Analysis of the Effect of Severe Accident Scenario on the Vessel Lower Head Failure in Nordic BWR using MELCOR code

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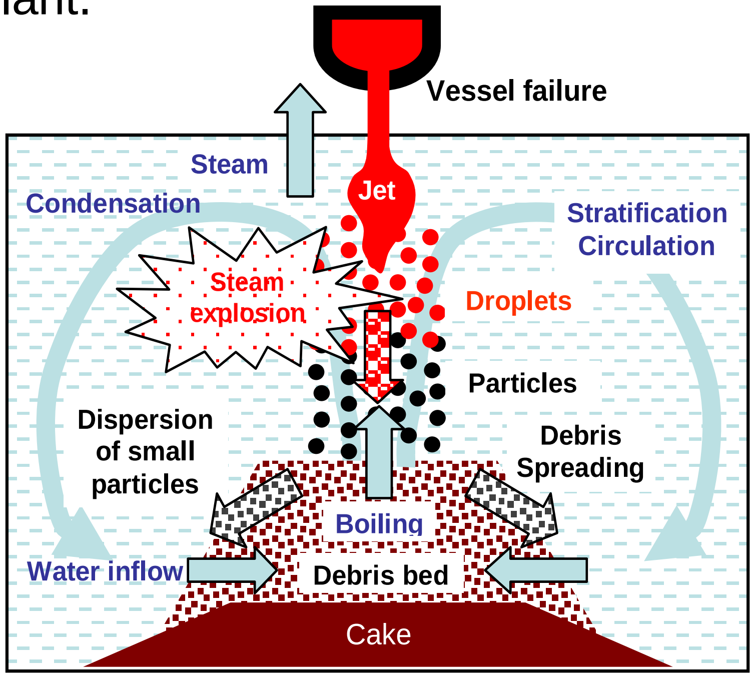
Background (1)

- 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.

- Depending on the timing of operator actions and different safety systems recovery:
  - There are different time dependent trajectories exist that can lead either to success of failure of SAM

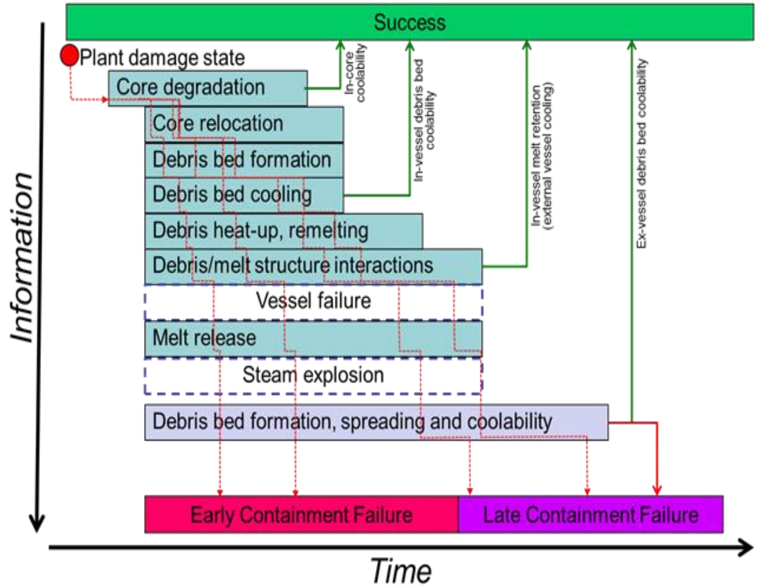


Figure: Severe Accident Progression in Nordic BWR

* 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 evaluate the effect of severe accident scenario on the vessel lower head failure mode and melt release conditions in Nordic BWR.

