Uncertainty Analysis of Fission Products Release in Filtered Venting Scenarios in Nordic BWRs: Assessing the Effect of Independent Spray System

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Abstract: Nordic Boiling Water Reactors employ filtered containment venting, an independent containment spray system and ex-vessel corium stabilization as a severe accident management (SAM) strategy. In the event of a severe accident involving core melt and vessel failure, the melt arrest and accident stabilization is provided by ex-vessel debris coolability in the deep pool of water under the reactor pressure vessel (RPV), in which the core melt, after its release from the RPV, is expected to fragment, quench, and form a coolable debris bed.

To maintain the containment integrity and residual heat removal, the containment will be depressurized (either manually or automatically) by opening of the containment depressurization line via the multi-venturi scrubbing system (MVSS). In addition, containment pressure and water inventory in the containment can be maintained by the independent spray system, connectable to mobile equipment.

This paper focuses on evaluating the impact of the independent spray system on severe accident progression and the source term released to the environment during scenarios resulting in filtered containment venting, using the MELCOR code. The analysis includes quantification of uncertainties related to the MELCOR code's epistemic modeling parameters and options, and their effects on the timing and magnitude of the source term. The performed MELCOR code simulations illustrate the effect of epistemic modelling parameters and options on the code's predictions of severe accident progression, event timing, and the magnitude of the source term released to the environment. Furthermore, the results highlight the importance of various retention mechanisms that mitigate the release of fission products into the environment.

Keywords: Severe accident, source term, uncertainty, MELCOR

1. INTRODUCTION

Nordic Boiling Water Reactors employ filtered containment venting and ex-vessel debris coolability in the deep pool beneath the reactor pressure vessel as a severe accident management (SAM) strategy. In the event of an accident involving severe core damage and melting, the molten core is expected to be released from the vessel into a deep pool of water in the lower drywell. The molten core is expected to fragment, quench, and form a debris bed that can be cooled by the natural circulation of water. At the same time the pressure in the containment will gradually increase prompting the opening (either manually or automatically) of the containment depressurization line via the multi-venturi scrubbing system (MVSS).

In Level 2 Probabilistic Safety Assessments (L2 PSA), the primary frequency estimate of interest is the unacceptable release frequency. Evaluating these frequencies involves summing over a large number of possible event sequences. This process implies, among other considerations, that radioactive releases (the source term) must be calculated for a set of representative scenario classes and then compared to a predefined threshold to classify them as acceptable or unacceptable. Typically, these assessments are conducted using integral plant response codes such as ASTEC, MAAP, or MELCOR. The assessments themselves are subject to uncertainty, both in terms of accident scenarios (aleatory uncertainty) and in the modeling of phenomena (epistemic uncertainty).

Aleatory uncertainty arises from the natural variability of stochastic processes and cannot be reduced beyond this level. In contrast, epistemic uncertainty pertains to our knowledge of systems, processes, or parameters and can therefore be reduced by gathering more knowledge.

Typically, source term evaluations are conducted for a limited set of accident scenarios, utilizing point-estimate values for epistemic uncertain parameters in the employed code. The uncertainty associated with the source term poses a challenge for any attempt to develop, use or increase the level of detail in L2 PSA results and merits targeted research solely on the basis of this.

Furthermore, within the field of nuclear emergency preparedness towards severe accidents, the ultimate goal is to perform relevant and efficient actions to protect the public. This is typically based on pre-calculated accident scenarios and their associated source terms. Therefore, the knowledge about source term uncertainty and timing of major release is of paramount importance.

The uncertainty analysis performed within the NKS-STATUS project showed that the magnitude of the source term released to the environment in unmitigated filtered containment venting scenarios initiated by a LB-LOCA may lead to exceedance of the acceptable release[1] threshold for some MELCOR modelling parameters combinations, such as the mode of debris ejection from the vessel (IDEJ) and decontamination factor for radioactive vapors (MVSSDFV), for further details refer to [10,11,13].

This, however, contradicts the grouping of accident scenarios into release categories (RC) in the L2 PSA for Nordic BWR, where these accident sequences belong to the RC7 - acceptable release category [10].

This issue can be addressed either by revising the PSA modeling of the MVSS in the PSA L2 or by considering additional mitigative safety functions in the analysis.

One of the mitigative safety functions that can limit fission products release to the environment in these scenarios is the independent containment spray system, which is typically activated after RPV failure, to scrub the containment atmosphere, reduce pressure in the containment, and flood the containment to ensure debris coolability. The purpose of this paper is to evaluate the effect of the independent spray system on the containment pressure response and the source term released to the environment in accident scenarios initiated by a LB-LOCA that leads to filtered containment venting to the environment.

2. METHOD

The analysis was performed using MELCOR code version 2.2 rev 18019 with the Nordic BWR model, originally developed in [9]. The Nordic-type BWR operates a nominal thermal power of 3900MW_{th}, and a primary system pressure of 7 MPa. The Nordic BWR core is comprised of 700 SVEA-96 Optima 2 fuel assemblies, divided into 5 radial rings and 8 axial levels. For additional details about the core and thermal hydraulic nodalization of the Nordic BWR, refer to [9-11].

In this work, we consider two accident scenarios: (i) an accident initiated by a Loss of Coolant Accident (LOCA), with all active safety systems unavailable, such as Emergency Core Cooling Systems (High and Low pressure ECCS) or containment sprays – denoted as LOCA-MVSS; (ii) a Loss of Coolant Accident (LOCA), with all active safety systems unavailable, such as Emergency Core Cooling Systems (High and Low pressure ECCS), however with activation of the independent containment spray system – denoted as LOCA-MVSS-SPR.

