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

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Abstract: Severe accident management (SAM) in Nordic boiling water reactors (BWR) relies on ex-vessel core debris coolability. In case of core melt and vessel failure, corium is poured into a deep pool of water located under the reactor. 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, and (ii) potential for energetic steam explosion. Both non-coolable debris bed and steam explosion are credible threats to containment integrity.

It is currently recognized that the time and the mode of vessel failure, melt release conditions are the major source of uncertainty in quantification of the risk of containment failure in Nordic BWRs in ROAAM+ Framework. The properties of relocated debris, time and the mode of vessel failure and melt release conditions, including in-vessel/ex-vessel pressure, lower drywell pool depth and temperature, are subject to aleatory (severe accident scenario) and epistemic (modeling) uncertainties.

In this work we perform sensitivity analysis for a set of representative cases, to evaluate the effect of MELCOR modelling parameters on the process of core degradation and relocation, and vessel failure mode. Major contributors to the uncertainty in the timing of the vessel failure and amount of melt available for release at the time of failure are identified and discussed in detail.

Keyword: Severe Accident Nordic BWR MELCOR ROAAM

1. INTRODUCTION

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 a natural circulation of water. Success of the strategy is contingent upon melt release conditions from the vessel which determine (i) properties and thus coolability of the bed, (ii) potential for energetic steam explosions. If decay heat cannot be removed from the debris bed, the debris can re-melt and attack containment basemat. Strong steam explosion can damage containment structures.

Melt release conditions are recognized as the major source of uncertainty in quantification of the risk of containment failure in Nordic BWRs [1,2,3].

Phenomena associated with vessel lower head behaviour under severe accident conditions are very poorly understood (e.g. penetration failure). Models implemented in severe accident codes widely use a lot of user-specified parameters, that allow user significant flexibility in controlling lower head behaviour. This work is focused on the evaluation of uncertainty in the time and mode of vessel failure and melt release conditions in Nordic BWR. We use MELCOR 2.1 code for prediction of the in-vessel phase of accident progression, vessel failure and melt release [11,12]. The main goal of this paper is to characterize the range of possible debris properties in the lower plenum at the time of the release, melt release conditions (e.g. debris ejection rate, enthalpy release rate) and its sensitivity to different modelling parameters, which is of paramount importance for the risk analysis in the ROAAM+ framework.

2. APPROCH

In the analysis presented in this paper we consider a severe accident initiated by the station blackout (SBO) scenario with a delayed power recovery. We consider a simultaneous loss of the offsite power (LOOP) and backup diesel generators. This results in the simultaneous loss of all water injection systems, including crud purge flow through the control rod drive tubes. This kind of accident is one of the most challenging accidents scenarios for BWR's as illustrated at Fukushima-Daiichi accident [4] and is among the major contributors to the core damage frequency (CDF) for Nordic BWR according to PSA Level 1 analysis. We consider that the power (external grid or diesel generators) can be recovered after some time delay and emergency core cooling system (ECCS) system can be restarted. According to the considered scenario, the operator can delay activation of the depressurization system to keep coolant in the vessel. Yet, for injection of water with low pressure ECCS, depressurization has to be activated.

2.2. MELCOR model of Nordic BWR

MELCOR input model for Nordic BWR was originally developed for accidents analysis in the power uprated plants [5]. Nordic BWR MELCOR model have total thermal power output of 3900 MW. The core consists of 700 fuel assemblies of SVEA-96 Optima2 type – which is divided into five non-uniform radial rings and eight axial levels. The primary coolant system is represented by 27 control volumes (CV), connected with 45 flow paths (FL) and 73 heat structures (HS). The core and lower plenum is represented by a 6-ring, 19-axial level control volume geometry. In the analysis of the vessel lower head behaviour we consider two options: i) with penetration modelling, i.e. we model one IGT and one CRGT in every radial ring from 1 to 5. So the vessel lower head can failure due to penetration failure and/or vessel wall creep rupture; ii) without penetration modelling, vessel lower head failure due to vessel wall creep rupture.

In this work we use MELCOR code version 2.1 (rev7544) [8,9] for prediction of the effect of MELCOR modelling parameters on the in-vessel phase of accident progression, the timing and mode of vessel failure and melt release.

MELCOR Modelling of Vessel Lower Head Failure and Melt Release

MELCOR Assumes the following mechanisms of RPV Lower Head (LH) breach (not mutually exclusive): (i) Vessel wall failure, which uses creep-rupture model (1D options was used [8,9]). Creep-rupture failure of a lower head segment occurs, in response to mechanical loading under conditions of material weakening at elevated temperatures; (ii) Penetration failure, due to 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, or a logical control function specified by user [8,9].

Whenever any failure condition is satisfied, an opening with an initial diameter defined by the user is established (either default value of 0.1m, or user-specified values that corresponds to penetrations diameters (e.g IGT – 0.07m, CRGT – 0.14m).

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). In the default option (ON, IDEJ = 0), the masses of each material available for ejection are the total debris and molten pool material masses, regardless of whether or how much they are molten. In the second option (OFF, IDEJ = 1), the masses of steel, Zircaloy, and UO2 available for ejection are simply the masses of these materials that are molten; the masses of steel oxide and control poison materials available for ejection are the masses of each of these materials multiplied by the steel melt fraction, based on an assumption of proportional mixing; the mass of ZrO2 available for ejection is the ZrO2 mass multiplied by the Zircaloy melt fraction. Additionally, the mass of solid UO2 available for ejection is the Zircaloy melt fraction times the mass of UO2 that could be relocated with the Zircaloy as calculated in the candling model using the secondary material transport model [8,9]. Furthermore, MECLOR puts additional constraints on the mass to be ejected at vessel failure: (i) the mass of molten material should be at least C1610(2) value (5000kg – default value, 0kg – was used in the analysis) or a melt fraction of C1610(1) (0.1 – default value, 0 – was used in the analysis) to initiate melt ejection. Additionally, in case of gross failure of vessel wall, it is assumed that all debris in the bottom axial level of the corresponding ring, regardless its state, is discharged linearly over 1s time step without taking into account failure opening diameter [8,9]. The maximum mass of all materials that can be ejected during a single COR package time step is calculated as [8,9]:

