Annals of Nuclear Energy 192 (2023) 109964

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Uncertainty and sensitivity analysis of the ASTEC simulations results of a MBLOCA scenario in a generic KONVOI plant using the FSTC tool

A. Stakhanova [a,*], F. Gabrielli [a], V.H. Sanchez-Espinoza [a], A. Hoefer [b], E.M. Pauli [c]

[a] Karlsruhe Institute of Technology, KIT, Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, Germany
[b] Framatome GmbH, Seligenstädter Strasse 100, 63791 Karlstein am Main, Germany
[c] Framatome GmbH, Paul Gossen Strasse 100, 91052 Erlangen, Germany

ARTICLE INFO

Keywords:
ASTEC
FSTC
KATUSA
KONVOI
MBLOCA
U&S analysis

ABSTRACT

This paper presents the results of uncertainty and sensitivity (U&S) analysis of Medium Break Loss-of-Coolant (MBLOCA) severe accident (SA) scenario simulations performed with the ASTEC code with a generic input deck prepared for a KONVOI-1300 nuclear power plant (NPP). The analysis was done with the in-house Fast Source Term Calculation Tool (FSTC) (currently: KArlsruhe Tool for Uncertainty and Sensitivity Analysis (KATUSA)). Part of the presented here results – analysis of MBLOCA scenario simulations up to the basemat rupture - were already shown at the ERMSAR conference in 2022. Here an extension related to the analysis of shorter MBLOCA simulations (up to 6000 s after lower head vessel failure (LHVF)) and investigation of the influence from adding correlations between uncertain input parameters is given. The analysis allows to identify which uncertain input parameters influence the release of fission products (FPs) in the containment and environment at the different stages of SA progression.

1. Introduction

Topic of this article is the uncertainty quantification of the radiological source term predicted by SA codes. Karlsruhe Institute of Technology (KIT) together with Framatome GmbH are participating in the European MUSA project (Herranz et al., 2021) within the H2020 program and in a German project named WAME, financed by German Federal Ministry of Economic Affairs and Climate Action (BMWi) (Strategy for Competence Building and the Development of Future Talent for Nuclear Safety, 2020). MUSA is fully devoted to the uncertainty quantification topic, and in the framework of that project, many severe accident sequences of different reactor types were analyzed by different institutions using different severe accident codes (ASTEC (Chailan et al., 2019), MAAP (Schlenger-Faber, 1996), MELCOR (Humphries et al., 2015), etc.) and U&S analysis tools such as DAKOTA (Dalbey et al., 2022), URANIE (Blanchard et al., 2019), SUSA (Kloos, 2015), SUNSET (Chevalier-Jabet et al., 2014), etc. The main goal of the WAME project was to develop and test the approach for a fast source term (ST) prediction tool in case of a SA in a NPP to support the emergency team. The implemented mathematical approach for a ST prediction was based on the Monte-Carlo Bayes procedure (MOCABA), developed by Framatome (Hoefer et al., 2015; Pauli et al., 2022).

In the framework of the WAME project, the Fast Source Term Calculation (FSTC) tool (Stakhanova et al., 2022) was developed in KIT. This tool combines the functionality for U&S analysis (similar capabilities as the other well know tools (SUSA, URANIE, etc.)) with that of the MOCABA prediction algorithm. After the end of the WAME project, the part of the tool related to U&S was extracted to form a separate tool – KArlsruhe Tool for Uncertainty and Sensitivity Analysis (KATUSA) –, which is currently under further development (adding graphical user interface (GUI) and coupling with other codes). For the purposes of the WAME project (and to the MUSA project) FSTC was coupled only with ASTEC SA code developed in IRSN and currently being co-developed by KIT.

This paper presents the results of U&S analysis of a MBLOCA SA scenario in a generic KONVOI NPP. The SA sequence is analyzed from the early phase up to the basemat rupture or, in a shorter version of the simulations, up to 6000 s after lower head vessel failure. In addition, the effect of correlating uncertain input parameters is investigated. The results presented here contributed to improve the expertise and understanding of the complexity of U&S analysis with large benefits for the joint KIT/Framatome participation to H2020 MUSA-project. Furthermore, the results of MBLOCA simulations were used to create a training database for the preliminary evaluations of the ST predictions for

* Corresponding author.
E-mail address: anastasia.stakhanova@kit.edu (A. Stakhanova).

https://doi.org/10.1016/j.anucene.2023.109964
Received 14 December 2022; Received in revised form 22 May 2023; Accepted 1 June 2023
Available online 9 June 2023
0306-4549/© 2023 Elsevier Ltd. All rights reserved.

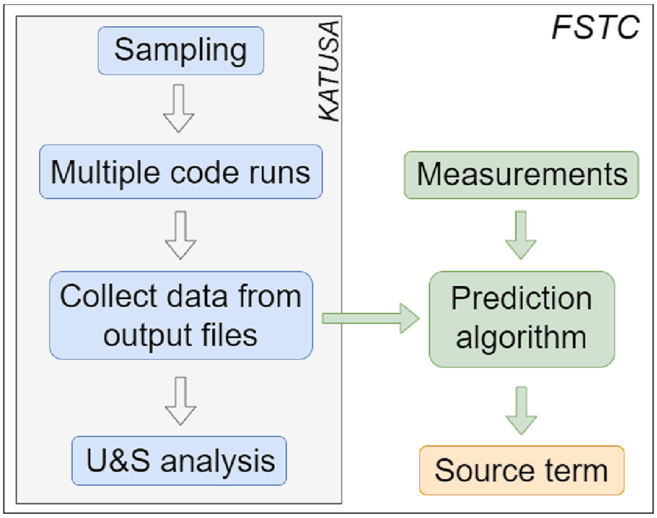

Fig. 1. FSTC and KATUSA tool schemes.