Additionally, the sensitivity and uncertainty analyses performed in [10,11,13] showed the mode of debris ejection from the vessel, represented by the physics model switch IDEJ in the MELCOR code [7,8], has a dominant effect of the code predictions of the Cs source term released to the environment in filtered containment venting scenarios initiated by a LB-LOCA. In the analysis presented in this paper, the mode of debris ejection from the vessel – IDEJ – will be considered as a phenomenological splinter, and the MELCOR code simulations will be performed considering combinations of accident scenarios and the mode of debris ejection from the vessel, resulting in four sets of calculations, denoted as follows:

- LOCA-IDEJ0 – LOCA-MVSS scenario with solid debris ejection on (IDEJ0)
- LOCA-IDEJ1 – LOCA-MVSS scenario with solid debris ejection off (IDEJ1)
- LOCA-IDEJ0-SPR – LOCA-MVSS-SPR scenario with solid debris ejection on (IDEJ0)
- LOCA-IDEJ1-SPR – LOCA-MVSS-SPR scenario with solid debris ejection off (IDEJ1)

The independent spray system is activated one hour after the initiating event and before RPV lower head failure to limit pressure and temperature in the containment. It is deactivated when the water level in the drywell reaches a predetermined setpoint, to avoid excessive reduction of the gas space in the containment that can lead to containment overpressure due to FCI phenomena at RPV lower head failure. After RPV lower failure and melt/debris ejection into the cavity, the system is activated again until the water level in the containment reaches the level where the RPV lower head hemisphere is covered by water. In both accident scenarios, the lower drywell is flooded with water from the condensation pool (as discussed in [11]), to prevent failure of cable penetrations and ensure ex-vessel debris coolability. Containment filtered venting via MVSS is initiated automatically when the pressure in the drywell exceeds 0.55 MPa (absolute) [10].

To conduct uncertainty analysis, discussed in this paper, first a set of MELCOR code modelling parameters, along with their respective ranges, which can influence severe accident progression and the source term released to the environment was identified. This identification was based on a literature review conducted in

[1] Releases over 0.1 % of the inventory of the cesium isotopes Cs-134 and Cs-137 in a core of 1800 MW_{Th}, excluding noble gases, which corresponds to a release of 160 TBq of Cs-134 and of 103 TBq of Cs-137 [12].

[10]. Subsequently, a screening analysis was performed to eliminate MELCOR code modeling parameters with a negligible effect on the predictions of severe accident progression and source terms. Additional details on parameter selection and the screening analysis can be found in [10].

Typically, the sources of uncertainty in a Level 2 PSA are numerous and it is impractical to address all of them quantitatively. Experience in performing uncertainty studies for limited aspects of severe accident phenomena suggests that the effects of uncertainties from some sources are larger and more dominant than the effects of uncertainties from other sources. In an integral sense, then, the aggregate uncertainty in Level 2 PSA results can be estimated by selecting the dominant sources of uncertainty and treating them in detail. To identify the dominant sources of uncertainty, the Morris method for sensitivity analysis was employed. The detailed results of the sensitivity analysis are presented and discussed in [11]. The most influential parameters identified by the Morris method are summarized in Table 1 and will be utilized in the uncertainty analysis presented in this paper.

For the uncertainty analysis, a sample size of 100 MELCOR code calculations was chosen for each accident scenario and IDEJ parameter combination (in total - 400 MELCOR code runs). This sample size is expected to yield adequate results based on the Wilks' method for 95% tolerance/confidence limits [16].

Table 1. MELCOR code modelling parameters considered in uncertainty analysis.

Parameter ID	**Parameter description and proposed distribution**	**Accident scenario**
STICK [-]	Particle sticking probability. Scaled beta (2.5, 1.0), scaled on [0.5, 1.0] [6]	All
FCELRA [-]	Radiative exchange factors. Truncated normal (0.1, 0.035) truncated on [0.020, 0.30] [2]	All
SC71521 [m]	Initial bubble diameter correlation coefficient in SPARC-90 model. Triangular M = 7.E-3, range [5.E-3, 8.E-3] [EJ][2]	LOCA-IDEJ0 LOCA-IDEJ0-SPR
SC1020 [-]	Multiplication factor for time constant for radial solid and molten debris relocation. Scaled beta (1.33, 1.67) scaled on range [1.0, 4.0] [4]	LOCA-IDEJ0 LOCA-IDEJ0-SPR
CORNSBLD [K]	NS failure temperature threshold. Uniform [1520-1700] [5]	All
VFALL [m/s]	Velocity of falling debris. Scaled beta (0.85, 1.14), scaled on range [0.01, 1.0] [4]	All
TZRSSINC [K]	Solidus temperatures for ZR/SS and ZR/INC eutectic pairs. Scaled beta (2.0, 1.0), scaled on range [1210, 1700] [EJ]	All
SC715010 [-]	Scaling factor for SPARC-90 model vent exit condensation decontamination factor. Triangular M = 2, range [1.0, 3.0] [EJ]	All
CHI [-]	Aerosol dynamic shape factor. Scaled beta (1.0, 1.5) scaled on [1.0, 5.0] [6]	All
MVSSDFV [-]	MVSS decontamination factor for radioactive vapors. Lognormal (4.6, 0.916) truncated on [10,1000], 0.99 – correlation with MVSSDFA [EJ]	All
SC71568[-]	Multiplicative constant in a temperature correction correlation in the SPARC-90 model. Triangular M = -0.00232, [-2.6691e-03, -1.9728e-03] [EJ]	All
TPFAIL [K]	Penetration failure temperature. Scaled beta (2.0, 2.0) scaled on [1273, 1600] [EJ]	All
HFRZZR [W/m^2K]	Refreezing heat transfer coefficient for Zr. Lognormal (8.9227, 0.55962) truncate on [2000, 22000] [2]	All
SC7170CSM [kg/kgH_2O]	Saturation solubility at high and low temperature reference for CsM. Triangular M = 0.67, range [0.5695, 0.7705] [EJ]	LOCA-IDEJ0 LOCA-IDEJ0-SPR
SC71555 [-]	SPARC-90 model multiplication constants in the DF factor correlations for and large Stokes numbers. Triangular M = 1.13893, range [0.9681, 1.3098] [EJ]	All
RHONOM [kg/m^3]	Aerosol density. Triangular M = 2000, range [870,4500] [1]	All
SC7111CS2 [K]	Characteristic energy of interaction between the molecules divided by the Boltzmann constant for CsI/CsM. Triangular M = 97, range [82.450,111.550] [EJ]	LOCA-IDEJ0 LOCA-IDEJ0-SPR

[2] EJ – expert judgement.