$$M_{ej} = \rho_m A_f v_{ej} \Delta t \tag{1}$$

where ρ_m – is density of material being ejected, A_f- failure area, v_{ej} – velocity of debris being ejected, Δt – COR package time step. The fraction of the total mass available for ejection that actually is ejected during the subcycle is M_{ej} divided by the total mass available to be ejected, up to a maximum value of 1.0. This fraction is applied to the mass of each material available for ejection [8,9]. The velocity of material being ejected is calculated by:

$$v_{ej} = C_d(2\Delta P/\rho_m + 2g\Delta z_d) \qquad (2)$$

where C_d – is flow discharge coefficient ($C_d = 1$ was used in the analysis presented in this paper), ΔP – pressure difference between LP and reactor cavity control volumes, g – gravitational acceleration constant, and Δz_d – debris and molten pool height (see references [8,9] for more details).

2.3. Sensitivity Analysis

Sensitivity analysis using Morris method [6] has been performed for a set of scenarios (in total 2400 code executions):

- HP1. Late depressurization, late water injection.
  - ADS Time 7200 sec; ECCS Time 7200sec;
- HP2. Late depressurization, late water injection.
  - ADS Time 10000sec; ECCS Time 10000sec;
- LP1. Early depressurization, late water injection.
  - ADS Time (according to control logic); ECCS Time = 7200sec.
- LP2. Early depressurization, late water injection.
  - ADS Time (according to control logic); ECCS Time = 10000sec.
- LP3. Early depressurization, no water injection.
  - ADS Time (according to control logic); No water injection; Unmitigated SBO scenario with low in-vessel pressure.

Morris method is a method for global sensitivity analysis. The guiding philosophy of the Morris method [6] is to determine which factors may be considered to have effect, on model outputs, which can be considered as either negligible, linear or non-linear with other factors. The experimental plan proposed by Morris is composed of individually randomized "one-factor-at-a-time" experiments; the impact of changing one factor at a time is evaluated in turn [7] (see references [6,7] for more details).

For the analysis we selected 8 parameters that can affect in-vessel accident progression and the timing of vessel failure and melt release. The list with names and correspondent ranges of the parameters selected for the MELCOR sensitivity study is presented in Table 1. The time of vessel lower head breach, time of the release, molten metallic/oxidic debris mass at the time of vessel breach, maximum debris ejection rate and maximum enthalpy release rate were considered as response functions in this analysis.

Table 1. Selected MELCOR parameters and their ranges.

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 (TPFAIL)[1]	[1273-1600]	K
Solid Debris Ejection (IDEJ)[2][3]	0/1	-

- Particulate debris porosity (PDPor) – Porosity of particulate debris for all cells in specified axial

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[1] Only for simulations with penetrations (IGT, CRGT) modeling.

[2] For simulations without penetration modelling the value of IDEJ=1 was considered, since it has very little effect on debris ejection in case of vessel wall failure.

[3] Morris sensitivity analysis was performed independently for every value of the solid debris ejection switch (IDEJ).

level.

- Lower Plenum Particulate debris equivalent diameter (DHYPDLP) - MELCOR idealizes particulate debris beds as fixed-diameter particulate spheres.
    - The extent of debris coolability depends among others on the space between the particles. The porosity of randomly packed spheres is found to be approximately 40 % independent of particle size both by experiments and sophisticated computational methods. The range of entrained particle size is considered to be 1-5 mm based on TMI-2 data [11].
    - Based on [14,13] – the following ranges for porosity of particulate debris [0.3-0.5] and LP particulate debris equivalent diameter [0.002-0.005]m were selected.
- Velocity of falling debris (VFALL) - the debris is assumed to fall with a user-specified velocity. This allows the debris to lose heat to surrounding water in the lower plenum as it falls to the lower head, following failure of the core support plate in each radial ring [10]. Based on [14] and [8,9] the following range for this parameter has been selected – [0.01-1.0](m/s).
- Heat transfer coefficient from in-vessel falling debris to pool (HDBH2O) – in MELCOR In-Vessel falling debris quench model, it is assumed that the debris fall with a user-specified velocity and heat transfer coefficient. This allows the debris to lose heat to surrounding water in the lower plenum as it falls to the lower head, following failure of the core support plate in each radial ring [10]. Based on [14,15] and [8,9] the following range for this parameter has been selected – [200-2000](W/m2-K).
- Time Constant for radial (solid\liquid) debris relocation (SC10201\SC10202) – Time constant for radial relocation of solid\liquid material.
    - These parameters are responsible for leveling of particular debris and molten pools in Radial Relocation of Solid (SC1020-1) and Molten (SC1020-2) materials. This model intended to simulate the gravitational leveling between adjacent core rings that tends to equalize the hydrostatic head in a fluid medium [8].
    - In this study the following ranges were considered:
        - SC1020-1 - 180-720 sec [8,9,15]
        - SC1020-2 - 30-120 sec [8,9,15].
- Penetration Failure Temperature (TPFAIL) – in MELCOR code, penetration failure occurs when temperature of a penetration (or the temperature of the innermost node of the lower head) reaches a failure temperature (TPFAIL) specified by the user (see Section 2.2).
    - Based on literature review the following values were considered – 1273-1600K [16].
- Solid Debris Ejection (IDEJ) – the switch controls debris mass release from the vessel (see Section 2.2 for details).

3. RESULTS

3.1. Vessel failure with IGT and CRGT modelling

Tables 2 and 3 present the summary of the results of the analysis of vessel failure and melt release with MELCOR code for scenarios with early and late depressurization and late water injection (see section 2 for details), with modelling of penetration (CRGT, IGT) failure.

Table 2. Descriptive statistics of the results of HP1 and LP1 scenarios with IDEJ=0&1 and penetration modelling.

