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Uncertainty quantification for a severe accident sequence in a SFP in the frame of the H-2020 project MUSA: First outcomes

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ABSTRACT

The Management and Uncertainties of Severe Accidents (MUSA) project, funded in HORIZON 2020 and coordinated by CIEMAT (Spain), aims at consolidating a harmonized approach for the analysis of uncertainties and sensitivities associated with Severe Accidents (SAs) focusing on Source Term (ST). In this framework, the objectives of the Innovative Management of Spent Fuel Pool Accidents (IMSFP – WP6), led by IRSN (France), are to quantify and rank the uncertainties affecting accident analyses in a Spent Fuel Pool (SFP), to review existing and contemplated SA management measures and systems and to assess their possible benefits in terms of reduction of radiological consequences.

To quantify the propagation of the uncertainties of the input parameters to the output uncertainties of severe accident codes (ASTEC, MELCOR, RELAP/SCDAP), a diverse set of uncertainty quantification (UQ) tools (DAKOTA, RAVEN, SUNSET, SUSA) are used. The statistical framework used by the different UQ-tools is similar e.g. pure random (Monte Carlo) and Latin hypercube sampling (LHS).

Fourteen partners from three different world regions are involved in the WP6 activities. The target of this paper is to describe the achievements during the first three years of the project. In a first part, a description is given of the SFP accidental scenario, of the key target variables and radionuclides chosen as ST Figures of Merit (FoM) and of the identified uncertainty sources in models and input parameters. A key element when defining the SFP scenario has been the consideration (or not) of the reactor building, as it is expected to significantly affect analyses. In a second part, the first insights coming out from the calculation phase of the project are presented. The review of existing SA management measures is also exposed, as well as systems whose benefits will be

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assessed in the second phase of the project. Finally, challenges that arise from such an exercise are discussed, as well as major difficulties found when applying UQ methodologies to SFP scenarios and solutions adopted.

1. Introduction

The community of Severe Accidents (SA) does not rely anymore entirely on the use of a conservative approach, since it showed its limitation in a number of situations. Because the phenomenology is complex and represents a hopefully closed system, being conservative in one aspect may result in being dramatically optimistic in another aspect (Cozeret et al., 2019). Consequently, a more realistic called "best-estimate approach" is followed worldwide and requires quantifying the embedded uncertainty of the codes used for safety assessment. This safety assessment approach is named Best Estimate Plus Uncertainty (BEPU).

The uncertainties of numerical codes can be quantified considering the latest developments in methods and algorithms as well as the availability of computing resources. Mathematical tools for quantification of code uncertainties and sensitivities have been under development for many years, with a huge, accumulated experience in performing Uncertainty Quantifications (UQ) with numerical tools applied for the analysis of events of the safety level 1 to 3 (NEA/CSNI/R, 2016). So far, this is not the case for SA codes and only a few investigations have focused on SA and UQ (Ghosh et al., 2021; Chevalier-Jabet et al., 2014). To address this gap, 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*" (Herranz et al., 2021; Mascari, 2021). MUSA project aims at establishing a harmonized approach for the analysis of uncertainties and sensitivities associated with SA analysis among EU and non-EU entities. It is coordinated by CIEMAT (Spain) and 28 Organizations from 16 Countries are involved. In this framework, the goal of MUSA-WP6, coordinated by IRSN, is to quantify uncertainties affecting accident analyses in a Spent Fuel Pool (SFP), to review existing and contemplated SA management measures and systems and to assess their possible benefits in terms of reduction of radiological consequences. WP6 is one of the applicative WPs of MUSA, with 14 partner organisations involved and about 20% of the total human resources.

To quantify the propagation of the uncertainties of the input parameters to the output uncertainties of SA codes, the statistical framework used by the MUSA partners is the sampling of a vector of input parameters characterized by a range of variations and a Probability Density Function (PDF), then performing the corresponding calculations, and getting a vector of output of the same size as the sample. These different steps will be detailed in this paper. In section 2, a description will be given of the SFP accidental scenario studied, of the key target variables and radionuclides chosen as Source Term (ST) Figures of Merit (FoM) and of the identified uncertainty sources in models and input parameters. In section 3, the results of the best estimate computations and the first insights coming out from the UQ phase will be presented. The review of existing SA management measures will be exposed, as well as systems whose benefits will be assessed in the second phase of the project. Finally, challenges that arise from such an exercise are summarized, as well as major difficulties found when applying UQ methodologies to SFP scenarios and solutions adopted.

2. Assessing the effect of uncertainties in a sfp accidental scenario

To assess the effect of uncertainties, it is necessary to (i) select a scenario, (ii) chose a set of uncertain parameters and define key variables as FoM, (iii) carry out the Uncertainty and Sensitivity Analysis (UaSA). These different steps are described hereafter.

2.1. Description of the SFP accidental scenario

Since accidents in SFP that lead to large Fission Product (FP) releases are practically eliminated since they are very unlikely with a high degree of confidence, the participants to MUSA-WP6 agreed to study an accidental scenario that leads to FP releases that are not too important and for which mitigation measures make sense. Consequently, the scenario computed has been chosen to fulfil these criteria and benefit from experience gained during the AIR-SFP NUGENIA + project (Coindreau, 2018).

