Uncertainty quantification of in-pool fission product retention during BWR Station BlackOut sequences

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Abstract

Suppression pools are an essential passive system for source term attenuation in boiling water reactor designs during severe accidents, particularly during Station BlackOut (SBO) sequences, as it happened in Fukushima.

This paper investigates how uncertain predictions of suppression pools decontamination can be. Based on MELCOR 2.2 calculations of Fukushima Unit 1, a stand-alone version of SPARC-90 (Suppression Pool Aerosol Removal Code) has been used in combination with DAKOTA-6.4, to propagate the uncertainties in the input deck variables affecting the Decontamination Factor (DF). The results indicate that Decontamination Factor (DF) uncertainties may spread around two orders of magnitude and the uncertainty margin stays roughly constant over time. In addition, a sensitivity analysis based on the Pearson and Spearman correlation coefficients has been carried out and pointed that uncertainties associated to particle inertia (i.e., particle density and size) and in-pool phase change (i.e., non-condensible gas fraction in the carrier gas) dominate the uncertainties found in the DF for this specific scenario.

Keywords: Fukushima Unit 1; pool scrubbing; uncertainty assessment

1. Introduction

Suppression pools are an essential system in boiling water reactor designs during severe accidents, particularly during Station BlackOut (SBO) sequences, in which active safeguards cannot be relied on. Their two-fold role as a sink of decay and chemical heat and as a passive trap of fission products (FP) and aerosols, makes its performance critical for the SBO accident evolution, as it was the case during the Fukushima accidents (Nuclear Emergency Response Headquarters, 2011).

Pool scrubbing was heavily investigated in the 80's and 90's of last century and, as a result, stand-alone codes were developed and partially validated at the time. Nowadays, such codes are embedded in integral severe accident analysis tools, like MELCOR or ASTEC. However, pool scrubbing modelling has been demonstrated to be far from being mature and further work has been found to be necessary (Herranz et al., 2014), so that a vast international project has been built to address this issue (Gupta et al., 2017) in the frame of NUGENIA (www.nugenia.org).

Beyond modelling maturity, uncertainties affecting highly influencing variables on pool scrubbing might result in large uncertainties in the decontamination capability estimates, particularly at high levels of in-pool retention (i.e., minor efficiency variations at high DF values, around 10^2, result in changes of orders of magnitude in DF). An assessment of such DF uncertainty band during a SBO accident sequence in a BWR3 Mark I reactor is the objective of this paper. To do so, based on MELCOR 2.2 calculations of Fukushima Unit 1 (Herranz et al. 2018), a stand-alone version of SPARC-90 (Suppression Pool Aerosol Removal Code) has been used in combination with DAKOTA-6.4 (Adams et al., 2014) to propagate the uncertainties in the input deck variables affecting the Decontamination Factor (DF).

Finally, it is worth noting that source term uncertainties, as a whole, might have a high impact on practical aspects, like accident management and, no less important, emergency preparedness. However, given the high complexity of applying Best Estimate Plus Uncertainty (BEPU) methods in the severe accident arena, a systematic application of BEPU has not been attempted yet, although a few pioneering works were done in the past (Herranz & Gauntt, 2018). There are international initiatives ready to be launch and address this issue in the coming future.

2. The SBO scenario

Modelling of the SBO accident in Unit 1 of Fukushima with MELCOR 2.2 (Herranz et al., 2018), resulted in airborne particles mass in the RPV (Reactor Pressure Vessel) dome (Fig. 1). Their transport to the suppression pool through the SRV is characterized by a set of variables, the most important of which (i.e., particle size distribution, gas mass flow rate and composition) are shown in Fig. 2. These, together with those characterizing the pool status (i.e., subcooling and submergence; Fig. 3) determine to a good extent the decontamination capability of the pool.

