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Uncertainty Analysis of Severe Accident Scenario in Krško NPP

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ABSTRACT

An uncertainty and sensitivity analysis of a severe accident scenario in the Krško NPP was performed, applying the MELCOR code version 2.2 and the SUSA code. As the initiating event, a strong earthquake was considered, resulting in a simultaneous station black-out and large break loss-of-coolant accident. It was assumed that only passive safety systems are available. Five uncertain model parameters were considered based on the State-of-the-Art Reactor Consequence Analysis performed recently by US NRC and SNL. The purpose of the study is mainly to demonstrate the conduction of the uncertainty and sensitivity analysis in such conditions and the application of the selected computational tools.

As in MELCOR the chemical reactions cannot be properly modelled directly, they were considered indirectly by adjusting the inventory of the Cs, I2, CsI, Mo, and CsM radionuclides classes in the core to already reflect the consequences of chemical reactions. The results for some selected radiological variables are presented. It turned out that the MELCOR VANESA model for radionuclide releases from debris in the cavity does not model the CsM compound class, but decomposes it into the basic component Cs and Mo classes, significantly influencing the simulation results. The scatter of simulation results typically reflects the scatter of the uncertain model parameters considering Pearson's correlation coefficients. But for some results it is much larger, indicating that the numerical variance or the stochastic influence of the considered uncertain parameters significantly contributes to the scatter. The calculated heat loads on the filters do not exceed the design values in any calculation.

1 INTRODUCTION

The uncertainty estimation for assessing the figure-of-merits characterizing the evolution of a severe accident scenario is a topic of current investigation in the development of the best-estimate plus uncertainty methodology (BEPU) [1]. The BEPU approach has become an internationally accepted method for assessing safety margins for a range of high-consequence systems. This approach has increasingly been adopted by the international nuclear safety community to characterize the true safety margin and remove analysis conservatism. Considering the key role of severe accident codes for deterministic safety analyses and source term evaluations, several research activities in national and international frameworks are in progress and are planned to reduce and/or estimate the uncertainty in severe accident phenomena prediction. Based on the maturity of severe accident codes in terms of phenomena addressed, extensive validation conducted, and reasonable numerical stability, the EC MUSA (Management and Uncertainties of Severe Accidents) project has been set up to explore uncertainty quantification in the severe accident domain including accident management [2]. The overall goal of MUSA is to quantify the uncertainty and sensitivities embedded in different severe accident codes when predicting the radiological source term for severe accident sequences of different nuclear power plant designs, using various uncertainty quantification tools. An extensive uncertainty analysis of the unmitigated short-term station blackout of the Surry NPP resulting in a severe accident was performed recently by the United States Nuclear Regulatory Commission (NRC) and Sandia National Laboratories (SNL) [3]. The probabilistic method to propagate the input uncertainty is one of the methodologies used to develop uncertainty analyses. Using this methodology, uncertainty analyses are performed by sampling probabilistic distributions that describe the range of possible values that computer simulation model input parameters can have. For each sample of a set of uncertain input parameters, a computer simulation is performed. From the range of code simulation results obtained for each input realization, a distribution of code results is obtained. In this process, the distribution of input uncertainties is propagated to obtain the distribution of code results uncertainty.

In line with the international research activities, an uncertainty analysis of a severe accident scenario in the Krško NPP was performed, applying the newest MELCOR 2.2 code version R2023.0 [4], [5]. As the initiating event, a strong earthquake was considered, resulting in a simultaneous station black-out (SBO) and large break loss-of-coolant accident (LBLOCA). It was assumed that the active safety systems are not operable and the following passive safety systems were considered: accumulators, passive autocatalytic recombiners, and passive containment filtered venting system (PCFVS). As the basis for the uncertainty analysis the upgraded Krško NPP MELCOR 2.2 standard input deck [6], [7], as applied in the studies [8], [9] for the unmitigated scenario, was used. The purpose of the study is mainly to demonstrate the conduction of the uncertainty and sensitivity analysis in such conditions and the application of the selected computational tools.

In Section 2 the modelling approach and the conduction of the uncertainty and sensitivity analyses are described. The simulation results are presented and discussed in Section 3. In Section 4 the conclusions are given.