	Expected Value/Standard Deviation				0.05/0.5/0.95 Quantiles			
	IDEJ 0		IDEJ 1		IDEJ 0		IDEJ 1	
	HP1	LP1	HP1	LP1	HP1	LP1	HP1	LP1
$\boldsymbol{T_{BR}}$ (sec)	8569 5901	8235 4464	8694 5999	8312 4445	5460 6623 19740	5210 5750 17150	5400 6750 20510	5165 5775 17020
$\boldsymbol{T_{REL}}$ (sec)	9999 7207	9149 4961	10170 7295	9211 4901	5513 6810 23050	5225 5839 18280	5400 6845 23240	5215 5874 18130

$M_{MET\|LIQ}$ (kg)	15790 12880	28630 17850	15180 12810	26420 16820	292 12790 40680	7046 24460 63290	399 12180 41710	6470 22890 62190
$M_{OX\|LIQ}$(kg)	1937 1652	1302 1137	1979 1802	1150 1086	0 1631 5296	32.6 1037 3587	0 1654 5627	19 864 2957
Max. Debris ejection rate (kg/s)	1697 1939	1209 1466	1008 1500	1553 2161	306 1095 6038	258 879 3004	166 388 5069	223 488 5728
Max.Enthalpy release rate (J/s)	1.428e9 1.629e9	9.895e8 1.009e9	1.069e9 1.487e9	1.11e9 1.158e9	2.225e8 9.197e8 5.609e9	1.933e8 6.528e8 2.491e9	1.995e8 4.969e8 3.843e9	2.711e8 6.286e8 3.035e9
Failure Location (Ring N)	1.95 1.22	2.1 1.3	1.95 1.22	2.1 1.29	1.0 2.0 5.0	1.0 2.0 5.0	1.0 2.0 5.0	1.0 2.0 5.0

Table 3. Descriptive statistics of the results of HP2 and LP2 scenarios with IDEJ=0&1 and penetration modelling.

	Expected Value/Standard Deviation				0.05/0.5/0.95 Quantiles			
	IDEJ 0		IDEJ 1		IDEJ 0		IDEJ 1	
	HP2	LP2	HP2	LP2	HP2	LP2	HP2	LP2
T_{BR} (sec)	8090 4476	7998 4126	8153 4473	8046 4147	5405 6690 18760.	5165 5750 16560	5460 6680 18810	5025 5750 16560
T_{REL} (sec)	8839 5437	8504 4322	8901 5428	8557 4334	5153 6820 19410	5215 5839 16700	5528 6820 19410	5180 5830 16700
$M_{MET\|LIQ}$ (kg)	24710 22810	33720 24320	24490 22480	32520 23880	2149 18130 69570	6865 27730 74060	2605 17730 64810	6734 27150 72130
$M_{OX\|LIQ}$(kg)	2055 1712	1265 1220	2012 1728	1216 1597	0.33 1892 5150	15 974 3747	0.26 1910 5111	15.2 828 3657
Max. Debris ejection rate (kg/s)	1393 1168	1310 1435	1398 1706	2024 2278	323 1000 3433	306 987 3198	197 550 4603	230 736 6221
Max.Enthalpy release rate (J/s)	1.279e9 1.263e9	1.196e9 1.262e9	1.285e9 1.476e9	1.255e9 1.075e9	2.922e8 9.01e8 3.336e9	2.474e8 8.210e8 3.662e9	2.46e8 6.731e8 4.422e9	2.891e8 8.386e8 3.548e9
Failure Location (Ring N)	1.98 1.26	2.12 1.37	2.03 1.24	2.13 1.37	1.0 2.0 5.0	1.0 2.0 5.0	1.0 2.0 5.0	1.0 2.0 5.0

3.2. Vessel failure without IGT and CRGT modelling

Table 4 present the summary of the results of the analysis of vessel failure and melt release with MELCOR code for scenarios with early and late depressurization and late water injection (see section 2 for details), without penetration modelling.

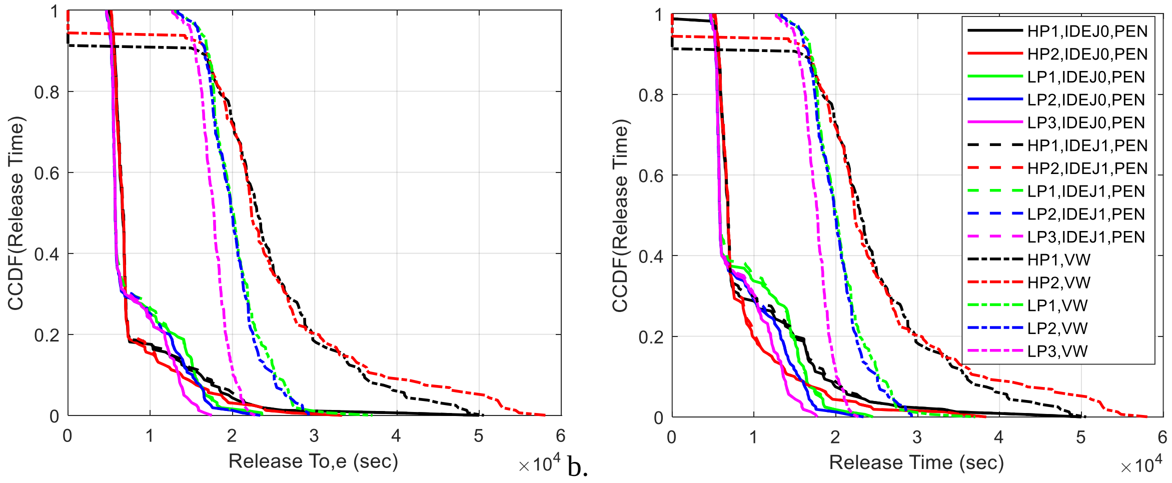
Table 4. Descriptive statistics of the results of HP1, HP2, LP1 and LP2 scenarios without penetration modelling.