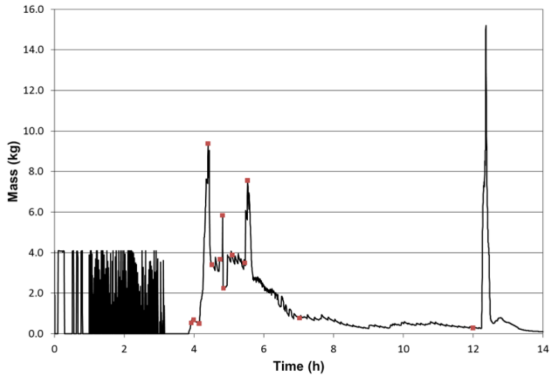
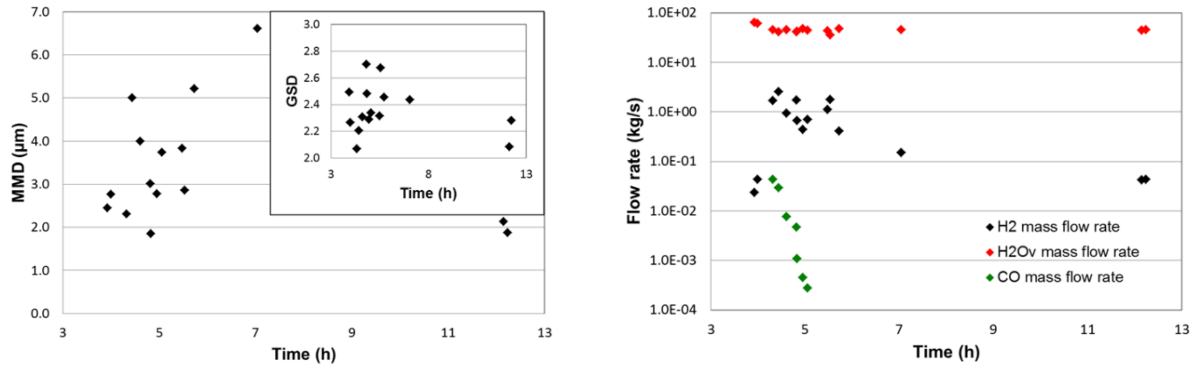
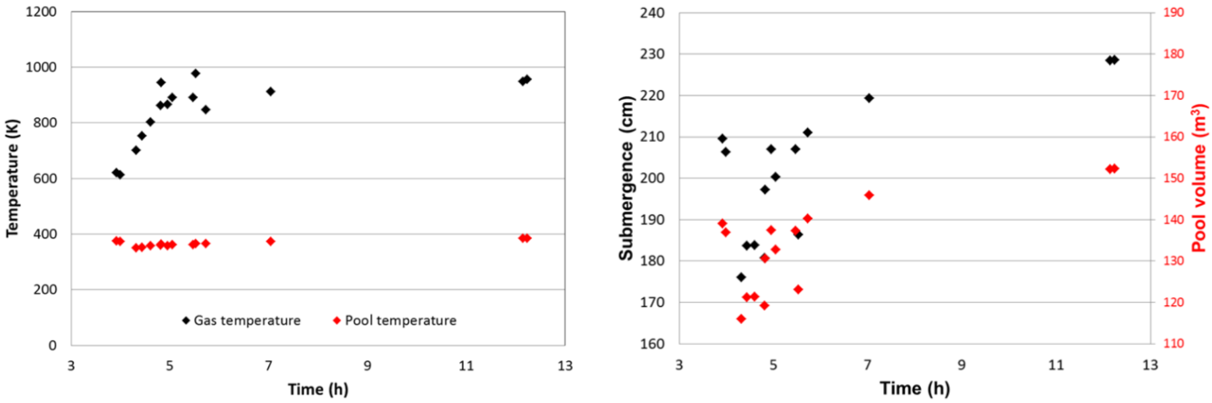


Fig. 1. RPV airborne particle mass



a. Particle size distribution b. Carrier gases

Fig. 2. Main characteristics of in-pool injection materials



a. Temperature b. Pool submergence

Fig. 3. Suppression pool characterization during particle injection

The DF results obtained in the 15 red-color points noted in Fig. 1 are shown in Fig. 4. As observed, at all times during the aerosol transport into the suppression pool the decontamination capability has been over 100 (i.e., scrubbing efficiencies higher than 99%). These results are named here after as Best Estimates (BE).