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

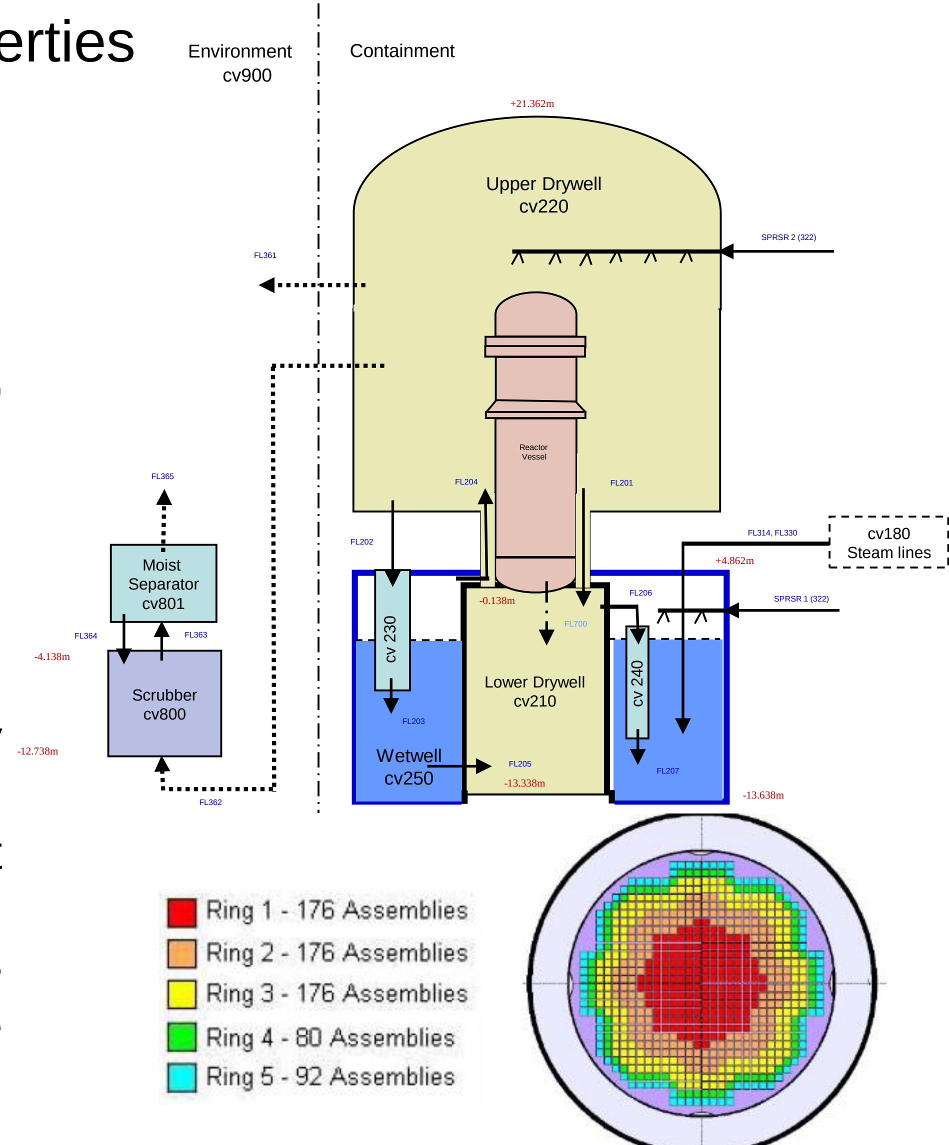
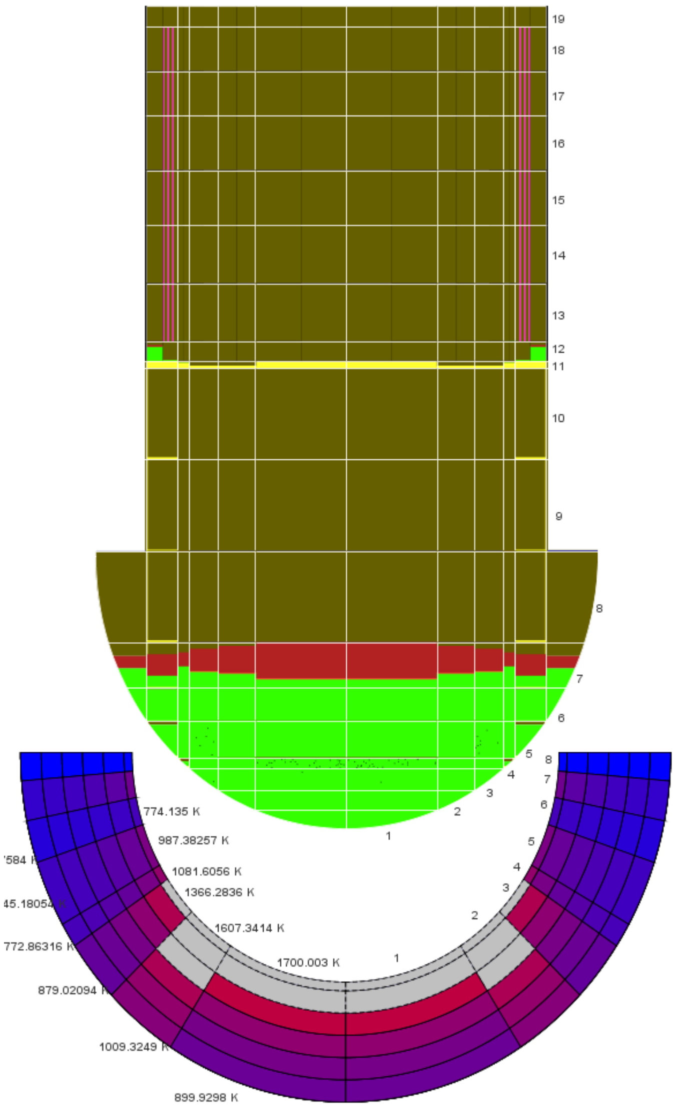


