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SYNTHESIS OF SOURCE TERM ASSESSMENTs FOR A LOSS-OF-COOLING ACCIDENT IN A SPENT FUEL POOL: INSIGHTS FROM UNCERTAINTY AND SENSITIVITY ANALYSES AND POTENTIAL BENEFIT OF WATER INJECTION BY SPRAY SYSTEM

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ABSTRACT

The recently completed Horizon-2020 project on “Management and Uncertainties of Severe Accidents (MUSA)” has applied uncertainty and sensitivity analysis in the assessment of Severe Accidents (SA), particularly in predicting the radiological source term of reactor and Spent Fuel Pool (SFP) accident scenarios. For SFP, the two main objectives were: 1/ to determine the main uncertainties affecting the accident progression and fission product release during an accident in a SFP and 2/ to assess the possible benefits, in terms of source term reduction, of water injection by spray systems. The target of this paper is to describe the main achievements at the end of the 4 years’ project, regarding SFP accident scenario. The uncertainty and sensitivity analyses were performed by eleven participants thanks to the propagation of the uncertainties of the input parameters to the output uncertainties of severe accident codes. A SFP accidental scenario was selected, uncertainty sources in models and input parameters were identified and key target variables were chosen as Figure of Merits (FOMs). It was found that spreading in SA code responses coming from the uncertainty quantification done by each participant was relatively small when compared to the variability between reference computations of all participants. It reveals that important uncertainty sources, such as the lack of modeling or the nodalization, have not been taken into account in the uncertainty quantification. The sensitivity analysis, based on statistical correlation coefficients and supported by the analysis of scatter plots, has put in light that uncertain parameters linked to aerosol phenomena in the building significantly affect the source term. It has also revealed that the relationship between the source term and uncertain parameters linked to degradation is not straightforward, due to the non-linear nature of the phenomena in play and due to cliff-edge effects. Concerning the benefits of spray systems, the mass flow rate and the injection time that can prevent cladding failure, and thus Fission Product (FP) release were determined by seven participants, thanks to ASTEC, RELAP/SCDAPSIM and MELCOR calculations. The results obtained are very preliminary and should not be considered as demonstrative, since SA codes are generally not validated to compute the cooling of an assembly by spray injection. It is thus mandatory to carry out a validation work of the thermal hydraulics and the POLCA OECD project would be an opportunity for this.

KEYWORDS: SFP, source term, uncertainty quantification, sensitivity analysis, spray system, SA codes

1. INTRODUCTION

Computer codes are widely used in nuclear industry to assess the behaviour of Nuclear Power Plants (NPPs) during postulated accidents, including SA. Since the models of these computer codes approximate the real physical behaviour, and since the data used to run these codes are also known with a limited accuracy, the code predictions are not exact, but uncertain [1]. The first way of dealing with these uncertainties in safety demonstrations is to use a conservative approach. However, due to the complexity of the phenomenology and the presence of counter-reactions, being conservative in one aspect may result in being optimistic in another aspect [2]. Consequently, a second way called “best-estimate approach” can be followed. If such best-estimate calculations are used for safety studies, it requires quantifying the uncertainty associated to this estimation. This safety assessment approach is named Best Estimate Plus Uncertainty (BEPU). The evaluation of safety margins around the best-estimate values can be estimated thanks to uncertainty methods and benefits from the latest developments in methods and algorithms as well as the availability of computing resources. Mathematical tools for quantification of code uncertainties have thus been under development for many years for the analysis of design basis accidents [3-5], supported by the existence of many experiments, essentially focused on thermal hydraulic phenomena.

Uncertainty analysis has also been applied to SA, but less systematically, and most of the studies were performed for specific SA-phenomena. Only some of them contained an uncertainty quantification of the radiological source term. For instance, tolerance limits of source term following a severe accident were established for a French 1300 MWe PWR [6], for an accident sequence similar to the accident at Unit 2 of the Fukushima Daiichi NPP [7], and, in the framework of the US-American SOARCA study, for different NPPs and different accident scenarios [8]. To involve the Severe Accident community in the use of uncertainty methods, the Management and Uncertainties of Severe Accidents (MUSA) project was funded in HORIZON 2020 EURATOM NFRP-2018 call on “*Safety assessments to improve accident management strategies for generation II and III reactor*” [9-10]. In the framework of MUSA-WP6, uncertainty methods have been applied to the analysis of a SFP accident [11]. Indeed, a renewed interest has been paid to the safety of SFP after the accident at the Fukushima Dai-ichi Nuclear Power Plants highlighted the vulnerability of nuclear fuels that are stored in SFPs in case of prolonged loss-of-cooling accidents, even if the accident progression is slow (in comparison with reactor core accidents) [12-13]. At the same time, simulations of postulated SFP scenarios were carried out [14-19], but strong differences were found between the computations.