2 MODELLING APPROACH

In MELCOR the radionuclides (RN) are modelled based on material classes, which are groups of elements that have similar chemical properties [4], [5]. The classes are named by their representative element or compound. In MELCOR the chemical reactions cannot be properly modelled directly. Combination of masses in these classes upon release to form compounds in other classes, such as Cs + I to CsI or Cs + Mo to CsM, is permitted and subject to stoichiometric constraints (e.g., excess Cs is retained in the Cs class). But in this case e.g. (nearly) all released iodine will react with caesium, if available, and thus there will be (nearly) no gaseous iodine. Consequently, the heat load on the iodine filters and the iodine releases will be greatly underestimated. On the other hand, without merging the Cs and I classes into the compound CsI class we would greatly overestimate the amount of gaseous iodine and all the related negative consequences. Chemical reactions are therefore adequately considered indirectly by adjusting the inventory of the radionuclides in the core to already reflect the consequences of chemical reactions. This approach was taken also in the recent NRC/SNL study [3] and we followed it, although it is quite demanding, since the decay heat must also be properly considered. In Table 1 the inventory of the Cs, I2, CsI, Mo, and CsM classes in the reference core with and without considering chemical reactions is presented. In the inventory with chemical reactions it was, based on the NRC/SNL study [3], considered that 1.7 % of iodine is in vapour form (class I2), 98.3 % of iodine is in CsI compound form (class CsI), 80 % of Cs, which is not in CsI form, is in Cs_2MoO_4 compound form (class CsM), and 20 % of Cs, which is not in CsI form, is in basic CsOH form (class Cs).

For the uncertainty and sensitivity analyses the SUSA (Software for the Uncertainty and Sensitivity Analyses) code [10], [11], which we managed to obtain from GRS, Germany, was chosen. SUSA combines well-established methods from probability calculus and statistics with a comfortable graphical user interface. The concept of SUSA enables the user to fully concentrate on the analysis input including the identification of the input parameters which represent the main uncertainty sources of the computational result and the formulation of the corresponding uncertainties. After this is done, SUSA provides support to quantify the uncertainties probabilistically and to perform the different steps of an uncertainty and sensitivity analysis.

Table 1: Reference core inventory without considering chemical reactions and based on assumed chemical reactions

RN class	Without chem. reac. (kg)	With chem. reac. (kg)
Cs	111.5	20.52
I2	8.614	0.1464
Mo	145.6	115.9
CsI	0	17.34
CsM	0	111.7

In the NRC/SNL study [3] an extensive analysis of the uncertain input model parameters was performed and a list of key uncertain parameters that were considered in the uncertainty analysis was prepared. They can be classified into the following areas: sequence (8 uncertain parameters), in-vessel accident progression (5), containment response (4), and radionuclide behaviour (4). From this list, we selected five uncertain parameters, which we estimated would have a significant impact on our chosen scenario and can be adequately addressed with the SUSA program. These independent uncertain parameters, denoted Par 1 to Par 5, are: Zircaloy melt breakout temperature (Par 1), Molten clad drainage rate (Par 2), Effective temperature at which the eutectic formed from zircaloy oxide and uranium oxide melts (Par 3), Fraction of iodine in vapour form (Par 4, provided as class I2 mass), and Fraction of Cs as Cs_2MoO_4 (Par 5, provided as class CsM mass). To preserve the radionuclides inventory mass the mass of radionuclide classes Mo, CsI and Cs had to be adjusted accordingly based on the randomly sampled mass of classes I2 and CsM, which was done by introducing dependent parameters Par 6 (class Mo mass), Par 7 (class CsI mass), and Par 8 (class Cs mass). The density functions of the independent uncertain parameters Par 1 to Par 5, which were defined based on the NRC/SNL study [3], are presented in Figure 1 as provided into the SUSA code.

The influence of an individual uncertain model parameter on the results is quantified with the sensitivity analysis, which was carried out with the SUSA code [11]. This influence may be evaluated with the Pearson's correlation coefficient, which is a measure of linear correlation between two sets of data and is calculated as:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}},$$

where n is the sample size, x_i, y_i are the individual sample points indexed with i, and $\bar{x}$, $\bar{y}$ are the sample mean. The correlation coefficient ranges from −1 to 1. The influence is large if the absolute value is larger than 0.5.