The geometry for MUSA-WP6 calculations is similar to that of the Unit 4 of the Fukushima Dai-ichi NPP set in the AIR-SFP NUGENIA + project (Coindreau, 2018). The SFP is 12.2 m long and 9.9 m wide. The total number of fuel assemblies (FA's) in the pool is 1535 with the average assembly decay heat pattern as displayed in Fig. 1a. For this study, the fuel loading is simplified and FA's are divided into three groups: recently unloaded (548 FA's named "hot" FA's), longer stored (783 FA's named "cold" FA's) and fresh fuels (204 FA's). The FP inventory for low and high decay heat has been provided to the participants, assuming a cooling time for hot (resp. cold) FA's of 3.7 months (resp. 3.15 years), a burnup of about 21 MWd/kg (resp. 42 MWd/kg) with a remaining enrichment of about 2.03 % (resp. 0.77 %). This corresponds to a total decay power of 1.9 MW for recently unloaded FA's and 0.5 MW for longer stored FA's. For the calculations, only one type of fuel assembly is used (9x9-9 assembly with a central squared water channel called STEP3B, see Fig. 1c). Each FA is surrounded by a steel rack cell and the spent fuel assemblies are stored in 3x10 spent fuel racks (see Fig. 1b), with 53 racks placed in the SFP. The steel walls of the racks are double walls with some space for water in between. Each participant can choose to model only the pool or to include the building in the spatial modelling. Indeed, even if the modelling of the building is more representative of the real situation, it requires time and resources that partners might not have. In case the SFP building is taken into account in the modelling, the SFP is considered to be located in the secondary containment of type Mark-I, on the top floor of the refueling bay. The building above the SFP is 46 m length, 34.2 m width and 16.4 m height. It is assumed a 10 m^2 opening of the fuel pool area outwards to avoid pressurization.

The accidental scenario is a loss-of-cooling scenario with a computation starting at the onset of fuel uncovery and ending when the amount of fuel matter lost from initially intact components and transferred to degraded components reaches 1 or 3%. It must be emphasized that the criterion to end the computation strongly depends on the code modelling. To determine if the criterion is reached, the amount of still intact fuel is computed at each time step and compared to the initial mass of UO_2. Initial conditions are a pressure in the SFP building of 1 bar, a water temperature of 100 °C and an atmosphere temperature of 80 °C with 100% relative humidity.

2.2. Identified uncertainty sources and key target variables

The identification of uncertainty sources and the definition of key target variables as FoMs were carried out during the 1st phase of the MUSA project in the framework of WP2.

A list of phenomena affecting the ST in SFP was proposed, divided in 5 categories: 1) Modelling uncertainties; 2) Initial conditions; 3) Boundary conditions (scenario); 4) Boundary conditions (systems, SA Management measures); 5) Mesh, numerics.

In MUSA-WP6, the SFP design and the accidental scenario to be addressed have been set as described in paragraph 2.1. Initial and boundary conditions, i.e. categories 2) and 3), are consequently excluded. It has also been decided that mesh and numerics should not come onboard the UQ exercise but are investigated separately. Finally, the impact of systems will be addressed in the second phase of the project. The uncertainty sources investigated in this paper consequently belongs to the first category. A PIRT for SFP accident boundary conditions was previously made in the frame of a OECD/NEA project (NEA/CSNI/R, 2017). Uncertain parameters (u.p.) have been grouped in the same categories as those identified in (NEA/CSNI/R, 2017):

1. Thermal-hydraulic in the pool
2. Power generation
3. Heat transfer
4. Fuel assemblies' behavior and degradation
5. FP release and transport
6. Thermal-hydraulic in the SFP building
7. Material properties

It was not straightforward to retrieve the most important parameters from the list of phenomena identified in (NEA/CSNI/R, 2017). The participants have consequently listed the u.p. available to the user in the SA codes and filled the table with the names of the u.p., their description and their probability density function (PDF). For most of the u.p., all participants used the same PDF. An extract, related to FP release and transport, is given in Table 1. For the first version of the UaSA, the number of input uncertain parameters considered by each participant is indicated in Table II, as well as the category they belong to. Most uncertain parameters are in categories 3, 4 and 5. The lack of uncertain parameters investigated in other categories can be due to the fact that only a few are available to the user (especially for thermal–hydraulic), that they have not been considered as having a high impact on the ST or that they are usually not investigated and are consequently missing. On this last point, additional and substantial work would be necessary to determine if important uncertain parameters are missing and should be added in the table.

Since the MUSA project is ST driven, only variables linked to FP release into the environment have been considered as FoMs. Radionuclides with greatest radiological impact have been determined based on the inventory in the SFP, release rates of the elements and dose coefficients of the isotopes for three different modes of exposition (inhalation, groundshine and cloudshine). It was found that most contributing isotopes are Sr90, Cs137, Cs134, Ru106, Ce144, Sr89, Ba137m and Ru103. Taking into account this result, the list of FoMs are:

- Total release of Cs, Ru and Sr from fuel. Unit is mass fraction of the initial inventory.
- Onset time of FP release from fuel. Unit is h.
- Total release into environment from SFP building of Cs, Ru and Sr (only if the SFP building is modelled). Unit is mass fraction of the initial inventory.
- Total Ruthenium release in gaseous form to environment (only if Ruthenium chemistry in the building is investigated). Unit is mass fraction of the initial inventory.
- Dose due to isotopes with the greatest radiological impact (i.e. Sr90, Cs137, Cs134, Ru106, Ce144, Sr89, Ba137m, Ru103) relative to that of total release of Cs137. Unit is fraction.

Additional variables are needed to describe and analyze the SA scenario and are worth keeping track on, like the FoMs. These additional variables are used to analyze the reference computation (see paragraph 3.1), but they should not be considered in the sensitivity analysis.

2.3. *Uncertainty analysis applications methodology and tools used*

The UaSA is carried out in the MUSA project by the probabilistic propagation of input uncertainties (Ghosh et al., 2021) which is particularly suitable for code simulation applications. The method is based on the random sampling of different selected input uncertain parameters values, see Fig. 2. All UQ-tools used in MUSA 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 files in the format required by the UQ-tool to be statistically post-processed. Statistics indicators (e.g. minimum, maximum values, mean, standard deviation, cumulative density function, probability density functions, quantiles) and sensitivity functionalities (correlation coefficients, standard regression coefficients, coefficients of determination, scatter plots) are then provided by the UQ-tools.