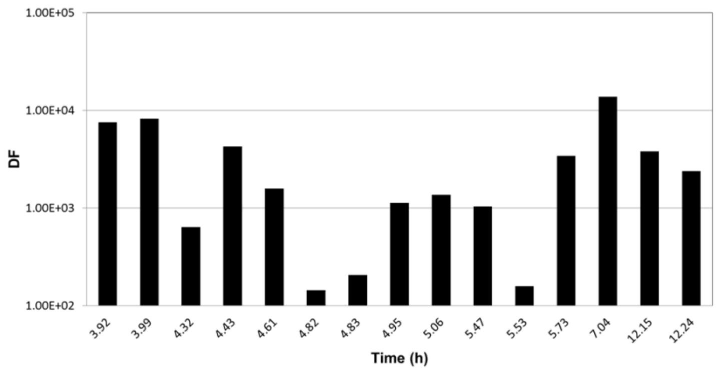


Fig. 4. DFs predicted during the FP injection in the suppression pool

3. The uncertainty quantification methodology

Fig. 5 shows a diagram of the uncertainty quantification methodology based on the DAKOTA 6.4 facility. As noted, once the rest of variable uncertainties in the SPARC90 input deck have been characterized in each individual time point, the particle sized distribution has to be developed from the MMD (Mass Median Diameter) and the GSD (Geometric Standard Deviation) resulting from the MELCOR calculation. Once this is done, the uncertainty domain of each SPARC90 input deck variable (lower and upper bounds given together with the probability density function; most times a uniform distribution is assumed) is randomly sampled through a Montecarlo calculation. The sampling size for each time point analysis has been set to 3000. Next just a time point analysis is synthesized.

The input variable uncertainty determination has been heavily based on technically supported engineering judgement[1]. The variability of some of those variables, stemming from the intermittent performance of SRV valves, has been assessed by analyzing the variables values at an earlier and at a later time step. Based on this information and the experience of the authors simulating severe accident scenarios, Table 1 has been set up for the time point # 5 (4.61 h). It is interesting to note that as for the carrier gas, the H_2 content in the mixture is highly uncertain, and as for particles, size and density have also a noticeable uncertainty.

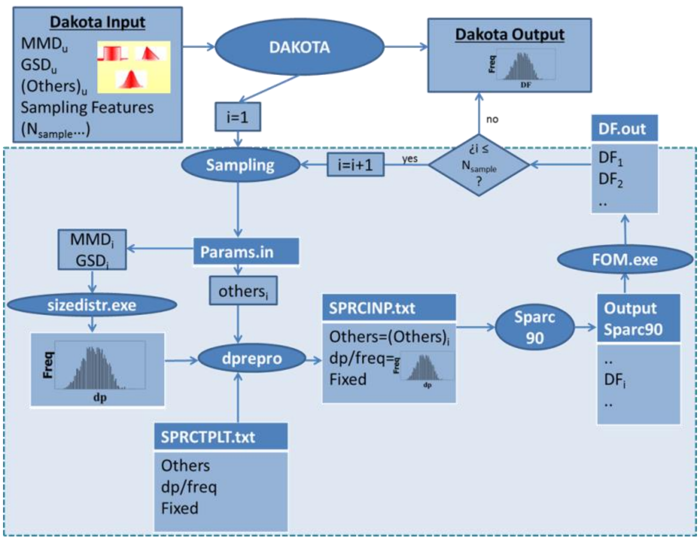


Fig. 5. Flowchart of the UQ methodology

[1] Engineering judgement was mostly based on the variability existing between two time data points in the MELCOR calculations of the variables affected.