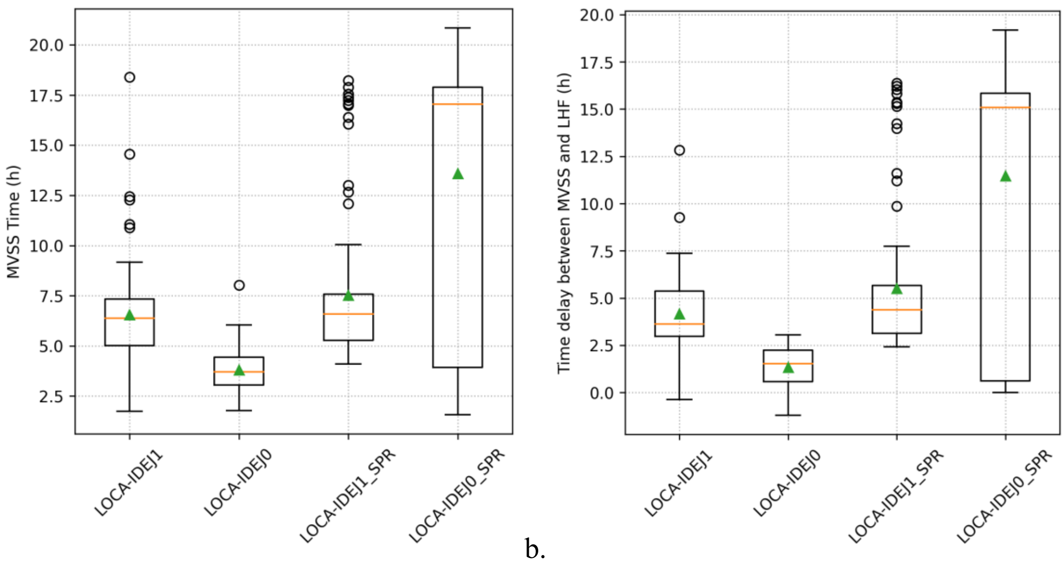
Parameter ID	Parameter description and proposed distribution	Accident scenario
SC7170CS [kg/kgH_2O]	Saturation solubility at low/high temperature reference for Cs. Triangular M = 3.95, range [3.3575, 4.5425] [EJ]	LOCA-IDEJ1 LOCA-IDEJ1-SPR
SC7111CS1 [Å]	Characteristic diameter of the molecule for Cs. Triangular M = 3.617, range [3.0745,4.1595] [EJ]	LOCA-IDEJ1 LOCA-IDEJ1-SPR
TURBDS m^2/s^3]	Turbulence dissipation rate. Uniform [7.5E-4, 1.25E-3] [3][EJ]	LOCA-IDEJ1 LOCA-IDEJ1-SPR
SC7111I1 [Å]	Characteristic diameter of the molecule for I. Triangular M = 4.982, range [4.2347, 5.7293] [EJ]	LOCA-IDEJ1 LOCA-IDEJ1-SPR
GAMMA [-]	Aerosol agglomeration shape factor. Scaled beta (1.0,1.5) scaled on range [1.0, 5.0] [6]	All
MVSSDFA [-]	MVSS decontamination factor for radioactive aerosols. Truncated normal (500, 250) truncated on [100,1000], 0.99 – correlation with MVSSDFV [EJ]	All
PDPor [-]	Particulate debris porosity. Truncated normal (0.38, 0.1) truncated on [0.25, 0.50] [2][EJ]	All
HFRZSS [W/m^2K]	Refreezing heat transfer coefficient for SS. Lognormal (7.824, 0.40547), truncated on [1000, 5000] [2]	All
DIAMO [m]	Initial spray droplet diameter. Triangular M = 1.E-3, range [1.E-4, 2.E-3].	LOCA-IDEJ0-SPR LOCA-IDEJ1-SPR

3. RESULTS

The results of MELCOR code simulations are summarized in Table 2 and Figure 1, which illustrate the time of automatic activation of the MVSS (via rupture disk, when pressure in the containment > 5.5 Bar), and the time delay between vessel lower head failure and MVSS activation; and in Figure 2, which illustrates the fraction of the core inventory of Cs released to the environment after 4, 8, 12, 24, 48 and 72 hours after initiating event.

Table 2. Summary of uncertainty analysis results (mean/median values and [range])

Scenario\FOM	MVSS Time (h)	Vessel lower head failure (h)	Cs release fraction[3] (-)	I release fraction[3] (-)
LOCA-IDEJ1	6.55/6.39 [1.75, 18.39]	2.39/1.92 [1.18, 7.20]	1.83E-3/1.26E-3 [2.27E-4, 1.65E-2]	2.49E-3/1.61E-3 [2.8E-4, 2.16E-2]
LOCA-IDEJ0	3.79/3.70 [1.78, 8.02]	2.45/1.98 [1.08, 7.64]	2.56E-4/1.67E-4 [5.03E-5, 1.82E-3]	2.67E-4/1.51E-4 [4.78E-5, 2.49E-3]
LOCA-IDEJ1-SPR	7.52/6.58 [4.10, 18.22]	2.01/1.90 [1.06, 3.92]	4.07E-5/3.69E-5 [1.49E-5, 1.11E-4]	4.39E-5/3.92E-5 [1.86E-5, 1.06E-5]
LOCA-IDEJ0-SPR	13.58/17.05 [1.57, 20.83]	2.11/2.02 [1.40, 6.10]	2.93E-5/2.55E-5 [1.22E-5, 8.78E-5]	3.34E-5/2.99E-5 [1.60E-5, 9.04E-5]



a. b.

Figure 1. (a) MVSS activation time [h] after IE; (b) Time delay between MVSS activation and vessel lower head failure [h].

[3] Fraction of the initial core inventory released to the environment.

The results indicate that the effect of the containment spray system has a relatively low impact on the timing of MVSS activation in LOCA-IDEJ1 (LOCA-IDEJ-SPR) scenarios. This can be explained by the effect of the mode of debris ejection from the vessel (IDEJ) on debris ejection rate and activation conditions of the independent spray system. Typically, when the modelling option IDEJ=1 is used, debris ejection from the vessel is protracted in time and typically starts with dripping mode directly after the failure of vessel lower head penetrations, followed by massive debris ejection from the vessel due to global failure of the vessel lower head wall due to creep-rupture, which typically occurs after ~1-1.5 h after initial failure of the lower head penetrations [14,15]. The activation of the independent spray system is triggered manually by operators, when there are clear indicators that the corium and debris are ex-vessel, to maintain an adequate gas space in the containment and avoid containment over-pressurization due to FCI phenomena in the water-filled drywell after RPV failure. Both these factors contribute to the late activation of the spray system, and, thus, relatively low impact of this system on the pressure response of the containment during the first hours after the vessel lower head failure and timing of activation of the MVSS in LOCA-IDEJ1(SPR) scenarios.