The UQ-tools used in MUSA-WP6 are listed in Table 2 as well as the SA codes. The coupling between the UQ-tool and the SA code as described in Table II was considered as functional at the beginning of the MUSA project since it had already been used. However, uncertainty applications carried out in MUSA-WP4 on the PHEBUS FPT1 test have put in light major challenges (Mascari, et al., 2022): 1) Identification

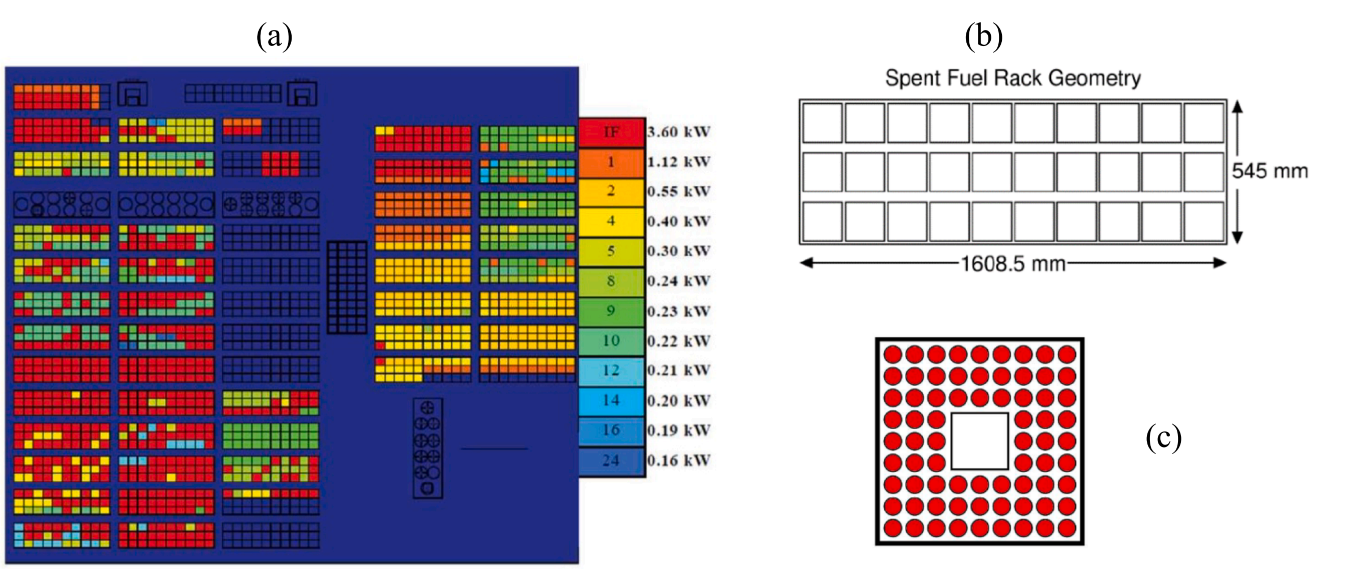


Fig. 1. Layout of Fukushima unit 4 SFP (a), scheme of a spent fuel rack (b) and of a STEP3B fuel assembly (c).

Table 1
Uncertain parameters considered for FP release, transport and deposition. For normal distributions, it should be considered that 95% of the distribution lies between the lower and upper bounds.

Phenomenon	SA code	Uncertain parameter	Distribution
FP release	ASTEC	DGRA: Average fuel grain diameter	Uniform distribution Lower bound: 10 μm Upper bound: 14 μm
	MELCOR	RN1_GAP00, CLFAIL: Gap release temperature	Uniform distribution Lower bound: 1073 K Upper bound: 1273 K
FP aerosol transport & deposition	ASTEC	lambda: Particle mean thermal conductivity	Normal distribution Ref: 3.5 W/m/K Lower bound: ref − 10% Upper bound: ref + 10%
	ASTEC	rho: Particle mean density	Normal distribution Ref: 3.10^3 kg/m^3 Lower bound: ref − 10% Upper bound: ref + 10%
	MELCOR	RHONOM: Aerosol density	Uniform distribution Lower bound:1000 kg/m^3 Upper bound: 4120 kg/m^3
	ASTEC	v_Stokes: Dynamic shape factor	Normal distribution Ref: 1. Lower bound: ref − 20 % Upper bound: ref + 20%
	MELCOR	RN, CHI: Dynamic shape factor	Uniform distribution Lower bound:1.0 Upper bound: 2.0
	ASTEC	Coagulation: Particle shape factor relative to coagulation	Normal distribution Lower bound: ref − 20 % Upper bound: ref + 20%
	MELCOR	RN, STICK: coagulation coefficient:	Uniform distribution Lower bound: 0.5 Upper bound: 1.0
	MELCOR	TURBDS: Turbulent dissipation	Uniform distribution Lower bound: 0. Upper bound: 0.03 m^2/s^3
	MELCOR	TKGOP: Gas thermal conductivity / Particle thermal conductivity	Triangular distribution Lower bound: 0.05 Upper bound: 1
	MELCOR	DELDIF: Diffusion boundary layer thickness	Uniform distribution Lower bound: 1. 10^{-5} m Upper bound: 8. 10^{-3} m

and characterization of the input uncertain parameters; 2) SA code and UQ-tool coupling in a powerful and flexible way (e.g. coupling by scripting instead of the Graphical User Interface); 3) Managing of the failed calculations and debugging; 4) Extraction of the data for the post-processing; 5) Eventual implementation in the cluster of the SA code and UQ-tool.