Figure: MELCOR Model of Nordic BWR

MELCOR Lower Head Breach Mechanisms (1)

MELCOR Assumes the following mechanisms of RPV Lower Head (LH) breach (not mutually exclusive):

- Vessel wall failure:
  - Due to Creep-Rupture:
    - Creep-rupture failure of a lower head segment occurs, in response to mechanical loading under conditions of material weakening at elevated temperatures.
  - Due to temperature of the bottom LH node:
    - Gross failure of the lower head segment is assumed when the temperature of the bottom lower head node (outer temp. of the LH wall) exceeds the penetration failure temperature TPFAIL defined by the user.
- Penetration failure:
  - The temperature of a penetration (or the temperature of the innermost node of the lower head) reaches a failure temperature (TPFAIL) specified by the user.
    - The default value TPFAIL = 1273K was used in the analysis.



MELCOR Modeling of Debris Ejection (1)

- After a failure has occurred, the mass of each material in the bottom axial level that is available for ejection (but not necessarily ejected) is calculated.
  - Two simple options exist (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
  - Constraints on the mass to be ejected at vessel failure:
    - A total molten mass of at least 5000kg (or user specified values as SC1610(2)
      - SC1610(2) = 0 – was used in the analysis.

    Or
    - A melt fraction(can be specified as SC1610(1)) of 0.1
      - SC1610(1) = 0 – was used in the analysis.
    - In case of gross failure all debris in the corresponding cell is discharged linearly over a 1s time step, regardless of the failure opening diameter.

Analysis of the effect of severe accident scenario:

- For the analysis of the effect of severe accident scenario on the process of core degradation and relocation into the LP we employ uniform mesh sampling in the space of scenario parameters.
- Considered Scenario:
  - LOOP + SBO:
    - Loss of onsite and offsite power supply
    - Loss of diesel generators
    - Different timing of safety systems recovery (power recovery (ECCS) + operator actions (ADS)
  - We consider:
    - The time delay for activation of the depressurization system - ADS (System 314) to be uniformly distributed in the range from 1000 to 10000 seconds after the initiating event;
    - The time delay for the activation of low-pressure coolant injection (System 323) is also in the range from 1000 to 10000 seconds after the initiating event, however low-pressure injection can be initiated only after depressurization.
- In MELCOR model of Nordic BWR the default modeling parameters of the MELCOR 2.1 code were used except for those recommended by the MELCOR Best Practices Guidelines and SC1610(1,2).

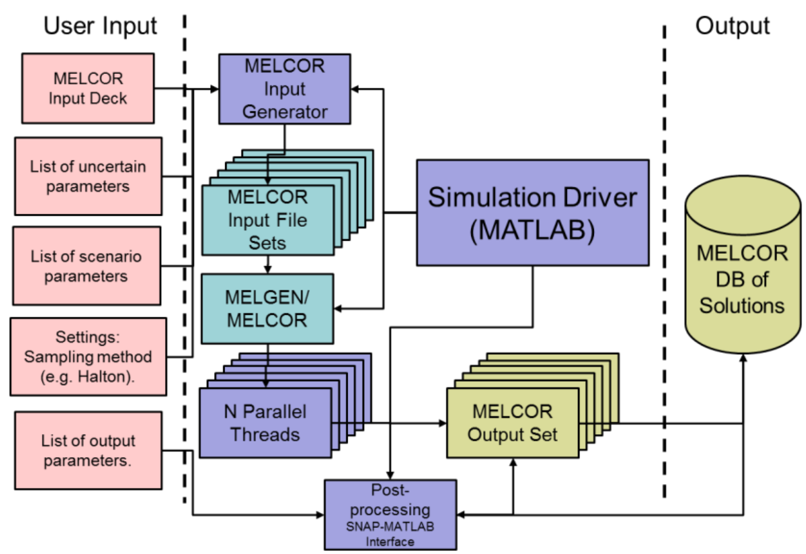


Figure. Simulation Driver Information Flow

MELCOR Results (v7544)

- No penetration failure <u>(only vessel wall can fail)</u>:
  - Creep rupture of the vessel lower head.
  - ADS, ECCS Timing – uniformly distributed within [1.e3-1.e4]sec. (In total 120x5(different max. time step) scenarios)
- Vessel Lower Head failure time:
  - In most of the cases Vessel Failure occurs within [~1.9-3.5e4] (sec) after initiating event.

