T_IRV_DP_nIN_nDv | I | 3rd highest individual risk | Confirm | |
| 2c | T_IRV_DP_nIN_nD_M | I | 2nd highest risk & consequences & individual risk | Confirm | |
| 2d | T_IRV_DP_nIN_nD_1in | I | 3rd highest societal consequences | Confirm | |
| 3a | T_DP_nIN_W2 | II | Containment failure prior to CD, CHR fails @ 24 hrs | Confirm | |
| 4 | T_IC24_nD | III | Representative of high-pressure scenarios. Add DCH, HPME/creep rupture of MSL nozzles and/or SRV | Explore | Drywell spray activation impact on LDL water level |
| 5 | n/a (similar to #3, 15 cm GDCS equalization line break) | II | Frequency-dominant low-pressure sequence. Highest CDF LOCA with initially intact containment | Explore | |
| 6a | T_AT_DP_2x | IV | 3rd high societal risk | Confirm | |
| 7a | BOC_SD_nECC | V | Highest societal consequences | Confirm | |

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