	Expected Value/Standard Deviation				0.05/0.5/0.95 Quantiles			
	HP1	LP1	HP2	LP2	HP1	LP1	HP2	LP2
$\boldsymbol{T_{BR}}$ (sec) $\boldsymbol{T_{REL}}$ (sec)	23590 10300	20570 3541	24630 11010	20220 3250	1.7e4 2.4e4 5.e4	1.61e4 2.e4. 2.7e4	1.69e4 2.32e4 5.09e4	1.58e4. 1.98e4 2.67e4.
$\boldsymbol{M_{MET\|LIQ}}$ (kg)	10600 7950	20100 8333	12450 8780	21020 8968	0.0 10210 26810	6005 18920 33670	0.0 10500 28300	9022 19990 37990
$\boldsymbol{M_{OX\|LIQ}}$(kg)	4751 5730	7077 5958	5322 5650	8175 6655	0.0 2817 16500.	362 5971 18970	0.0 3326 16010	472 8023 18930
Max. Debris ejection rate (kg/s)	9046 6907	11330 8094	9386 6794	11920 8909	0.0 9341 18780	1277 9472 2594	0.0 9288 19080	1558 9999 28220
Max.Enthalpy release rate (J/s)	6.958e9 5.672e9	9.219e9 6.628e9	7.114e9 5.795e9	1.022e10 7.769e9	0.0 5.864e9 1.769e10	1.58e9 7.83e9 2.18e10	0.0 5.79e9 1.78e10	1.85e9 8.93e9 2.68e10
Failure Location (Ring N)	1.63 0.6	1.71 0.5	1.67 0.5	1.733 0.5	0.0 2.0 2.0	1.0 2.0 2.0	0.0 2.0 2.0	1.0 2.0 2.0

3.3. Discussion

The timing of vessel failure and melt release

The results presented in Tables 2, 3 and 4 show that the expected value of the timing of vessel breach is approximately 8000 sec for scenarios with penetration modelling and approximately 20000-27000 (~20000sec for scenarios with early depressurization, ~27000sec for scenarios with late depressurization) for scenarios without penetration modelling using creep-rupture model in MELCOR code [8,9]. The observed difference in the timing of vessel breach (see Figure 1) is due to modelling approaches used in the analysis. MELCOR modelling of penetration failure is controlled by the temperature threshold, defined by a user. Larger values of the penetration failure temperature together with user-defined parameters that promote LP debris coolability (e.g. PDPor, VFALL and DHYPDLP in debris quench model in MELCOR) can result in larger values of the time of vessel breach. On the other hand, it is still significantly smaller compared to the MELCOR predictions of the vessel failure using vessel wall creep-rupture model.



a. b.

Figure 1. CCDF of (a) the time of vessel failure (b) Melt release time (sec).

Sensitivity analysis results, presented in figures 2 and 3, show that the most influential parameters for the time of vessel breach are TPFAIL, PDPor and SC10201 (only in late depressurization scenario) in case of penetration modelling. In case of vessel wall failure due to creep-rupture, the most influential parameter is SC10201, which is responsible for radial relocation (levelling) of solid debris.

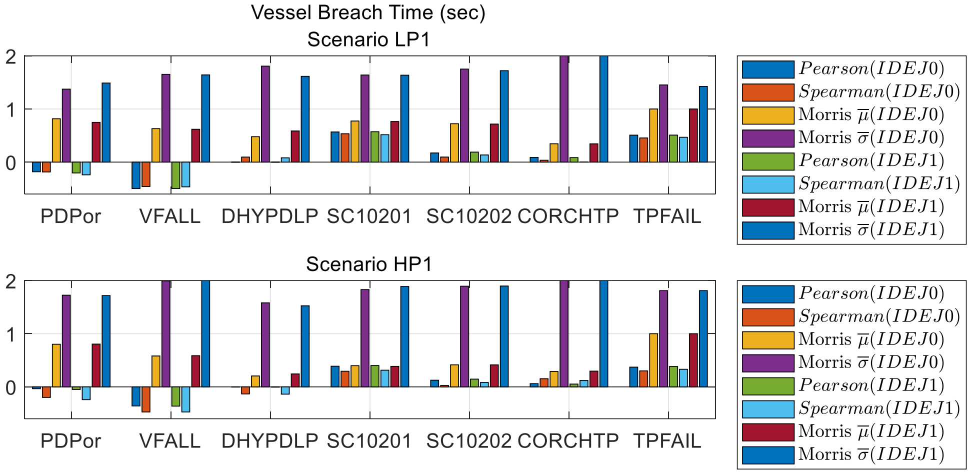


Figure 2. Sensitivity Vessel Breach time to modelling parameters in MELCOR. Scenario LP1 and HP1 with penetration modelling

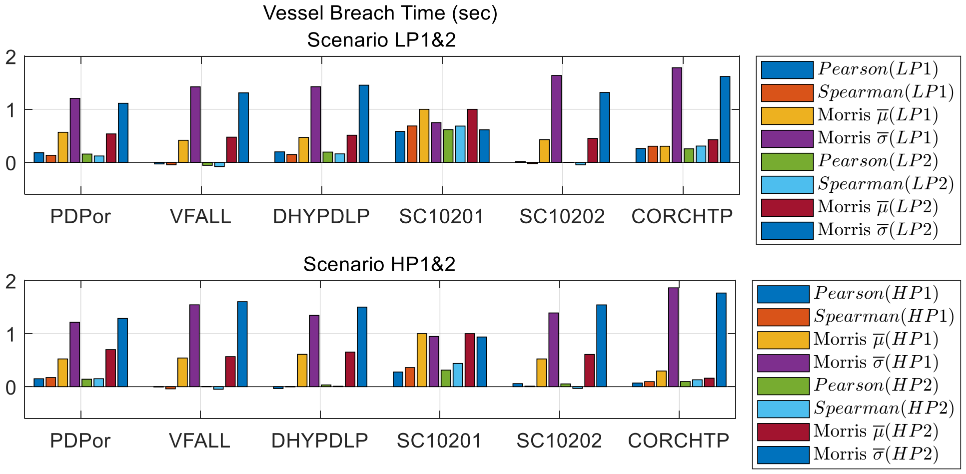


Figure 3. Sensitivity Vessel Breach time to modelling parameters in MELCOR. Scenario LP1&2 and HP1&2 without penetration modelling.

