UaSA APPLICATION in SEVERE ACCIDENTS ANALYSIS: CHALLENGES and PATH FORWARD

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ABSTRACT

The HORIZON-2020 project on "Management and Uncertainties of Severe Accidents (MUSA)" meant a sound step forward in the application of UaSA (Uncertainty and Sensitivity Analysis) in Severe Accidents (SA) analysis. While a massive application was conducted for reactor and Spent Fuel Pool (SFP) scenarios, major challenges were found that might hinder an effective and systematic implementation of UaSA in the SA domain. This paper synthesizes the major accomplishes achieved by MUSA and it identifies the challenges found out and, through their discussion, the path forward to move ahead is outlined.

1.   INTRODUCTION

Uncertainty quantification (UQ) was proposed in the area of thermal-hydraulic modelling as part of the Best Estimate Plus Uncertainty (BEPU) methodology to analyze Design Basis Accidents (DBA) and, more specifically, to the licensing of the Emergency Core Cooling System (ECCS) [1]. In the last couple of decades, notable development of methods and insightful applications have been conducted in international frameworks, like OECD/NEA. As an illustration, the Working Group of Analysis and Management of Accidents (WGAMA) launched several activities: BEMUSE (2004-2010), PREMIUM (2012-2015), SAPIUM (2017-2019) and ATRIUM (2021-present). A synthesis of the progress made can be read in [2].

Much of the progress made in BEPU has fed some attempts of application in the SA field but, given the intrinsic and major differences between both domains, BEPU application in SA modelling has been proved far more complicated. Uncertainties when modelling an accident scenario grow when moving from the DBA to the SA realm, and the experimental database available supporting any uncertainty characterization is far less complete than in the case of DBAs. Hence, the quantification of any kind of uncertainties in SA codes estimates is a challenging undertaking.

"Pioneering" works were carried long ago [3, 4]. More recently, USNRC launched the so called "State Of the Art Reactor Consequences Analyses (SOARCA)" [5], an Uncertainty and Sensitivity

Analysis (UaSA) focused on unmitigated SBO scenarios in 3 US NPPs (Peach Bottom, Surry, and Sequoyah). Despite the relevant insights gained, the scope of the UaSA was limited and expert judgement was noted as an essential tool.

In 2019, a broad application (30 international organizations) of UaSA in SA scenarios was initiated under the frame of EURATOM HORIZON-2020. The project on Management and Uncertainties of Severe Accidents (MUSA) extended for 4 years (2019-2023) with the focus on Source Term (ST) of Gen. II and Gen. III reactors and Spent Fuel Pool (SFP) accident sequences. Accident Management (AM) measures were considered. This paper synthesizes the outcomes of the project and identifies and discusses the major challenges found for a systematic application of UaSA in the SA domain.

Also in 2019, a Coordinated Research Project (CRP) on the matter was launched under the auspices of IAEA. It is still running and it is out of the scope of this paper.

2.   SYNTHESIS OF MUSA

The specific MUSA outcomes are shortly described next. A thorough description may be found in [6,7].

2.1   Uncertainty database

A matrix containing the selected variables, parameters and models together with its uncertainty ranges has been built. More than 450 uncertain parameters directly related to ST have been characterized through their reference value, lower and upper bounds (uncertainty range) and Probability Density Function (PDF). Additionally, another about 150 parameters, indirectly involved in ST variables, were also characterized. The database includes references supporting the specific values. Table 1 shows the mentioned structure through the piece of the database concerning particle sedimentation.

Table 1: Uncertainty database structure (particle sedimentation).

Phenomena	Uncertain Parameter	Reference value	Lower bound	Upper bound	pdf	References
Sedimentation	Gas viscosity [kg/ms]	1.0 / N/A	-5% / N/A	+5% / N/A	Uniform	Expert Judgment
	Gas temperature [K]	N/A	N/A	N/A	N/A	N/A
	Gas pressure [Pa]	1.55E+07 / N/A	-1.5% / N/A	+1.5% / N/A	Normal	Expert Judgment
	Gas mean free path	N/A	N/A	N/A	N/A	N/A
	Particle diameter Lower Bound [m]	0,000000011	0,00000001	0,0000002	Triangular	1986 Helton et al. "Uncertainty and Sensitivity Analysis of a Model for Multicomponent Aerosol Dynamics"; 2009 NEA/CSNI. "State-of-the-Art Report on Nuclear Aerosols"
	Particle diameter Upper Bound [m]	0,000199	0,000005	0,00002	Triangular	1986 Helton et al. "Uncertainty and Sensitivity Analysis of a Model for Multicomponent Aerosol Dynamics"; 2009 NEA/CSNI. "State-of-the-Art Report on Nuclear Aerosols"
	Slip factor (default = 1.257)	1,257	1,14	1,28	Triangular	1990 D. J. Rader. "Momentum slip correction factor for small particles in nine common gases"; MELCOR Default; Expert judgment (pdf)