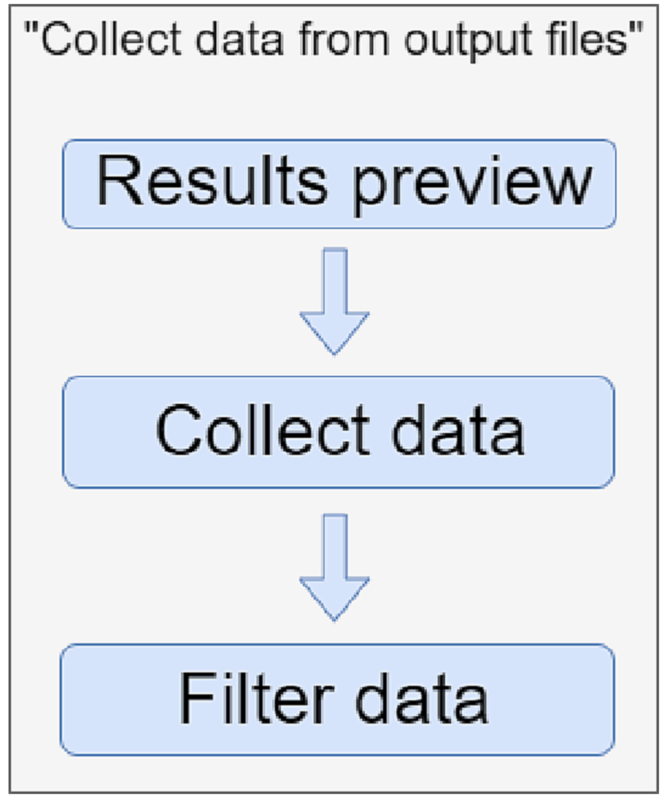

Fig. 2. Collecting data for U&S analysis representing in three KATUSA modules.

MBLOCA scenario in the generic ASTEC KONVOI NPP, described in (Pauli et al., 2022).

Paper organized as following:

- Chapter 2 introduces the key features of the FSTC and KATUSA tools;
- Chapter 3 describes the ASTEC model of the KONVOI NPP;
- Chapter 4 gives a list of the selected uncertain parameters and information about correlations between them;
- The description of the MBLOCA SA scenario presented in Chapter 5;
- Chapter 6 discusses the main results of the U&S analysis regarding the selected Figures-of-Merit (FoMs);
- Chapter 7 summarizes the main conclusions and provides an outlook.

2. FSTC and KATUSA tools

In the framework of the WAME project, the FSTC tool was developed in KIT to address the project's needs. The FSTC tool can be divided into two parts, which potentially could be treated as separate tools (see Fig. 1) – the first one is preparing the input data for the prediction algorithm and performing U&S analysis, the second one is performing the ST prediction.

It was decided that the U&S part becomes a separate tool named KATUSA, which will be further developed in KIT to address other projects' needs. While for the purposes of the WAME project only ASTEC simulations were used, for other projects different codes could be used, therefore KATUSA will be coupled with other codes (it is already working with TwoPorFlow (Jauregui Chavez et al., 2018) and will have a GUI. Both FSTC and KATUSA are written in Python programming language and have modular structure. Each module runs independently with its own set of input data. The tool runs on both Windows and Linux, thanks to the fact that Python is a cross-platform programming language.

In this work only the U&S analysis is addressed. A description of the prediction algorithm implemented in the FSTC tool can be found in (Pauli et al., 2022). Performing an U&S analysis using the KATUSA tool involves the following standard steps:

1. Identify the list of uncertain input parameters and their probability density functions (PDFs) and use this information as input for the sampling algorithm. Currently, two options are available – Simple Random Sampling (SRS) and Latin Hypercube Sampling (LHS) (McKay et al., 1979). Input parameters can be correlated, and sampled values are rearranged according to the provided correlation matrix using the Iman-Conover method (Iman and Conover, 1982);
2. Next, multiple simulations are run. Each simulation has its own input deck with a specific set of values of uncertain input parameters. Simulations can be run in parallel;
3. The step marked as "collect data from output files" on Fig. 1 combines three separate KATUSA modules (see Fig. 2):

- In principle, some simulations could fail, due to problems with convergence, for example, and, therefore, the correctness of all code runs will be checked. Failed runs are excluded from the further analysis. Another task is to provide the user with enough information about the differences in SA progression among the simulation set. This is done by collecting the points in time when characteristic events occur, like start of FP release, lower head vessel failure, etc. The U&S analysis is performed in the pre-defined time window. And if some of the simulations, for example, finished earlier than the time window, such simulations should be excluded from analysis or the time window should be narrowed;
- After a list of the runs, which should be excluded, has been formed, data for selected FoMs is collected from code output files;
- Different values of uncertain input parameters lead to different accident progressions, and therefore, the main events (like start of FP release and LHVF) occur at different times, which makes the further analysis trickier. Hence, the user can specify two specific time points or names of the two main events, between which the data should be extracted. For example, the user wants to analyze the data between start of the FP release and the basemat rupture. To do so, the data is extracted between the maximum time point, when the FP release occurred, and the minimum time point, when the basemat rupture has been detected. Taking this part of the data, selecting the common time scale (all simulations due to the individual progression can have in principle different time scales) and interpolating all collected data into one common time scale is performed in the "filter data" module of the KATUSA tool.

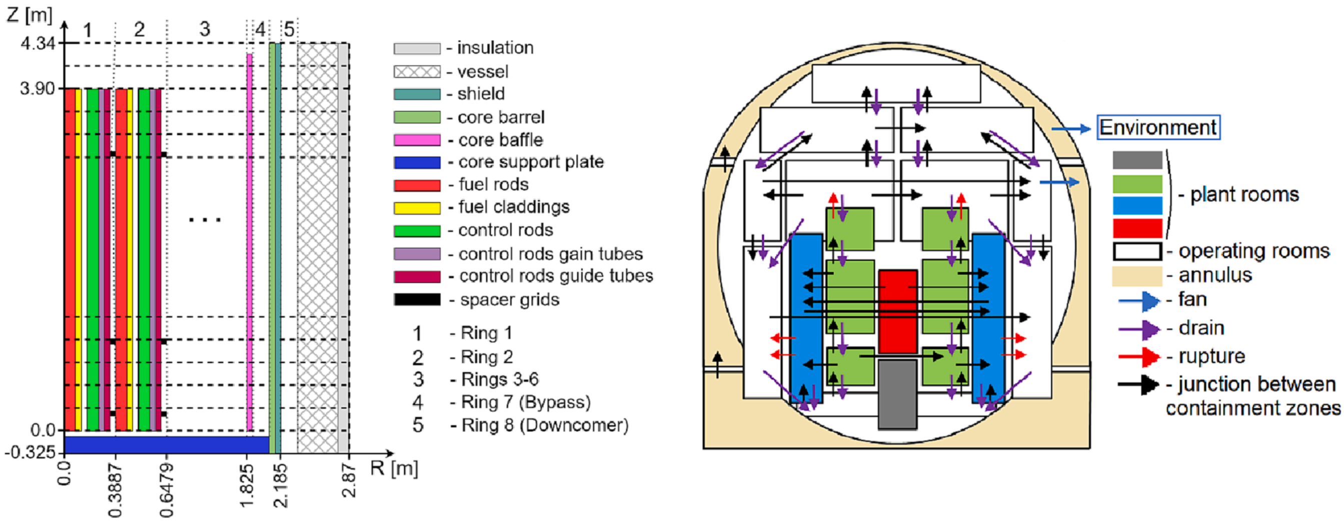

Fig. 3. Core (left) and containment (right) nodalization. Based on (Gabrielli et al., 2022).

