THE MUSA PROJECT: MANAGEMENT AND UNCERTAINTIES OF SEVERE ACCIDENTS

F. Mascari, L.E. Herranz**, S. Beck***, V. Sánchez-Espinoza****, S. Brumm*****, O. Coindreau******, S. Paci*******

*Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile, ENEA, Italy
**Unit of Nuclear Safety Research, CIEMAT, Spain
**+Gesellschaft für Anlagen- und Reaktorsicherheit, GRS, Germany
****Karlsruhe Institute of Technology, KIT, Germany
*****Joint Research Centre (Petten), European Commission, The Netherlands
******Institut de Radioprotection et de Sûreté Nucléaire, IRSN, France
*******University of Pisa, UNIPI, Italy

Abstract:

Management and Uncertainties Of Severe Accidents (MUSA) project was founded in HORIZON 2020 EURATOM NFRP-2018 call on *"Safety assessments to improve Accident Management strategies for Generation II and III reactors"*. The project aims to consolidate a harmonized approach for the analysis of uncertainties and sensitivities associated with Severe Accidents (SA) by focusing on Source Term (ST) Figure of Merits (FOM). MUSA has an "innovative research agenda" in order to move beyond the state-of-the-art regarding the predictive capability of SA analysis codes by combining them with the best available Uncertainty Quantification (UQ) tools. The achievement of the overall objective is assured by a consistent and coherent work programme, reflected in the technical Work Packages (WP) structure. The objective of this paper is to briefly describe the main project pillars and summarize the progress made over the first two years of research activity. Based on the current projects results, the first observations and leassons learned on the uncertainty application in the SA domain will be presented.

1 INTRODUCTION

MUSA project was founded in HORIZON 2020 EURATOM NFRP-2018 call on "Safety assessments to improve accident management strategies for generation II and III reactor, and it is coordinated by CIEMAT (Spain) [1,2]. The project started on June 1st, 2019 and the planned duration is 48 months. The overall project cost is 5.768,452.50 Euros and 28 Organizations from 16 Countries are involved. On July 7th, 2018, MUSA project received the NUGENIA label recognizing the excellence of the project proposal.

MUSA project aims to establish an harmonized approach for the analysis of uncertainties and sensitivities associated with SA analysis among EU and non-EU entities [1,2]. The main objective of the project is to assess the capability of SA codes when modelling Nuclear Power Plant (NPP)/ Spent Fuel Pool (SFP) accident scenarios of GEN II, GEN III designs through the:

- Identification of UQ methodologies to be employed, with emphasis on the effect of both existing and innovative SA Management (SAM) measures on the accident progression, particularly those measures related to the ST mitigation;

- o Determination of the state-of-the-art prediction capability of SA codes regarding the ST that potentially may be released to the external environment, and to the quantification of the associated code's uncertainties applied to SA sequences in NPPs and SFPs.

MUSA has an innovative research agenda in order to move beyond the state-of-the-art regarding the predictive capability of SA analysis codes by combining them with the best available UQ tools. By doing so, not only the prediction of timing for the failure of safety barriers and of radiological ST will be possible, but also the quantification of the uncertainty bands of selected analysis results, considering any relevant source of uncertainty, will be provided. The achievement of the overall objective is assured by a consistent and coherent work programme [1,2] reflected in the technical WP structure, Figure 1. MUSA project includes: WP1, MUSA COordination and project management (MUCO) led by CIEMAT, WP2, Identification and Quantification of Uncertainty Sources (IQUS) led by GRS, WP3, Review of Uncertainty Quantification Methodologies (RUQM) led by KIT, WP4, Application of UQ Methods against Integral Experiments (AUQMIE) led by ENEA, WP5, Uncertainty Quantification in Analysis and Management of Reactor Accidents (UQAMRA) led by JRC, WP6, Innovative Management of SFP Accidents (IMSFP) led by IRSN, and WP7, COmmunication and Results DISsemination (COREDIS) led by UNIPI.

