Sensitivity Analysis of the Vessel Lower Head Failure in Nordic BWR using MELCOR Code

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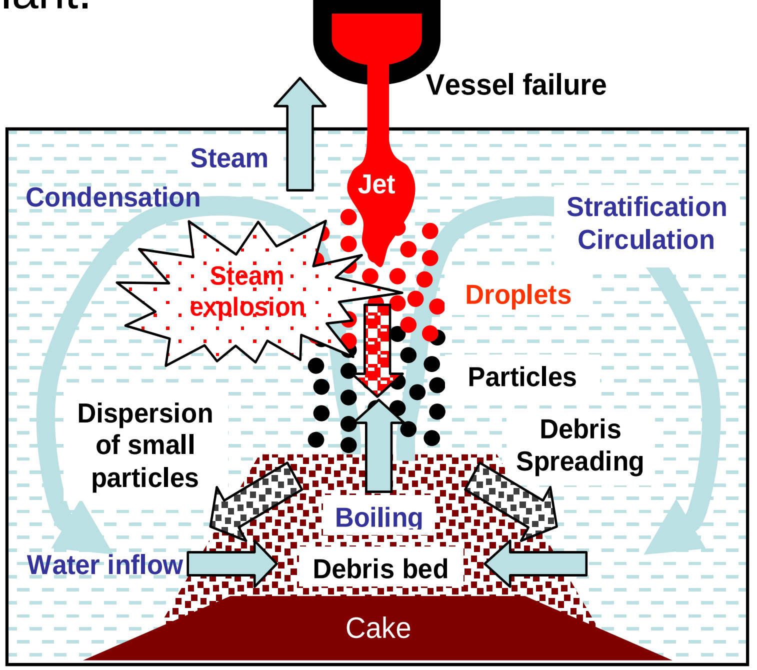
Background (1)

- Severe accident management in Nordic Boiling Water Reactors (BWR) relies on ex-vessel core debris coolability.
  - In case of core melt and vessel failure, melt is poured into a deep pool of water located under the reactor (lower dry well (LDW)).
  - The melt is expected to fragment, quench, and form a debris bed, coolable by natural circulation of water.
- Success of the strategy is contingent upon melt release conditions from the vessel which determine
  - (i) properties of the debris bed and thus if the bed is coolable or not
  - (ii) potential for energetic interaction (steam explosion) between hot liquid melt and volatile coolant.



Background (2)

- Melt release conditions were identified as a major source of uncertainty for success of SAM strategy for Nordic BWR*
  - Massive melt release can results in:
    - Formation of non-coolable debris configuration.
    - Strong ex-vessel steam explosions.
  - Melt release in dripping mode results in:
    - Either no or weak steam explosions.
    - Coolable debris configuration.

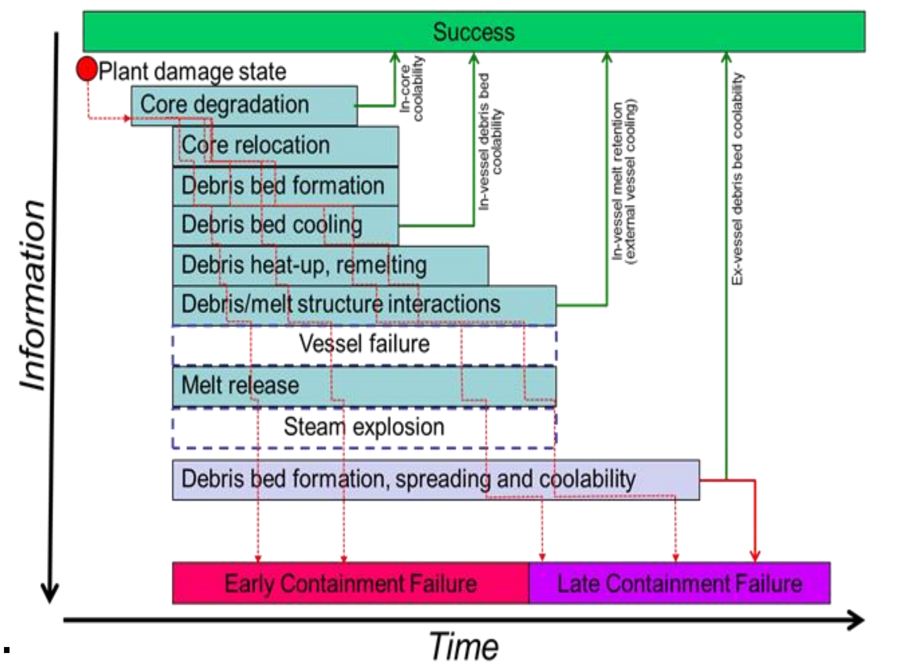


Figure: Severe Accident Progression in Nordic BWR

* P. Kudinov, S. Galushin, D. Grishchenko, S. Yakush, S. Basso, A. Konovalenko, M. Davydov, "Application of Integrated Deterministic-Probabilistic Safety Analysis to Assessment of Severe Accident Management Effectiveness in Nordic BWRs," The 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17) Paper: 21590, Qujiang Int'l Conference Center, Xi'an, China, September 3-8, 2017.

Background (3)

- For prediction of the in-vessel phase of accident progression in Nordic BWR, timings and modes of vessel failure and melt release conditions in different accident scenarios the MELCOR code is used.
  - Currently MELCOR best practices guidelines and several tests performed on lower head failure (LHF) in SNL suggest that the gross creep rupture of the vessel lower head is the most probable mode of vessel failure.
  - On the other hand, failure of penetrations in the lower head might be an important mode of vessel failure in BWRs since there is a forest of control rod guide tubes (CRGTs) and instrumentation guide tubes (IGTs).
- The goal of this work is to perform sensitivity analysis of the vessel lower head failure mode and melt release conditions in Nordic BWR to MELCOR modelling options and sensitivity parameters in different accident scenarios, and identify the major contributors to the uncertainty in timing of vessel failure and melt release conditions.

Nordic BWR MELCOR Model

- MELCOR was chosen as a full model for prediction of the properties of debris bed and vessel failure mode in Nordic BWR.