To get a better understanding of the SFP behaviour under accidental conditions, use has been made in MUSA-WP6 of uncertainty and sensitivity analysis. The main results obtained at the end of the project are summarized in this paper. The scenario studied is a loss-of-cooling accident, possibly mitigated by a spray system. The uncertainty sources that have been investigated are linked to modeling uncertainties and to the spray system. The uncertainty analysis has been performed by eleven participants thanks to the propagation of the uncertainties of the input parameters to the output uncertainties with three severe accident codes (ASTEC, RELAP/SCDAPSIM and MELCOR). Main outcomes resulting from the uncertainty analysis are presented. Then, results of the sensitivity analysis, that aims at evaluating the relative importance of uncertainties of the different input parameters on the output uncertainty, are discussed. In the conclusion, focus is put on the input of uncertainty and sensitivity analysis in the understanding of SFP behavior under accidental conditions, and in the identification of further R&D needs in SA codes.

2. SPENT FUEL POOL ACCIDENTAL SCENARIO and UNCERTAINTY SOURCES

2.1. Scenario, models and key target variables

The geometry for the calculations is similar to the one of the Unit 4 of the Fukushima Dai-ichi NPP, as set in the AIR-SFP NUGENIA+ project [17] and described in [11]. The main characteristics are summarized hereafter. The size of the pool is 12.2 m x 9.9 m x 11.5 m, with a total number of Fuel Assemblies (FAs) in the pool of 1535. The layout of Unit 4 was simplified for the computation as follows:

- 548 FAs (named “hot” FAs) with a fission power of 1.9 MW,
- 783 FAs (named “cold” FAs) with fission power of 0.5 MW,
- 204 FAs are fresh fuel.

The FP inventory for hot and cold FAs has been provided to the participants. The axial power profile was considered as flat in order to avoid additional complication in the modeling. It was assumed that a given mass fraction of the initial radionuclide inventory (i.i.) is in the fuel-cladding gap at the beginning of the transient (Xe, Kr: 3% i.i., I: 1.7 % i.i., Cs: 5 % i.i., Te, Sb: 10^{-2} % i.i., Ba, Sr: 10^{-4} % i.i.). The fuel assembly type used in the calculations is a 9x9-9 assembly with a central squared water channel called STEP3B. Each FA is surrounded by a steel rack cell and the spent fuel assemblies are stored in 3x10 spent fuel racks, with 53 racks placed in the SFP. The accidental scenario is a loss-of-cooling scenario. The temporal and spatial domains are defined as follows:

- **Spatial domain:** each participant was free to decide whether including in their modeling the SFP building. Indeed, even if more representative of the real situation, the modeling of the SFP building adds variability in the simulations. In case SFP building is modeled, its free volume is supposed to be 25800 m³ with an opening to the environment of 10 m².
- **Temporal domain:** the computation starts at the onset of fuel uncovering and ends at the onset of fuel melting when the fraction of relocated fuel (liquefied or debris) reaches 1-3 %.

The SFP has been modeled by 11 participants with the SA codes MELCOR [20-21], ASTEC [22-23] and RELAP/SCDAPSIM, [24-25]. The SA codes in this study were initially developed for reactor pressure vessel applications and the space meshing is thus adapted to describe axisymmetric cores or multi-channels cores. For this reason, the SFP is represented by a cylinder divided into concentric rings, inside which the FAs are placed. Main characteristics of the modeling developed by the participants are given in Table I. Modeling choices were discussed, but each participant had its own set of input data and differences illustrate the so-called “user effect”. Some participants modeled the 3 different types of FAs (hot, cold, and fresh), whereas the other ones gathered cold and fresh FAs to have only 2 types of FAs. One participant modeled only one representative FA. The number of rings in the SFP also differs between the participants. In most cases, each FA type is put in a dedicated ring. In some cases, an empty ring (called by-pass channel) models the zone of the SFP that does not contain any FAs. The axial nodalization also shows some variability (more or less fine, from 8 to 26 axial meshes in the FA zone). When modeled, the SFP building is discretized in 1 to 7 meshes. In most cases, rectangular structures (water channel, channel box, rack cell and SFP concrete wall) are represented by cylinders.

Table I. List of participants, codes and nodalizations adopted for the simulations.