Some of these issues have been solved in the framework of WP4 (for instance 2, 4, 5) and the experience gained was consequently extremely useful for WP6. Other issues are still open and point of discussion.

3. Results from preliminary analyses

3.1. Reference computation

All participants were asked to fill a table to retrieve the main outputs of the reference computation (see Table 3). It must be emphasized that this study is not a benchmark, but it is essential to check the consistency of the input data deck before performing the UaSA. This comparison has enabled the participants to improve their input data deck, to correct some mistakes and to share procedures to retrieve the results, especially the FoMs.

In lack of cooling, and due to decay heat, the pool water, which is at saturation temperature, evaporates and the amount of water progressively decreases. 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. First FP release occurs when the cladding of hot fuel assemblies' bursts (more than 80 h after the beginning of the transient). Depending on the criterion chosen to stop the computation (from 1 to 3% relocated fuel), and on the modelling options, the simulation ends between 100 and 185 h.

The analysis of the reference case has put in evidence that the thermal-hydraulics in the SFP and in the building are strongly influenced in ASTEC computations by the use of the 5 or 6 equations modelling for diphasic thermal-hydraulics (Glantz et al., 2018). It was found that the evaporation flow rate increases unexpectedly due to downward flow of the steam in the bypass channel. In MELCOR computations, it was observed that the way of setting the specified decay heat is not straightforward and can lead to differences between the computations carried out with different decay heat modelling. These results are discussed with the development teams of the SA codes and should result in improvement in the models or to recommendations for the input data deck. In the meantime, the UaSA has started with the most consistent input data decks and latest versions of the SA codes. During the interpretation of the results, it is essential to keep in mind the limitations that the analysis of the reference computation have put in evidence. It is also worth mentioning that once operational, all the tools developed to carry out the UaSA can be used to re-evaluate the uncertainties of the results and the sensitivity of input parameters with a new version of the code and/or of the input data deck.

3.2. First results of uncertainty and sensitivity analyses

For the UaSA phase, it was decided that each partner should consider a unique ending simulation time. This ending simulation time is the computation time of the reference computation that ends upon the criterion described in paragraph 2.1. This makes the hypothetical assumption that the accidental scenario ends at a given time (i.e. the computation time of the reference computation).

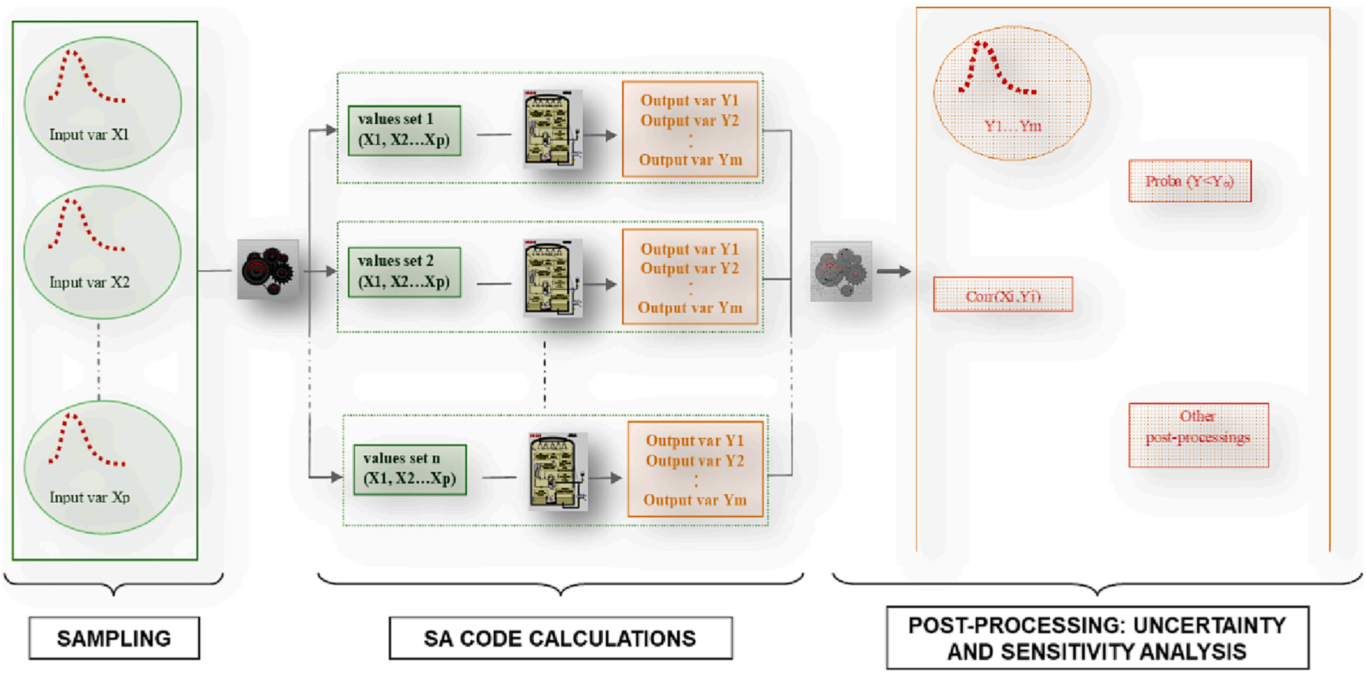


Fig. 2. Probabilistic propagation of input uncertainties applied in MUSA to perform the uncertainty analysis.

Table 2
List of participants, SA codes and UQ-tools used and characteristics of the simulations: modelling (or not) of the SFP building, number of uncertain parameters investigated and category they belong to.