2.2   Methodologies

Methodologies rely on two major elements: the integral SA code capable of predicting SA progression; and the analytical tool in charge of statistics behind each realization (from sampling PDF of uncertain parameters to the final sensitivity analyses). There are several statistical tools available that can be coupled with SA codes (i.e., DAKOTA, SUNSET, SUSA, RAVEN or URANIE), but still some UaSA applicants might develop their own tools to tailor the statistical processes and analyses and to gain further flexibility when managing data. In Table 2 the pairing used in MUSA between SA codes and the statistical tool is displayed; the shadowed boxes are the most popular among partners.

Table 2: Pairing of SA codes and statistical tools in MUSA.

SA Code	UQ Tools
ASTEC 2.2	SUNSET
ASTEC 2.1	URANIE
MELCOR 2.2	DAKOTA
MELCOR 2.2	In-house scripts
MELCOR 2.2	SUSA
MELCOR 2.2	RAVEN
MAAP 5.0	DAKOTA
AC^2	SUSA
RELAP/SCDAP	SUSA

The size of the realization campaign, usually lands in the approximation of order statistics (usually referred to as the Wilks' theorem [8]).

Some generic lessons have been learned:

- The best estimate plant model is the reference case for the follow-up quantification of the uncertainty representing the optimal model regarding the accidental scenario for a specific reactor design characterized by robustness and computational efficiency.

- The selection of the size and composition of the uncertain parameters set is a crucial step that should be based on a sound background. A balanced choice, between comprehensiveness and potential impact should orient the final selection. To do so, experimental data, analytical data and expert judgement are necessary.

- Expert judgement should be considered during several steps of the entire process. The selection of the input parameters has been already mentioned, but it should be also involved in the post-processing of the realizations campaign.

- Sensitivity analysis should make use of various techniques. Drawbacks of different techniques have been identified and the "single-bullet" strategy seems not to be the best option.

There are further issues still open when applying UaSA in SA: the suitability of purely random techniques to sample input parameter PDFs (versus other options like Latin Hypercube Sampling, LHS); or the consideration of failed cases in the realization campaign. These aspects demand further work to explore consequences and to substantiate recommendations.

2.3 Applications to real scale scenarios

The real scale applications in MUSA came after an insightful "hands-on-training" exercise based on the PHEBUS-FPT1 scenario [9].

As for reactor scenarios, MUSA addressed a large variety of reactor designs (PWR, BWR, VVER, etc.) and scenarios (LB- and MB-LOCAs, SBOs, SGTRs, etc.), with and without AM actions [10]. Table 3 shows an example of the PWR database. Likewise, the employed methodologies were also quite diverse. Beyond the specific SA codes and UQ tool used, the size of the sets of uncertainty parameters and FOMs were also notably diverse. As for the number of realizations, even if most times the order statistics was adopted and the number of calculations were around 100, occasionally some partners ran hundreds of cases (300, 900). This broad database demonstrates the ability achieved to bring UaSA into SA scenarios, no matter the reactor design, the accident sequence, or the methodology used.

Table 3: PWR scenarios database and methodologies used.

NPP	Scenario(s)	SAM	SA Code	U&S Tool	#UPs	#FoM	#Calcs. for UQ
PWR-1000	LBLOCA		MELCOR	URANIE			
PWR (Surry)	SBO		MELCOR	DAKOTA	24	3	93
HPR-1000	LBLOCA		ASTEC	SUNSET	5	8	100
PWR-900	SBO		MELCOR	DAKOTA	8	1	130
PWR 4-Loops	LT-SBO at Low P		RELAP/SCDAP	IUA2.0	19	26	124
PWR (Surry)	ELAP w/o SAM / ELAP+SAM	AC restored at RPV failure	MAAP	Python	232	12	500
KONVOI	MBLOCA+SBO		AC2	SUSA	81	10	100
PWR-900	SBO+Loss of aux. FW	Sump flooding, CFVS	ASTEC	SUNSET, Python	43	12	100
APR-1400	C-SGTR by SBO		MELCOR	DAKOTA	6	4	300
KONVOI	MBLOCA w/o SAM / MBLOCA+SBO / MBLOCA+SAM	CFVS	ASTEC	KATUSA	18	6	900 (300*3)
PWR-1100	SBO+SGTR	SG re-flooding	MELCOR	DAKOTA, Python	17	2	100
CAP-1400	LOCA+SBO		MAAP	DAKOTA			
PWR-1000	SBO	Cavity flooding+CFVS	MELCOR	Python	15	6	111

Figure 1 shows two FOMs examples picked from independent calculations for a similar but not identical scenario.