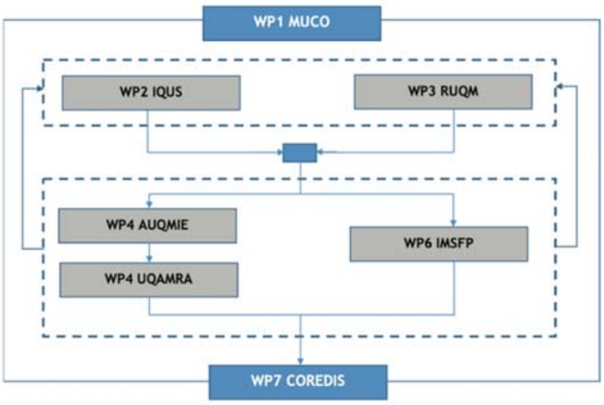


Figure 1: Musa Work Package interlink.

2 MUSA TECHNICAL WP' DESCRIPTION AND CURRENT PROGRESS

The ambitious MUSA scope and the 28 Organizations involved need a technically sound and well-structured work plan. As shown in Fig. 1 above, MUSA is structured in five technical WPs and one for coordination and another for dissemination.

In all uncertainty application cases (WP4, WP5 and WP6), ST-related variables will be selected as FOM. Finally, it is worth noting that these activities will extend over several reactor designs (BWR, VVER, PWR GEN II, PWR GEN III) and will also include consideration of SAM actions, with particular emphasis on those linked to ST mitigation.

Most of the activities developed during the first 24 months of the project have been focused on WP2 IQUS and WP3 RUQM, together with the finalization of the WP4 AQUMIE activities. WP5 and WP6 start to be in the core part [1]. Considering this, in the following sections the technical WPs will be briefly described together with the current advancements [1,2]. Then the major observations and current leassons learned from the project will be briefly discussed based on the WP4 application, that is the WP currently in the more advanced status as scheduled.

2.1 Identification and Quantification of Uncertainty Sources (WP2-IQUS)

The activity developped in this WP, coordinated by GRS, aims at identifying and partially quantifying the major sources of uncertainties of any type of processes and phenomena during SAs affecting the ST. This would entail both uncertainties in the existing models and uncertainties due to the lack of specific models in the codes. Considering the huge number of complex and often interacting phenomena occurring during a SA and their differing level of importance on the ST, it is reasonable to break down the full sequence into manageable phases. This strategy is consistent with the way experimental campaigns have been conducted over the years. In this respect, phenomena can be classified according to the "in-vessel" and "ex-vessel" phases of the accident. Within each of them, FP and activation products release, transport and chemistry will be considered. In addition, NPP type, SFP, SA scenario and SAM specific phenomena will also be taken into account.

Along the first 24 months of activity, it has already determined the specific ST FOMs, and a second group of additional variables have already been highlighted as necessary for being able to discuss any potential trend and/or divergence that might be observed in these FOMs. The work is presently focused on the selection of relevant phenomena during SAs affecting the ST and the definition and characterization of the input uncertain parameters. A directory with the important uncertain phenomena affecting the ST is being built as a guide to identify input uncertainty parameters, which will be characterized by the uncertainty range and PDFs. The consolidation phase of the directory was started in a tabular form, and it will be a living document throughout the course of the project, in order to also integrate all users' experiences and outcomes of WP4, WP5, and WP6.

2.2 Review of Uncertainty Quantification Methodologies (WP3-RUQM)

The activity developed in this WP, coordinated by KIT, aims at reviewing and assessing state-of-art methodologies and codes used for UQ and sensitivity analyses and their applicability for the analysis of SA scenarios with/without AM for NPPs and SFPs. In particular, the strengths and weaknesses of each UaSA methodology/code to be applied will be identified and evaluated, and whenever possible, enhancements for such an application will be proposed. Within this regars, guidelines for the use of UaSA codes/methods in the SA domain will be developed. The state-of-art most suitable methodologies to achieve the project goals are currently used by partners in the WP focused on uncertainty applications (WP4, WP5, WP6). Uncertainty applications will provide feedback to WP3 to optimize methodologies and guidelines.