According to the Wilks formula [12], [13], 93 computer runs with random sampling of uncertain input parameters are needed to obtain results with the planned 95 % confidence interval for 95 % probability. Thus, with the SUSA code 100 input models were prepared and run on our Skuta cluster [14]. The first 300,000 s (~3.5 days) of the accident were simulated. Unfortunately, the simulations were very unstable, and only 16 were successfully finished. The others stopped already during the core degradation phase less than 3,500 s from the start of the accident. Various attempts to stabilize the calculations were made. It turned out that the stability of calculations can be significantly improved if the eutectic model for core melt is switched off. In this case, 87 calculations out of 100 were successful. By performing additional 20 calculations we finally got 105 successful calculations, even more than the required 93 for the target tolerance limits.

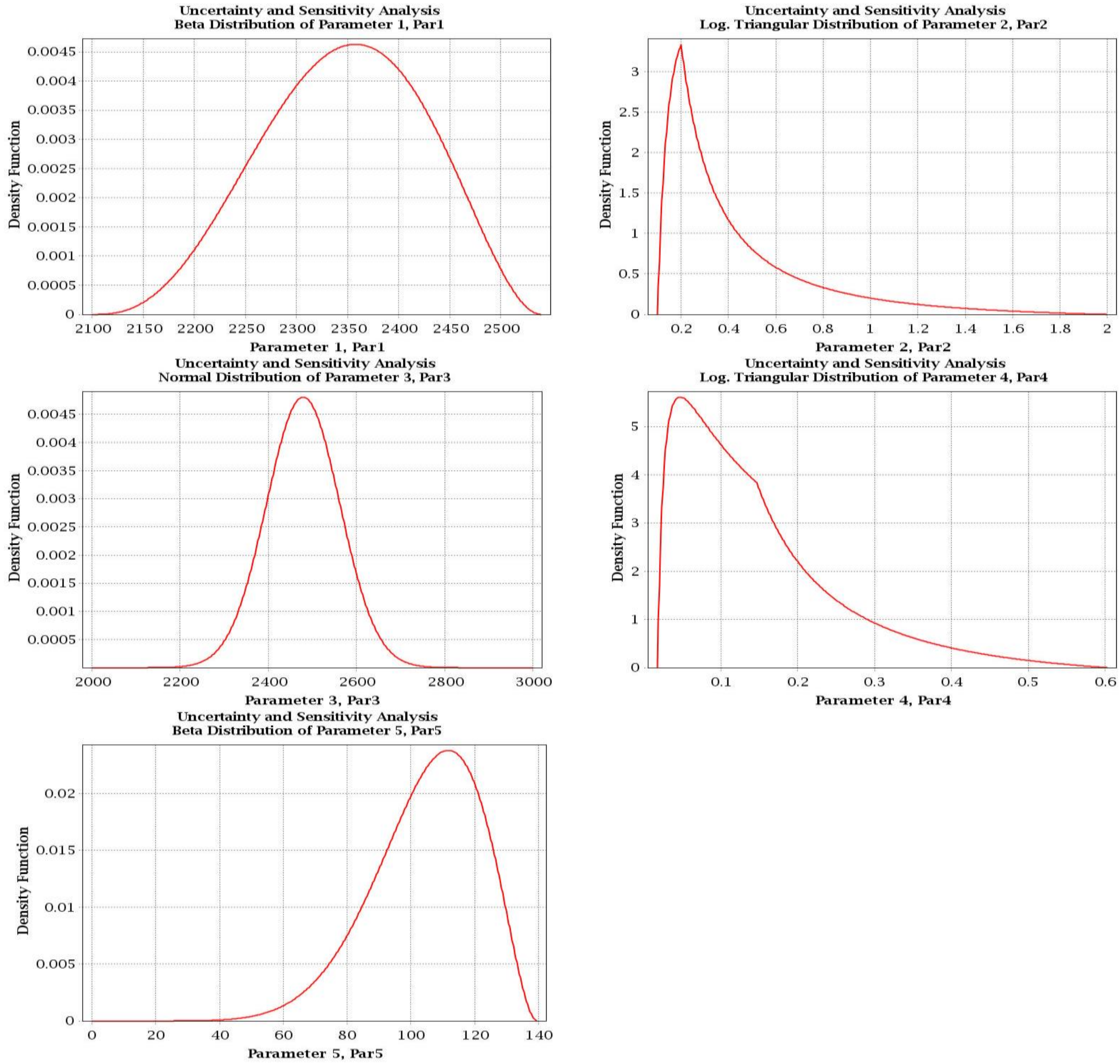

Figure 1: Density functions of the five independent uncertain input model parameters, as provided into the SUSA code. Par 1 - Zircaloy melt breakout temperature (K), Par 2 - Molten clad drainage rate (kg/m·s), Par 3 - Effective temperature at which the eutectic formed from zircaloy oxide and uranium oxide melts (K), Par 4 – Mass of gaseous iodine (kg), Par 5 - class CsM mass (kg).

In the turned off eutectic model three eutectic reactions are considered that lead to early failure of fuel and control rods: (1) the eutectic reaction between Zircaloy cladding and Inconel grid spacers can lead to early failure of fuel rods, (2) the eutectic reaction between Zircaloy guide tubes and steel cladding can lead to early failure of PWR control rods and (3) the eutectic reaction between B_4C powder and steel cladding can lead to early failure of BWR control rods [5]. Thus, the eutectic model is not linked with the uncertain parameter 3, which defines the temperature to which oxidized fuel rods can stand in the absence of unoxidized Zr in the cladding considering ZrO_2/UO_2 eutectic formation [4]. It is anticipated that turning off the eutectic model has only a minor influence on our analysis.

3 RESULTS

In the graphs, the results for some selected radiological variables are presented. In addition to the results of all 105 calculations (grey curves), the results of the reference calculation (red curve “ref”), minimum and maximum value (green curves “min” and “max”), arithmetic mean (black curve “avg”) and median (orange curve “med”) are shown. For each presented result, the Pearson’s correlation coefficient for all five independent uncertain input model parameters Par 1 to Par 5 is provided.