4. Finally, the U&S analysis is done on the prepared data. For each selected FoM the following is calculated: simple statistics (minimum, mean, maximum, 5th, 50th and 95th percentiles values); time-dependent correlation coefficients for all *output* – *input* parameters pairs.

In the next chapter, the ASTEC model of a generic KONVOI NPP will be described briefly.

3. ASTEC model of KONVOI NPP

The ASTEC model of a generic KONVOI NPP used in this paper is based on the input deck developed in the frame of the EU CESAM project (EC, 2015). A more detailed description of this input used earlier for the ASTEC simulations earlier performed at KIT can be found in (Gómez-García-Toraño, 2017).

The original input deck has been improved for the WAME project:

1. All ASTEC modules were activated to fully consider the main in-vessel and ex-vessel phenomena occurring during the severe accident scenarios;
2. Fine nodalization of the reactor coolant system (RCS) in order to improve the analysis of the fission product transport from the RCS to the containment;
3. The fuel inventories have been computed with ORIGEN ARP tool (Bowman et al., 2000);
4. The model for the containment leakage to the annulus is improved, by using more detailed plant data like annulus leakage;

Note, that compared with the original input deck, no filtering has been modelled.

Core and containment nodalization are presented in Fig. 3. One the left-hand side of the figure the core nodalization is depicted: the active zone is divided into slices 300 mm thick; radially, the core and vessel are divided into eight rings. One the right-hand side of Fig. 3, where the containment nodalization is shown, the plant rooms are labeled by green, red, gray, and light blue boxes; the operating rooms – by white boxes; the annulus by light yellow boxes. The containment and the annulus, as well as the annulus and the environment are connected with the fan (marked with light blue arrows).

In the next chapter the information about selected uncertain input parameters will be given.

4. Uncertain input parameters

For the U&S analysis in total 16 parameters were selected. Detailed information about them is presented in Table A-1 Appendix A. The parameters *par1* – *par5a* are from the ASTEC ELSA model (Brillant et al., 2013; Brillant et al., 2013), which is modelling the FP release from the

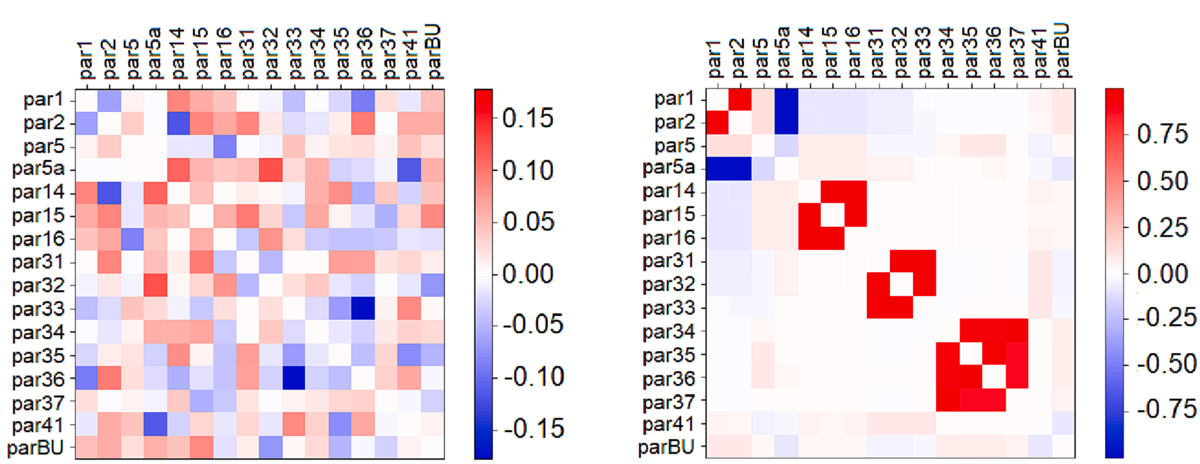

Fig. 4. Output of the KATUSA sampling module in case of uncorrelated (left) and correlated (right) uncertain input parameters.

Table 1
Summary of the presented MBLOCA scenario simulations.

Simulation set identificator	Simulation stopped at	Number of runs	Number of failed runs	Number of additionally excluded runs	Figure-of-Merit
'short'	6000 s after LHVF	300	22	13	Xe, Cs, I, Ba and Mo release (as fraction of initial inventory) into the containment and environment. Spearman correlation coefficient between the release of the given element and uncertain input parameters.
'full'	Basemat rupture	200	10	5	
'uncorr'	6000 s after LHVF	300	15	15	

fuel. The parameters *par14 – par16* are related to the integrity criteria of the fuel cladding and, therefore, influence the degradation process in the reactor core. The parameters *par31 – par37* are from the ASTEC SOPHAEROS model and related to the modeling of the aerosol behavior in the primary system and in the containment. Parameters *par41* and *parBU* are not from the ASTEC models. *Par41* refers to the uncertainty of the leakage rate from containment to annulus. *ParBU* – to the uncertainties on the fuel burn-up, namely the number of effective full power days.

The choice of the uncertain input parameters should be based on good understanding of the physical processes occurring during the accident progression, which can help to focus on a particular set of the code models. The choice of PDFs and their parameters for the selected parameters is based on information derived from the literature, i.e. (Brillant et al., 2013; Brillant et al., 2013; Schwarz et al., 1999) and on engineering judgment.

To represent the actual physics of the process as well as possible, correlations between selected uncertain input parameters were introduced. The correlation values are presented in the left-hand side of Fig. 4 for non-correlated input parameters. One can see that the sampling algorithm is trying to minimize the possible correlation between parameters to zero. On the right-hand side the values are shown for correlated input parameters after applying the Iman-Conover (Iman and Conover, 1982) method to reorder the sampling data output according to the correlation matrix. For example, the correlation between *par1* and *par2* is set to 1, based on the suggestion that increasing the roughness of the fuel pellet surface will make the access of oxygen to its surface more difficult. Namely, the employment of correlations between uncertain input parameters, allows a more reliable representation of the physics of different processes during SA.