Current MELCOR model of Nordic BWR has

- Total thermal power output of 3900 MW.
- The core consists of 700 fuel assemblies of SVEA-96 Optima2 type – which divided into five non-uniform radial rings and eight axial levels.
- The primary system is represented by 27 control volumes (CV), connected with 45 flow paths (FL) and 73 heat structures (HS).
- The vessel is represented by a 5(+1)-ring,19-axial level control volume geometry

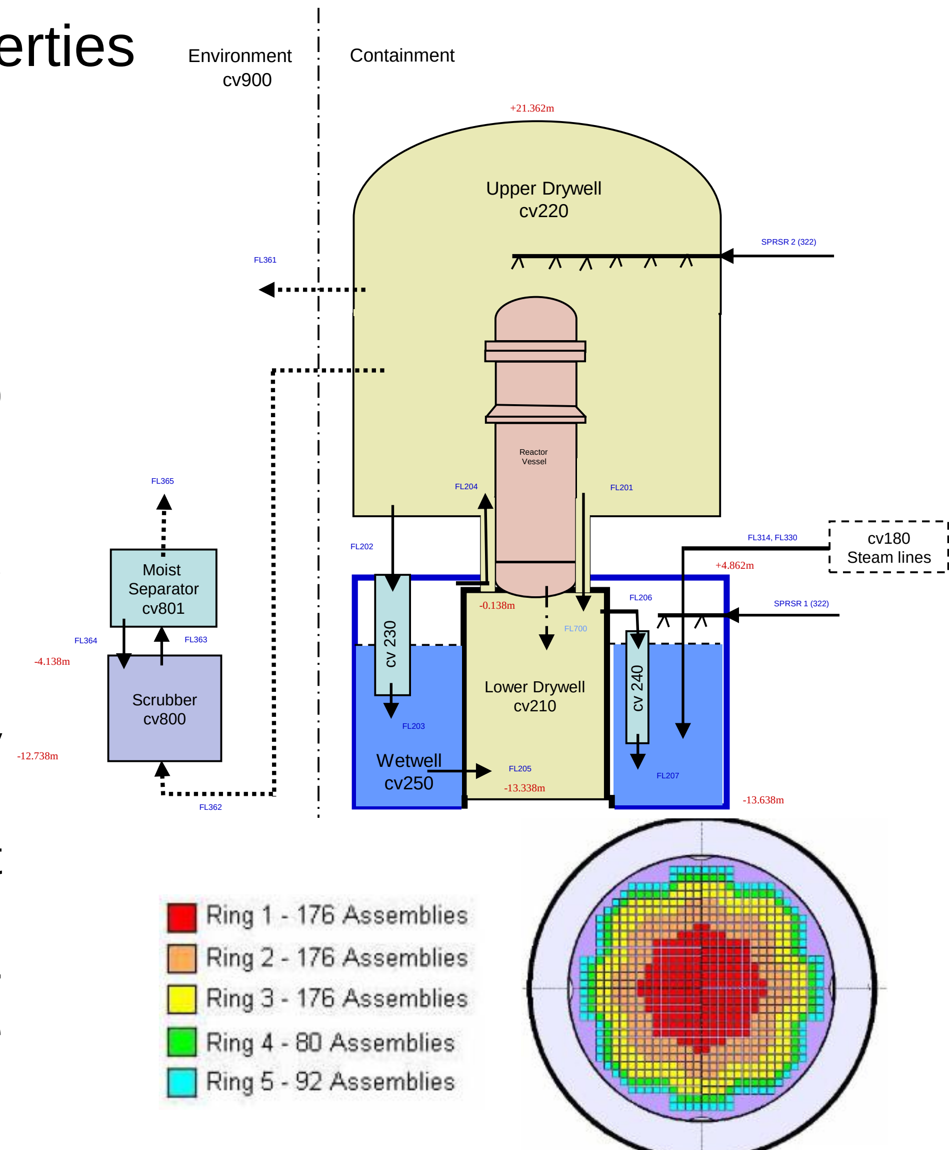


Figure: MELCOR Model of Nordic BWR

Sensitivity Analysis (1)

- "Phenomena associated with lower head failure are very poorly understood, such as penetration failure, the models are very simple and parametric, allowing the user significant flexibility in controlling lower head behavior".
  - MELCOR Reference Manual.

- Sensitivity analysis for a set of representative cases, can help us to evaluate the effect of MELCOR modelling parameters on:
  - The process of core degradation and relocation.
  - Vessel failure mode.
  - Identify major contributors to the uncertainty in the timing of the vessel failure and amount of melt available for release at the time of failure.

Sensitivity Analysis (2)

- For the analysis we selected 7+1 parameters that can affect the properties of relocated debris in LP, timing and mode of vessel failure:

Parameter name	Range	Units
Particulate Debris Porosity (PDPor)	[0.3-0.5]	-
Velocity of falling debris (VFALL)	[0.01-1.0]	m/s
LP Particulate debris equivalent diameter (DHYPDLP)	[0.002-0.005]	m
Time Constant for radial (solid) debris relocation (SC10201)	[180-720]	sec
Time Constant for radial (liquid) debris relocation (SC10202)	[30-120]	sec
Heat transfer coefficient from in-vessel falling debris to pool (CORCHTP)	[200-2000]	W/m2-K
Penetration Failure Temperature (TPF)*	[1273-1600]	K
Heat transfer coefficient from LP debris to LH node ()	[]	W/m2-K