Organisation	SA code	UQ-tool	Building modeled	Nb of input u.p.	1.	2.	3.	4.	5.	6.	7.
CIEMAT	MELCOR	DAKOTA	No	n.a.							
ENEA	ASTEC	RAVEN + Python script	Yes	15	*			*	*		
Energorisk	MELCOR	DAKOTA	Yes	8			*	*			
INRNE	ASTEC	SUNSET	Yes	5				*	*		
IRSN	ASTEC	R + Python script	Yes	13				*	*		
LEI-ASTEC	ASTEC	SUNSET	Yes	12			*	*	*		
LEI-SCDAP	RELAP/SCDAP	SUSA	No	25		*	*	*			*
PSI	MELCOR	DAKOTA	No	15	*		*	*			
SSTC	MELCOR	SUSA	Yes	24	*		*	*	*		
TUS	ASTEC	SUNSET	Yes	5				*	*		
UNIRM1	MELCOR	RAVEN	Yes	25				*	*		
CNPRI	ASTEC	SUNSET	Yes	n.a.							

To carry out the UQ, the partners adopted the Wilks' formula (Wilks, 1941; Wilks, 1942) to evaluate the minimum number of code runs for a selected probability content (γ) and confidence level (β). The Wilks' method, based on order statistics, is used for setting tolerance limits with a relatively small number of computations (in comparison to pure Monte-Carlo). The minimum and maximum values of a FoM among N code runs can be considered as the limits of the two-sided tolerance interval if N satisfies the following equation (Guba et al., 2003):

$$\beta = 1 - \gamma^N - (N-1)(1-\gamma)\gamma^{N-1} \quad (1)$$

For a probability content and a confidence set to 95 % and 95 % (values generally taken by the participants), the minimum number of code runs given by Equation (1) is 93. In most cases, the number of performed runs has been slightly increased to have a minimum of 93 runs successfully terminated. It must be outlined that Wilks' formula is strictly valid only if: code uncertainties are quantified and minimized; there are no calculation failures; all input parameters relevant for code results are considered; distribution of uncertain input parameters is well known (Porter, 2019). Even if mentioned constrains are not all met in our application, it is though that Wilks' formula is 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.

First results of the uncertainty analysis are displayed in Fig. 3, focused on the evolution of Cs release. Uncertainties on Cs release from the fuel and into the environment computed by ENEA is shown in Fig. 3a and b. In these figures, dispersion plot enables the visualization of the results of all code runs. Given the number of runs, the lower and upper bounds indicated on the graphs correspond to the limits of the 95% tolerance interval with a 95 % confidence-level. The mean and median values are also indicated. Uncertainties on Cs release from the fuel computed by SSTC is displayed in Fig. 3c with the evolution of the upper and lower limits of the 95 % tolerance interval with a 95 % confidence-level.

It must be emphasized that the evolution of Cs release must be considered as as many FoMs as the number of saving times. Consequently, the determination of the tolerance interval of Cs release for each saving time simultaneously would require a huge number of computations. Consequently, the limits of the tolerance interval that are plotted here are for each saving time separately and not simultaneously.

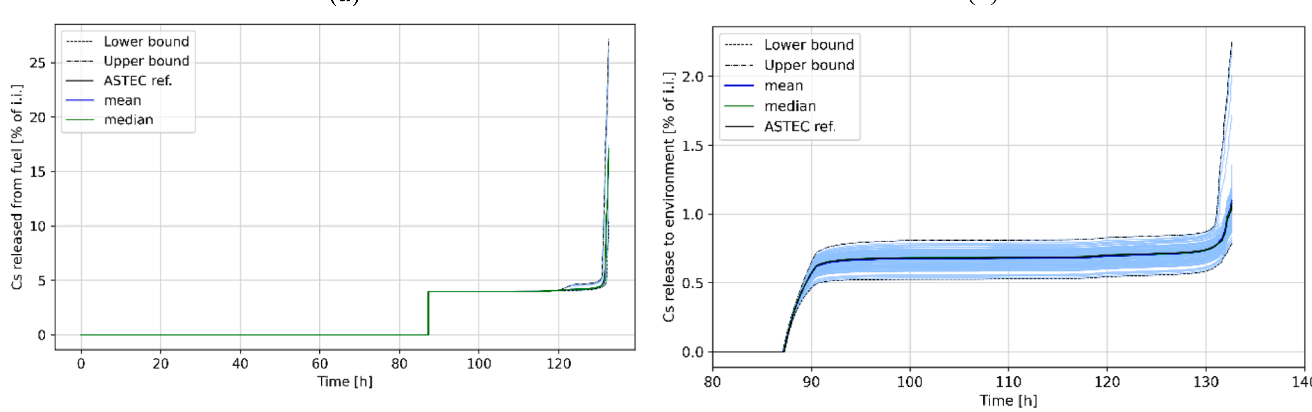
The uncertainties results put in evidence a different behaviour of the two sets of computations. The cladding failure occurs, in both cases, a little before 90 h and leads to the release of Cs gap inventory (assumed to be 5 % of the initial inventory in the computations). But in one case (see

Table 3
Results of the reference computations. The fraction of relocated (x %) fuel considered to end the computation varied between 1 and 3 %.