5. Accident scenario description

The simulation of the MBLOCA scenario starts at time $t = 0$ s, when the break (size – 440 cm^2) occurs in the cold leg. After that (at $t = 1$ s) the SCRAM happens, and the admission to the turbine and main feed water pumps is closed. The Emergency Core Cooling System (ECCS) is activated, when conditions are fulfilled – at 2.8 s and 6 s, and then the main coolant pumps (MCPs) are coasted down, and the pressure regulation in the pressurizer is switched off. The Emergency Feed Water System (EFWS) is activated when the water level in one of the steam generators drops below 4.5 m. The High and Low Pressure Injection Systems (HPIS/LPIS) are activated when the gas temperature in the primary system exceeds 650 °C. Water injection continues until the tanks are empty. After that, core melt starts. The cavity is flooded when the horizontal erosion reaches 0.5 m.

6. Results of U&S analysis

In the current chapter, the results of the U&S analysis shown for the three sets of the MBLOCA scenario simulations to illustrate the consistency of the results and the effect from introducing the correlations between uncertain input parameters. The short summary of the simulation sets provided in Table 1. Results of the U&S analysis are presented for the following FPs with different volatility – Xe, Cs, I, Ba and Mo. Focus is on their release (as fraction of initial inventory) into the containment and environment and on the correlation values between the amount of released FPs and uncertain input parameters.

First, to illustrate how the accident progression varies with the uncertain input parameters values, the time of lower head vessel failure and basemat rupture is shown in Fig. 5. Lower head vessel failure varies between 1971 s (~0.55 h) and 29894 s (~8.30 h), and basemat rupture varies between 148306 s (~41.20 h) and 280846 s (~78.01 h). It is worth mentioning, that the minimum values of LHVF and basemat

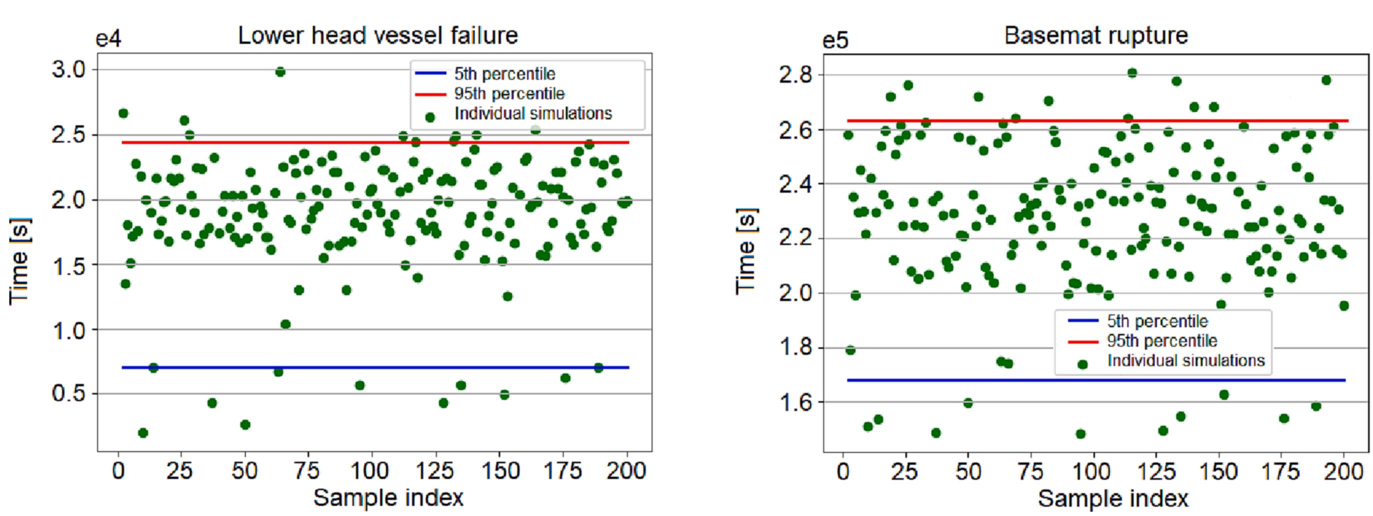

Fig. 5. Time of lower head vessel failure and basemat rupture. MBLOCA scenario.

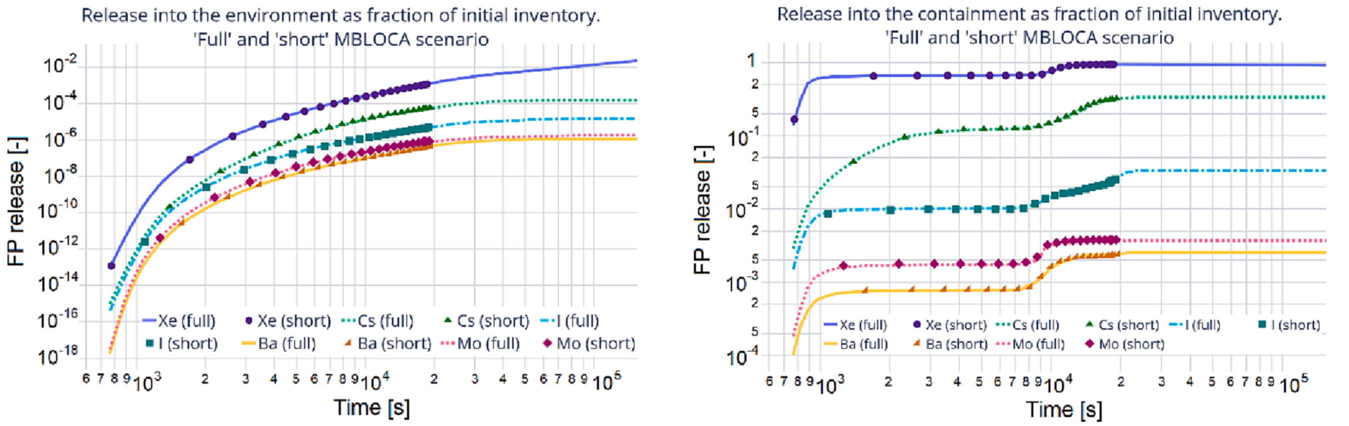

Fig. 6. Median amount of FPs released into the environment (left-hand side) and containment (right-hand side). For ‘full’ and ‘short’ MBLOCA scenario with correlated input parameters.