On the contrary, when the IDEJ=0 option is used, debris ejection from the vessel occurs gradually over time directly after the initial failure of the vessel lower head penetrations. This triggers the activation of the independent spray system relatively early in the sequence. Consequently, it can reduce pressure in the containment by condensation of steam and delay the activation of the MVSS by ~12 hours when compared to the MVSS-IDEJ0 scenario (vs. MVSS-IDEJ0-SPR).

The fraction of the core inventory of Cs released to the environment after 4 h, 8 h, 12 h, 24 h, 46 h and 72 h after the initiating event, illustrated in Figure 2a-f, show that in the case of LOCA-IDEJ1 the acceptable release threshold is exceeded already after 8 hours in a few cases and 12 hours after initiating event in over 50% of simulated cases. After 72 hours, the fraction of Cs released to the environment increases to 90% of simulated cases in the LOCA-IDEJ1 scenario and 16% in the LOCA-IDEJ0 scenario.

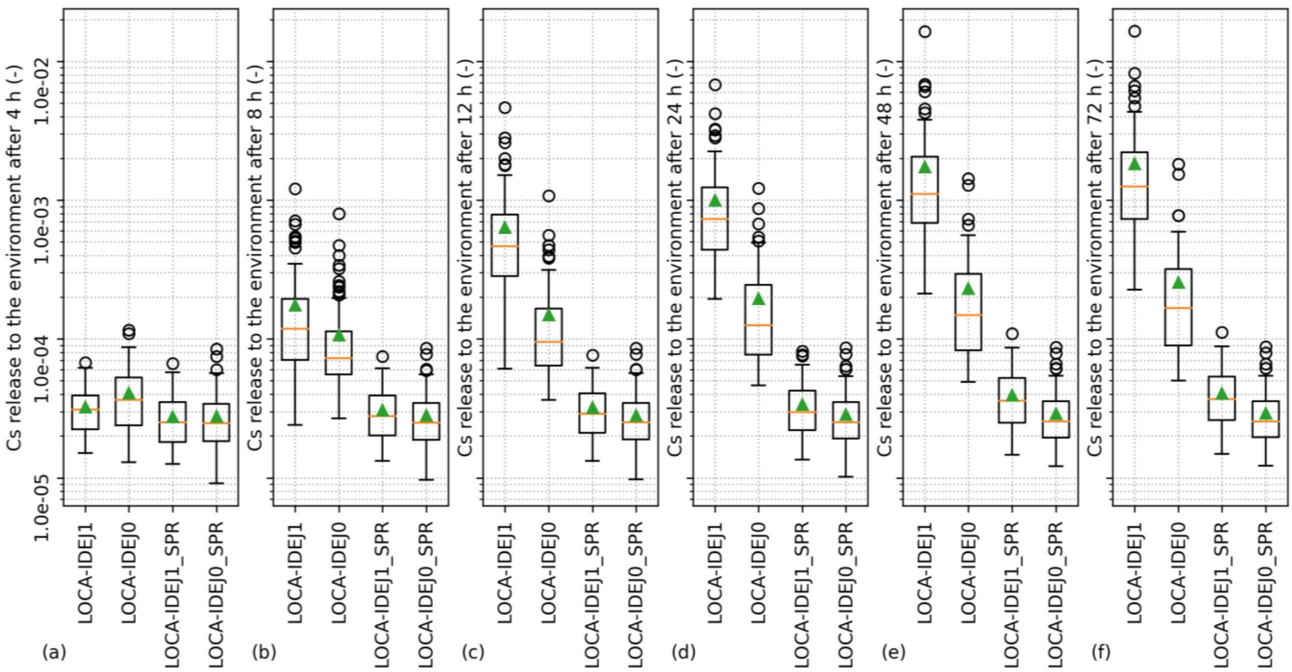


Figure 2. Fraction of core inventory of Cs [-] released to the environment after (a) 4 hours; (b) 8 hours; (c) 12 hours; (d) 24 hours; (e) 48 hours; (f) 72 hours after initiating event.

Based on the simulation results, spraying inside the containment with the independent spray system can significantly reduce the fraction of Cs released to the environment below the acceptable release threshold in all simulations performed for LOCA-IDEJ1-SPR and LOCA-IDEJ-SPR scenarios, regardless uncertainty in the MELCOR code modelling parameters considered in the analysis.

The analysis performed in [13] suggest that elevated temperatures inside the RPV and the drywell in the accident scenarios initiated by a LOCA, especially in the case of IDEJ=1, is the main driving factor for remobilization of Cs deposited on the heat structures inside the reactor pressure vessel and the containment, resulting in a larger release of Cs released from the containment to the MVSS and to the environment.

Figure 3 illustrate the speciation of Cs released to the environment in different accident scenarios considered in this analysis, which clearly show that Cs is majorly released in form cesium hydroxide (MELCOR RN Class 2 [7,8]).

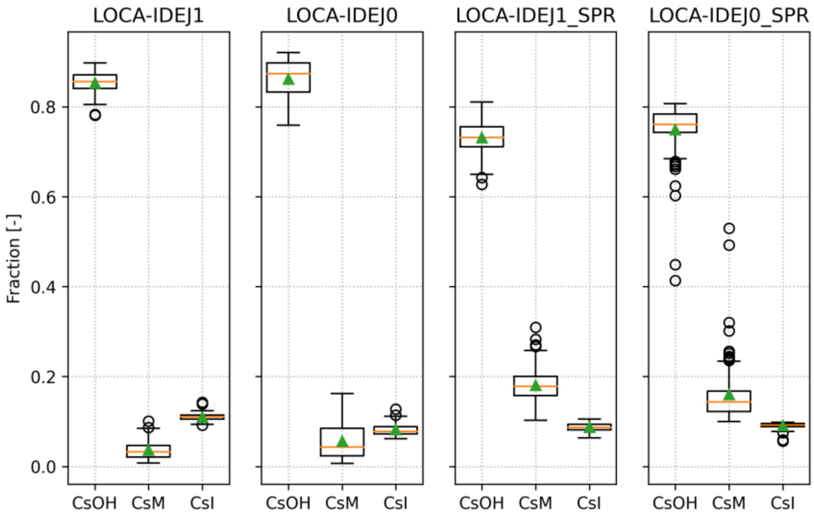


Figure 3. Speciation of Cs released to the environment [-]

When it comes to the filtering efficiency of the MVSS, it depends on the state of Cs being released from the containment into the MVSS (vapor or aerosol) and, for aerosols, aerosols size, since the srubbing efficiency of the self-priming venturi greatly depends on aerosols size. Smaller aerosol particles are trapped less efficiently in the venturi scrubber by the processes of impactation, interception and diffusion with water droplets.