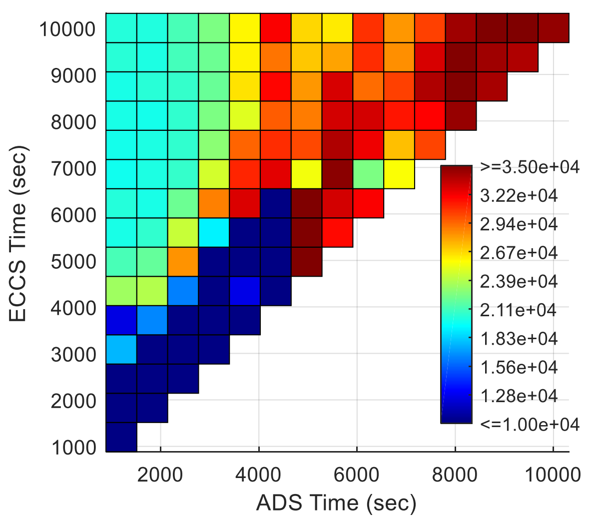


Figure. Expected value of the time of vessel failure and the onset of the release (sec), without penetration modelling; as a function of ADS and ECCS Timing (sec)

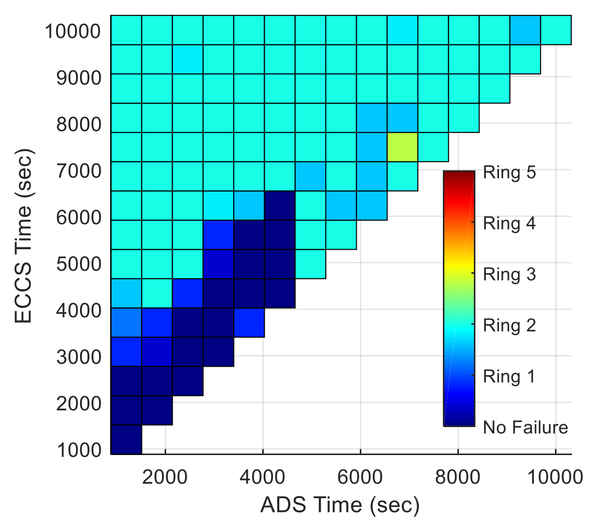


Figure. Expected Failure Location (Ring Number) without penetration modelling; as a function of ADS and ECCS Timing (sec)

MELCOR Results (v7544)

- No penetration failure (only vessel wall can fail):
  - Creep rupture of the vessel lower head.
  - ADS, ECCS Timing – uniformly distributed within [1.e3-1.e4]sec. (In total 120x5(different max. time step) scenarios)
- Properties of the debris in LP at the time of vessel failure:
  - Molten metallic and oxidic debris at the time of the release:
    - ~1-17 tons for oxides;
    - ~5-27 tons for metals;
  - Significant superheat of molten metallic debris.