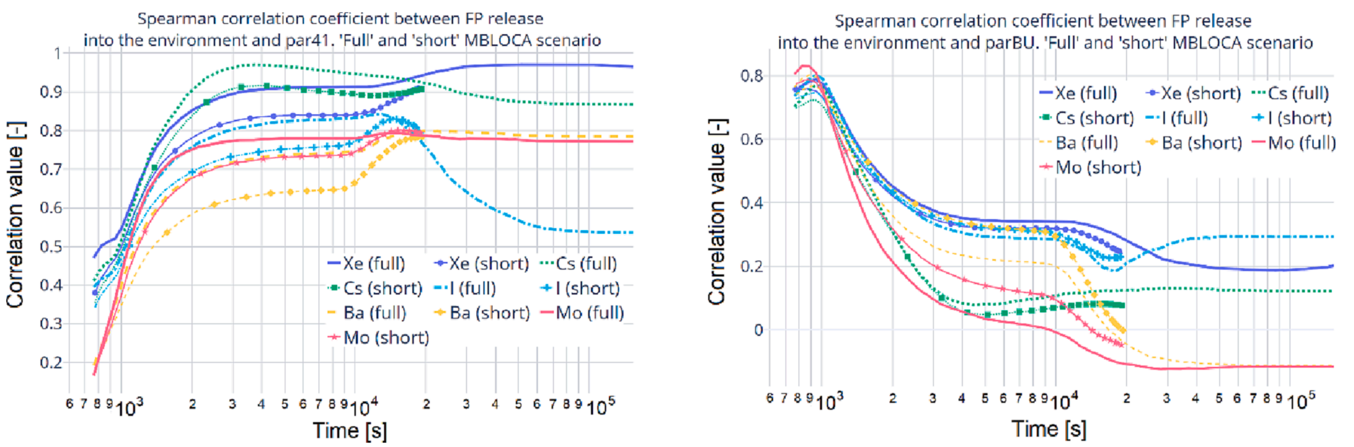

Fig. 7. Spearman correlation coefficient between FP release into the environment and *par41* (left-hand side) and *parBU* (right-hand side). For ‘full’ and ‘short’ MBLOCA scenario with correlated input parameters.

rupture do not necessary belong to the same run.

A tricky part of the analysis is to combine all simulations with different accident progression together. In our case the analysis was performed in a straightforward way – the user specifies the starting and ending points of the analysis – which can be just two points on a time scale or the names of the events, for example, the analysis could be performed between start of FP release and basemat rupture. In case of the second option, KATUSA finds in all considered code runs the maximum time value when the *‘start’* event happens and the minimum time value when the *‘final’* event happens. KATUSA extracts the FoMs values between those time points and interpolates all collected data on the one time scale. All presented results were obtained following that approach. In case of the ‘full’ MBLOCA scenario the U&S analysis was made between start of FP release and basemat rupture; for ‘short’ MBLOCA – between start of FP release and up to 6000 s after LHVF.

The median total amount (as fraction of the initial inventory) of Xe, Cs, I, Ba and Mo released into the environment and containment are shown in Fig. 6. Results are presented for the ‘full’ and ‘short’ versions of MBLOCA scenario simulations; both had correlated uncertain input parameters. The release to the environment (***left-hand side of*** Fig. 6) continues during the whole course of the accident, the fastest release rate can be observed at the beginning of the process – in the first $1{\cdot}10^4$ s, when the active degradation of the core takes place. After that, the release rate is very slow. The total FP release into the containment presented in the ***right-hand side*** of Fig. 6. One can see that the release into the containment reaches its final plateau quite fast – in the first $2{\cdot}10^4 - 3{\cdot}10^4$ s, which corresponds to the instant of LHVF and the end of corium slump. The first plateau of release into the containment occurs at around $1{\cdot}10^3$ s for all elements except for Cs (for Cs this plateau occurs at about $3{\cdot}10^3$ s). The second increase of the FP release into the containment happens around the time of first slump of the corium into the lower plenum. There is no difference between ‘short’ and ‘full’ scenarios, which prove the consistency of simulation results.

In the previous works (Stakhanova et al., 2022; Stakhanova et al., 2022) the differences between Pearson and Spearman correlation coefficients values were observed, due to the presence of outliers in the FP release values at the given time point. Considering those, in the current work only Spearman correlation values are shown.

In Fig. 7 Spearman correlation coefficient values between release into the environment and the two most significant uncertain input parameters (*par41* and *parBU*, respectively) are presented. It was expected, that the most important parameters for the release into environment would be *par41*, governing the leakage from the containment and *parBU*, governing the inventory itself, which obviously affects the release. The influence of *parBU* on the release is high at the very beginning of the process, around the time of start of FP release and start of core degradation. After that, its influence decreases very fast and reaches a plateau around $4{\cdot}10^4 - 5{\cdot}10^4$ s when the release to the environment also reaches a plateau. Parameter *par41* has a high Spearman correlation value for the whole accident, which is expected also from a physical point of view. The remaining uncertain parameters have practically no impact on the release to the environment for all considered elements, and the Spearman correlation values are mostly lying in the range of $[-0.1; 0.1]$.

One can see from Fig. 7 that there is a slight difference between

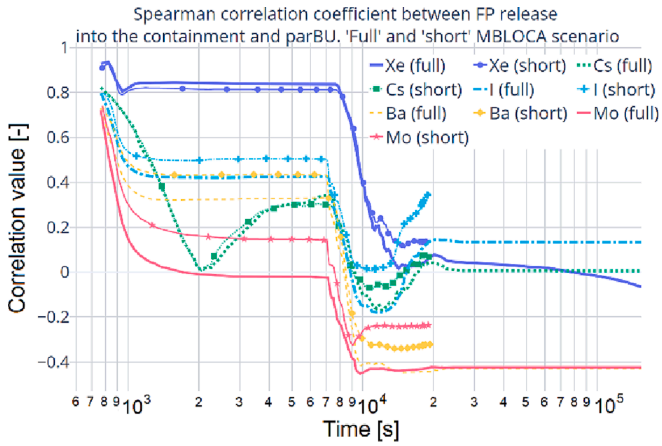

Fig. 8. Spearman correlation coefficient between FP release into the containment and parBU. 'Full' and 'short' MBLOCA scenario with correlated input parameters.

Spearman correlation values for 'full' and 'short' MBLOCA scenario simulations. The first guess would be that there should be no difference – uncertain input parameters were varied in the same range in both 'full' and 'short' simulation cases and the ASTEC input also did not change. The observed difference results from sampling randomness, and was observed and described already in (Stakhanova et al., 2022) in the context of QUENCH-08 experiment (Stuckert et al., 2005) simulations.