Furthermore, the results show that there is a delay between the timing of vessel breach and the timing of the onset of melt release from the vessel in approximately 20% of the scenarios simulated with penetration modelling. The results of sensitivity analysis show that the most influential parameter for this time delay is VFALL in scenarios with early depressurization, and SC10201, PDPor and (TPFAIL only in HP2 scenarios) in scenarios with late depressurization. The solid debris ejection switch (IDEJ) also has a significant effect on the results, where IDEJ=0 (solid debris ejection – on) results in earlier release from the vessel, compared to IDEJ=1 (solid debris ejection – off, see section 2.2 for details). The solid debris ejection switch (IDEJ) has no or little effect on the time and the mode of melt release from the vessel in case of vessel wall failure due to creep-rupture, since in case of gross failure all debris in the bottom cell of the corresponding ring is discharged linearly over a 1s time step, regardless of the failure opening diameter [8,9].

The properties of the debris at the time of vessel failure

The properties of the debris in LP at the time of vessel failure, such as molten metallic debris mass, molten oxidic debris mass, judging by the results are significantly affected by the accident scenario and vessel failure modelling.

In scenarios with early depressurization, the expected value of the mass of molten metallic debris is approximately 28/32 tons for the scenarios with penetration modelling and approximately 20 tons for the scenarios without penetration modelling. The values for the scenarios with late depressurization are 15/24 and 10 tons correspondingly.

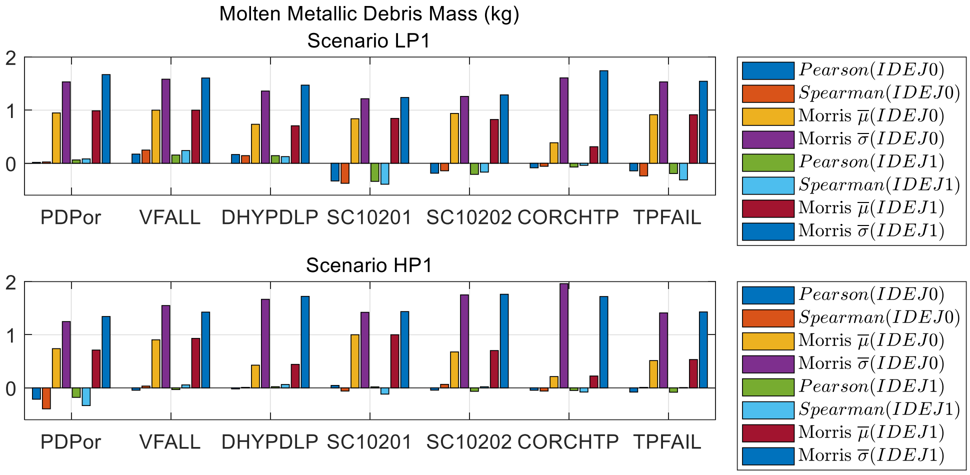


Figure 4. Sensitivity of Molten Metallic Debris Mass to modelling parameters in MELCOR. Scenario LP1 and HP1 with penetration modelling.

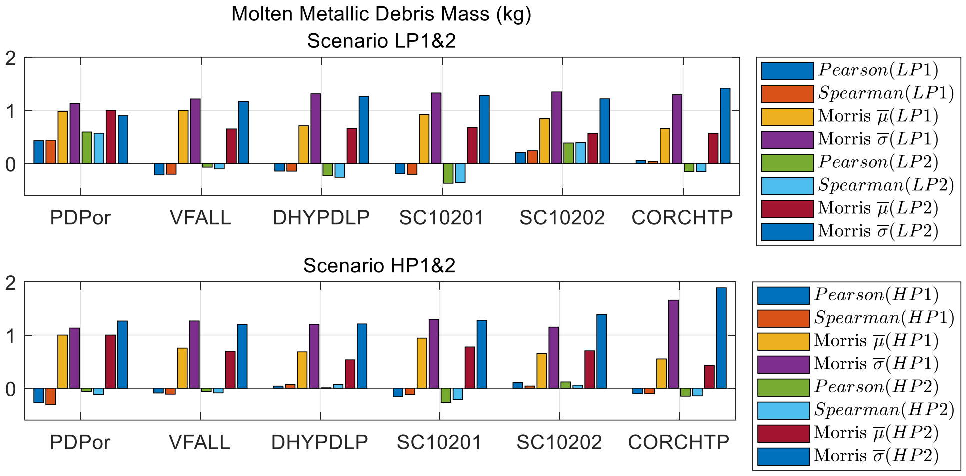


Figure 5. Sensitivity of Molten Metallic Debris Mass to modelling parameters in MELCOR. Scenario LP1&2 and HP1&2 without penetration modelling.

Sensitivity analysis results, presented in figures 4 and 5 show that the most influential parameters on the mass of molten metallic debris at the time of vessel failure are PDPor, VFALL and SC1020-1, in both MELCOR modelling options of the vessel failure (with\without penetration modelling). The difference in the molten metallic debris mass between MELCOR modelling of vessel failure with and without penetrations can be explained by the effect of molten pool models in MELCOR code. It is assumed in MELCOR that particulate debris will sink into a molten pool, displacing the molten pool volume. Thus, 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.

Vessel failure location

The location of the vessel failure (radial ring in MELCOR model) is mostly determined by the modelling approach used in MELCOR (i.e. with/without penetration modelling). In case of penetration modelling, vessel failure occurs mostly between the 1st and 3rd radial rings (with expected value of ~1.96/2.06 for scenarios with early and late depressurization, see Table 2 and 3). The most influential parameters, according to sensitivity analysis results, are VFALL, PDPor and SC1020-2 (see Figure 6). In case of vessel wall failure (without penetration modelling), failure occurs mostly between the 1st and 2nd radial rings (with expected value of ~1.65/1.71 for scenarios with early and late depressurization, see Table 4), and, according to sensitivity analysis results presented in Figure 7, all parameters (with exception to CORCHTP, DHYPDLP) have relatively high influence on the results; on the other hand, judging by the Table 4, the distribution of the vessel wall failure location is relatively narrow, therefore it can be concluded that the overall effect of MELCOR modelling parameters used in this study is insignificant in the case of vessel wall failure.