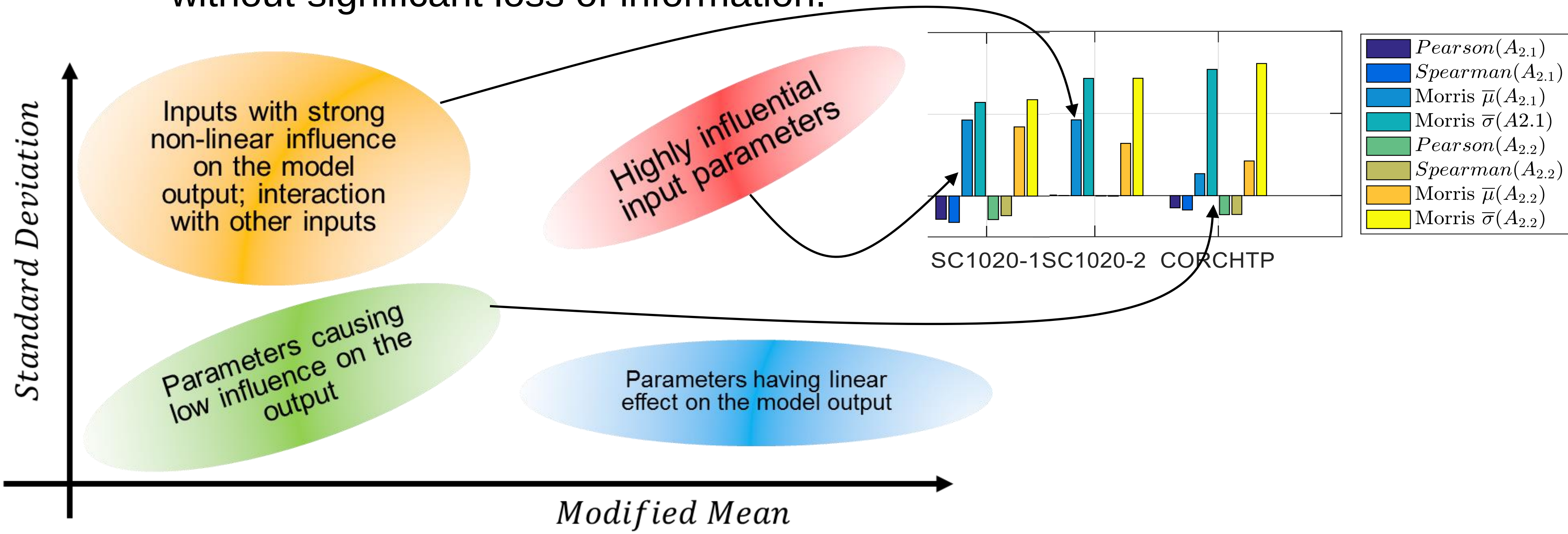
- Sensitivity analysis using Morris method has been performed for a set of scenarios:
  - HP1. Late depressurization, late water injection.
    - ADS Time 7200 sec; ECCS Time 7200sec; (160 Cases)
  - HP2. Late depressurization, late water injection.
    - ADS Time 10000sec; ECCS Time 10000sec; (160 Cases)
  - LP1. Early depressurization, late water injection.
    - ADS Time (according to control logic); ECCS Time = 7200sec. (160 Cases)
  - LP2. Early depressurization, late water injection.
    - ADS Time (according to control logic); ECCS Time = 10000sec. (160 Cases)

Sensitivity Analysis (3)

- MELCOR uses two options for debris ejection: (Solid debris ejection switch):
  - Solid debris ejection – ON (default)
    - All debris regardless of whether or how much they are molten.
  - Solid debris ejection – OFF (optional)
    - Molten materials + some fraction of solid debris
- 3 sets of calculations has been performed for:
  - Solid debris ejection – on (IDEJ0); With penetration modelling.
  - Solid debris ejection – off (IDEJ1); With penetration modelling.
  - Solid debris ejection – on (IDEJ1)*; Without penetration modelling.
    - In case of gross failure all debris in the corresponding cell is discharged linearly over a 1s time step, regardless its state and failure opening diameter.

Morris Approach for Model sensitivity analysis Results and Interpretation

- Morris approach is a screening method, it is usually used to identify parameters with a negligible effect on the output target function.
  - Once identified those factors can be fixed at any value in the original range without significant loss of information.



- Scaled Morris $\bar{\mu}_{\mathrm{i}}$ - values of Morris μ_i scaled between 0 and 1.
- Standard deviation - $\overline{\sigma_i} = {}^{\sigma_i}/_{\mu_i}$

Results: Timing of vessel breach (1)

- Vessel breach due to penetration failure in most of the cases occurs rather early:
  - Median values ~6000-7000sec after initiating event.