Figure 2 shows the mass of released classes Cs, I2, CsI and CsM from the fuel. It may be observed that about 100 kg of Cs is released (Figure 2a), which is much more than the initial inventory with considering chemical reactions (Table 1). It turned out that the MELCOR VANESA model for radionuclide releases from debris in the cavity does not model the CsM compound class, but decomposes it into the basic component Cs and Mo classes. Thus, the entire CsM class, which was not released during the in-vessel core degradation, is converted into the Cs and Mo classes and then released as Cs and Mo. Typically the key radionuclides are already released during the in-vessel core degradation, so this modelling approach in MELCOR is not apparent. But in our considered scenario, where we have in addition to the SBO also a LBLOCA, the failure of the reactor vessel and the release of part of the reactor core into the reactor cavity occurs rapidly, already about an hour after the start of the accident, when the key radionuclides have not been released yet. The calculated large amount of released Cs therefore mainly represents Cs, which should be in the CsM class, but was due to the simplified modelling in VANESA transferred to the Cs class. This shortcoming occurs only in the CsM class, which VANESA cannot adequately handle, while e.g. there are no such problems with the CsI class, which VANESA treats as its own class and does not convert into the Cs and I2 classes. The absolute value of the Pearson’s correlation coefficient for parameter Par 5 is large for most of the simulation, typically around 0.8, which means that the fraction of Cs as Cs_2MoO_4 has a great influence on the mass of released class Cs. This is expected because the more Cs is in class CsM, the less it is in class Cs and less can be released.

Figure 2b shows the mass of released I2 class, i.e. gaseous iodine. The remaining iodine has reacted with Cs and is in the form of CsI. It was assumed that gaseous iodine is in the fuel rods gap and released when the integrity of the fuel rods is lost. The scatter of the released class I2 is large, in accordance with the assumed probability distribution (Par 4). The Pearson’s correlation coefficient for parameter Par 4 is 1 after the integrity of the fuel rods is lost, which is expected as at that time all the gaseous iodine in the gaps is released.