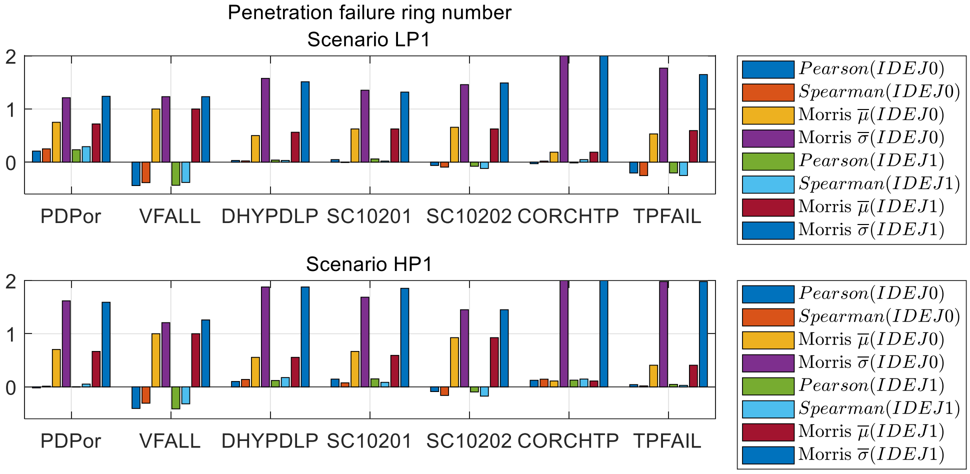


Figure 6. Sensitivity of vessel failure location due to penetration failure to modelling parameters in MELCOR. Scenario LP1 and HP1 with penetration modelling.

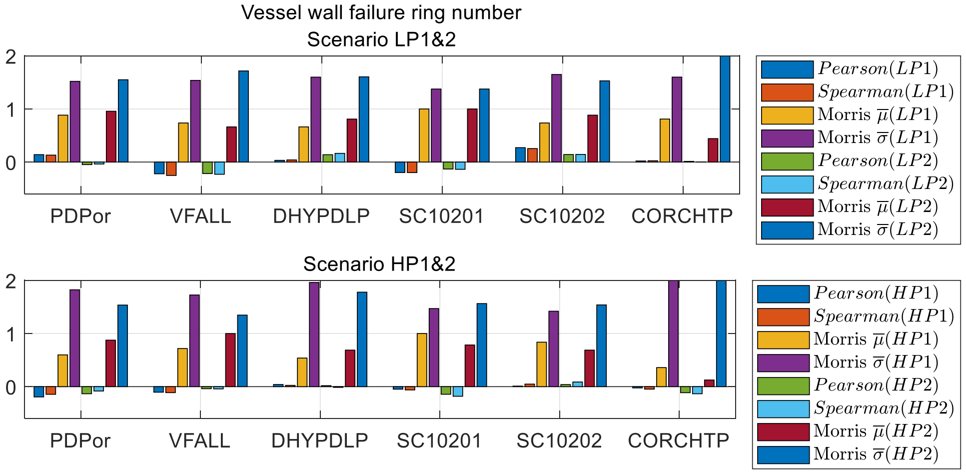


Figure 7. Sensitivity of vessel failure location due to vessel wall failure to modelling parameters in MELCOR. Scenario LP1&2 and HP1&2 with penetration modelling.

Melt release conditions

The rate of melt release is determined by equations (1) and (2), and the solid debris ejection switch (IDEJ). Based on sensitivity analysis results, presented in Figure 8 (with penetration modelling), the most influential parameters are SC1020-1, SC1020-2, DHYPDLP and VFALL, however depending on IDEJ switch. In case of vessel wall failure (without penetration modelling) the most influential parameter is VFALL (see Figure 9), however further analysis is necessary to explain the effect of this parameter on debris (enthalpy) ejection rates.

Debris ejection and enthalpy release rates vary in quite significant range (e.g. from several hundred (kg/s) to several thousands (kg/s)) depending on MELCOR modelling parameters, vessel failure modelling (i.e. with\without penetrations) and MELCOR modelling of melt release (IDEJ switch).

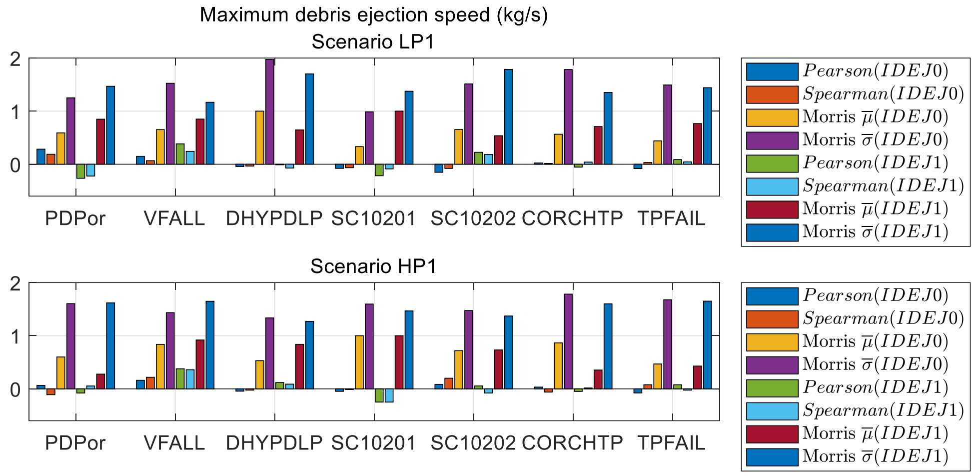


Figure 8. Sensitivity of maximum debris ejection rate in case of penetration failure to modelling parameters in MELCOR. Scenario LP1 and HP1 with penetration modelling.