Concerning the fission product release into the containment *par41,* which related to the leakage rate between containment and annulus, cannot obviously influence the release, therefore only *parBU* left as the most influencing parameter – see Fig. 8. Again, the Spearman correlation values for other parameters are mostly lying again in the range [−0.1; 0.1]. The same slight difference in the correlation values due to re-sampling effect is observed for 'short' and 'full' scenarios. However, the result mostly stays consistent.

At the later phase of the accident, there is a non-negligible correlation between amount of aerosols released into the containment and the two uncertain input parameters *par32* and *par37*, see in Fig. 9. For example, the Spearman correlation value between *par37* and amount of Cs aerosols in the containment reaches 0.5 around $5–6{\cdot}10^5$ s; for I the Spearman correlation values reaches 0.3 around the same time as for Cs. As it was found in (Stakhanova et al., 2022), low correlation values are affected by sampling randomness, which also could be observed on the presented data in the regions, where correlation values are smaller – for example, the difference between 'short' and 'full' scenario results for the correlation between amount of Cs aerosols and *par37* in the time interval $1{\cdot}10^3 – 8{\cdot}10^3$ s, and the same is observed for the I in the same time interval. In this work, the effect of the sampling randomness has not been investigated deeper due to the time-consuming simulations. Nevertheless, the correlation curves for both 'short' and 'full' scenario are going in the same direction, which indicated the consistency of results.

The effect from introducing the correlations between uncertain input parameters can be seen from available simulation results for Ba release

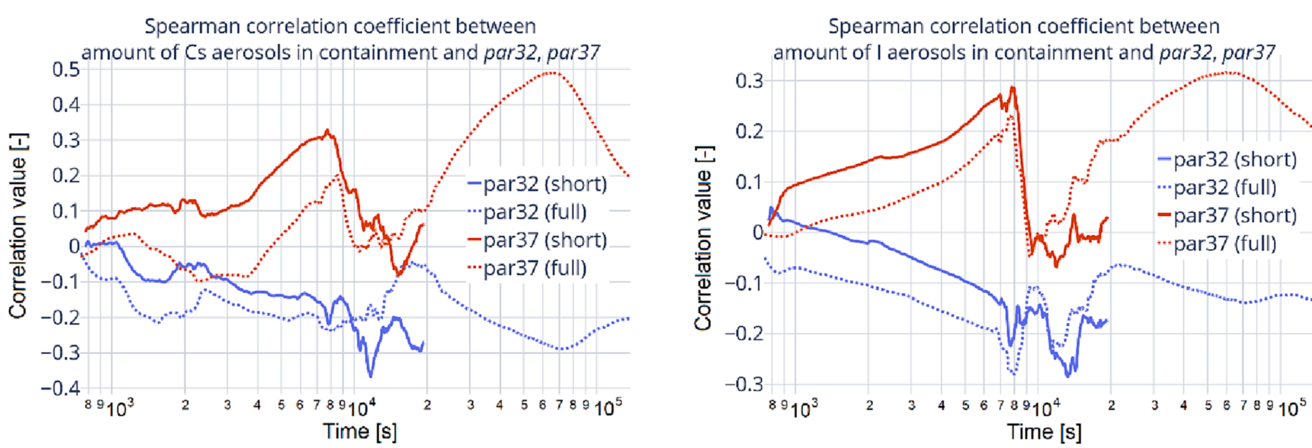

Fig. 9. Spearman correlation coefficient between Cs (left-hand side)/I (right-hand side) aerosols in containment and two uncertain input parameters - par32 and par37. Data for 'full' and 'short' MBLOCA scenario simulations with correlated input parameters.

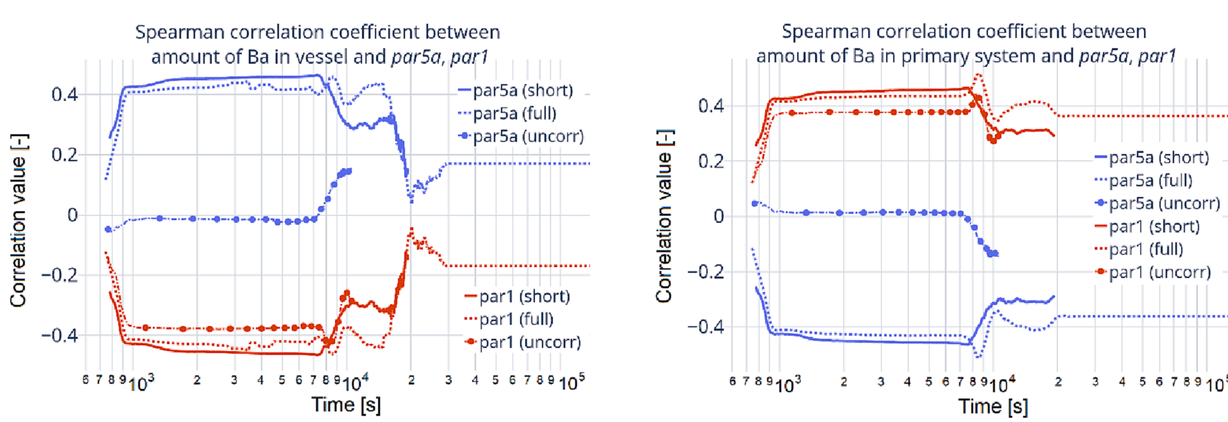

Fig. 10. Spearman correlation coefficient between Ba in the vessel (left-hand side) / Ba in the primary system (right-hand side) and two uncertain input parameters – par5a and par1. Data for 'full' and 'short' MBLOCA scenario simulations with correlated input parameters; for 'short' scenario without correlations between input parameters.

into the vessel and primary system for the input parameters *par1* and *par5a*. The correlation between Ba release in the vessel and *par1* at the beginning of the process reaches 0.4 and stays at that level up to the LHFV is all cases, even for the simulation sets with non-correlated parameters. However, correlation values for *par5a* will be around zero, if the correlation between *par 1* and *par5a* is not taken into account – see in Fig. 10 ***(left-hand side)***. A similar picture can be observed for Ba release in the primary system – Fig. 10 ***(right-hand side)***. Introducing the correlations between other uncertain input parameters did not affect the release values and Spearman correlations values between release and the most significant input parameters like par41 and parBU. Nevertheless, correlating input parameters could play a significant role in observing and judging the effect from some parameters.