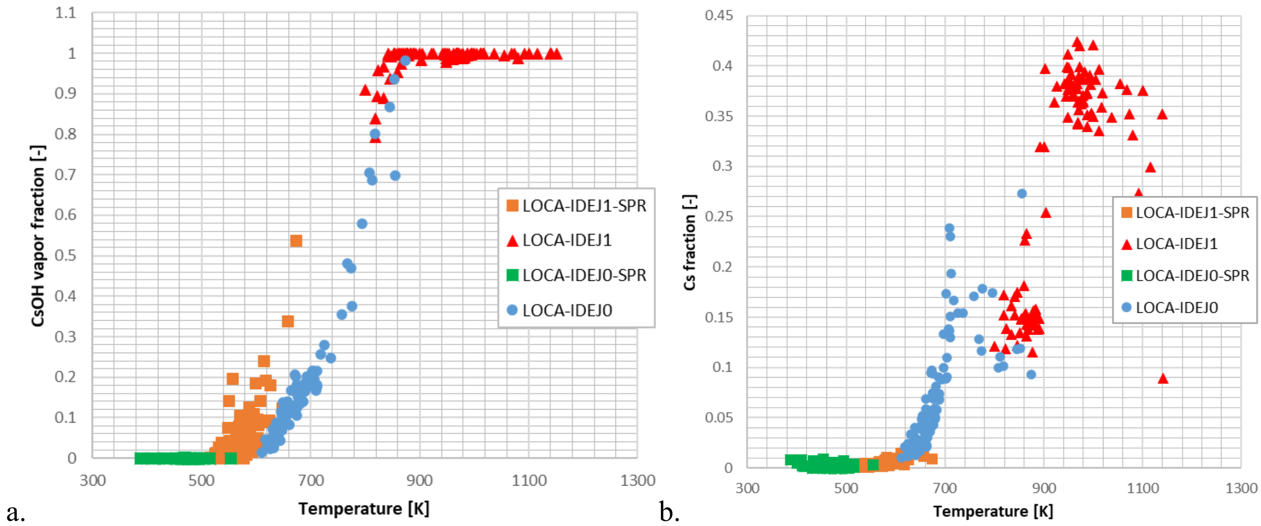


Figure 4. Mass averaged temperature in the drywell [K] vs. (a) Vapor fraction of CsOH (RN2) released from the containment to the MVSS [-]; (b) Fraction of core inventory of Cs deposited in the MVSS [-]

Figure 4a illustrate the mass fraction of CsOH vapor (vs. the total mass of CsOH) released from the containment to the MVSS as a function the temperature in the drywell averaged against the mass of CsOH released from the containment to the MVSS (as illustrated in Eq (1)).

$$T_{DW_M} = \sum T_{DW_i} \frac{\Delta m_{i_{CsOH_{DW \to MVSS}}}}{m_{CsOH_{DW \to MVSS}}} \quad (1)$$

It shows that the mass fraction of the vapor form of CsOH increase with increasing temperature inside the containment, and becomes dominant when the temperature exceeds 800 K. A similar trend can be observed in the fraction of Cs deposited in the scrubber as a function of the mass averaged temperature in the drywell.

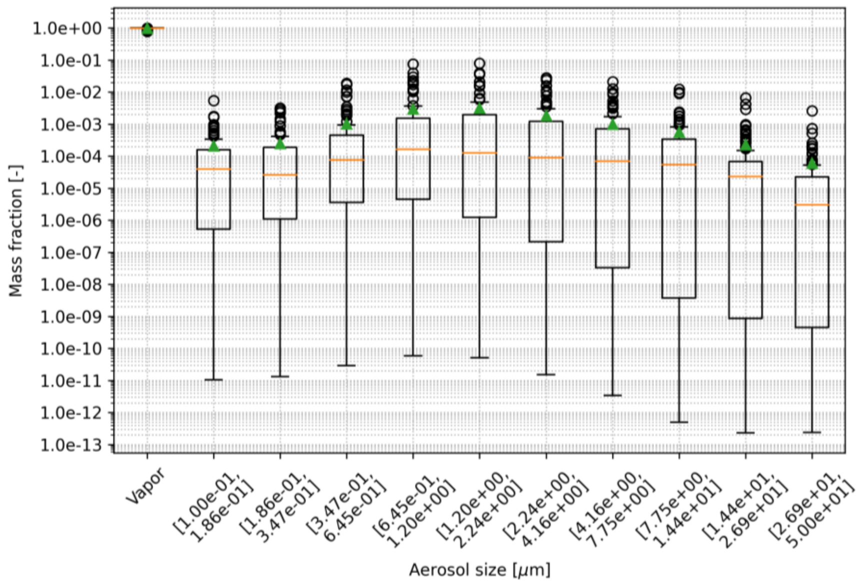


Figure 5. Size distribution of CsOH aerosols released from the containment to the MVSS in LOCA-IDEJ1 scenario.

This is also evident from Figure 5 (LOCA-IDEJ1) and Figure 6 (LOCA-IDEJ0), which show that the major part of CsOH is released in vapor form in the LOCA-IDEJ1 scenario, and approximately ~15% in the LOCA-IDEJ0. It is also important to note that in the LOCA-IDEJ0 scenario, and the LOCA-IDEJ0-SPR and LOCA-IDEJ1-SPR scenarios, the major bulk of aerosols released into the scrubber is composed of very fine aerosol particles (0.1-1 μm). Therefore, the scrubbing efficiency of the MVSS and its decontamination factor can be on the lower end of the range of the MVSSDFA parameter considered in the analysis. However, this aspect is not considered in the present analysis, and the same decontamination factor is applied to all aerosol sizes.