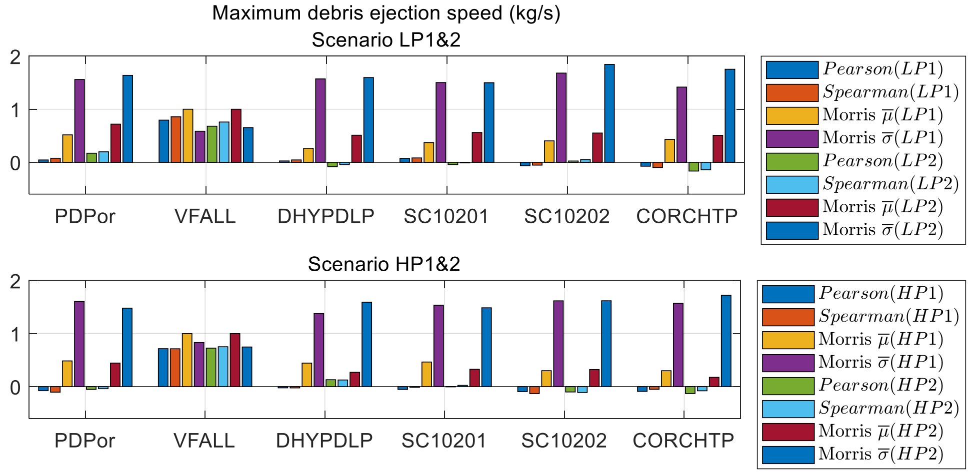


Figure 9. Sensitivity of maximum debris ejection rate in case of vessel wall failure to modelling parameters in MELCOR. Scenario LP1 and HP1 with penetration modelling.

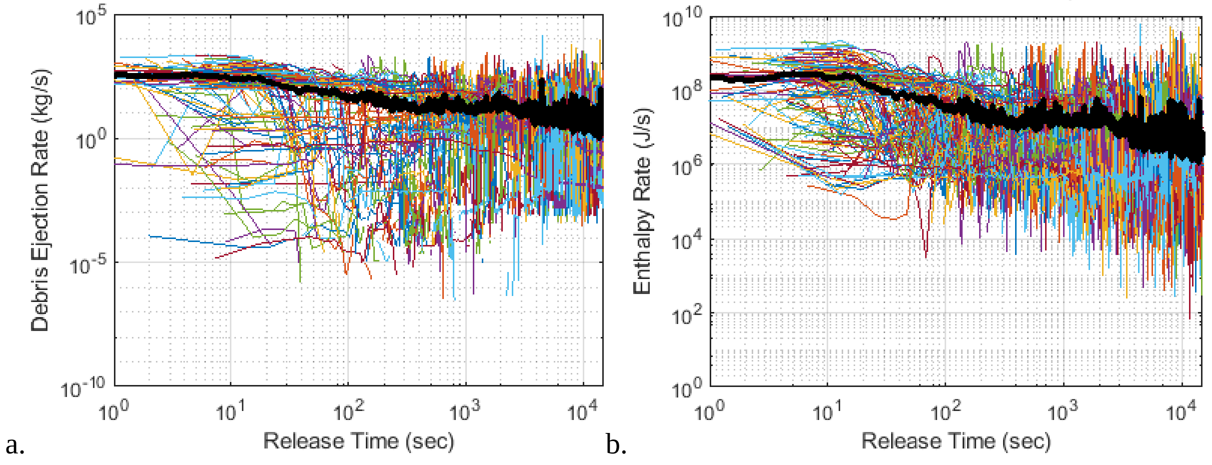
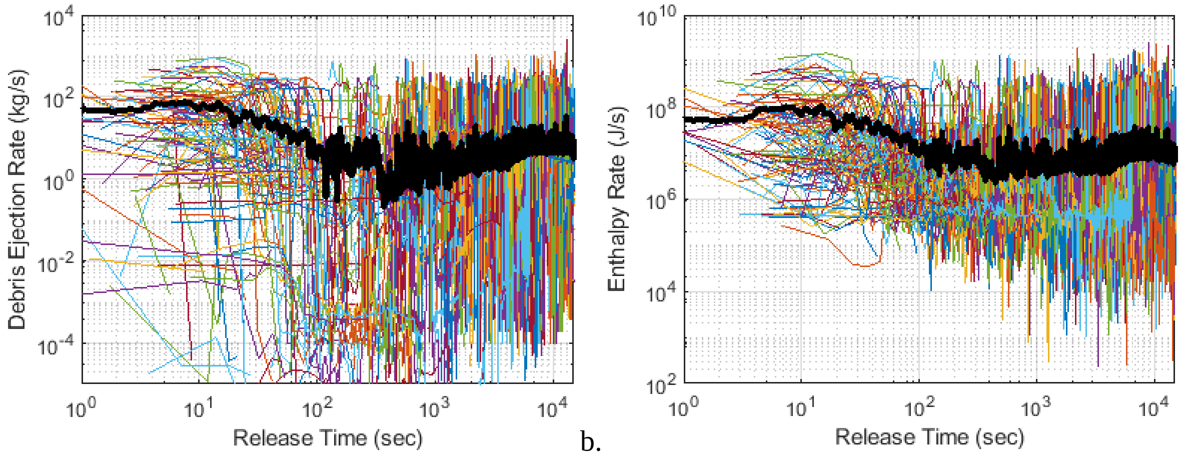
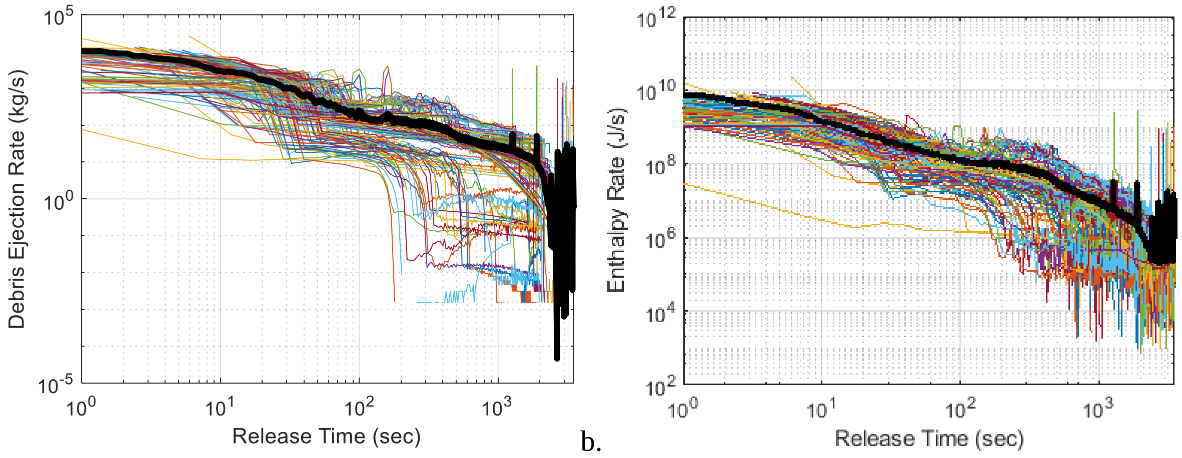