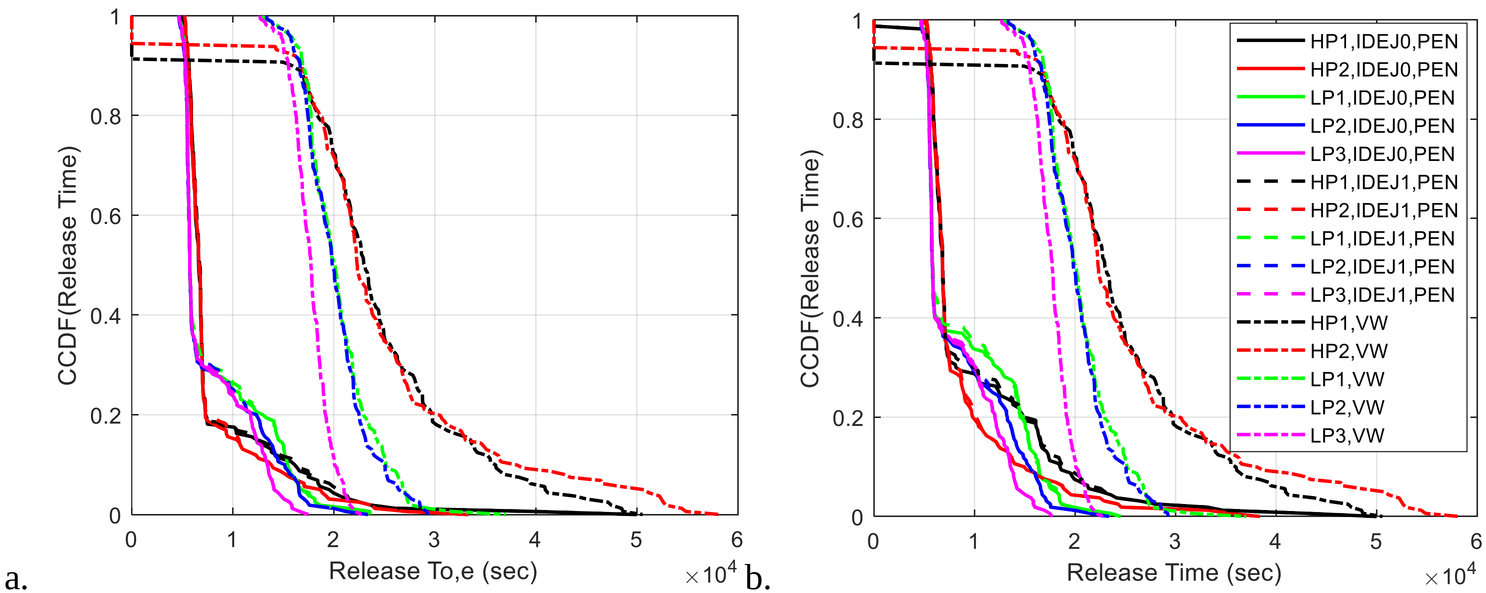


Figure. CCDF of (a) the time of vessel failure (b) Melt release time (sec).

Results: Timing of vessel breach (2)

- In most of the cases vessel breach due to penetration failure occurs directly after core support plate failure and debris slumping into the LP:

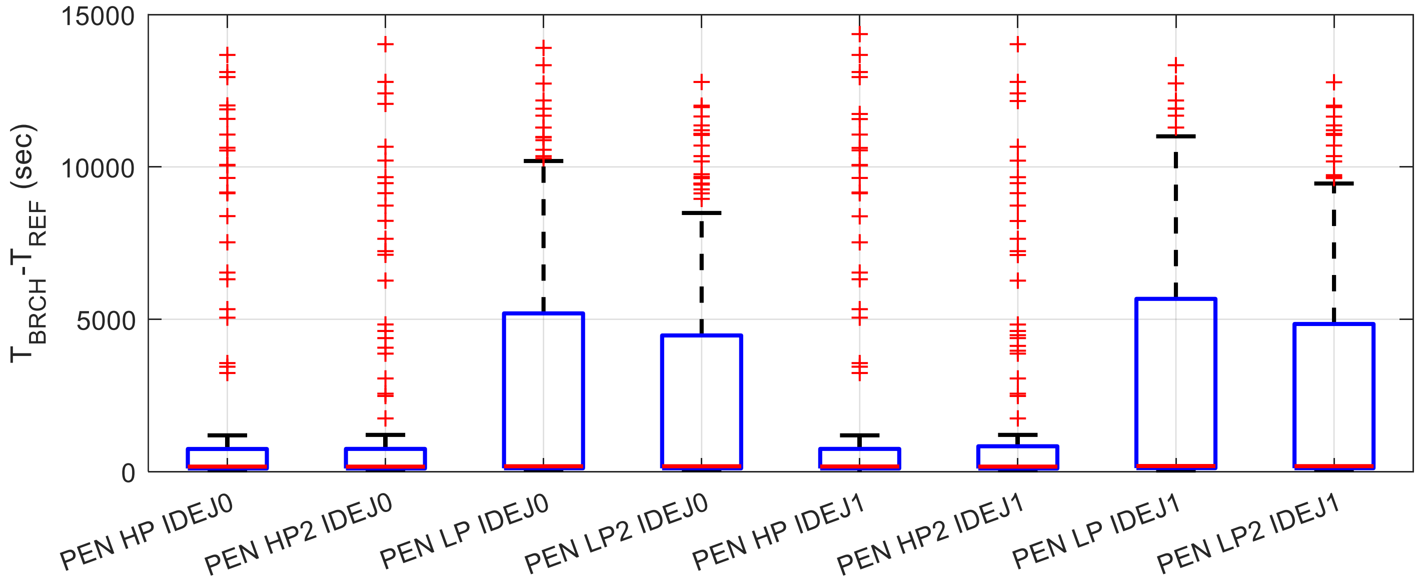
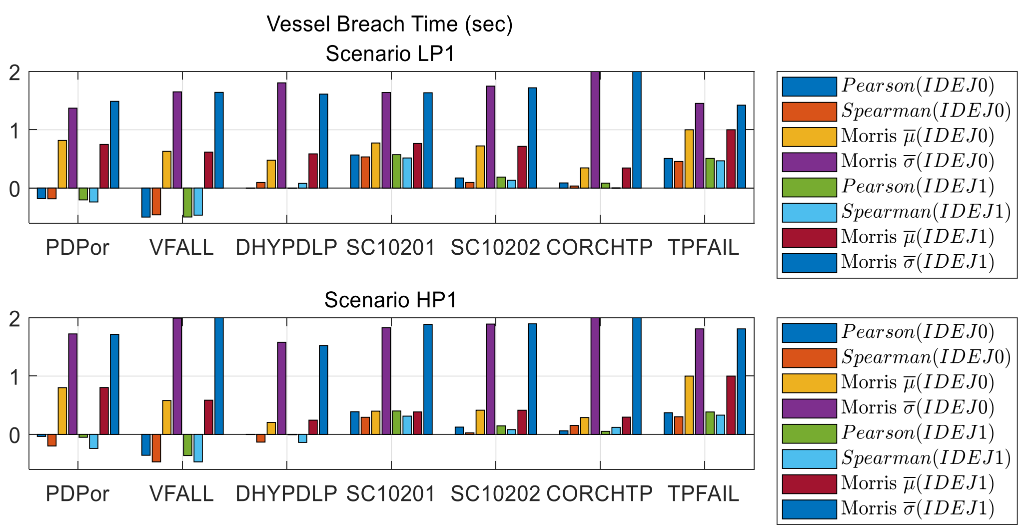


Figure: Time delay between Core support plate failure (T_{REF}) and vessel breach (T_{BRCH})