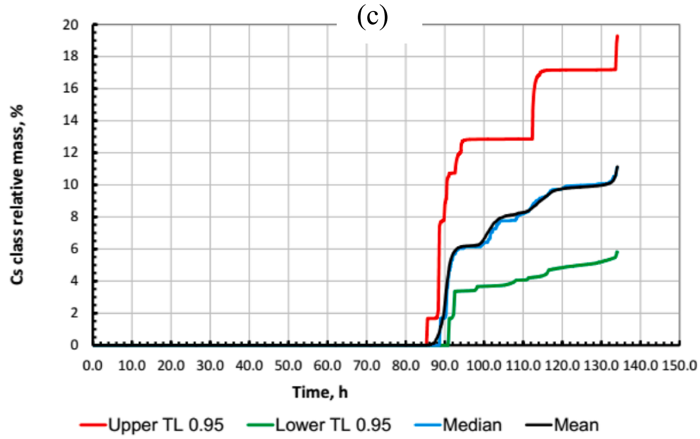
	Maximum cladding T° at (h)				x% reloc. fuel (h)	Mass of water in the SFP at (h)				
	500 K	1000 K	1500 K	2000 K	end of the sim.	400 t	300 t	200 t	100 t	50 t
ENEA	29.2	96.5	130.9	131.6	132.6	15.3	43.6	81.2	–	–
Energorisk	61.8	92.9	99.9	101.1	101.9	15.9	43.6	74.9	111.9	131.3
INRNE	68.7	89.1	101	105	130	17	44	74	112	–
IRSN	29.2	96.5	130.9	131.6	132.6	15.3	43.7	81.2	–	–
LEI-ASTEC	33.2	103.2	123.6	125.3	126.2	15.5	43.3	75.7	122.7	–
LEI-SCDAP	37.2	88.4	95.9	116.2	184.2	20.8	46.3	64.1	82.0	100.0
PSI	57.7	100.7	105.3	105.7	106.4	32.6	60.3	94.3	–	–
SSTC	63.5	81.9	90.4	90.9	140.8	15.0	41.6	70.1	105.7	120.8
TUS	60	85	97	101	117	21	46	65	102	–
UNIRM1	36.6	85.8	97.9	110.7	160.	16.7	43.47	73.4	122.4	153.8

	Start of (h)			At the end of the simulation		
Organisation	**H2 Prod°**	**Gap release**	**Mass relocation**	**Collapsed water level (m)**	**Amount of H2 generated (kg)**	**Amount of magma and/or debris (kg)**
ENEA	52.1	87.2	131.4	1.05	323.2	13,005
Energorisk	98.1	98.5	101.9	0	1716	531,589
INRNE	95	97	100	0.6	780	47,500
IRSN	52.1	87.3	132.6	1.04	322.1	12,843
LEI-ASTEC	57.6	100.9	124.5	0.84	1078	18,456
LEI-SCDAP	88.4	86.5	161.9	0.18	1012	n.a.
PSI	104	105.58	106.39	1.74	366.21	11231.17
SSTC	88	88.9	140.8	0.11	1146	n.a.
TUS	89	81	104	0.70	1544	60,100
UNIRM1	40.9	91.9	139.1	0.35	1042	30,299

(a) (b)



(c)



(d)

Cs release	Minimum value	Maximum value	Average	Standard deviation
From fuel	13.6	38.0	23.4	5.5
To env.	2.6	11.6	5.7	2.2

Fig. 3. Time dependent dispersion plot of % of the initial inventory (i.i.) of Cs released from fuel (a, c) and into environment (b). Uncertainty quantification at the ending simulation time (d). UQ done by ENEA (a, b), SSTC (c) and LEI (d).

Fig. 3a), there is no more Cs release until approx. 120 h meaning that fuel temperature stays relatively low. In the other case (see Fig. 3c), there is a continuous increase of Cs release in relation to a relatively high fuel temperature. Scattering in the results is more important in Fig. 3c, given that degradation comes into play and that most u.p. are related to degradation phenomena. At the end of the simulation, the upper tolerance limit for the Cs release from the fuel is slightly less than 20 % in SSTC quantification and slightly more than 25 % in ENEA quantification. Uncertainties results at the end of the simulation evaluated by LEI is also provided in Fig. 3d. In these simulations, the criterion to end the computation is 3% of relocated fuel, which leads to more fuel degradation and subsequent Cs release. The upper tolerance limit for the Cs release from the fuel is approx. twice higher than in the quantifications of ENEA and SSTC.

The impact of the SFP building can be shown in Fig. 3b. Taking the SFP building into account leads to a reduction of a factor ranging from 5 and 10 between Cs release from fuel and Cs release to the environment. The effect of retention in the SFP building is a bit less important in the results displayed in Fig. 3d.

For the sensitivity analysis, the post-processing approaches presented by the partners are the characterization of the statistical correlation between the uncertain input parameters and the FoMs through Pearson and Spearman correlation coefficients. The correlation coefficients are scale-free measures of association between the uncertain input parameters and the FoMs, either based on the values (Pearson coefficient) or on the ranks of the values (Spearman coefficient). A correlation coefficient close to 1 (resp. −1) indicates a positive (resp. negative) dependence. It must be highlighted that, for a given sample size, the Bravais-Pearson confidence threshold matches the correlation coefficient to a level of confidence. For instance, for a sample size of 100, the confidence threshold is ≈ 0.2 for a confidence level of 95 %.

The statistical and correlation analysis can be done on a single selected time value, see Fig. 4a, or on time dependent values, see Fig. 4b. In Fig. 4a, the bar plot shows the Spearman and Pearson coefficients between the Cs release into the environment and the uncertain input parameters after 105 h. This sensitivity analysis, carried out by ENEA, put in light that Cs release into environment is very strongly positively correlated to Vsto and negatively correlated to Coag and Rho. These three parameters are linked to aerosol deposition in the building. Vsto is the particle shape factor relative to Stokes velocity. Since the sedimentation velocity is a decreasing function of Vsto, an increase of Vsto leads to a decrease of the amount of aerosols that settle down in the SFP building and consequently to an increase of Cs release into environment. Coag is the particle shape factor relative to coagulation and Rho the particle mean density. An increase of Coag (resp. Rho) leads to an increase of the mass of a single particle due to an increase of its diameter (resp. its density) and consequently to an increase of the amount of aerosols that settle down in the SFP building and a decrease of Cs release into environment. The correlation coefficients for other input parameters are not high enough to be considered as significant.