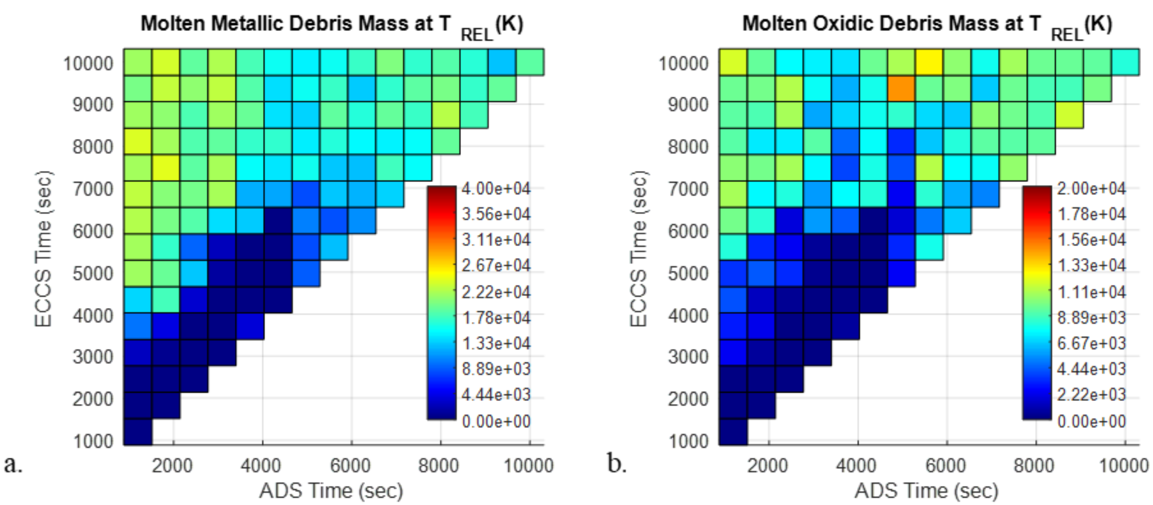


Figure. Expected value of (a) molten metallic debris mass (kg) (b) molten oxidic debris mass (kg), at the time of the release without penetration modelling; as a function of ADS and ECCS Timing (sec)

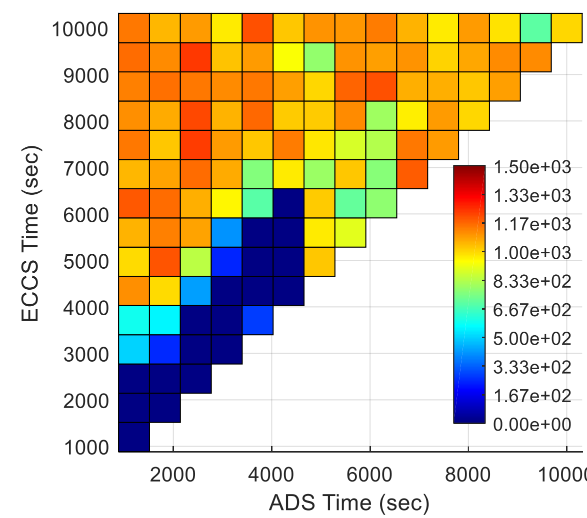


Figure. Expected value of Molten Stainless Steel in LP mass averaged superheat (K) at the time of the release without penetration modelling; as a function of ADS and ECCS Timing (sec)

MELCOR Results (v7544)

- No penetration failure (only vessel wall can fail).
- Melt release conditions:
  - – Debris ejection rates can reach over 2000 kg/s.
  - – “Massive” release right after failure followed by “dripping” mode.

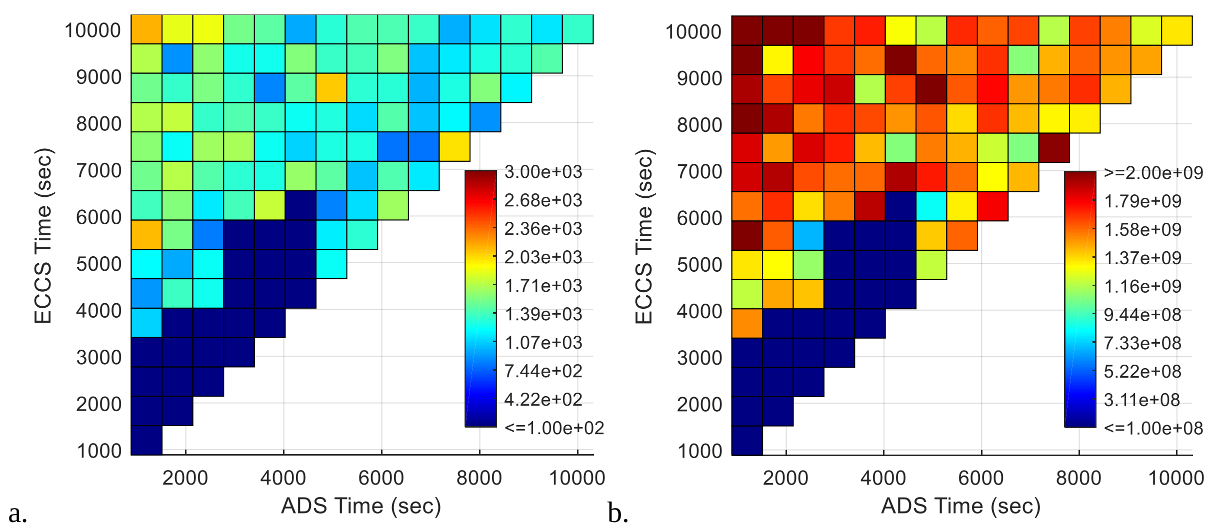
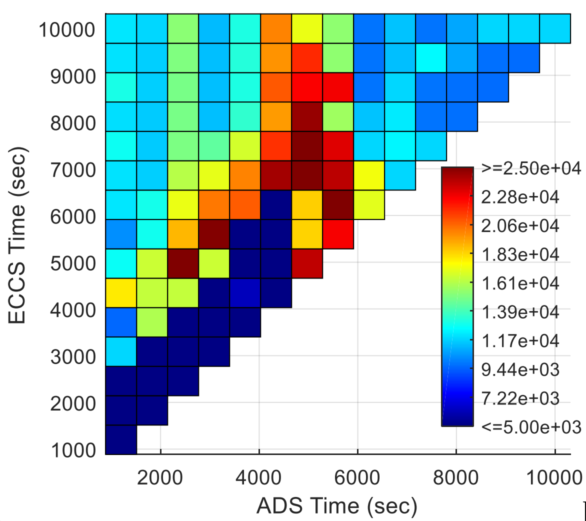