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a. In-containment airborne aerosol (PWR-SBO)   b. Iodine release to the environment (PWR-SBO)
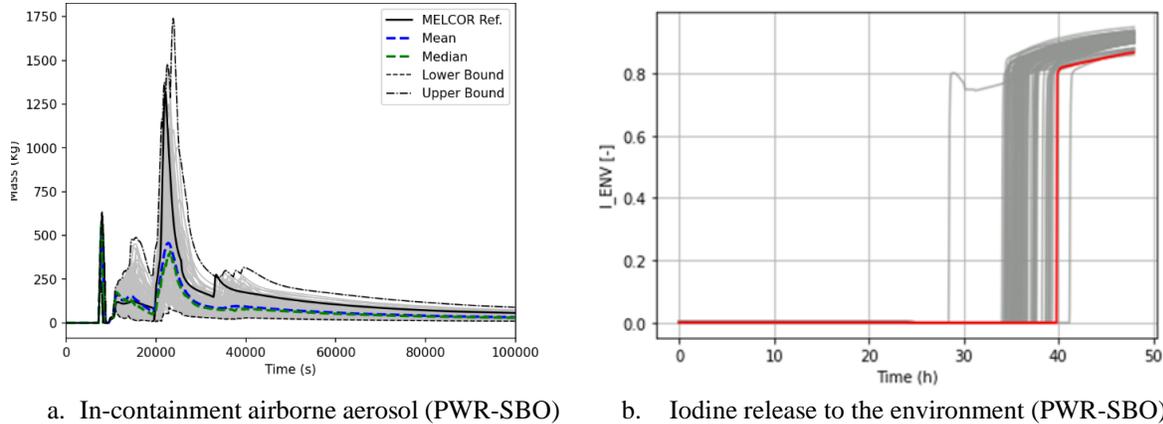
Figure 1: Example of FOMs for 2 independent PWR-SBO UaSA analysis.

As for UaSA applications in SFP scenarios, they were to a good extent similar to the reactor applications in terms of employed methodologies. A single scenario, though, was addressed: a loss-of-cooling accident in a SFP similar to the one in Unit 4 of Fukushima Daiichi NPP with a limited damage of spent fuel rods [11]. Major differences were noted in the best estimate, coming from diversity in scenario modelling (Table 4). In comparison, the variability observed in the results of the BEPU application were moderate.

Table 4: Codes and scenario modelling in SFP BE.

SA code	Nb of rings	Nb of FA types	By-pass channel*	Nb of axial meshes		Modelling of the building
				in the FAs zone	above FAs	
MELCOR	4	3	Yes	12	1	No
ASTEC	3	2	Yes	24	5	Yes, 7 zones
MELCOR	2	2	Yes	10	2	Yes, 3 zones
ASTEC	4	3	Yes	15	10	Yes, 1 zone
ASTEC	3	2	Yes	24	5	Yes, 7 zones
ASTEC	3	2	Yes	10	10	Yes, 7 zones
RELAP/ SCDAP	1	1	No	8	12	No
MELCOR	4	2	Yes	15	0	No
MELCOR	3	3	No	14	1	No
ASTEC	4	3	Yes	15	10	Yes, 1 zone
MELCOR	3	3	No	26	4	Yes, 6 zones

Sensitivity analyses were associated with BEPU (UaSA) both in reactor and SFP applications. Most times FOMs correlations with input parameters were sought through correlation coefficients, which proved to be a too simple approach and provide just a partial view of potential correlations. Occasionally, more advanced techniques were intended.

3. MAJOR CHALLENGES

Application of UaSA in SA analysis domain has been proved to be doable at a large scale, both in reactor and SFP scenarios. Nonetheless, a systematic application still requires developing a procedure that guide practitioners across the intrinsic options UaSA poses and the multiple

decisions entailed. This entails to investigate strengths/weaknesses of any assumption/hypothesis needed, and most importantly, the best way to handle the massive information resulting from any UaSA realization campaign. Next, some specifics are highlighted.