The evolution through time of the Spearman coefficient is shown in Fig. 4b. It puts in evidence that the correlation of an input parameter can be significant only at a given time or during a phase of the transient. For instance, shortly after the cladding failure, the Spearman coefficient shows a very strong positive relationship between the Cs release into the environment and TBEGox uncertain parameter (minimum temperature to start Zr oxidation). It is probable that the TBEGox uncertain parameter is correlated to the instant of cladding burst (that corresponds to the onset time of FP release). The high Spearman coefficient of TBEGox is thus of limited duration, in the short phase of the transient when cladding burst occurs. During the final phase at very high temperature, the Spearman coefficient dealing with CRACcr (axial extension of the cracking after clad burst) increases. CRACcr defines the number of axial nodes considered as cracked after the cladding burst and then involved on the internal oxidation of Zr. It consequently affects the thermal behavior and drives the progression of the degradation. However, it was found that this u.p. exhibits a discontinuous behavior due to the axial nodalization and leads to the presence outliers corresponding to extremity values of CRACcr parameter. This u.p. is consequently responsible of the bifurcation of results and it would be worth to improve the modelling to avoid such a behaviour.120 calculations were carried out to perform this statistical analysis.

At this stage, the UaSA has not been carried out in detail. Only the feasibility has been checked, with first runs performed and post-processing done. The results presented in this section should consequently not be considered as quantitatively but only as first outcomes of

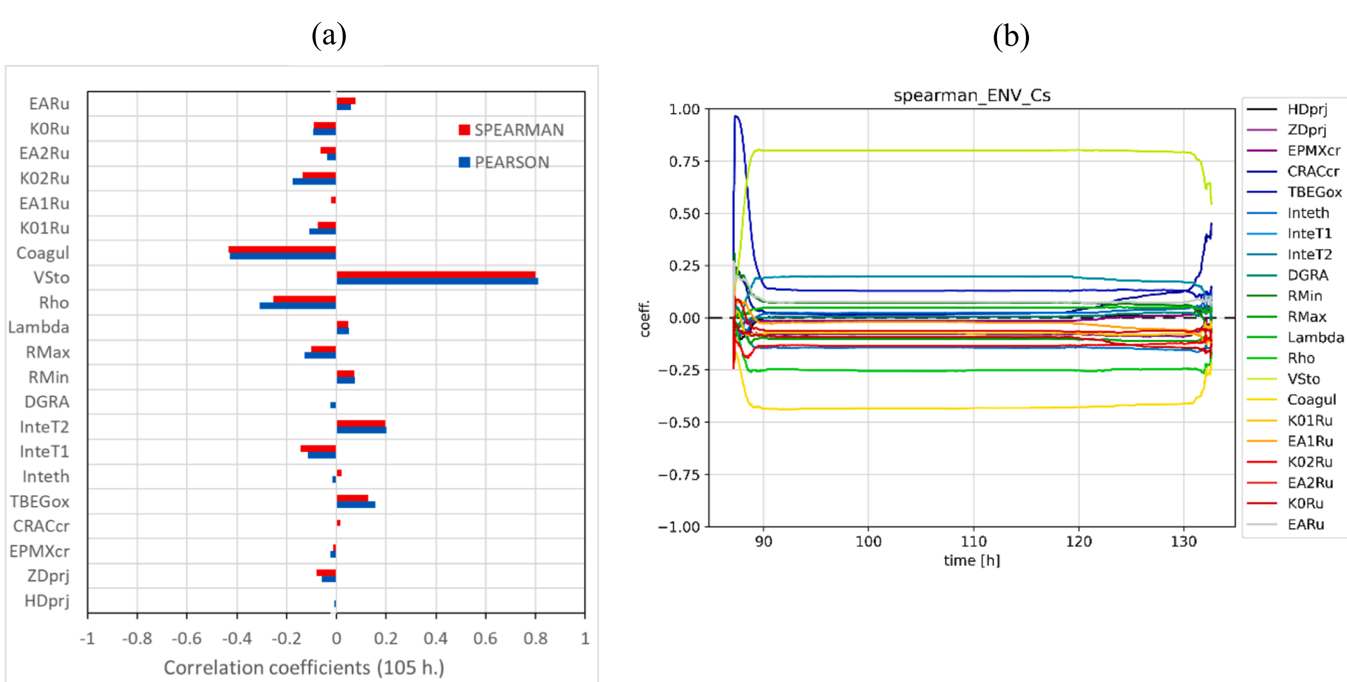


Fig. 4. Correlation coefficients between Cs release in environment and input uncertain parameters (a) at a given time (105 h), (b) variation through time. Sensitivity analysis done by ENEA.

MUSA-WP6. In particular, it must be reminded that simulations differ from one participant to another one by: 1) the modelling domain (i.e. the consideration, or not, of the reactor building, 2) the criterion to end the computations, 3) the uncertain parameters considered for the UQ phase. On this last point, it must be emphasized that results strongly depend on the input parameters selected. The interpretation of the results must consequently be done carefully, considering the u.p. investigated. A detailed analysis of the results is consequently ongoing to quantify and rank the uncertainties affecting the SFP accident and will be presented in a further publication.

3.3. *Review of existing SA management (SAM) measures*

A review of existing and innovative SAM measures in the partner countries was carried out. For this, the MUSA partners from 10 countries provided information about the accident management measures and related safety systems employed in the nuclear power plants in their countries. The review showed that a large number of systems are in place and used to prevent and mitigate accidents in SFPs both for pools in- and outside of the containment. The most common systems used to monitor the SFPs and their status are temperature and water level measurements, monitoring of the activity and dose rate in the SFPs and buildings, as well as measurement of pressure and flow of the coolant, ventilation flow rate, and concentration of combustible gases. Safety systems are redundant and focused on ensuring and if needed, restoring cooling of the SFP by different means, and when necessary locating and isolating a leak in the pool. In many countries, the monitoring and safety systems were reviewed and upgraded after 2011.