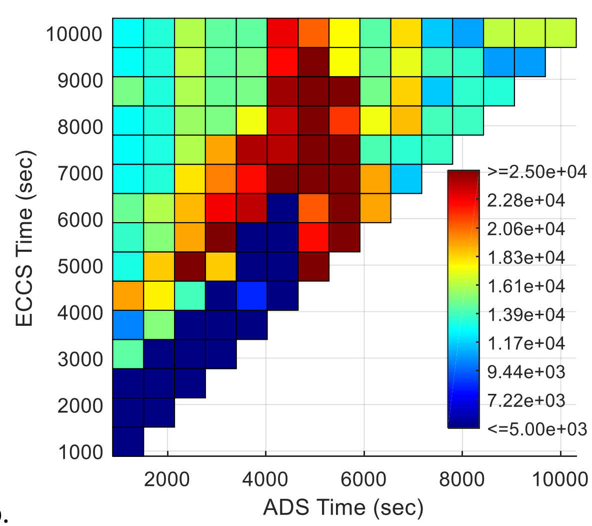
Figure. Expected Value of (a) Maximum debris ejection rate (kg/s) (b) Maximum enthalpy rate (J/s) without penetration modelling.; as a function of ADS and ECCS Timing (sec)

MELCOR Results (v7544)

- **<u>With penetration failure modelling</u>** (2 penetrations per ring):
  - ADS, ECCS Time – uniformly distributed within [1.e3-1.e4]sec. (In total 120x5(different max. time step) scenarios)
- The timing of vessel breach due to penetration failure:
  - In most of the cases Vessel Failure occurs within [~0.8e4-2.5e4] (sec) after initiating event.
  - In case of penetration failure release starts with some time delay
    - Due to numerical constraints:
      - Based on MELCOR simulations, ejection starts when there is some molten material in the lowermost cell, adjacent to failed LH node with failed penetration..
      - Some other MELCOR constraints on the mass to be released, such as SC1610-1, SC1610-2 – were switched off (set to 0).
  - Failure location is sensitive to severe accident scenario (ADS timing).



a.



b.

Figure. Expected value of (a) time of vessel failure (sec) (b) time of the onset of the release (sec), with penetration modelling; as a function of ADS and ECCS Timing (sec)