Organisation	SA code	Modeling of the SFP					Modeling of the building	End of the sim. **
		Nb of rings	Nb of FA types	By-pass channel*	Nb of axial meshes			
					FAs zone	above racks		
CIEMAT	MELCOR 2.2.15254	4	3	Yes	12	1	No	1 %
ENEA	ASTEC 2.2.0.1	3	2	Yes	24	5	Yes, 7 zones	1.5 %
Energorisk	MELCOR 1.8.6	2	2	Yes	10	2	Yes, 3 zones	1 %
INRNE	ASTEC 2.2.0.1	4	3	Yes	15	10	Yes, 1 zone	3 %
IRSN	ASTEC 2.2.0	3	2	Yes	24	5	Yes, 7 zones	1.5 %
LEI - A	ASTEC 2.2.0.1	3	2	Yes	10	10	Yes, 7 zones	3 %
LEI - R	RELAP/SCDAPSIM 3.4	1	1	No	8	12	No	1 %
PSI	MELCOR 2.2.18019	4	2	Yes	15	0	No	1 %
SSTC	MELCOR 2.2	3	3	No	14	1	No	1 %
TUS	ASTEC 2.2b	4	3	Yes	15	10	Yes, 1 zone	3 %
UNIRM1	MELCOR 2.2.18019	3	3	No	26	4	Yes, 6 zones	1 %

* by-pass channel corresponds to an empty ring, without any FA

** fraction of relocated fuel considered to end the computation

The following phenomena were modeled in the simulations:

- **thermal hydraulics** in the SFP (and in the SFP building when it is modeled),
- **heat transfer** by conduction in the structures, convection, and radiation. Concerning radiative heat transfers, the users faced some difficulties: the models developed for SFP-BWR type of reactor lead to code crashes (MELCOR), or do not allow the simulation of radiative heat transfer between the steel rack cell of cold and hot FAs (ASTEC).
- **FA behaviour and degradation:** failure of fuel rods, oxidation, and eutectic reactions, melting and candling, fuel rods collapse. In MELCOR, the temperature at which claddings fail (and gap inventory is released) is a user parameter. Fuel rods collapse is given in terms of a lifetime failure function table that specifies the time remaining to collapse versus the local oxidized cladding temperature. In ASTEC, failure of the fuel rods corresponds to the burst occurrence, which is based on a stress or a strain condition. Fuel rods collapse (also named “loss of fuel rods integrity”) relies on a set of criteria (temperature and cladding oxidation state). A reduced melting temperature of UO₂ - ZrO₂ is usually considered to account for eutectic reactions.
- **fission product modeling:** radionuclide release is predicted by ASTEC and MELCOR. With RELAP/SCDASIM, only cumulative releases of fission product from fuel rods could be calculated. In MELCOR, a fixed cladding temperature for gap release is set, whereas it is computed in ASTEC (and corresponds to burst occurrence as explained previously).

Since the MUSA project is focused on Source Term (ST) evaluation, the figures of merit that have been investigated are linked to FP release. Due to its inventory in the SFP, its volatility and the dose coefficients of its isotopes (Cs137, Cs134), Cs was found to be one of the elements with the greatest radiological impact. Cs release, and the onset time of FP release from fuel have thus been selected as the key target variables. Additional variables (water mass in the SFP, maximum cladding temperature) have been used to analyze the reference computation but have not been considered in the uncertainty/sensitivity analysis.

2.2. Reference computations

In lack of cooling, and due to decay heat, the pool water, which is initially at saturation temperature, evaporates and the amount of water progressively decreases (see Figure 1a). The theoretical evolution of the water level has been computed with the assumption that heat load of the immersed part of the fuel

assemblies leads to the evaporation of the water. Right from the beginning, some of the computed water masses differ from the theoretical curve. Differences between the theoretical curve and the computations increase after 50 h as phenomena not accounted in the theoretical curve come into play (oxidation and heat transfer of the uncovered part of the FAs, material relocation, radiation, ...). It was noticed that the water mass evolution is affected by the modeling of the SFP (axial and radial nodalization, setting of the specified decay heat, interfacial friction model) and of the SFP building.