Along the first 24 months of activity, a review of the various practices and tools to be used by the partners for the quantification of the uncertainties embedded in the different SA codes (e.g., ASTEC, AC^2, MELCOR, MAAP, etc.) has been recently conducted. Besides, the main features of the UQ tools (e.g., SUSA, DAKOTA, URANIE, RAVEN) and data assimilation tools such as MOCABA have been compiled and illustrated. The study has concluded that all the tools provide the basic necessary capabilities for the UQ of SA codes applied to predict the radiological ST. Some issues were identified that should be given attention in any UQ application: how to properly select the range of variation of the input uncertainty parameters, criteria for selection of appropriate PDFs, applicability of the Wilks formula [5] in case of multiple FOMs, etc. Currently, partners are reviewing the methodologies, the main features, capabilities, and interfaces with regards to SA codes of the different UQ tools to be used in MUSA. The result of this work will be part of a deliverable where recommendations for their use will be reported. In addition, guidelines will be written for the use of UQ in connection with SA codes, considering the experience gained applying these tools in MUSA.

2.3 Application of UQ Methods against Integral Experiments (WP4-AUQMIE)

The activity developpped in this WP, coordinated by ENEA, aims at applying and testing UQ methodologies against the PHEBUS FPT-1 test. This exercise represents the first MUSA UaSA application, and its main targets are to identify issues throughout the uncertainty application and to develop a critical analysis of the partners' uncertainty applications, giving feedback to WP3, WP5, and WP6. The PHEBUS FPT-1 test [3] has been selected because it has been the subject of the OECD/CSNI ISP46 [4], which provides a sound basis for WP4 uncertainty analysis. Considering that FPT1 is a simplified experiment but remains a representative SA scenario, the main objective of the WP4 is to train project partners to applicate UQ to SA analyses. WP4 is also a collaborative platform for highlighting and discussing results and issues arising from the application of UQ methodologies, already used for design basis accidents, or in MUSA used for SA analyses. Consequently, WP4 application creates the technical background useful for the full plant and SFP applications planned along the MUSA project (WP4 and WP5). In addition, it provides a first contribution for MUSA best practices and lessons learned collected in WP3.

Currently, partners have developed the calculations including the application of the UQ methodologies and the critical analyses of the results is in progress. After a first preliminary analyses, it is possible to underline that in the process of evaluation of applicable state-of-art-methods of UQ to the SA field and definition of best UQ application practices in SA analyses, the WP4 exercise contributed to identify, discuss and eventually solve some of the issues encountered in these first uncertainty applications.

2.4 Uncertainty Quantification in Analysis and Management of Reactor Accidents (WP5-UQAMRA)

The activity developped in this WP, coordinated by JRC, aim at applying the UQ methods in SA sequences of different reactor types including SAM actions. FOMs in the domain of ST will be defined, based on WP2 activity, for a selected set of key radionuclides. Relevant sources of uncertainty involved will be accounted for in the Best Estimate Plus Uncertainty (BEPU) analysis. Input uncertainty parameters identified and characterized in WP2, as well as the methodologies investigated in WP3, will be used. WP5 will have a strong feedback on WP2 and WP3 activity.