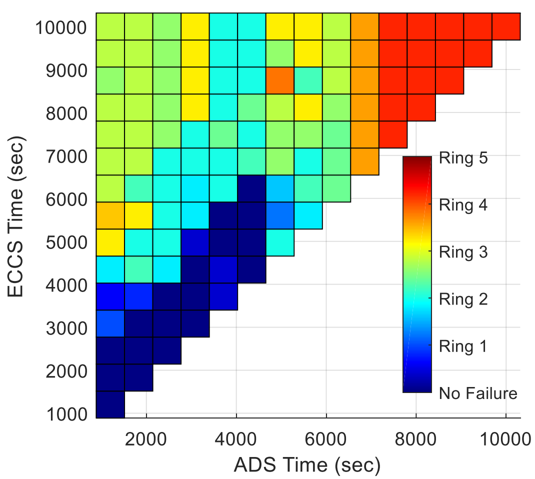
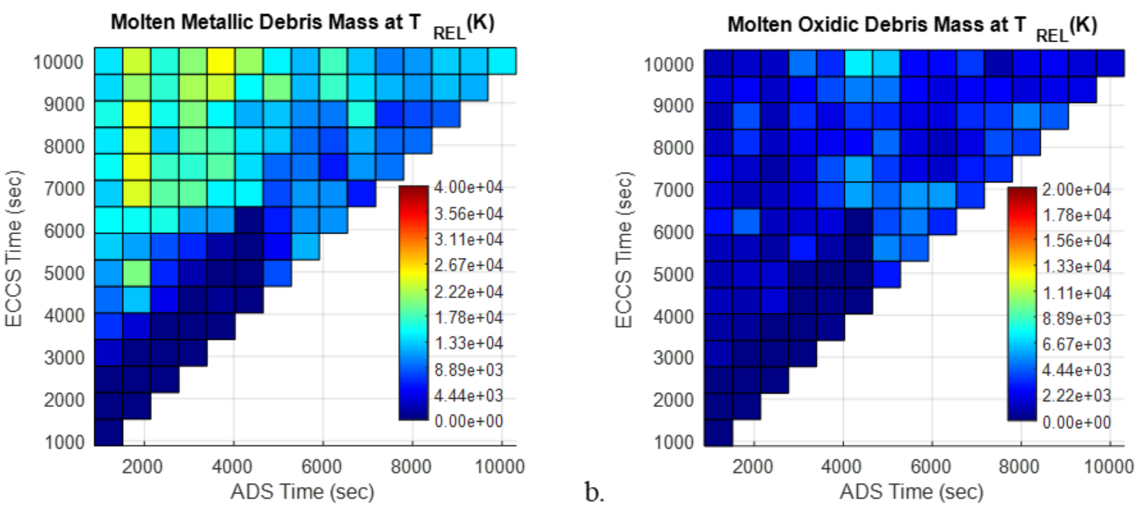


Figure. Expected Failure Location (Ring Number) with penetration modelling as a function of ADS and ECCS Timing (sec)

MELCOR Results (v7544)

- **<u>With penetration failure modelling</u>** (2 penetrations per ring):
  - ADS, ECCS Time – uniformly distributed within [1.e3-1.e4]sec. (In total 120x5(different max. time step) scenarios).
- Properties of the debris in LP at the time of the onset of the release:
  - Molten metallic and oxidic debris at the time of the release:
    - ~1-5 tons for oxides;
    - ~5-25 tons for metals;
  - Significant superheat of molten metallic debris.



a. b.

Figure. Expected value of (a) molten metallic debris mass (kg) (b) molten oxidic debris mass (kg), at the time of the release with penetration modelling; as a function of ADS and ECCS Timing (sec)

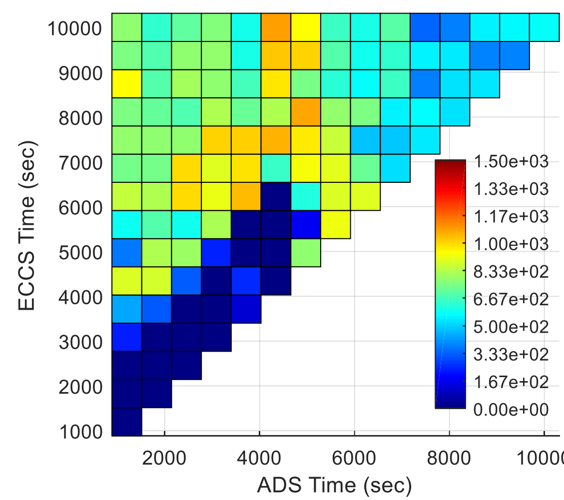
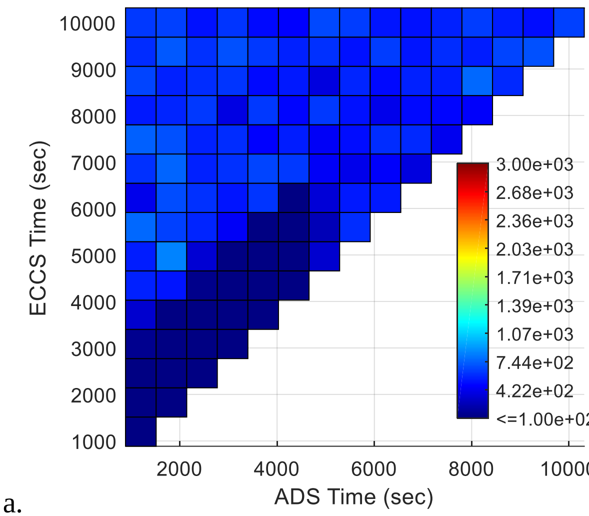