Figure 2c shows the mass of released CsI class. The scatter of the results is relatively small, as the fraction of iodine not reacting with Cs is relatively small, only up to a few percent. The variation of the fraction of iodine in vapour form (Par 4) thus has no significant effect on the final fraction of iodine in the form of CsI (dependent parameter Par 7). The sensitivity analysis confirms the dependence of the final released mass of class CsI on the mass of class I2, as the Pearson’s correlation coefficient for parameter Par 4 is nearly -1, except in the initial part of the simulation. Namely, during the CsI release from the fuel, the dynamics of the release depends mainly on the dynamics of the core degradation, so during that time the mass of released CsI does not correlate with the mass of class I2.

Figure 2d shows the mass of released CsM class. We can see that the scatter of the results is large and that the released mass, which is in the range of ~2 to ~16 kg, is significantly smaller than the initial inventory considering chemical reactions, which is more than 110 kg (Table 1). The reason is the already described deficiency of the VANESA model, which does not consider the CsM class. Thus, the mass of the released CsM class represents only the release of CsM during in-vessel core degradation. The sensitivity analysis shows that the Pearson’s correlation coefficients for all considered uncertain parameters are low, also for parameter Par 5, revealing that the CsM release during in-vessel core degradation depends mainly on the core degradation dynamics and less on the CsM inventory.