The work carried out is presented and discussed in 3-monthly meetings of four subgroups for the reactor designs investigated: BWR, VVER plus CANDU, PWR GEN II, PWR GEN III. At present, the reference plant models are developed for all designs and the BE base case for their selected accident scenario has been run by almost all 26 partners. The coupling of SA and UQ tools – that is essential for automating the running of simulations and collecting/interpreting results – is based on the work done in WP4 against PHEBUS FPT1 test and has been extended in its functionality by many in their effort to provide a proof of concept of their UA approach. A majority of partners have now performed preliminary UQ using a reduced number of input uncertainty parameters and using the corresponding PDFs and the related characterization identified in WP2. These applications have highlighted a range of issues that require addressing. Examples are (i) the high computational cost of simulating the in-vessel and the ex-vessel phases of the transient, and possible solutions are under discussion (e.g., use of high-performance computing clusters, reduction of the input-deck complexity, etc); and, (ii) the experiencing of, in some cases, a substantial number of code failures for the varied uncertain parameters in the input deck. Aspects of solving this issue range from understanding origins of, and ways of reducing, these code failures to ensuring they are properly dealt with in the UA. The next steps for the full uncertainty quantification with uncertain parameter sets and FOM reflecting the scientific investigation of the partners, and with detailed post-processing and analysis of the data generated are under preparation.

2.5 Uncertainty Quantification and Innovative Management of SFP Accidents (WP6-IMSFP)

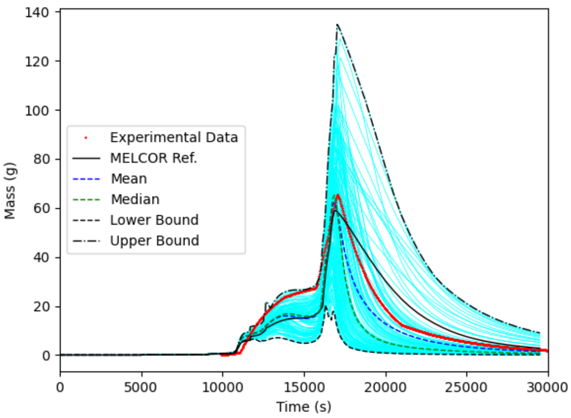
The activity developped in this WP, aims at quantifying and ranking the uncertainties affecting SFP accident analyses by applying UQ methodologies, investigated in WP3, to the computation of a Fukushima-like scenario in an SFP. The review of existing or contemplated SAM mitigation measures and systems worldwide will be done as well. In addition some innovative measures might be proposed and their potential benefits, in terms of radiological consequences reduction, will be assessed. Feedback from this activity to WP3 concerning identification of difficulties and strengths of UQ methodologies application to SFP scenarios is expected. This activity will be also fed with input uncertainty parameters identified in WP2.

Currently the identified FOMs have been adapted to the SFP scenarios selected, and it was agreed that the transient scope will be limited to a moderate damage of spent fuel rods. The development of the reference case has been done by all the partners together with the uncertainty analyses preparation; some partners already presented preliminary UQ results. In this first phase, also for the SFP uncertainty application, the high computational cost of the analyses has been identified and discussed. In the meantime, traditional AM actions have been reviewed. A brainstorming about innovative AM actions has been carried out, and it was envisaged that prevention measures (e.g., use of spray systems) will be considered when conducting the analyses

3 MUSA CURRENT OBSERVATIONS AND LEASSONS LEARNED

Currently, the main MUSA observations related to the uncertainty application in the SA domain comes from the WP4 application. The first critical analyses of the results showed that:

- Partners adopted the probabilistic method to propagate input uncertainties [7]. The Wilks formula [5,6] has been in general used in order to evaluate the minimum number of code runs for the selected probability and confidence level (e.g. 95%, 95%);
- In order to couple SA code with UT, scripting is in general necessary to automate the process; it is a time consuming activity and it requires major efforts. The use of scripting in general showed to be more flexible (e.g. post-processing), compared to UT that has a more user friendly GUI. GUI shows a limited flexibility compared to scripting.
- SA codes could be sensitive to the choice of the input uncertainty parameters and the related range. Moreover, the choice of values not varied (i.e. not sampled) in the UQ can influence the stability of the calculations.
- Codes crashed have been in general observed along the code applications and currently the way to handle is under discussions;
- Different post processing approaches can be used in order to characterize the different phases of the UA study (e.g. characterization of the input uncertainty parameters sampling space, characterization of the FOMs from a statistical point of view, characterization of the statistical correlation of the FOMs with the input uncertain parameters, etc). Time dependent or single time value approaches can be used. Fig. 2 shows an example of time dependent statistical analyses of one of the FOM investigated.