The criteria to enter accident management in SFPs were mainly related to the water level in the pool, e.g., loss of water, decrease in the water level, and an exceptionally fast water level decrease in the pool. Similarly, most of the accident management measures had the aim of restoring the water injection by different water sources. In some cases, opening the fuel pool area outwards was done to avoid pressurization. In some cases, the irradiated fuel bay atmosphere was vented by using fans and filters to manage combustible gases and to maintain active areas at a negative pressure. Absorber injection was also considered in some SFPs. No country has reported to plan any major new accident management measures specific to SFPs to be implemented in the near future. Several countries reported that further analytical activities will be carried out to validate the SFP accident management measures.

A review was also made of the work that has been carried out to analyze the accidents in SFPs with the focus on international activities and on accident management measures specific to SFPs. Reports of source term assessment from postulated SFP accidents were found to be scarce. Several reports emphasized the challenge of calculating the ST from SFPs using current severe accidents codes which have been developed for reactor accidents. Several other challenges and recommendations for analyzing SFP accidents were also identified. It was agreed that the benefits of systems that have been installed to prevent SA in a SFP, like water injection by spray systems, will be assessed in the second phase of the project.

4. Conclusions

The paper has given a view of the extent of work carried out by the fourteen partners involved in MUSA-WP6 and described main achievements during the first three years of the project. The first steps required to carry out the UaSA have been completed: selection of an accidental scenario, creation of an input deck and check of its consistency, determination of uncertainty sources in models, choice of key target variables as ST FoMs. In the meantime, a review of SAM measures and systems in SFP has been done. The partners agreed to assess, in the second phase of the project, the benefits of spray systems. Then, the uncertainty analysis phase has started with the use of UQ-tools to propagate input uncertainties. To achieve this task, WP6 participants have benefited from the experience gained in WP4. In particular, the coupling by scripting between the SA code and UQ-tool and the automation of data extraction for the post-processing were very useful. The implementation in the cluster of the SA code and UQ-tool for those who have access to such a system has required some time but issues have been handled (for instance by adding libraries in the cluster).

The first results of the UaSA have be obtained and led to the following main conclusions:

- Concerning the uncertainty quantification, the results obtained must be interpreted with caution, due to the constrains for the application of order statistics that are not all met in our computations. In particular, only a limited number of u.p. have been considered. UQ has enabled us to quantify the spreading of the different SA codes when applied to a transient in a SFP. It is also very useful to see how the dispersion evolves through the transient and if a phenomenon gives rise to spreading.
- Concerning sensitivity analysis, Spearman and Pearson coefficients have been used to determine the monotonic and linear association between the uncertain input parameters and the FoMs and have enabled us to determine most significant parameters. It must be kept in mind that the results obtained are strongly linked to the u.p. investigated and the FoM considered. It must also be reminded that the input–output relationship must be monotonic for such methods. More advanced methods should be envisaged to overcome this limitation (Saltelli et al., 1999). In addition to order the input factors, the sensitivity analysis has enabled us to see unexpected dependencies, to search for the reason of such behaviour and to have a deeper understanding of the accident progression. It has also put in evidence discontinuities in the input modelling parameters, and this will lead to recommendations for the development teams of the SA codes.

The UaSA is ongoing, and the participants aim at elaborating a harmonized approach. In particular, arguments for the selection of uncertain parameters, criteria for the determination of the number of runs and the significance threshold of correlation coefficients should be provided. A template will be distributed to the participants to get the results with the same units, to have common standard for post-processing and make the analysis more easily comparable from one participant to another one.

Major challenges have been found when applying UQ methodologies to SFP scenarios and difficulties are addressed by the participants:

- Computational aspects with large CPUs (from a few hours to 4 days for one computation). The use of multi-core processor or PC cluster seems necessary to perform the UQ with more than 100 runs.
- Code crashes. Some partners decided to perform a number of runs larger than the minimum required number according to Wilks' formula in order to be sure to have enough computations with a normal end. But this raises questions about the statistical treatment of failed calculations.
- Identification and characterization of the input uncertain parameters. A review is ongoing to identify if input parameters are lacking. But the input uncertainty quantification, which has been identified as an important step in the UQ phase (NEA/CSNI/R, 2020), is a long task which is out of the scope this project.

CRediT authorship contribution statement

O. Coindreau: Supervision, Software, Formal analysis, Writing – original draft. **L.E. Herranz:** Project administration, Funding acquisition. **R. Bocanegra:** Software, Formal analysis. **S. Ederli:** Software, Formal analysis, Visualization. **P. Maccari:** Software, Formal analysis. **F. Mascari:** Methodology. **O. Cherednichenko:** Software, Formal analysis. **A. Iskra:** Software, Formal analysis. **P. Groudev:** Software, Formal analysis. **P. Vryashkova:** Software, Formal analysis. **P. Petrova:** Software, Formal analysis. **A. Kaliatka:** Software, Formal analysis. **V. Vileiniškis:** Software, Formal analysis. **M. Malicki:** Software, Formal analysis. **T. Lind:** Conceptualization, Methodology. **O. Kotsuba:** Software, Formal analysis, Visualization. **I. Ivanov:** Software, Formal analysis. **F. Giannetti:** Software, Formal analysis. **M. D'Onorio:** Software, Formal analysis. **P. Ou:** Software, Formal analysis. **L. Feiye:** Software, Formal analysis. **P. Piluso:** Conceptualization. **Y. Pontillon:** Conceptualization. **M. Nudi:** Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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