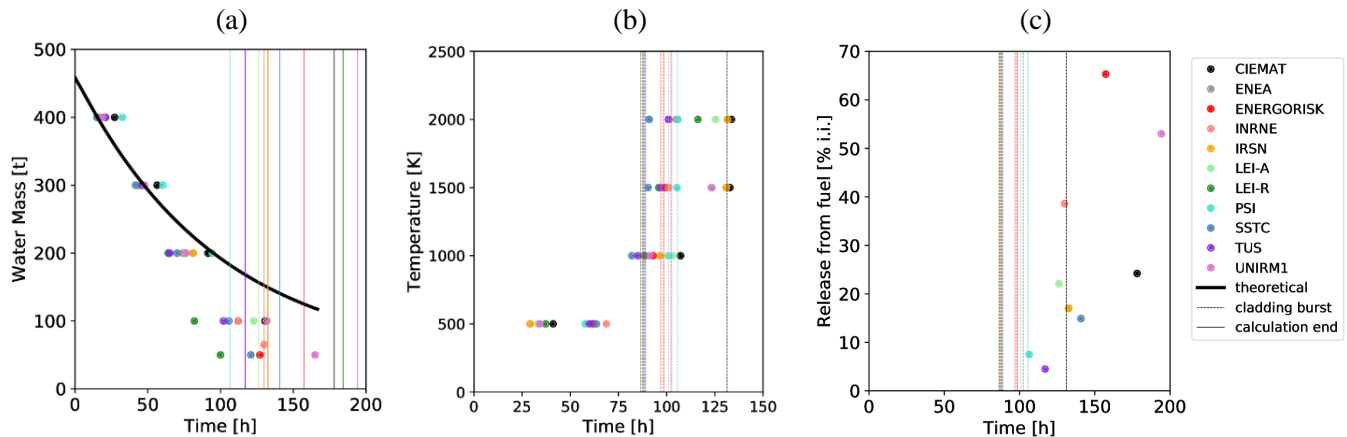


Figure 1. Reference computations. (a) Evolution of water mass in the SFP, (b) Evolution of the maximum cladding temperature, (c) Final Cs release from fuel. Lines are the ending times (fraction of relocated fuel between 1 and 3%), dotted lines correspond to cladding burst (i.e. gap release)

The maximum cladding temperature is stable until approx. 1 m of FA is uncovered (see Figure 1b). Then, the temperature of the uncovered part of the fuel assemblies increases regularly in a first time, and then more rapidly when oxidation comes into play. The maximum cladding temperature is strongly linked to the water level. So, differences in water level lead to differences in maximum cladding temperature. First FP release occurs when the cladding of hot FAs bursts, triggering the release of the fuel-cladding gap content (dotted lines in Figure 1c). This event occurs more than 80 h after the beginning of the transient, and for 10 over 11 computations, in a 20 h time-window. In some computations, the cladding of cold FAs also bursts, whereas in the other ones the cladding failure of cold FAs is not predicted. In all computations, a steep temperature rise is observed when the cladding reaches a temperature at which oxidation starts to be significant. This temperature excursion leads to the loss of cladding geometry and the relocation of either molten materials or solid debris. Depending on the amount of relocated material and on the criterion chosen to stop the computation, the computation can either end or continue. The temperature excursion initiates a fast FP release from the fuel matrix, that mostly occurs at the end of transient. However, it must be highlighted that FP release resulting from cladding burst is already very significant, given the large FP inventory in the SFP and the assumption made on the fuel-cladding gap content (see 2.1).

2.3. Uncertainty sources

The first uncertainties investigated in this study are the modeling one. As previously mentioned, the SA codes were initially developed for reactor pressure vessel applications. Even if some phenomena are close to those that occur in reactor scenarios, others are quite different due to the specificities of SFPs compared to reactor pressure vessels [12]: arrangement of the FAs (that can have very different burnup) in storage racks, flow patterns that can be three-dimensional (3D), relatively low decay power, atmospheric pressure surrounded by air, only one safety barrier (the cladding) in case the SFP is located outside the containment. Some phenomena consequently suffer from a lack of modeling in SA codes when they are applied to SFP accident conditions [26]. Uncertainties that result from modeling inaccuracies or from a modeling that has

no uncertain parameters (u.p.) available to the user have not been evaluated in this study. Focus has been put on the u.p. in the existing models. The phenomena have been divided in categories, closely linked to the models developed in most SA codes. The participants have listed the u.p. available to the user in the SA codes and filled a table with their description and their Probability Density Function (PDF). Finally, each participant has selected a number of u.p., as reported in Table II. Most uncertain parameters are related to FAs' behaviour and degradation, FP release and transport and heat transfer. This includes the uncertainties on material properties related to these phenomena. For instance, thermal properties (thermal conductivity, specific heat, emissivity) for heat transfer and vapor diffusivity for FP release and transport. The last column in Table II includes other u.p. on material properties (density and fuel-cladding gap thickness).

Table II. modeling uncertain parameters investigated by the participants

Organisation	Nb of u.p.	TH in the pool	Heat transfer	FAs' behavior and degradation	FP release and transport	Material properties
CIEMAT	15			2	13	
ENEA	21	2		6	13	
Energorisk	8			4	3	1
INRNE	7			4	3	
IRSN	18			7	11	
LEI - A	12		2	5	4	1
LEI - R	22		10	11		1
PSI	15		5	10		
SSTC	24	5	5	8	6	
TUS	7			3	4	
UNIRM1	29	1	7	11	10	

The second type of uncertainties investigated in this study is linked to SA Management (SAM) measures. A review of existing and innovative SAM measures in the partner countries carried out during the MUSA project has shown that emergency sprays can be used in the event of an accident. The water sprayed at the top of the SFP would cool the pool, maintain the water level in the pool, reduce the pressure in the building and retain fission products from the building atmosphere. To assess the benefits of spray systems, sensitivity calculations, varying the water mass flow rate and the injection time (see Table III), were carried out to determine whether the cladding burst (and thus the onset of FP release) can be avoided within the simulation time of the reference calculation.