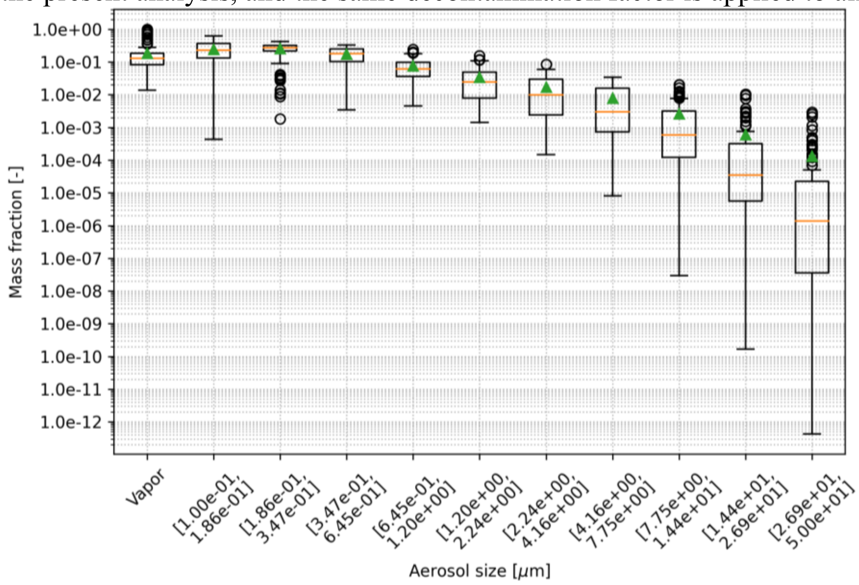


Figure 6. Size distribution of CsOH aerosols released from the containment to the MVSS in LOCA-IDEJ0 scenario.

Another important observation from Figure 7 and 8, is that, even though the fraction of the vapor form of CsOH is significantly higher in LOCA-IDEJ1-SPR than that in LOCA-IDEJ0-SPR, the major part of CsOH in LOCA-IDEJ0-SPR is released from the containment to the scrubber in the form of fine aerosol particles (0.1-0.2 μm), whereas in the case of LOCA-IDEJ1-SPR, the aerosol particles are distributed in a wider range between 0.1 and 10 μm. This difference can positively affect the scrubbing efficiency when using a more detailed filtering model in MELCOR, where the MVSS decontamination factor will depend on the aerosol size (in the MELCOR code, different values of decontamination factors can be assingned for every aerosol size section [7,8]).

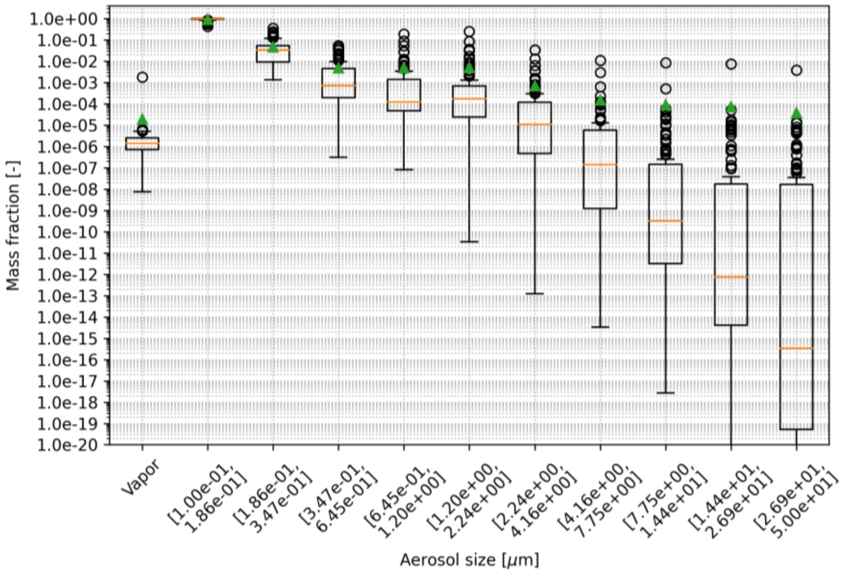


Figure 7. Size distribution of CsOH aerosols released from the containment to the MVSS in LOCA-IDEJ0-SPR scenario.

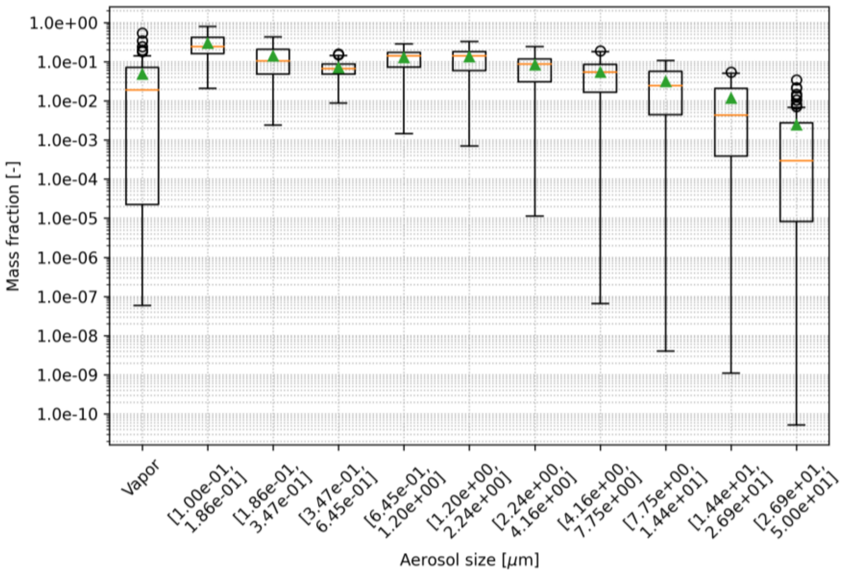


Figure 8. Size distribution of CsOH aerosols released from the containment to the MVSS in LOCA-IDEJ1-SPR scenario.