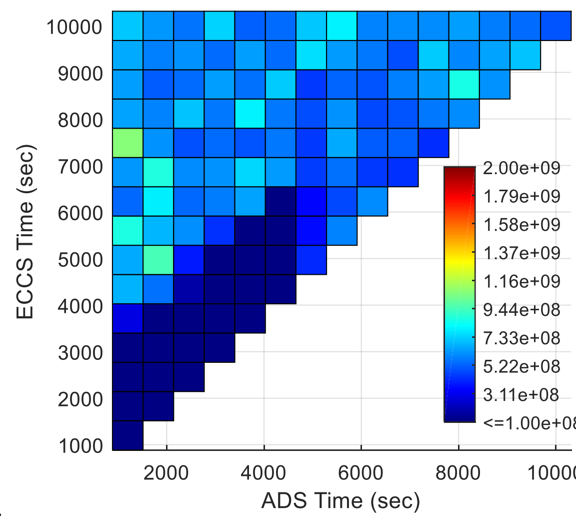
Figure. Expected value of LP molten stainless steel mass averaged superheat (K) at the time of the release with penetration modelling; as a function of ADS and ECCS Timing (sec)

MELCOR Results (v7544)

- With penetration failure modelling
  - 2 penetrations per ring;
- Gradual release in both with/without solid debris ejection.
  - Slightly larger values of max. debris ejection rates in case of IDEJ0 compared to IDEJ1.

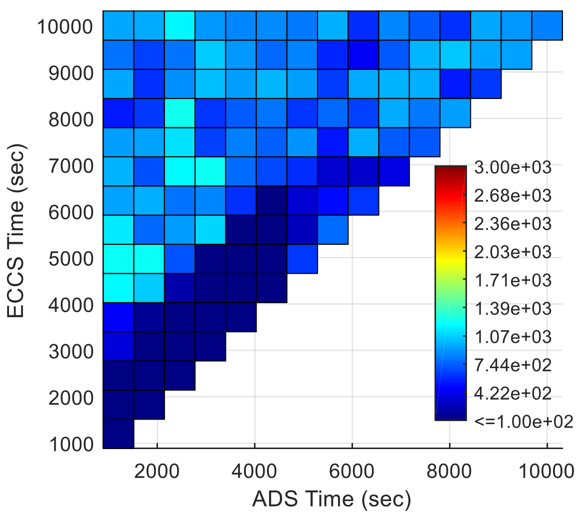


a.

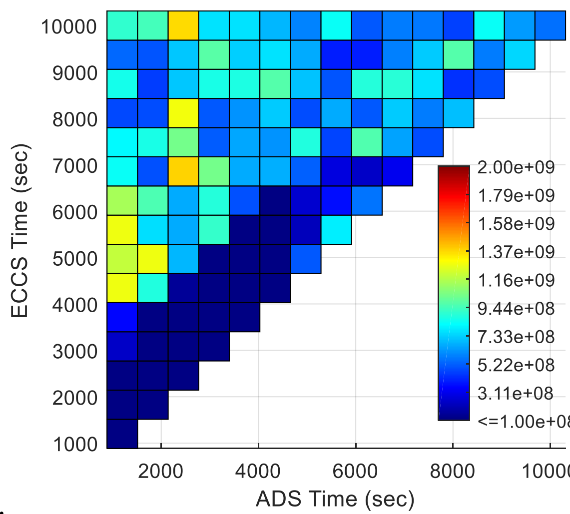


b.

Figure. Expected Value of (a) Maximum debris ejection rate (kg/s) (b) Maximum enthalpy rate (J/s) with penetration modelling, solid debris ejection OFF (IDEJ=1); as a function of ADS and ECCS Timing (sec)



a.



b.

Figure. Expected Value of (a) Maximum debris ejection rate (kg/s) (b) Maximum enthalpy rate (J/s) with penetration modelling, solid debris ejection ON (IDEJ=0); as a function of ADS and ECCS Timing (sec)

Conclusions

- Analysis of the vessel failure mode and melt release conditions has been performed with MELCOR code.
  - MELCOR predicts early penetration failure as the most probable mode of vessel LH failure.
- Severe accident scenario has quite significant effect on the properties of the debris in LP at the time of vessel breach and melt release.
- In case of penetration failure, solid debris ejection mode (IDEJ) in MELCOR code has larger contribution to the uncertainty in debris ejection rate compared to severe accident scenario.