3.1   Completion of uncertainty database

MUSA database was mostly focused on in-code physical model parameters. The database should be peer reviewed, fed with additional model parameters and extended to components and safety systems parameters. In addition, its structure should be revisited, to make it flexible enough to guarantee its full usefulness no matter the focus of the UaSA analysis. The extension and optimization of the UP database would come along a critical review of the material already included. As said, the extension should focus particularly on component related UPs and AM measures. Some methods, like inverse uncertainty quantification, should prove their usefulness, and algorithms to identify pre-correlated UPs should be settled, as this might be a substantial impact in the propagation of correlated UPs which values were picked stochastically (MC) in between their bounds.

3.2   Assembling of a systematic UaSA procedure

The consolidation of (a) robust and statistically reliable method/methods for the forward propagation of uncertain input parameters and quantification of the uncertainties of the FOMs addressed is imperative. There are still several open issues related to management of aspects like bifurcations, outliers, realizations crashes and many others (i.e., noding, numerics, numerical noise, etc.) that need some guiding. The final aim is to build a systematic and sound application of the mathematical formulations behind the forward propagation methodologies (i.e., Wilks/Walds, FFT, and others). In each of the steps, options need to be explored, and their strengths and weaknesses discussed, so that any potential practitioner becomes aware of them and properly assesses their impact in the results of the analysis. Among those steps: identification of FOMs according to the purpose; selection criteria for the UP set; with the new approach of AM; adoption of the propagation path (MC; Wilks'; Wald; …); identification and discussion of bifurcations; identification and treatment of outliers; identification and solution for code crashes; analysis of bias in the realizations campaign.

In addition to the intrinsic issues to the propagation methodology, there are some external factors that have the potential to drastically affect uncertainty propagation and need also to be investigated to include recommendations within the systematic methodology. Some of them are nodalization, phasing of uncertainty propagation (i.e., in-vessel and ex-vessel accident phases), numerical noise, and numerics.

Finally, innovative technologies dealing with models and data should be explored and, accordingly, prospects in the methodology should be formulated. Examples might be the use of meta-models for specific phenomena and development of deep learning methods (i.e., convolutional neural networks). A deep analysis of strengths and weaknesses when brought in an UaSA methodology should be carefully explored.

3.3   Sensitivity analysis

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Investigation of advanced techniques alternative to traditional correlation coefficients (i.e., Pearson, Spearman and the like), is highly recommended. Use of advanced techniques, like stepwise regularization; Lasso regularization; principal component analysis; Sobol indices; variance decomposition; or multiple regression should be explored to maximize the insights gained when interpreting the BEPU results. Aspects such as trade-off between computational cost and insights gained, user friendliness and where and how to bring expert judgement in should be considered.

3.4   Extensive application

The resulting methodology requires to be proven through an extensive application against selected SA scenarios for several Gen. II and Gen. III reactor designs, with specific emphasis on the uncertainties effect on AM measures and vice versa. Given the vast database of scenarios built in MUSA a comparison of the outcomes from the consolidated methodology and the previous one would provide insights worth reporting. Additionally, showcases for innovative technologies (water-cooled SMRs and Accident Tolerant Fuels, ATFs) would be beneficial to forthcoming nuclear technologies, likely to be installed in Europe and elsewhere. Contrary to what done in MUSA, SFP scenarios should not be considered at this time, as codes cannot be considered at the same maturity state to address them.

As a side effect, the outcomes from the resulting database might inspire code developers in the identification of further areas for code development.

4.   FINAL REMARKS

A huge progress in the application of UaSA into SA analysis has been recently achieved. The HORIZON MUSA project managed to cluster 30 organizations sharing and building experience together for a vast application campaign extended over various reactor designs of Gen. II and Gen. III, and a Fukushima-Daiichi Unit 4 SFP based scenario. Databases on full UP characterization of over 500 input parameters and UaSA applications to multiple scenarios are two of the most visible outcomes. However, despite the achievements made, a sound application of UaSA in the SA domain requires addressing a number of still open issues:

- Extension and restructuring of UP database.

- Consolidation of a sound methodology for UP uncertainty propagation (BEPU).

- Recommendations for a balanced approach for sensitivity analysis.

No less important, a thorough consolidation would demand to prove the methodology soundness in a good number of applications, advanced technologies included. The HORIZON EUROPE might be the best frame to carry out this work, as MUSA was also rooted in the EURATOM frame.

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