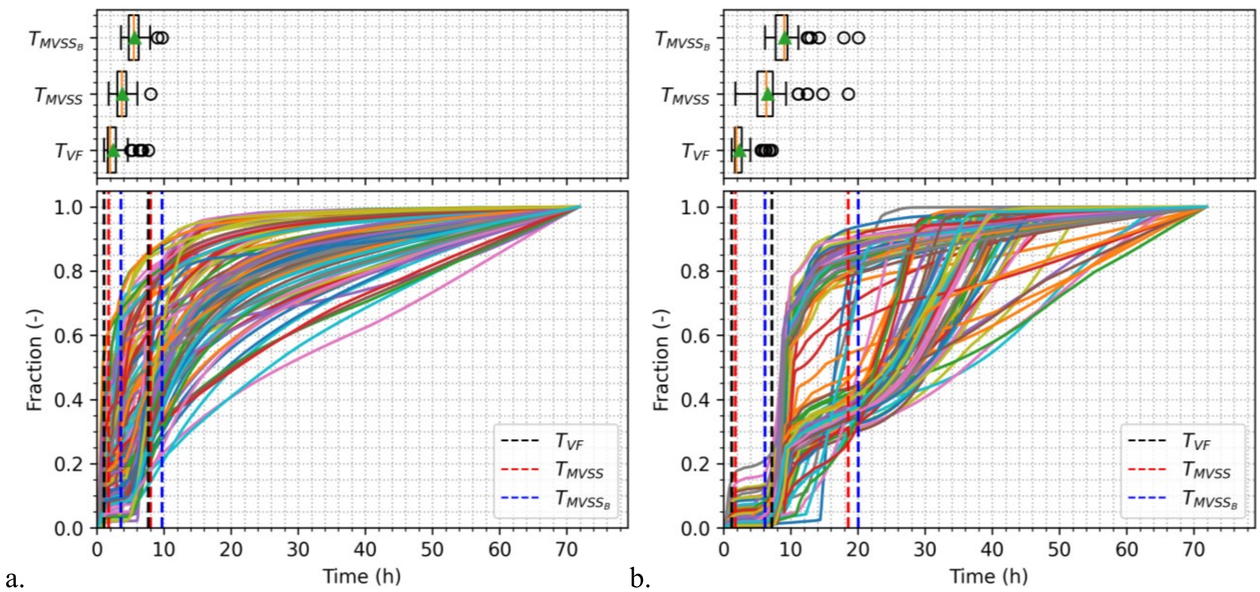


Figure 9. Fraction of total Cs release to the environment [-] as a function of time [h] in (a) LOCA-IDEJ0; (b) LOCA-IDEJ1 scenario.

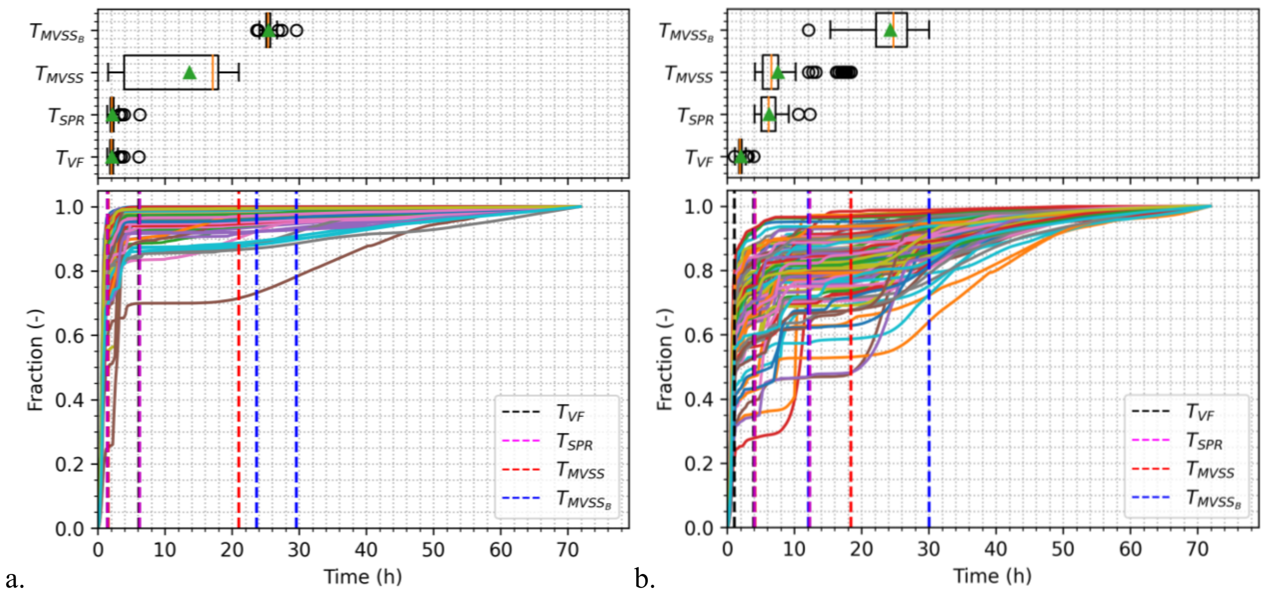


Figure 10. Fraction of total Cs release to the environment [-] as a function of time [h] in
(a) LOCA-IDEJ0-SRR; (b) LOCA-IDEJ1-SPR scenario.

Figure 9 and 10 illustrate the release rate of Cs to the environment in the form of the fraction of the total release for every simulated case for the accident scenarios considered in the analysis, accompanied by the timing of key events (dashed lines representing ranges and distributions are presented in box and whisker plots), such as T_{MVSS} – timing of MVSS activation, T_{MVSS_B} – time when the water pool in the MVSS start to boil, T_{VF} – timing of the vessel lower head failure and T_{SPR} – timing of activation of the independent spray system (in spray scenarios). The release rate in LOCA-IDEJ0 (Figure 9a) follows a similar pattern in all simulated cases, where a significant fraction of Cs is released after the initiation of the MVSS release (within first 10-15 hours after the initiating event), gradually increasing and reaching 100% towards the end of the simulation (72 hour). The release rate in LOCA-IDEJ1 (Figure 9b) follows two slightly different patterns. In the first pattern, it behaves similarly to the LOCA-IDEJ0 scenario, where the release occurs rather gradually over time, after MVSS activation. In the second pattern, the release plateaus in the range 25-35% approximately 10 hours after the initiating event, then starts to increase rapidly 20-30 hours after the initiating event, approaching 100% towards 30-50 hours after the initiating event.
Spraying inside the containment reduces the Cs source term released to the environment in both LOCA-IDEJ0-SPR and LOCA-IDEJ1-SPR scenarios. In the LOCA-IDEJ0-SPR scenario the major bulk of Cs is released within the first 5-10 hours after the initiating event, and the release plateaus afterwards. In the LOCA-IDEJ1-SPR scenario, we still observe a more protracted Cs release to the environment, with a significant fraction of Cs being released during several hours after the initiation of the MVSS release, stabilizing after 30-50 hours.