Table 1. Uncertainty bounds

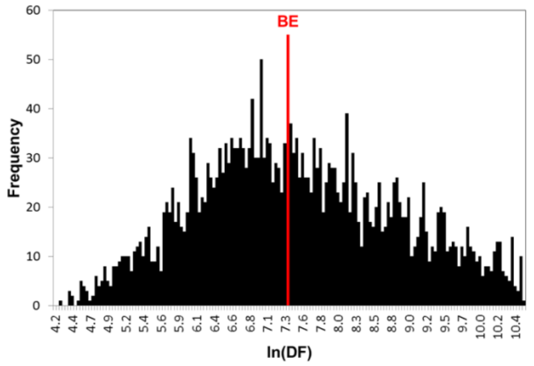
	Variable	Units	Lower bound	Upper bound
POOL GEOMETRICS	Submergence	cm	-10%	+10%
	Pool volume	m^3	-10%	+10%
THERMALHYDRAULICS	Pool temperature	ºC	$-(T_{N1}-T_{Ncold})/2$	$+(T_{N1}-T_{Ncold})/2$
	Pool pressure	atm (abs)	-10%	+10%
	Gas temperature	ºC	-30%	+30%
	Gas pressure	atm (abs)	-5%	+5%
CARRIER GASES	H_2 mass flow rate	g/s	-100%	100%
	H_2Ov mass flow rate	g/s	-10%	+10%
	CO mass flow rate	g/s	-50%	+50%
PARTICLES	MMD	μm	-50%	+50%
	GSD	-	-20%	+20%
	Particles mass	g	-100%	+100%
	Total particles mass flow rate	g	-100%	+100%
	Particles density	g/cm^3	-67%	+67%

4. Results and discussion

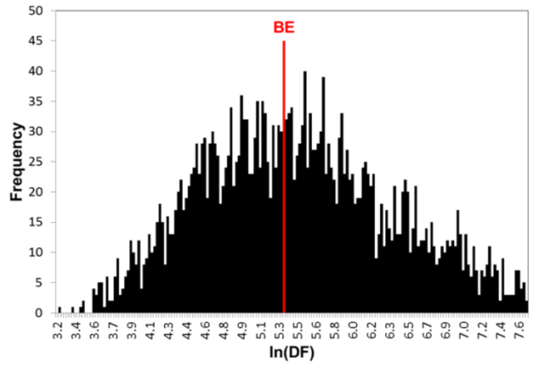
The highest 5% of the resulting DF sampling has been withdrawn (IAEA, 2008), so that DF values of the 95% of the entire sampling is calculated.

4.1. Uncertainty analysis

Fig. 6 shows the results of the uncertainty analyses for two time points: 4.61 h ($DF=1.6\cdot10^3$; η=99.94%) and 4.83 h ($DF=2.1\cdot10^2$; η=99.52%). They correspond to a sample size of 3000, Probability Density Functions (PDF) defined as uniform and a Monte Carlo random sampling method Nevertheless, sensitivity of the results assuming a Gaussian PDF, using an alternative sampling method like Latin Hypercube Sampling (LHS), and increasing the sampling size to 10000, have been carried out. Table 2 provides the numerical results comparison and supports that sampling mode is hardly influencing while the PDF type has a very minor effect. It is worth noting that the median DF is the distribution momentum closer to the Best Estimate.



a. 4.61 h



b. 4.83 h

Fig. 6. DF uncertainty distributions

Table 2. Uncertainty analysis results

	Sampling and distribution	Base Case	Dakota – SPARC-90			
		DF	Mean DF	Median DF	DF max	DF min
4.61 h	MC uniform	1.58E+03	4.27E+03	1.58E+03	3.71E+04	7.16E+01
	MC normal		1.98E+03	1.56E+03	6.92E+03	1.76E+02
	LHS uniform		4.56E+03	1.62E+03	4.37E+04	6.88E+01
	LHS normal		2.01E+03	1.55E+03	7.15E+03	1.73E+02
4.83 h	MC uniform	2.07E+02	3.57E+02	2.24E+02	2.07E+03	2.49E+01
	MC normal		2.35E+02	2.15E+02	5.49E+02	5.29E+01
	LHS uniform		3.64E+02	2.21E+02	2.29E+03	3.11E+01
	LHS normal		2.33E+02	2.12E+02	5.67E+02	4.33E+01

Despite the large uncertainty intervals calculated, it should be highlighted that given the high DF values estimated in the scenario, their impact in terms of mass coming out from the suppression pool would be rather moderate. In other words, in all cases scrubbing efficiency has been estimated to be higher than 99%, the suppression pool behaving as an effective filter of the fission products released regardless the uncertainties associated to the boundary conditions in the SBO case analyzed.