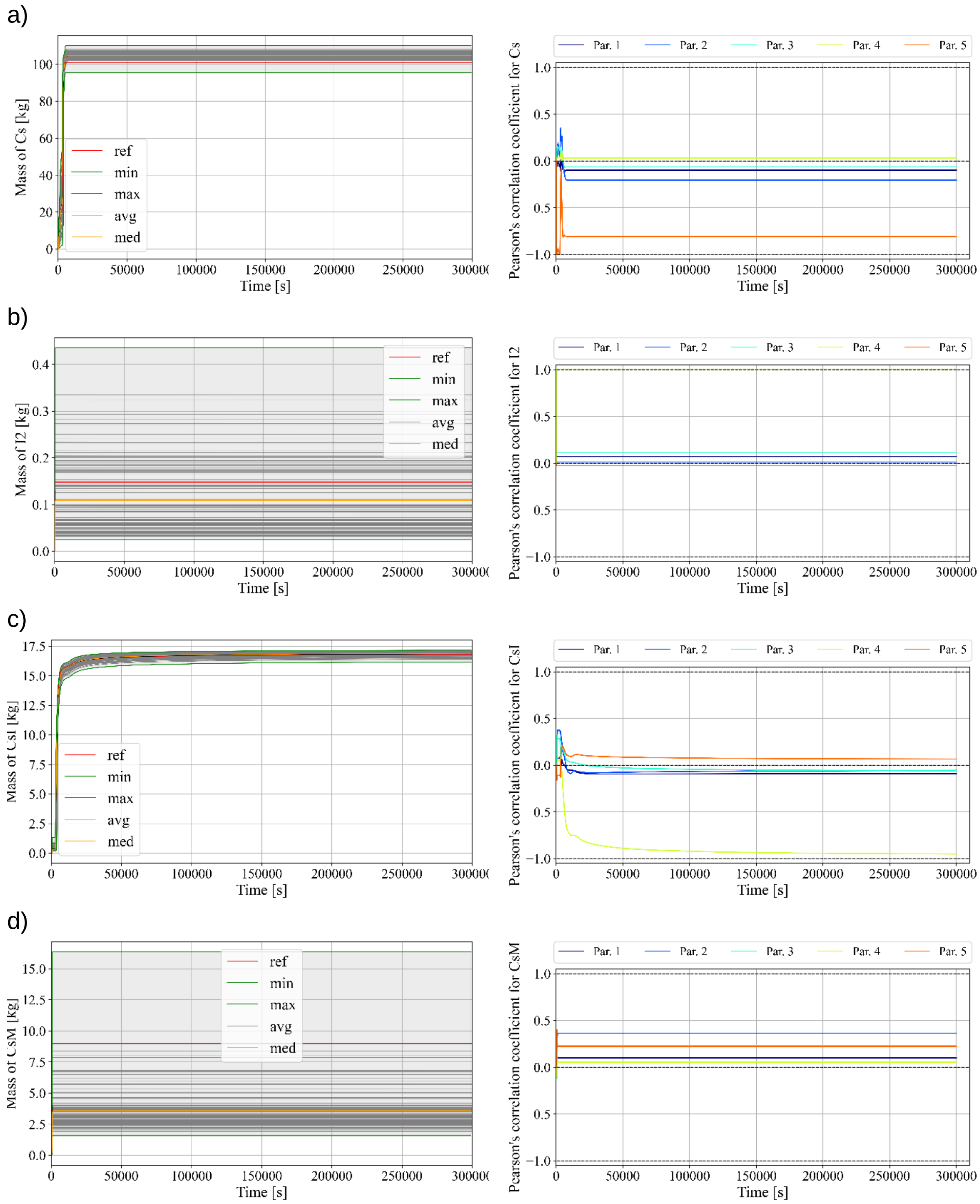

Figure 2: Mass of released classes Cs, I2, CsI, and CsM from fuel (left side) and corresponding Pearson's correlation coefficients (right side).

Figure 3 shows the mass of classes Cs, I2, CsI, and CsM on PCFVS filters. It may be observed that the scatter of the mass of the Cs class on the aerosol filters (Figure 3a) is much larger than the scatter of the mass of released Cs class from the fuel (Figure 2a), which indicates that the scatter of the containment atmosphere flow through the PCFVS filters and/or its Cs content between various calculations is large. As the Pearson's correlation coefficients are relatively small for all considered uncertain parameters, this indicates that the numerical variance or the stochastic influence of the considered uncertain parameters significantly contribute to the scatter. We see that typically around 1 % of the released Cs accumulates on the filters, less than a thousandth of which is released into the environment according to the filters characteristics [15], the rest settles in the containment. Due to the deficiency of the VANESA model, this Cs mass includes also Cs, which is released in form of CsM in the cavity.

The mass of gaseous iodine on the filters (Figure 3b) is only slightly smaller than the mass of gaseous iodine released from the fuel (Figure 2b), which means that during the repeated containment depressurisation, almost all of the released gaseous iodine flows through the PCFVS filters and only a small amount remains in the containment atmosphere. According to the filters characteristics [15], almost 1 % of gaseous iodine is thus released into the environment. Due to the causal relationship, the Pearson's correlation coefficient for parameter Par 4, which determines the fraction of iodine in vapour form, is 1 when iodine starts to accumulate on the filters.

The gaseous iodine mass uncertainty does not have a significant effect on the CsI mass uncertainty, as more than 90 % of iodine is always in the form of CsI. The relatively large scatter of the CsI class mass on filters (Figure 3c) is thus probably due to the same reasons as described above for the Cs class. Similarly, the small Pearson's correlation coefficient values indicate that the numerical variance or the stochastic influence of the considered uncertain parameters significantly contribute to the scatter. We see that typically a little more than 1 % of the released CsI accumulates on the filters, less than a thousandth of which is released into the environment according to the filters characteristics [15], the rest settles in the containment.

The CsM mass on the filters (Figure 3d) considers only the in-vessel release of CsM due to the deficiency of the VANESA model. Therefore, the CsM class mass on filters is significantly underestimated, and the mass of the Cs and Mo classes is consequently significantly overestimated due to the preservation of the individual elements mass. The values of the Pearson's correlation coefficients are low due to the same reasons as described for the mass of released CsM class.

In Figure 4 the decay heat release on the aerosol and vapour (iodine) filters is presented. It can be seen that the scatter of the results is large. The scatter for the aerosol filter (Figure 4a), which is especially large in the last part of the simulation, is probably due to numerical variance or the stochastic influence of the considered uncertain parameters, as the absolute values of the Pearson's correlation coefficients are relatively small. The large scatter for the vapour filter (Figure 4b) is consistent with the assumed probabilistic distribution of gaseous iodine (Par 4), which was already reflected in the large scatter of the released mass of the I2 class (Figure 2b). The performed sensitivity analysis confirms the link between the gaseous iodine mass and the heat load on the vapour filter as the Pearson's correlation coefficient increases to 1 when the PCFVS opens and iodine begins to accumulate on the vapour filter.