Figure 10. Moving average (black curve) of (a) debris ejection rate (kg/s) (b) enthalpy rate (J/s) with penetration modelling, solid debris ejection ON (IDEJ=0); LP1 scenario.



a. b.

Figure 11. Moving average (black curve) of (a) debris ejection rate (kg/s) (b) enthalpy rate (J/s) with penetration modelling, solid debris ejection OFF (IDEJ=1); LP1 scenario.



a. b.

Figure 12. Moving average (black curve) of (a) debris ejection rate (kg/s) (b) enthalpy rate (J/s) without penetration modelling. LP1 scenario.

4. CONCLUSIONS

In this work we address sensitivity of the time and the mode of vessel failure and melt release and respective properties of the debris relocated into the lower plenum of Nordic BWR at the time of the release to MELCOR modelling parameters and options. MELCOR modelling parameters were sampled using Morris method for global sensitivity analysis. The results of the analysis show that different MELCOR modelling parameters have different importance depending on the system response quantity and severe accident scenario (i.e. early or late depressurization). Furthermore, MELCOR predicts the vessel breach to due to penetration failure to occur significantly earlier when compared to vessel breach due to vessel wall failure, which results in quite significant difference in the properties of ejected debris. The mode of melt (debris) release from the vessel is majorly affected by MELCOR modelling options, such as penetration modelling\no penetration modelling and solid debris ejection switch. For example, vessel wall failure due to creep-rupture results in gross failure and rapid discharge of the debris to the cavity regardless its state, on the other hand, in the case of penetration failure, a gradual release is predicted by MELCOR.

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References

1. Pavel Kudinov, Sergey Galushin, Dmitry Grishchenko, Sergey Yakush, Simone Basso, Alexander Konovalenko, Mikhail 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.
2. P. Kudinov, S. Galushin, W. Villanueva, S. Yakush, D. Grishenko, Development of Risk Oriented Approach for Assessment of Severe Accident Management Effectiveness in Nordic BWR, PSAM12, Hawaii, USA, June (2014).
3. D. Grishchenko, S. Galushin, S. Basso, P. Kudinov, “Application of TEXAS-V surrogate model to assessment of the containment failure risk due to steam explosion in a Nordic type BWR”, *NUTHOS-11: The 11th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety*, Gyeongju, Korea, October 9-13, (2016).
4. Randall Gauntt, Donald Kalinich, Jeff Cardoni, Jesse Phillips, Andrew Goldmann, Susan Pickering, Matthew Francis, Kevin Robb, Larry Ott, Dean Wang, Curtis Smith, Shawn St.Germain, David Schwieder, Cherie Phelan, “Fukushima Daiichi Accident Study”, SAND2012-6173, Sandia Report, SNL, (2012).
5. Lars Nilsson. “Development of an Input Model to MELCOR 1.8.5 for Oskarshamn 3 BWR”, SKI Report, 2007:05, (2007).
6. Morris, M. D. (1991) “Factorial sampling plans for preliminary computational experiments. Technometrics”, Vol **33**(2), 161–174. (1991).
7. A. Saltelli, S. Tarantola, F. Campolongo and M. Ratto, “Sensitivity Analysis in Practice. A Guide to assessing scientific models”. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England. (2004).
8. L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips, “MELCOR Computer Code Manuals”, **Vol. 2**: Reference Manual Version 2.2.9541, SAND2017-0876 O, (2017).
9. L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips, “MELCOR Computer Code Manuals”, **Vol. 1**: Primer and Users’ Guide Version 2.2.9541, SAND2017-0455 O, (2017).
10. Randall O. Gauntt, Nathan E. Bixler, and Kenneth C. Wagner, An Uncertainty Analysis of the Hydrogen Source Term for a Station Blackout Accident in Sequoyah Using MELCOR 1.8.5, SANDIA report, SAND2014-2210, March (2014).
11. Müller, C. Review of Debris Bed Cooling in TMI-2 Accident. Garching: GRS Forschungsinstitute, (2006).
12. Kudinov, P., Karbojian, A., Tran, C.-T., Villanueva, W., “Experimental Data on Fraction of Agglomerated Debris Obtained in the DEFOR-A Melt-Coolant Interaction Tests with High Melting Temperature Simulant Materials,” Nuclear Engineering and Design, 263, October 2013, Pages 284-295, 10.1016/j.nucengdes.2013.06.011, 2013.
13. Magallon, D., “Characteristics of corium debris bed generated in large-scale fuel-coolant interaction experiments”, *Nuclear Engineering and Design*, **236**, 2006, pp.1998–2009. (2006).
14. Kyle Ross, Jesse Phillips, Randall O. Gauntt, Kenneth C. Wagner, MELCOR Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project, NUREG/CR-7008, (2014).
15. “Fukushima Daiichi Unit 1 Accident Progression Uncertainty Analysis and Implications for Decommissioning of Fukushima Reactors – Volume **I**”, Sandia National Laboratories, SAND2016-0232, (2016).
16. J.L. Rempe, S.A. Chavez, G.L. Thinnes, C.M. Allison, G.E. Korth, R.J. Witt, J.J. Sienicki, S.K. Wang, L.A. Stickler, C.H. Heath, S.D. Snow, “Light Water Reactor Lower Head Failure Analysis”, NUREG/CR-5642, EGG-2618, Idaho National Engineering Laboratory, USA (1993).