Table III. SAM uncertain parameters investigated by the participants

Org.	Injection time*	Water flow rate	Temperature of injected water	Injection location	Number of calculations
ENEA	2 → 14 h	0.5 → 2 kg/s	20°C	Top of the SFP	44
INRNE	1 → 16 h	1 → 2 kg/s	40°C	Top of the SFP	12
IRSN	2 → 24 h	0.75 → 2 kg/s	20°C	Top of the SFP	23
LEI - A	0 → 8 h	1 → 2 kg/s	20°C	Top of the SFP	19
LEI - R	0 → 0.5 h	0.5 → 2 kg/s	10°C	Top of the SFP	11
SSTC	5.9 → 17.9 h	0.7 → 5 kg/s	60°C	Bottom of the SFP	8
TUS	3 → 15 h	1 → 2 kg/s	40°C	Top of the SFP	8

* before cladding failure

3. UNCERTAINTY ANALYSIS

3.1. Methodology

The methodology developed in the frame of the MUSA project to perform uncertainty and sensitivity analysis relies on the propagation of input uncertainties which is particularly suitable for code simulation applications [27]. The method is based on the random sampling of different selected input u.p. values. The Uncertainty Tools (UTs) used in this study have the capability for pure random (Monte Carlo) and Latin Hypercube Sampling (LHS). The set of sampled values is used for running several code calculations, in which all the input uncertain parameters are sampled based on their own PDF. After the simulations are performed with the SA code, the data of interest are extracted from the result files and written in the format required by the UT to be statistically post-processed. The uncertainty analysis presented in this study is based on the following statistics indicators: minimum/maximum value, mean, standard deviation (σ). The number of simulations carried out by the participants is based on the minimum number of runs necessary to determine the two-sided tolerance interval statistics according to the Wilks' non-parametric method [28-39]. For a probability content of 95 % and a confidence level of 95 %, it corresponds to approx. 100 runs. However, it must be considered that the probability content and confidence levels cannot be ensured, since some hypotheses of Wilks' formulation [30] (identification and quantifications of all uncertainty sources, absence of calculation failures) are not met in our application. However, we consider that Wilks' formula as a valid method to estimate a "reasonable" number of runs to be performed for uncertainty analysis. It is nevertheless mandatory to do an accurate and critical analysis to identify possible misleading results.

3.2. Results and discussion

The results obtained are presented in Figure 2. In section 2.2, it was highlighted that the onset times of FP release were in relatively good agreement between the reference computations. However, the uncertainty range computed by the participants (see Figure 2a) exhibits significant differences: in the simulations where the cladding fails when a given temperature is reached, the uncertainty range is noticeable: either because the temperature criterion is considered as an u.p. (CIEMAT, SSTC and UNIRM1) or because another u.p. influences the temperature evolution and thus the timing of gap release (PSI). In the simulations where the cladding rupture is computed by a mechanistic model implemented in the SA code, the uncertainty range is very small (only noticeable for LEI-R). Since there are uncertainties in the parametrization of the cladding burst model, this should have led to a greater uncertainty range than that observed in Figure 2a. This comes from the u.p. considered, which is the maximum hoop strain, whereas burst occurs upon another criterion (NUREG-0630 [31]). It is also probable that some uncertainties sources linked to the modeling of thermal hydraulics and heat transfer, that should influence the cladding temperature evolution and the subsequent cladding failure, are also lacking.