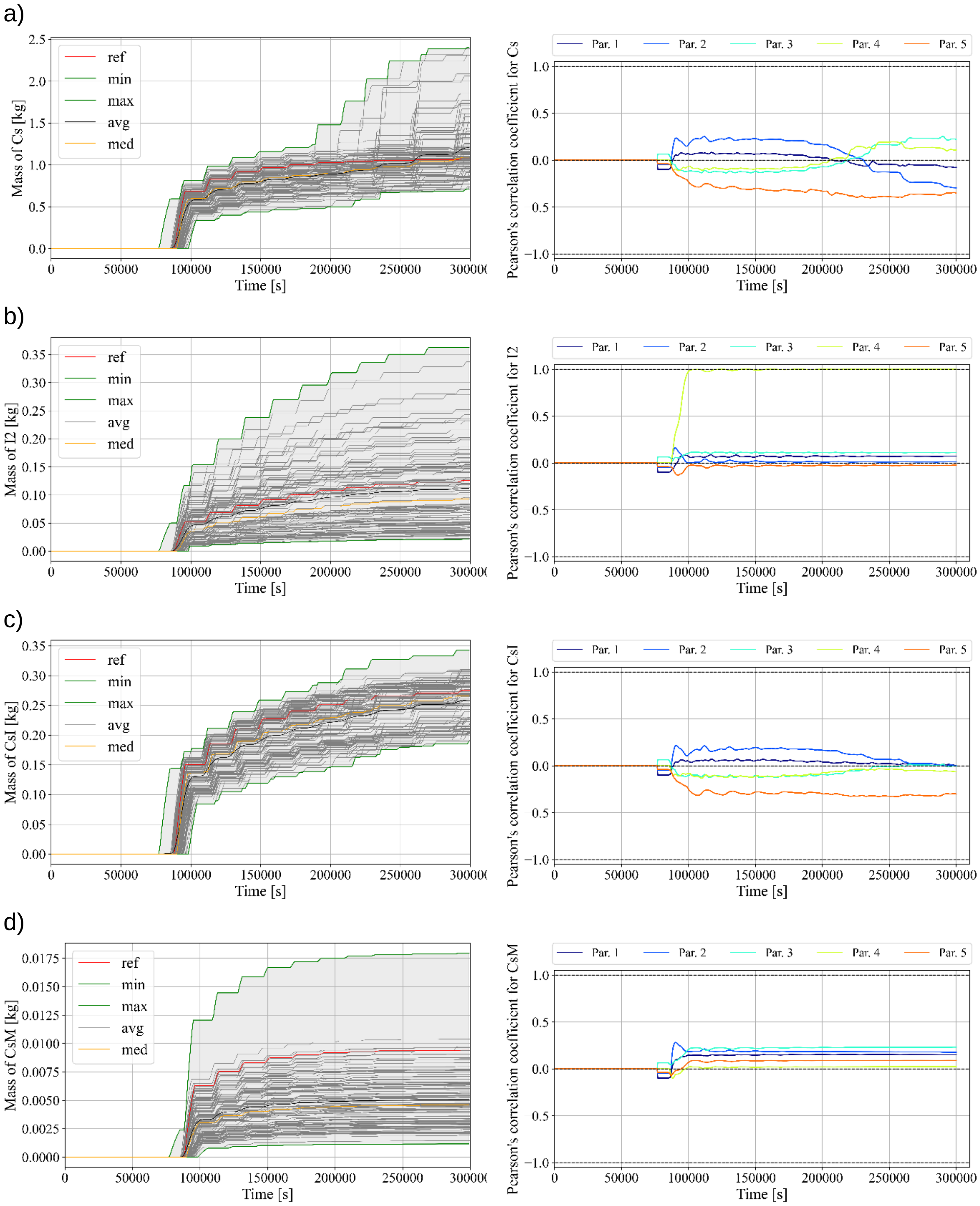

Figure 3: Mass of classes Cs, I2, CsI, and CsM on PCFVS filters (left side) and corresponding Pearson’s correlation coefficients (right side).