o

o Figure 2: Aerosol suspended mass in the containment atmosphere; example of the statistical analyes against PHEBUS FPT1 data [8]

The current major leassons learned identified through the WP4 application are:

- There is the general needs to a compromise between robustness and user friendly in the UT/SA coupling.
- The proper choice of the input uncertainty parameters and their characterization is a crucial task. This choice in general has to be based on a sound background, e.g. experimental and analytical data, references, engineering judgment, etc.

- The management of the failed calculations is a crucial task, because, as example, the failed runs can affect the calculated FOM PDF, etc
- Computational time is a key element to perform UA and for plant applications the use of clusters may be necessary.
- Post processing is a key element of the uncertainty application.

4 CONCLUSIONS

MUSA is a well structured project that aims to consolidate a harmonized approach for the analysis of uncertainties and sensitivities associated with SA by focusing on ST FOMs. Currently two years of activity have been carried out and the first results of the project are coming out. In term of identification and quantification of uncertainty sources in SA (WP2), the specific ST FOMs have been agreed between the partners and the main sources of uncertainty have been identified and charactecterized in term of PDF and range of input uncertainty parameters. The review of uncertainty quantification state-of art methodologies (WP3) has been developped together with the critical analyses of UaSA methodology/code to be applied. WP4 application against the simplified but representative FPT1 scenarions has been developed and it was able to train partners to applicate UQ to SA analyses; this gives the possibility to identified and solve some of the issues encountered in this first applications as SA/UT coupling, scripting development, post processing, etc. The experience gained along the WP4 activity is the base for the NPP and SFP applications, that are currently on-going with preparatory work (e.g., development of the reference case, first reduced uncertanty applications, etc). Specific issues of NPP and SFP application have been already identified (e.g. high computational time) and partners are currently working and discussing solutions (e.g. use of HPC, reduction of the input-deck complexity, etc). The next steps of the project will be the finalization of NPP and SFP uncertainty application and, based on their feedback, develops the guidelines and reccomandation for the use of UQ in connection with SA codes.

ACKNOWLEDGMENTS

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

REFERENCES

[1] Herranz, et al, The EC MUSA Project on Management and Uncertainty of Severe Accidents: Main Pillars and Status. Energies 2021, 14, 4473. https://doi.org/10.3390/en14154473

[2] F. Mascari, Application of Uncertainty Quantification Methods against Integral Experiments (AUQMIE) in the EU-MUSA project, ETSON news, March 2021.

[3] D. Jacquemain, S. Bourdon, A. de Braemaeker, M. Barrachin, "FPT1 Final Report (Final version)", IPSN/DRS/SEA/PEPF report SEA1/00, IP/00/479 (2000)

[4] B. Clément, et al., "Thematic network for a Phebus FPT1 international standard problem (THENPHEBISP)," Nuclear Engineering and Design, 235 (2–4), pp. 347-357 (2005)

[5] Wilks, S.S. Determination of Sample Sizes for Setting Tolerance Limits. Ann. Math. Stat. 1941, 12, 91–96.

[6] S.S. Wilks, "Statistical prediction with special reference to the problem of tolerance limits," Annals of Mathematical Statistics, 13(4), pp. 400–409 (1942)

[7] H. Glaeser, "GRS Method for Uncertainty and Sensitivity Evaluation of Code Results and Applications," Science and Technology of Nuclear Installations (2008)

[8] M. Schwarz, et al., "Applicability of Phebus FP results to severe accident safety evaluations and management measures", Nuclear Engineering and Design 209, pp. 173-181 (2001).