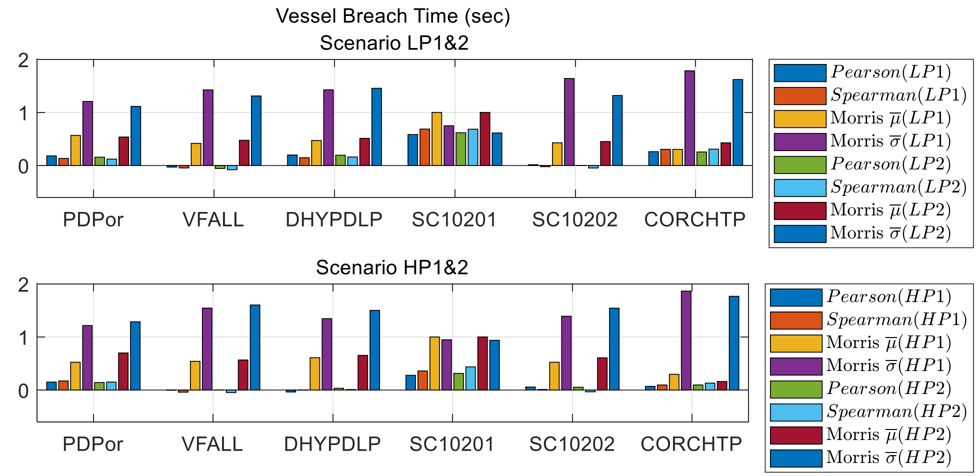
Results: Timing of vessel breach (3)

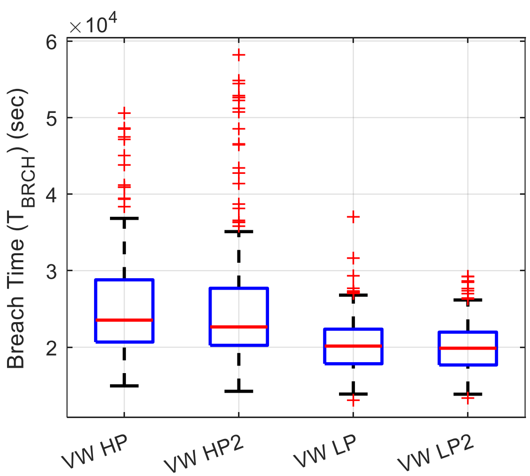
- Based on sensitivity analysis results, the most influential parameters are:
  - Penetration failure temperature (TPFAIL)
  - Particulate debris porosity (PDPor)
  - Velocity of falling debris (VFALL)
  - Time constant for radial debris relocation (only in LP scenario).



Results: Timing of vessel breach (4)

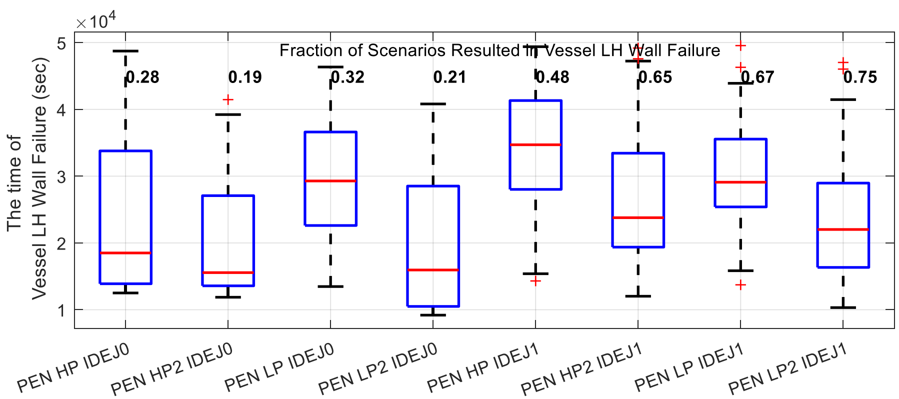
- Without penetration modelling (only vessel LH wall failure is considered) vessel failure occurs at ~ 20-25e3 sec (median) after the initiating event.
- The most influential parameters on the timing of vessel LH wall failure:
  - Radial solid debris relocation (SC1020(1)).

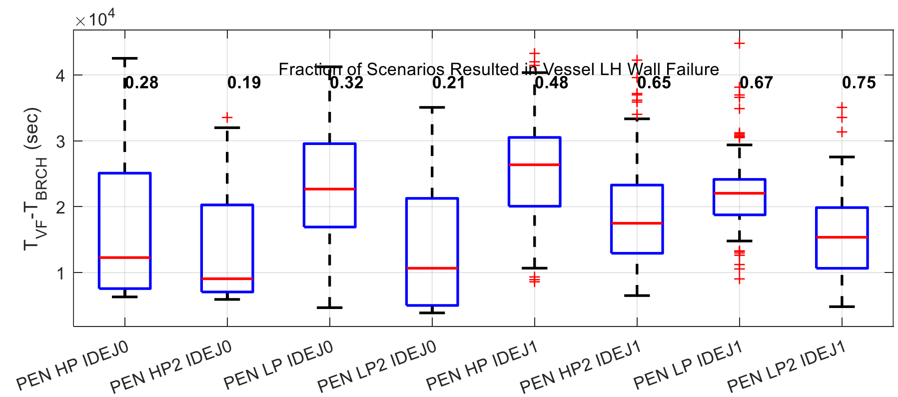




Results: Timing of LH wall failure(1)