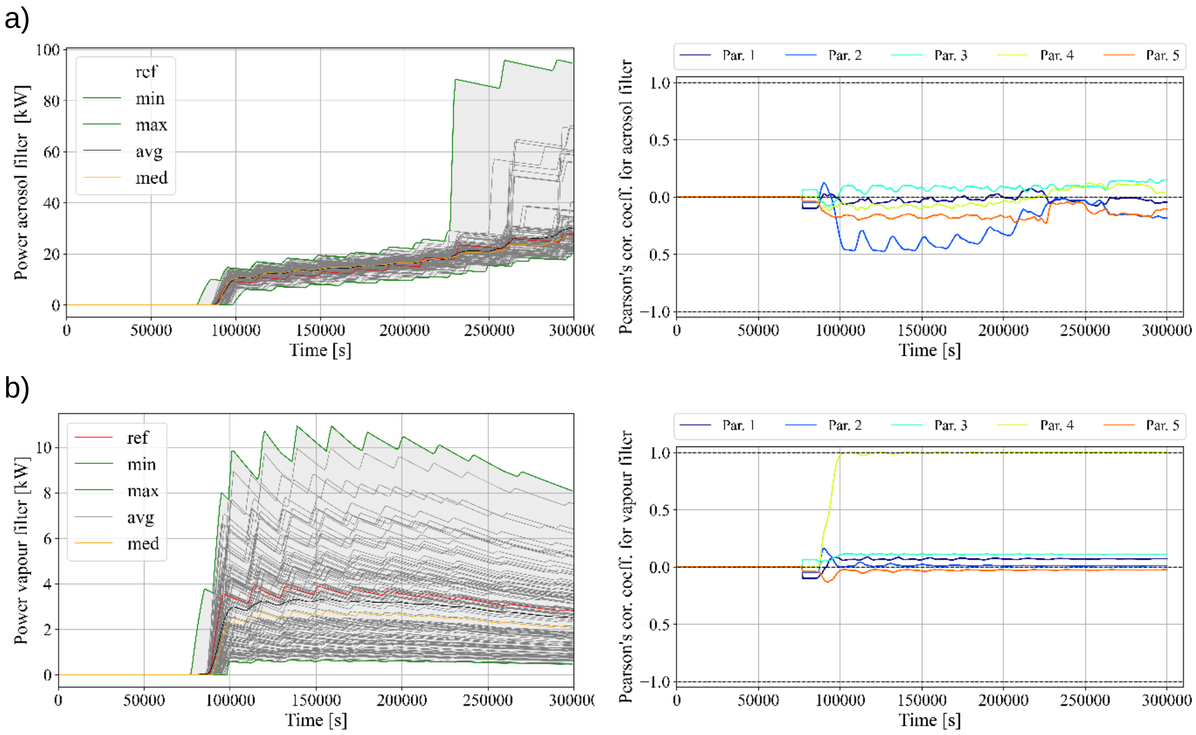

Figure 4: Decay heat release on aerosol and vapour filters (left side) and corresponding Pearson's correlation coefficients (right side).

The aerosol filter is designed for a heat load of 170 kW, and the iodine filter for 20 kW [15]. We can see that the calculated heat loads on the filters do not exceed the design values in any calculation. Even in the most unfavourable calculation, the maximum heat load reaches only a little more than half of the design value.

4 CONCLUSIONS

An uncertainty analysis of an unmitigated station blackout with large break loss-of-coolant accident in the Krško NPP was performed. It should be emphasized that the analysis covers only the considered uncertain model parameters, which do not cover all uncertainties. Therefore, the actual uncertainty of the results is expected to be greater than the one presented.

The results for some selected radiological variables are presented. It turned out that the MELCOR VANESA model for radionuclide releases from debris in the cavity does not model the CsM compound class, but decomposes it into the basic component Cs and Mo classes. Thus, the entire CsM class, which was not released during the in-vessel core degradation, is converted into the Cs and Mo classes and then released as Cs and Mo. As in our scenario the failure of the reactor vessel and the release of part of the reactor core into the reactor cavity occurs rapidly, already about an hour after the start of the accident, when only a small fraction of the CsM class has been released, the benefits from considering the Cs-Mo chemical reaction are thus mainly lost. The scatter of simulation results typically reflects the scatter of the uncertain model parameters considering the Pearson's correlation coefficients. But for some results it is much larger (mass of classes Cs and CsI on filters, decay heat release on aerosol filter), indicating that the numerical variance or the stochastic influence of the considered uncertain parameters significantly contribute to the scatter. The Pearson's correlation coefficients revealed that the CsM class release during in-vessel core degradation depends mainly on the core degradation dynamics and less on the CsM class inventory.

The calculated heat loads on the filters do not exceed the design values in any calculation. Even in the most unfavourable calculation, the maximum heat load reaches only a little more than half of the design value.

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