7. Conclusions and outlook

U&S analyses of three sets of MBLOCA scenario simulations was presented in this work. One set ('full') of simulations was carried out up to the time of basemat rupture with correlated uncertain input parameters. A second set ('short') was calculated only up to 6000 s after lower head vessel failure with correlated input parameters, the third one – also up to 6000 s after lower head vessel failure, but with un-correlated input parameters. All simulations were made with the ASTEC V2.2b SA code and with the KATUSA tool developed in KIT for U&S analysis. The work was done in the framework of the WAME project, devoted to the development and application of fast source term prediction methodology.

Sixteen input parameters were selected for uncertainty propagation. Their uncertainty bands have been chosen based on the literature review and engineering judgement. Uncertain parameters refer both to the ASTEC physical models and to the plant modeling.

FPs with different level of volatility – Xe, Cs, I, Ba and Mo - were selected for the U&S analysis and presentation of the results. Simple statistics and Spearman correlation coefficients were calculated for the amount of these FPs released into the containment and environment. The release into the environment is governed by two input parameters - *par41* and *parBU* related to the containment leakage and the fuel burnup, respectively. The release into the containment is mostly governed by *parBU*. For the release into the containment in the late phase of the accident, which could be observed only in case of modelling up to the basemat rupture, parameters related to the aerosol behavior (*par32* and *par37*) are also playing a role. As there is no correlation between the important parameters *par41* and *parBU,* no significant correlation effect is expected and observed. More significant effect from correlating input parameters can be seen for the release of low-volatile elements, like Ba, in the vessel and primary system and uncertain input parameters related to the FP release from the fuel (*par1*, *par5a*).

Effect from re-sampling observed in (Stakhanova et al., 2022) was also visible here, when comparing results of 'full' and 'short' simulation sets. This sampling randomness is not affecting simple statistics (median values), but could change the correlation values.

To summarize, the huge amount of data obtained during the WAME project and results of U&S analysis made on that data provide a firm ground for further analysis and give an overall perspective about the most important uncertain input parameters at the different stages of SA scenario.

CRediT authorship contribution statement

A. Stakhanova: Conceptualization, Software, Writing – original draft, Visualization. **F. Gabrielli:** Conceptualization, Writing – review & editing, Supervision. **V.H. Sanchez-Espinoza:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **A. Hoefer:** Writing – review & editing. **E.M. Pauli:** Writing – review & editing.

Table A1
Uncertain input parameters for MBLOCA scenario simulation.

Parameter name	Probability density function (PDF)	PDF parameters	Parameter meaning and corresponding ASTEC model	Source
par1	Normal	μ = 5.0; σ = 30%	Correction factor for the ratio S/V of the fuel pellets due to roughness	(Brillant et al., 2013; Brillant et al., 2013; Ikeda et al., 2003)
par2	Normal	μ = 0.03; σ = 30%	Correction factor for the ratio S/V of the fuel pellets for the limited steam access	(Brillant et al., 2013; Brillant et al., 2013; Ikeda et al., 2003)
par5	Normal	μ = 1.2E-5; σ = 30%	Geometrical diameter of the grain	(Pastore et al., 2015; Song et al., 2000)
par5a	Triangular	mode = 2.0E-6; min = 1.6E-6; max = 3.4E-6	Standard deviation of geometrical diameter of the grain	(Pastore et al., 2015; Song et al., 2000)
par14	Normal	μ = 2500.0; σ = 10%	Threshold Temperature of the cladding Dislocation [K]	(Osborn et al., 2017; Pontillon et al., 2005)
par15	Normal	μ = 2300.0; σ = 10%	Threshold Temperature of the oxide layer Dislocation [K]	(Hofmann et al., 1999)
par16	Normal	μ = 250.0E-4; σ = 20%	Threshold thickness of the oxide layer [mm]	(Hofmann et al., 1999)
par31	Uniform	min = 2.975; max = 4.025	Particle mean thermal conductivity (J/m/K)	Engineering judgement
par32	Uniform	min = 714.0; max = 966.0	Average specific heat (J/kg K) of the aerosol	Engineering judgement
par33	Triangular	mode = 3000.0; min = 2610.0; max = 10000.0	Particle mean density (kg/m3)	(Mattie et al., 2015)
par34	Triangular	mode = 1.1E-8; min = 1.0E-8; max = 2.0E-07	Particle minimum geometrical radius (m)	(Helton et al., 1986)
par35	Triangular	mode = 1.99E-5; min = 5.0E-6; max = 2.0E-5	Particle maximum geometrical radius (m)	(Helton et al., 1986)
par36	Triangular	mode = 1.0; min = 0.9, max = 1.0	Shape factor relative to particle coagulation	(Mattie et al., 2015)
par37	Beta	α = 1.0; β = 5.0, min = 1.0; max = 3.0	Shape factor relative to Stokes velocity	(Osborn et al., 2017)
par41	Uniform	min = 1.0; max = 30.0	Coefficient for the leakage rate between containment and annulus	Engineering judgement
parBU	Uniform	min = 10.0; max = 328.0	Effective full power days	Engineering judgement

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

The authors do not have permission to share data.

Acknowledgments

The project was funded by the German Federal Ministry of Economic Affairs and Energy, funding code FZK 1501582 (WAME project).

Appendix A

Table A1.

References

, 2020"Strategy for Competence Building and the Development of Future Talent for Nuclear Safety," https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/strategy-for-competence-building-and-the-development-of-future-talent-for-nuclear-safety.pdf (2020).

Blanchard, J.-B., Damblin, G., Martinez, J.-M., Arnaud, G., Gaudier, F., 2019. The Uranie platform: an open-source software for optimisation, meta-modelling and uncertainty analysis. EPJ Nuclear Sci. Technol. 5, 4.

Bowman, S.M., et al., 2000. ORIGEN-ARP: automatic rapid process for spent fuel depletion, decay, and source term analysis. *Vol. I, Sect. D1 of SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation, NUREG/CR-0200, Rev, 6*.

Brillant, G., Marchetto, C., Plumecocq, W., 2013. Fission product release from nuclear fuel II. Validation of ASTEC/ELSA on analytical and large scale experiments. Ann. Nucl. Energy 61, 96–101.

Brillant, G., Marchetto, C., Plumecocq, W., 2013. Fission product release from nuclear fuel I. Physical modelling in the ASTEC code. Ann. Nucl. Energy 61, 88–95.