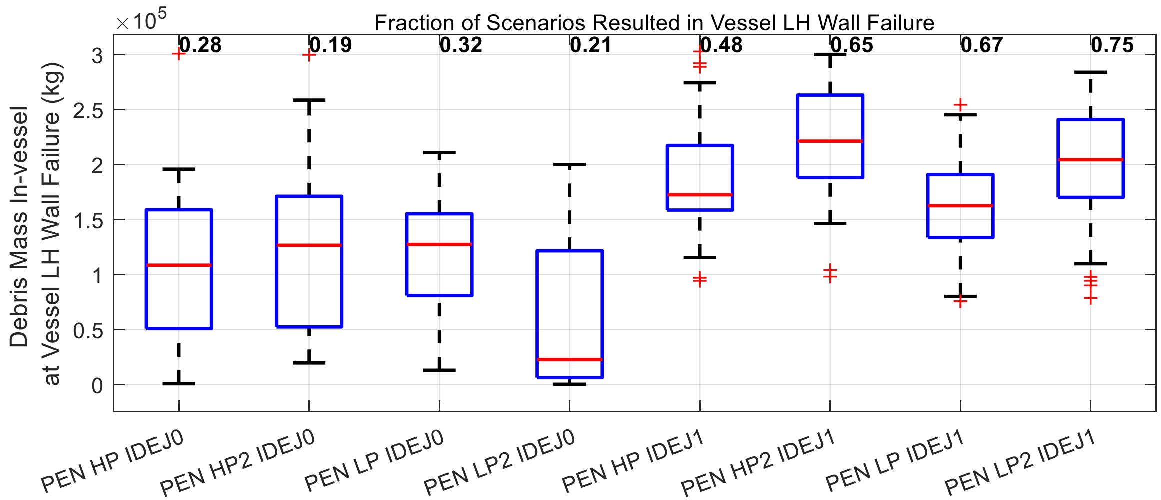
- In cases with penetration modelling:
  - The fraction of scenarios resulted in in eventual failure of the vessel LH wall:
    - ~20-30% in case of solid debris ejection – on (IDEJ0)
    - ~50-75% in case of solid debris ejection – off (IDEJ1).
  - The time delay between initial vessel breach due to penetration failure and vessel LH wall failure is ~10-40e3 sec depending on MELCOR uncertain parameters considered in the study.





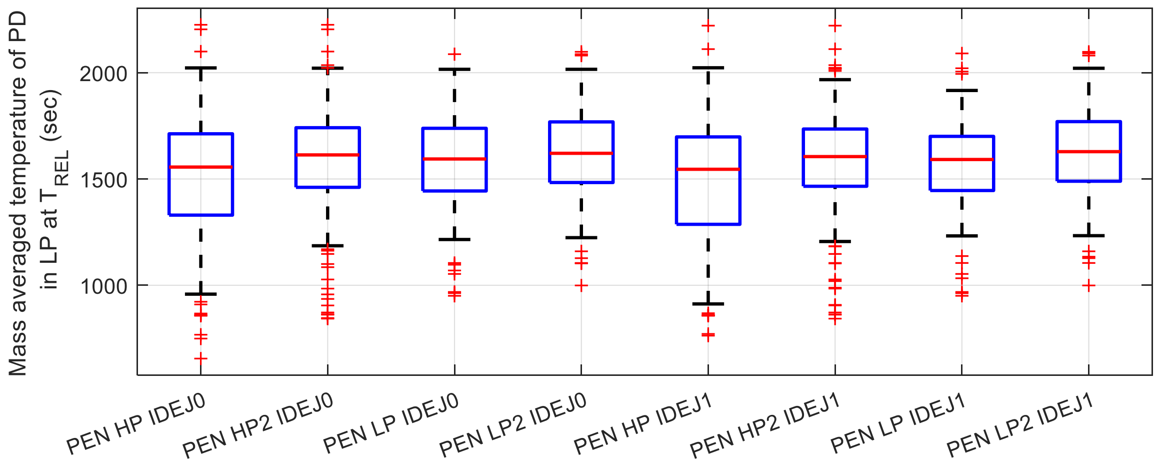
Results: Timing of LH wall failure(2)

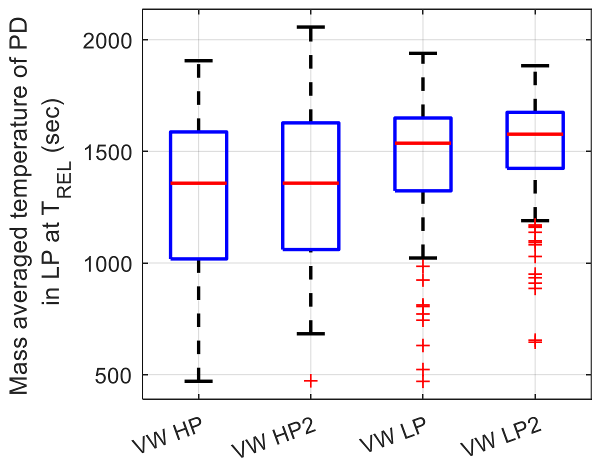
- The mass of remaining in-vessel debris at the time of vessel LH wall failure:
  - Ranges from ~0 to 200 tons in case of solid debris ejection – on (IDEJ0).
  - Range from ~100- over 250 tons in case of solid debris ejection – off (IDEJ1).



Results: Properties of the debris at T_{REL}(1)

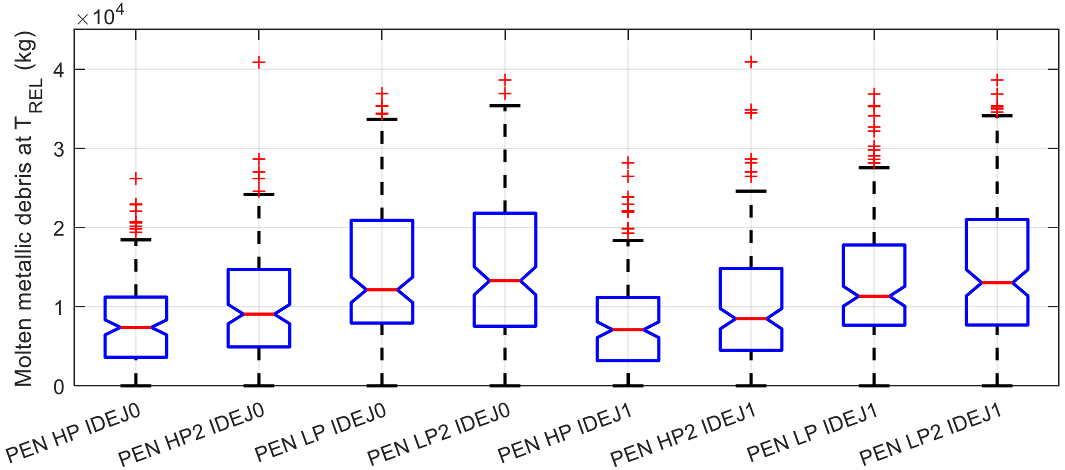
- Mass averaged temperature of the debris in the LP at the time of the onset of the release (T_{REL}). Ranges from ~1000 to 2000K in cases with penetration modelling and from ~500 to over 2000K in cases without penetration modelling.