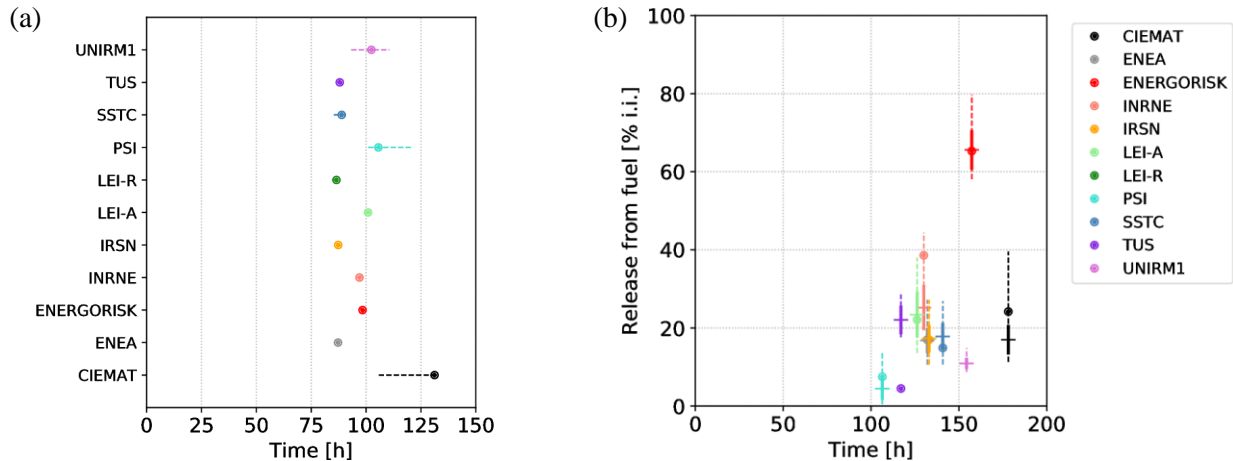


Figure 2. Uncertainty quantification. (a) onset time of FP release from fuel, (b) final Cs release from fuel. Points correspond to the reference case, dashes to the mean, dotted lines to the [minimum, maximum] range and lines to the [mean- σ , mean+ σ range]

The magnitude of the first FP releases (not shown here) is computed without any uncertainty since the fuel-cladding gap inventory was set as a fixed input parameter (see 2.1). However, this parameter is not precisely known. It was estimated that the gap inventory considered in the present study (i.e. Cs: 5 % i.i) is overestimated since the global release fraction measured in the VERCORS tests RT6 and RT8 is less than 0.6 % up to 1200°C for Cs and I [32]. It would consequently be worth in further studies to take the fuel-cladding gap inventory as an u.p. Variability in FP release increases with time, when Booth diffusion model [33], that describes FP diffusion through the fuel grain to the grain surface, comes into play. Finally, the uncertainty range of Cs release at the ending computations time (see Figure 2b) is very different among participants (very small in some cases and not very large in most cases), which can be explained by the list of u.p. that have been propagated, which differ from one participant to another one. It is also noticeable that spreading in SA code responses coming from the uncertainty quantification done by each participant is relatively small when compared to the variability between reference computations of all participants. This can be attributed to the limited number of uncertainties that have been considered, i.e. only uncertainties linked to models developed in SA codes with input parameters available to the user.

Finally, it was found that a code limitation can lead to errors in FP release that exceeds the uncertainty range which has been determined by the propagation of a limited number of uncertain parameters. For instance, the distribution of a mean FPs inventory between modeled FAs according to user defined factors leads to an inaccurate radionuclides repartition. If the factors are set to correctly distribute the decay power between hot and cold+fresh FAs, the amount of some radionuclides is overestimated in hot FAs. In the configuration studied here, this is the case for Cs137 and Sr90 for instance. It leads to overestimate by a factor of 2.8 the amount of Cs in hot FAs and the subsequent Cs release when the cladding of hot FAs fails.

4. SENSITIVITY ANALYSIS

4.1. Sensitivity to modeling uncertain parameters

To carry out the sensitivity analysis, the participants have assessed the relative importance of uncertainties of the different input parameters on the output uncertainty. Methods based on Monte Carlo regression and correlation analysis [34] have been used with the following indicators for the association between the input uncertain parameters and the output: correlation coefficients on the values (Pearson) or on the ranks (Spearman), partial correlation coefficients, standardized regression coefficients. Partial correlation

coefficients are used to evaluate the correlation of an u.p., not with the response, but with the response from which the part explained by all the other u.p. has been removed. The use of partial correlation coefficient avoids a misleading interpretation, for instance in case of correlation between the uncertain parameters. Scatterplots have also been used. One example of the results obtained is displayed in Figure 3a, with the evolution of the Spearman coefficient for Cs released from fuel, showing the association between the u.p. and the output. Correlation coefficients (absolute value) below 0.2, that corresponds to the Bravais-Pearson confidence threshold for a sample size of 100 and a confidence level of 95 %, will be considered as insignificant.

Despite the difficulty of drawing generic conclusion, due to the diversity of modeling and u.p. considered, the following issues have been pointed out by the participants:

- The correlation coefficients between input u.p. and Cs release strongly evolve with time. An u.p. can be the most important one but only for a while. It puts in evidence that the statistical analysis at the final time only is very restrictive and can be very different from that performed during the long-lasting transient. This is especially true in the present scenario that ends during a fast increase of temperature and FP release.
- It was found that the onset time of Cs release (i.e. cladding burst) is positively correlated to the cladding failure temperature for gap release (for the simulations where the cladding fails when a given temperature is reached). It was also observed that the onset time of Cs release is correlated to u.p. that influence thermal evolution and cladding oxidation: a positive correlation with the radiative exchange factor (axial) and a negative correlation with the metallic cladding oxidation rate constant coefficients. Results of the sensitivity analysis show that oxidation cutoff temperature is correlated to the onset time of Cs release, but with 2 opposite directions: positively if the cladding fails when a given temperature is reached, negatively if a model predicts the cladding burst. It was also found that the onset time of Cs release occurs sometime before with pre-oxidized cladding. Finally, no correlation was found with u.p. linked to the cladding burst model, due to an unsuitable choice of u.p. (see 3.2).
- The sensitivity of Cs release from fuel to degradation parameters is not straightforward: u.p. that drive degradation are generally positively correlated to the maximum fuel temperature and FP release. However, after loss of integrity and fuel relocation, this is not true anymore. For this reason, correlation coefficients related to degradation parameters fluctuate significantly and their sign can change also during the degradation. At the beginning of fuel heat-up, the following correlations were found (resulting from the correlations with the onset time of Cs release): Cs release from fuel is negatively correlated with the radiative exchange factors (axial and radial) and positively correlated with the metallic cladding oxidation rate. A positive correlation with the CORSOR-Booth scaling factor for Cs was also evidenced, but no significant correlation with the fuel grain diameter. Some correlations were computed with u.p. linked to oxidation (positive correlation with the axial extension of the cracking after cladding burst for instance), and material properties.
- When the building is modeled, FP release in the environment is generally significantly affected by uncertain parameters linked to aerosol phenomena in the building. Uncertain parameters that lead to an increase of the settling velocity are negatively correlated to the Cs source term, whereas u.p. leading to a decrease of the settling velocity are positively correlated to the Cs source term. It was thus computed a positive correlation with the aerosol dynamic shape factor and a negative correlation with the particle shape factor relative to coagulation. For the mean particle density, a negative correlation has been computed (relationship as expected) by two participants, whereas one participant computed a positive correlation.

4.2. Sensitivity to spray systems

The results obtained by the 5 institutions that participated to the sensitivity analysis are displayed in Figure 3b. It represents 113 simulations performed with ASTEC, RELAP/SCDAPSIM or MELCOR, covering a

large range of injection times and mass flow rates. It must be highlighted that the modeling is not completely uniform, with different temperatures of injected water and a participant who injected water at the bottom of the SFP (see Table III). Moreover, the model used in this study to inject water is not dedicated to spray system: the water is put at the top of the FA, but is not dispersed in the gas phase, and flows by gravity through the SFP. The droplet size is consequently not considered in the current modelling. In general, it was observed that:

- Within the time window investigated (i.e., later than 18 h before cladding burst), a minimum of 1 kg/s is required to prevent (or delay) cladding burst.
- Safe and failure regions have been identified. In the safe region, the conditions (injection time and mass flow rate) prevent cladding burst within the simulation time of the reference calculation for all participants. Nonetheless, in some cases, even if cladding failure was not predicted within the simulation time, it could be reached in the very long term, especially for low mass flow rate that does not compensate the evaporation flow rate. In the failure region, the conditions (injection time and mass flow rate) do not prevent cladding burst for all participants.
- Between the safe and the failure regions, a region of unclear/unreliable results emerges: a same condition (injection time and mass flow rate) prevents cladding burst in a simulation, whereas it does not in another one (for instance 1 kg/s, 8 h before cladding burst). This can be explained by differences in the thermal hydraulic and burst models.

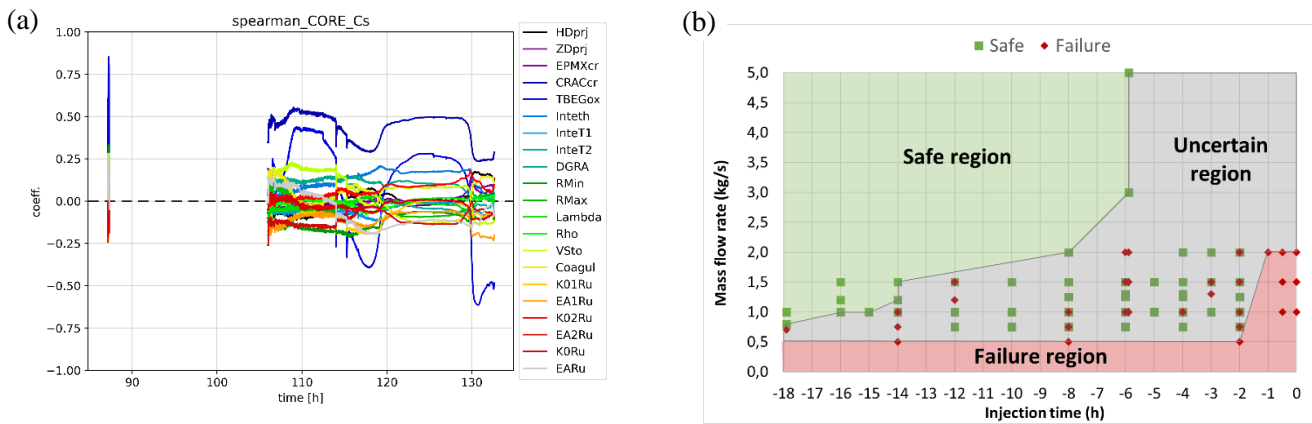


Figure 3. Sensitivity to (a) modeling uncertain parameters (evolution of the Spearman coefficient for Cs release from fuel) and (b) spray systems

The results obtained are very preliminary and should not be considered as demonstrative, since SA codes are generally not validated to compute the cooling of an assembly by spray injection. However, the work performed has shown the feasibility of such computations and the obtained results suggest that the spray system could be a very efficient mean of cooling the FAs and preventing cladding burst. To consolidate these evaluations, it is mandatory to carry out first a validation work of the thermal hydraulics and an extension of the fuel rod burst model to SFP conditions. The POLCA OECD project [35] would be an opportunity to get the experimental data needed to validate the models in existing thermal hydraulic system codes.