4.2. Sensitivity analysis

To determine the sensibility of DF with the input variables, the Pearson correlation coefficient and the Spearman's rank correlation coefficient are used (Ikonen & Tulkki, 2014). The first one determines the linearity of the relationship between both factors and the second one determines how monotonous the ratio is, increasing or decreasing. Fig. 7 shows the results obtained (dark color meaning positive value while light color means negative values).

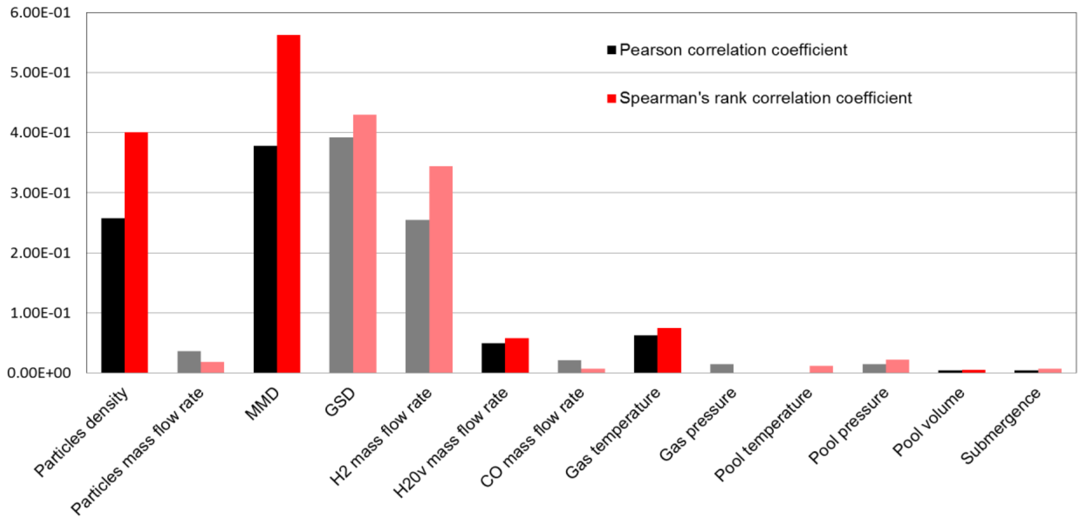


Fig. 7. Pearson and Spearman coefficient for DF for Time 5 MC uniform

It is noticeable that exists a strong dependence with particles density, MMD, GSD and H_2 mass flow rate. This is conveying a physically sound message: particle inertia at the inlet of the pool and drag by steam condensation are the two dominant particle removal processes in the scenario analyzed and make suppression pool such a good fission product filter.

5. Concluding remarks

This paper quantifies uncertainties in the decontamination capability estimates calculated with MELCOR 2.1 for a SBO sequence in a BWR3 Mark I containment. The resulting uncertainty intervals should be seen as a minimum since they encapsulate just those embedded in the pool scrubbing boundary conditions, but not in the existing and non-existing models in codes. Nevertheless, some good insights have been gained:

- DF uncertainty spreads over roughly two orders of magnitude, which given the high DF values might not have a major impact on source term predictions.
- In the scenarios being analyzed, the major removal processes responsible for most of particle scrubbing are inertial and phase change (i.e., steam condensation) mechanisms. Both of them are heavily located at the pool inlet.

This study is specific to the scenario modeled and not a generic statement on pool scrubbing DF uncertainty width can be concluded. Nonetheless, it does illustrate how sensitive high DFs can be to slight changes in those variables dominating retention in the pool. Finally, it is worth noting that the uncertainty band estimated does not include the uncertainties associated to modeling; in other words, the actual uncertainty band should be expected to be broader.

Further work will proceed through the application of the methodology adopted to the determination of uncertainties when modelling risk-dominant accident sequences.

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