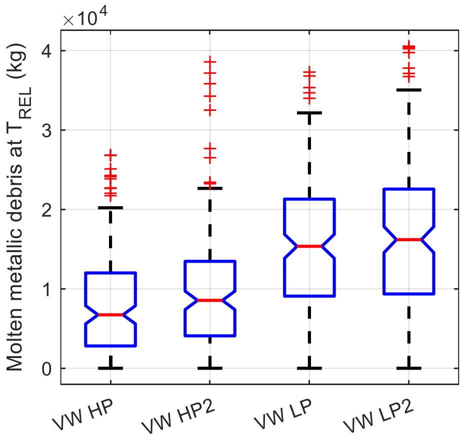




Results: Properties of the debris at T_{REL}(2)

- High temperatures can result in large amounts of molten materials:
  - In cases with penetration modelling:
    - Molten metallic debris at T_{REL} range from ~0kg to 35 tons.
  - In case without penetration modelling:
    - Molten metallic debris at T_{REL} range from ~0kg to 25-35 tons, depending on severe accident scenario.
  - We can see the effect of severe accident scenario:
    - Larger time delay for water injection results in larger amounts of liquid melt.
    - The amount of melt in low pressure scenarios is significantly large compared to high pressure scenarios.





Results: Properties of the debris at T_{REL}(3)

- The most influential parameters on the mass of molten mantellic debris are:
  - Particulate debris porosity (PDPor)
  - Velocity of falling debris (VFALL)
  - Time constant for radial debris relocation (SC1020(1/2)).

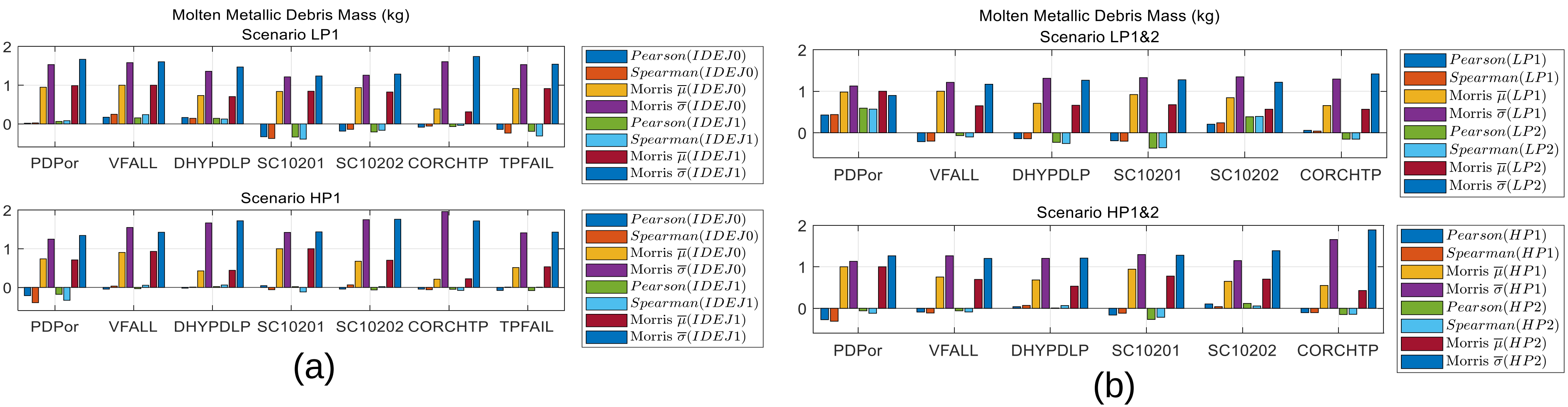
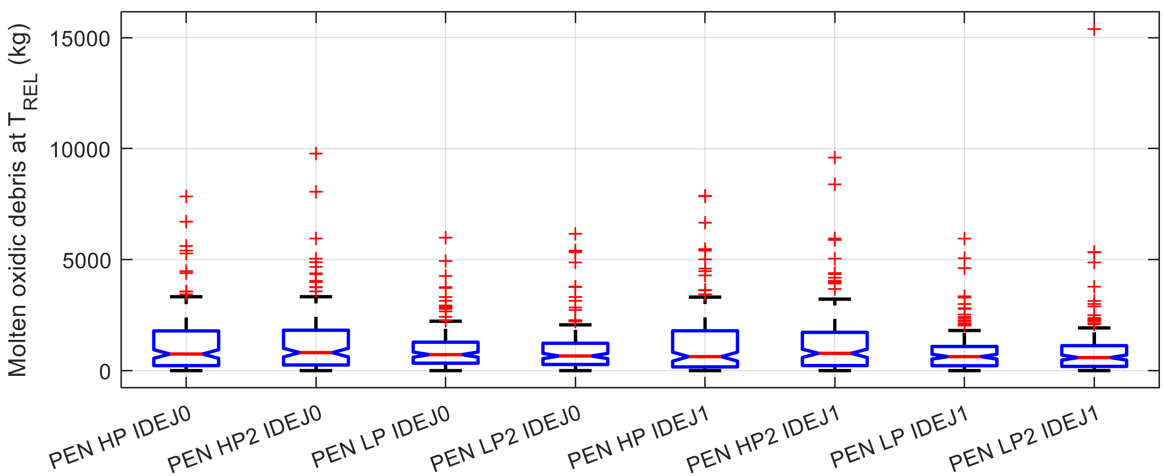
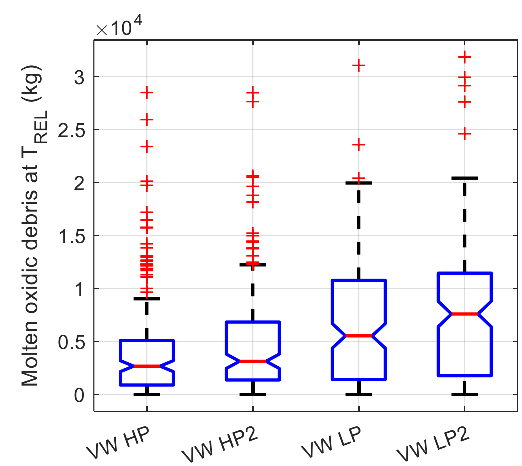


Figure: Sensitivity analysis results for scenarios (a) with penetration modelling, (b) without penetration modelling

Results: Properties of the debris at T_{REL}(1)

- Molten oxidic debris mass at T_{REL}:
  - Ranges from 0 to 3000-5000kg, depending on accident scenario in cases with penetration modelling.
  - Ranges from 0 to 10000-20000kg, depending on accident scenario in cases without penetration modelling.