L. Chailan, et al., 2019. Overview of ASTEC integral code status and perspectives. In *The 9TH European Review Meeting on Severe Accident Research (ERMSAR2019) Log* (No. 096, pp. 18-20).

Chevalier-Jabet, K., Cousin, F., Cantrel, L., Séropian, C., 2014. Source term assessment with ASTEC and associated uncertainty analysis using SUNSET tool. Nucl. Eng. Des. 272, 207–218.

K. Dalbey et al., 2022. *Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.16 Theory Manual* (No. SAND2022-6172). Sandia National Lab. (SNL-NM), Albuquerque, NM (United States).

EC. "D40 .42 – 1st set of reference NPP ASTEC input decks", CESAM FP7-GA-323264, (2015).

F. Gabrielli, et al., 2022. Impact of Realistic Fuel Inventories on the Radiological Consequences of a Severe Accident Scenario in a Generic Konvoi Plant by Means of the ASTEC Code, Proc. of KERNTECHNIK 2022, June 21-22, Leipzig, Germany.

Gómez-García-Toraño, I., 2017. Further development of Severe Accident Management Strategies for a German PWR Konvoi Plant based on the European Severe Accident Code ASTEC. KIT, Germany. PhD Thesis.

Helton, J.C., Iman, R.L., Johnson, J.D., Leigh, C.D., 1986. Uncertainty and sensitivity analysis of a model for multicomponent aerosol dynamics. Nucl. Technol. 73 (3), 320–342.

Herranz, L.E., Beck, S., Sánchez-Espinoza, V.H., Mascari, F., Brumm, S., Coindreau, O., Paci, S., 2021. The EC MUSA Project on Management and Uncertainty of Severe Accidents: Main Pillars and Status. Energies 14 (15), 4473.

Hoefer, A., Buss, O., Hennebach, M., Schmid, M., Porsch, D., 2015. MOCABA: A general Monte Carlo-Bayes procedure for improved predictions of integral functions of nuclear data. Ann. Nucl. Energy 77, 514–521.

P. Hofmann, et al., 1999. "ZrO2 Dissolution by Molten Zircaloy and Cladding Oxide Shell Failure. New Experimental Results and Modelling," FZKA 6383, INV-CIT(98)-P-026, Forschungszentrum Karlsruhe.

L. L. Humphries et al., 2015. *MELCOR computer code manuals* (No. SAND-2015-6692R). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).

Ikeda, T., Terada, M., Karasawa, H., Nakahara, K., Yamagishi, M., 2003. Analysis of core degradation and fission products release in Phebus FPT1 Testat IRSN by detailed severe accidents analysis code, IMPACT/ SAMPSON. J. Nucl. Sci. Technol. 40 (8), 591–603.

Iman, R.L., Conover, W.J., 1982. A distribution-free approach to inducing rank correlation among input variables. Commun. Stat.-Simul. Comput. 11 (3), 311–334.

Jauregui Chavez, V., Imke, U., Sanchez-Espinoza, V., 2018. TWOPORFLOW: A two-phase flow porous media code, main features and validation with BWR-relevant bundle experiments. Nucl. Eng. Des. 338, 181–188.

M. Kloos, 2015, May. Main features of the tool SUSA 4.0 for uncertainty and sensitivity analyses. In *Proceedings of the 1st International Conference on Uncertainty Quantification in Computational Sciences and Engineering, Crete Island, Greece* (pp. 25-27).

Mattie, P.D., et al., 2015. State-of-the-Art Reactor Consequence Analyses Project Uncertainty Analysis of the Unmitigated Long-Term Station Blackout of the Peach Bottom Atomic Power Station. U.S. Nuclear Regulatory Commission, NUREG/CR-7155, Washington, DC.

McKay, M.D., Beckman, R.J., Conover, W.J., 1979. A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. Technometrics 21 (2), 239–245.

D. Osborn, et al., 2017. "State-of-the-Art Reactor Consequence Analysis (SOARCA) Project Sequoyah Integrated Deterministic and Uncertainty Analyses", NUREG/CR-Draft, U.S. Nuclear Regulatory Commission, Washington, DC.

Pastore, G., Swiler, L.P., Hales, J.D., Novascone, S.R., Perez, D.M., Spencer, B.W., Luzzi, L., Van Uffelen, P., Williamson, R.L., 2015. Uncertainty and Sensitivity Analysis of Fission Gas Behavior in Engineering-Scale Fuel Modeling. J. Nucl. Mater. 456, 398–408.

E. Paulil et al., 2022. Prediction of the radiological consequences of a severe accident scenario in a generic KONVOI nuclear power plant. In *The 10th European Review Meeting on Severe Accident Research (ERMSAR2022)*.

Pontillon, Y., Malgouyres, P.P., Ducros, G., Nicaise, G., Dubourg, R., Kissane, M., Baichi, M., 2005. Lessons learnt from VERCORS tests: Study of the active role played by UO_2-ZrO_2-FP interactions on irradiated fuel collapse temperature. J. Nucl. Mater. 344 (1-3), 265–273.

Schlenger-Faber, B.J., et al., 1996. Severe-accident analysis using the MAAP code: Modeling and applications. Trans. Am. Nucl. Soc. 75 (CONF-961103-).

Schwarz, M., Hache, G., von der Hardt, P., 1999. Phebus FP: a severe accident research programme for current and advanced light water reactors. Nucl. Eng. Des. 187 (1), 47–69.

Song, K.W., Kim, K.S., Kim, Y.M., Jung, Y.H., 2000. Sintering of mixed UO_2 and U_3O_8 powder compacts. J. Nucl. Mater. 277 (2-3), 123–129.

A. Stakhanova, et al., 2022. Preliminary uncertainty and sensitivity analysis of the ASTEC simulations results of a MBLOCA scenario in a generic KONVOI plant by using the FSTC tool. ERMSAR-2022, May 16-19, 2022, Karlsruhe, Germany.

Stakhanova, A., Gabrielli, F., Sanchez-Espinoza, V.H., Hoefer, A., Pauli, E., 2022. Uncertainty and sensitivity analysis of the QUENCH-08 experiment using the FSTC tool. Ann. Nucl. Energy 169, 108968.

J. Stuckert, et al., 2005. *Experimental and computational results of the QUENCH-08 experiment (reference to QUENCH-07)* (No. FZKA–6970). Forschungszentrum Karlsruhe GmbH Technik und Umwelt (Germany). Inst. fuer Materialforschung.