4. CONCLUSIONS

In this work the effect of the independent spray system on severe accident progression and the source term released to the environment during scenarios resulting in filtered containment venting was evaluated using the MELCOR code.
The uncertainty analysis results considering the MELCOR code's epistemic modeling parameters and options, show that spraying in the containment with the independent spray system can significantly limit fission products release to the environment. In the accident scenarios with the independent spray system (LOCA-IDEJ0-SPR and LOCA-IDEJ1-SPR) the release of Cs to the environment is below the acceptable release threshold[1] regardless uncertainties in the MELCOR code modelling parameters. To compare, the fraction of Cs released to the environment in unmitigated scenarios (LOCA-IDEJ0 and LOCA-IDEJ1) exceeds the acceptable release threshold in 16% and 90% of the simulations performed, respectively.
Furthermore, the results of this analysis emphasize the importance of a more detailed modelling of the multi-venturi scrubbing system (MVSS). This includes modelling of the structures and components between the containment and the scrubber, and the multi-venturi manifold. This can be done in the form of control volumes and associated heat structures to account for cooling and condensation of gases released from the containment. Additionally, a more detailed modelling of the venturi scrubbing is necessary, where scrubbing efficiency accounts for the size of the aerosols.

Another crucial aspect that needs to be considered in the future analysis is the long-term behavior of the scrubber. This involves consideration the effects of scrubber water temperature and level, as well as the impact of decay heat from fission products deposited in the filter pool on the scrubbing efficiency of the MVSS. This may necessitate modelling of additional operator actions, such as scrubber inventory makeup, which are currently not considered in either the MELCOR model of Nordic BWR or in the PSA L2 for Nordic BWR.

Acknowledgements

The authors would like to express gratitude to Patrick Isaksson, Elisabeth Tengborn, Sara Ojalehto, Tuomo Sevón, Ilona Lindholm, Naeem Ul-Syed and Anders Riber Marklund for very useful discussions, insights and contributions to the NKS-STATUS project.
The work is supported by the Nordic Nuclear Safety Research (NKS), under the NKS-R STATUS activity (Contract: AFT/NKS-R(23)133/5) and by the Swedish Radiation Safety Authority (SSM).

References

[1] R. Bocanegra, L.E. Herranz, CIEMAT's outcomes from the PHEBUS-FPT1 uncertainty analysis in the framework of the EU-MUSA project, The 10th European Review Meeting on Severe Accident Research (ERMSAR2022), Karlsruhe, Germany, May 16-19, (2022)

[2] P. Darnowski, P. Mazgaj, M.Włostowski, Uncertainty and Sensitivity Analysis of the In-Vessel Hydrogen Generation for Gen-III PWR and Phebus FPT-1 with MELCOR 2.2. Energies 2021, (2021)

[3] R. Bocanegra, L.E. Herranz, The importance of characterizing input uncertainties in severe accident analyses. The effect on pool scrubbing modeling in a Fukushima Unit 1 sequence, Sociedad Nuclear Española, Reunion Virtual, (2020)

[4] Fukushima Daiichi Unit 1 Accident Progression Uncertainty Analysis and Implications for Decommissioning of Fukushima Reactors, SAND2016-0232, Sandia National Laboratories (2016)

[5] L.I. Albright, N. Andrews, L.L. Humphries, D.L. Luxat, T. Jevremovic, Material Interactions in Severe Accidents – Benchmarking the MELCOR V2.2 Eutectics Model for a BWR-3 Mark-I Station, Nuclear Engineering and Design Volume 383 (2021)

[6] F. Mascari, M. Massone, G. Agnello, M. Angelucci, S. Paci, M. D'Onorio, F. Giannetti, Comparison of PHEBUS FPT1 uncertainty applications using MELCOR 2.2 with three different methodologies The 13th Meeting of the "European MELCOR and MACCS User Group" 27th –29th (2022).

[7] L.L. Humphries, B.A. Beeny, F. Gelbard, T. Haskin, D.L. Louie, J. Phillips, R.C. Schmidt, MELCOR Computer Code Manuals Vol. 2: Reference Manual Version 2.2.18019, SAND2021-0241 O, (2021)

[8] L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips, MELCOR Computer Code Manuals Vol. 1: Primer and Users' Guide Version 2.2.19018, SAND2021-0252 O, (2021)

[9] L. Nilsson, "Development of an Input Model to MELCOR 1.8.5 for Oskarshamn 3 BWR" SKI Report 2007:05 (2006)

[10] S. Galushin, A.R. Marklund, D. Grishchenko, P. Kudinov, T. Sevón, S. Ojalehto, I. Lindholm, P. Isaksson, E. Tengborn, N. Ul-Syed, Source Term And Timing Uncertainty in Severe Accidents (NKS-STATUS), NKS-461, 978-87-7893-554-0, (2022)

[11] S. Galushin, G. Acharya, D. Grishchenko, P. Kudinov, T. Sevón, S. Ojalehto, I. Lindholm, P. Isaksson, N. Ul-Syed, Source Term And Timing Uncertainty in Severe Accidents (NKS-STATUS), NKS-475, 978-87-7893-570-0, (2023)

[12] J-E. Holmberg, M. Knochenhauer, Probabilistic Safety Goals, Phase 1 – Status and Experiences in Sweden and Finland, NKS-153, ISBN 978-87-7893-216-7, (2007)

[13] S. Galushin, G. Acharya, D. Grishchenko, P. Kudinov, Source Term Uncertainty Analysis of Filtered Containment Venting Scenarios in Nordic BWR, The 11th European Review Meeting on Severe Accident Research (ERMSAR2024), Stockholm, Sweden, May 13-16, (2024)

[14] S. Galushin and P. Kudinov, Uncertainty Analysis of Vessel Failure Mode and Melt Release in Station Blackout Scenario in Nordic BWR Using MELCOR Code, The 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH 2019). Portland, OR, August 18-23, (2019)

[15] S. Galushin and P. Kudinov, Sensitivity and uncertainty analysis of the vessel lower head failure mode and melt release conditions in Nordic BWR using MELCOR code, Annals of Nuclear Energy, Volume 135, (2020).

[16] N. W. Porter, Wilks' Formula Applied to Computational Tools: A Practical Discussion and Verification, SAND2019-1901J