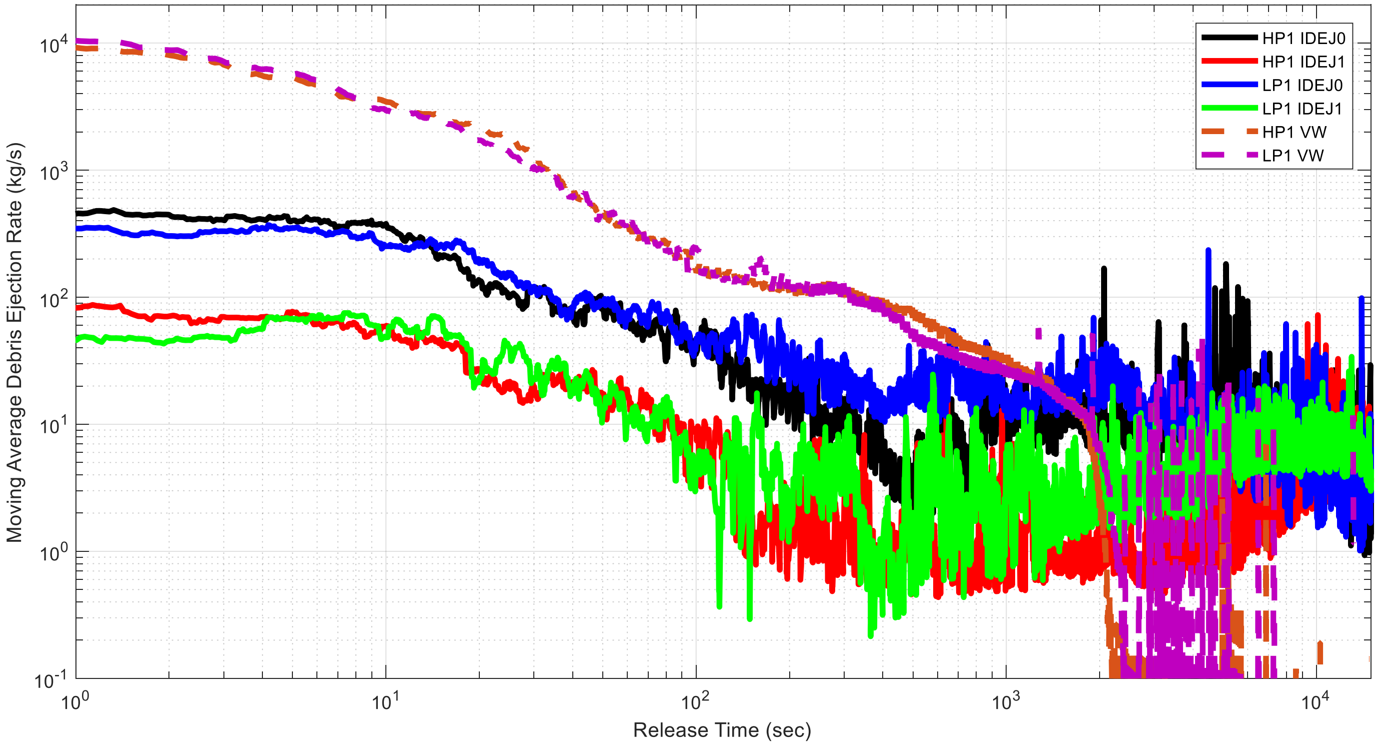


Discussion: Properties of the debris at T_{REL}

- This behaviour can be explained by the modelling of debris behaviour in MELCOR code.
  - MELCOR assumes that particulate debris will sink into a molten pool, displacing the molten pool volume.
  - Once solid debris components with lower melting point (such as stainless steel) start to melt, the volume occupied by the solid debris decreases, the molten materials will occupy empty volume within the solid debris (reducing solid debris porosity) and the remaining part will form a molten pool on top of the particulate debris, which will be displaced by the particulate debris from the cell located above, which eventually can result in stainless steel-rich layer on top of the solid debris.

Results: Melt release conditions (1)

- The rates of debris ejection from the vessel depend on:
  - Penetration modelling.
    - Vessel LH wall failure without penetration modelling results in massive debris ejection from the vessel with ~10000kg/s initial debris ejection rates (mean value).
    - With penetration modelling initial debris ejection rates depend on solid debris ejection option:
      - In case of solid debris ejection – on, the release starts with ~50-100kg/s (mean value).
      - In case of solid debris ejection – off, the release starts with ~400-500 kg/s (mean value).



Conclusions.

- In this work we addressed the sensitivity of the time and the mode of vessel failure and melt release conditions to MELCOR modelling parameters and options in different accident scenarios.
  - MELCOR modelling parameters were sampled using extended Morris method for global sensitivity analysis.
- The properties of relocated debris in the lower plenum of Nordic BWR are significantly affected by severe accident scenario and MELCOR modelling options.
- We found that ~20-30% of the cases with penetration modelling resulted in eventual failure of the vessel LH wall in case of solid debris ejection – on, while in case of solid debris ejection – off it ranges from ~50-75% of scenarios.
- We found that the solid debris ejection mode (IDEJ) in MELCOR code have the dominant effect of melt release from the vessel in case with penetration modelling.