5. CONCLUSIONS

This paper aims at providing an overview of the uncertainty and sensitivity analyses performed by the MUSA participants on a loss-of-cooling scenario in a SFP, with two kinds of uncertainty sources investigated: modeling uncertainties and characteristics (timing and mass flow rate) of a spray system.

Despite differences in the modeling and in the list of u.p. that have been propagated the participants, the study has provided very valuable results and important lessons. Firstly, it was found that spreading in SA code responses coming from the uncertainty quantification done by each participant is relatively small when compared to the variability between reference computations of all participants. Discrepancies between reference computations come from differences in the nodalization, in the models, in the consideration or not of the building and in the criterion chosen to stop the computation (from 1 to 3% relocated fuel). The strong impact of the nodalization thus reflects part of the uncertainty associated to an incorrect representation of the SFP geometry (FA's stored in racks) with axisymmetric codes.

The relatively small uncertainty computed by each participant reveals that there are important uncertainty sources that have not been considered in the study. Some of them were excluded from this exercise (fuel-gap inventory for instance), and it would be worth investigating them in a further study. However, a review of modeling u.p. listed by the participants has also put in evidence that some u.p. are lacking, because they are not available to the user (especially for thermal hydraulics), that there is a lack of modeling (and consequently no u.p.) or that they have not been considered as having a high impact on the ST. Consequently, the results obtained in the present study cannot be used to establish tolerance limits.

By ascertaining the relative importance of uncertainties of the different input parameters on the output uncertainty, this study has provided results in terms of sensitivity analysis. As the release of the fuel-cladding gap inventory already leads to huge radiological consequences in case of an accident in a SFP, prediction of cladding burst is of prime importance. On the one hand, it was found that the onset time of Cs release (i.e. cladding burst) is correlated to u.p. that influence thermal evolution and cladding oxidation (for instance radiative exchange factor, metallic cladding oxidation rate, and presence of a pre-oxide layer). These findings support the developments that are currently underway to adapt the radiation model to SFP geometry in SA codes and the necessity of quantifying the input uncertainty in the models developed. On the other hand, the absence of correlation with the u.p. linked to the cladding burst model in ASTEC demonstrates an unsuitable choice of u.p. and the necessity to use another set of u.p. in further studies. This study has also shown the difficulty of establishing a correlation that would last during the whole transient between the u.p. linked to the degradation models and Cs release. However, at the beginning of fuel heat-up, it was computed that Cs release is correlated to the radiative exchange factors, the metallic cladding oxidation rate, the release of Cs from the UO₂ fuel matrix, and the axial extension of the cracking after cladding burst. Cs release in the environment was found to be correlated to u.p. linked to aerosol phenomena in the building (aerosol dynamic shape factor, particle shape factor relative to coagulation and particle density), with a negative correlation for the parameters that lead to increase the settling velocity. Concerning the benefits of spray systems, the results obtained, although very preliminary, confirm that the spray system could be a very efficient mean of cooling the FAs and preventing cladding burst but the conditions (injection time and mass flow rate) to gain this benefit are relatively different among the participants. A validation of the models in existing thermal hydraulic system codes would be necessary to have a better confidence in the results and reduce the region of unclear/unreliable results. The POLCA OECD project [33] would be an opportunity to get the experimental data needed for such a validation.

Finally, some recommendations can be made for the development of an uncertainty/sensitivity analysis with a SA code. At first, it is very important to establish a good quality reference case, as robust as possible. Then, a consistency screening of u.p. sets is highly recommended and pre-correlation should be used to avoid unphysical parameter combinations. The entire transient should be considered since just end time Figures Of Merit would miss substantial insights into models performance and key processes affecting final results. It must be kept in mind that setting tolerance limits requires some constraints that are not met in SFP calculations. But substantial insights can be gained by using sensitivity analysis: better understanding of the behaviour of a model and of its coherence, identification of interactions between processes and of the most influential parameters. If correlations found in sensitivity analyses cannot be physically supported, analysis of single realizations must be performed and eventually, code developers might be recommended to review some of the models embedded in the code if limitations or inconsistencies are found.

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