Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 78, No 9, 2025

PHYSICS

Nuclear physics

SENSITIVITY ASSESSMENT OF THE ASTEC CODE RESULTS FOR A SEVERE ACCIDENT IN A SFP BY USING THE SUNSET TOOL

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Received on June 17, 2025
Presented by P. Atanasov, Member of BAS, on July 29, 2025

Abstract

The present work focuses on the sensitivity assessment of simulation results for a severe accident scenario in the Spent Fuel Pool of Fukushima Daiichi Unit 4, using a simplified case study. The analysis is performed using the ASTEC code, based on an input deck developed by INRNE-BAS under the EU Horizon 2020 MUSA project. A probabilistic approach is applied for the propagation of input uncertainties using the SUNSET statistical tool. A total of 100 ASTEC simulations are conducted, enabling the estimation of 95%/95% probability and confidence levels for key outputs using Wilks' formula. The paper outlines the step-by-step application of the ASTEC/SUNSET methodology, its adaptation, and the main results.

Key words: sensitivity assessment, severe accident, SFP, ASTEC, SUNSET

Introduction. The analysis of a postulated severe accident in a Spent Fuel Pool (SFP) has been an important area of research efforts in recent years, especially after 2011 accident at the Fukushima Daiichi NPP [1]. Furthermore, in the recently successfully finalized MUSA project [2], there was a dedicated work

The authors acknowledge the EC for supporting the MUSA project in the frame of Horizon 2020 research and training programme 2014–2018 under grant agreement No. 847441 for funding this research. This work reflects only the authors' view, and the European Commission is not responsible for any use that may be made of the information it contains.

https://doi.org/10.7546/CRABS.2025.09.01

package on the Innovative Management of SFP Accidents (IMSFP) [3]. In this work package, one of the main tasks was devoted to the investigation of the main uncertainties on accident progression and fission products (FPs) release in a severe accident (SA) in a SFP [4, 5]. As a participant in the activities in this WP, the Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences (INRNE-BAS) was involved in the analysis covering the scope and goals set up at the project. A part of the INRNE's MUSA project contribution and corresponding results from the dedicated work package are presented in the paper. In the context of the present work, dealing with the sensitivity assessment of the ASTEC (Accident Source Term Evaluation Code) results, emphasizing on the key output parameters/FPs release from the postulated accident scenario (simplified) applied to the SFP, the analysis methodology used compiles the several important stages that require special attention, incorporating a few specific elements. The probabilistic assessment of the uncertainty was conducted. In this regard, through the embedded statistical methods in the SUNSET [6] tool, in order to achieve desired tolerance limits, considering the Wilks' formula [7], the required ASTECv2.2.0.1 code [8] runs were determined. By the use an ASTEC/SUNSET coupling scheme, 100 ASTEC code runs, without crashes, were achieved. The present sensitivity analysis assesses the influence of the selected 7 input parameters on the 10 ASTEC code output parameters, i.e. Figures of merit (FOMs). As a sensitivity measure, the Pearson's correlation coefficients were used to identify the main influencing parameters on the ASTEC code results.

Methodology. The methodology used in this study combines deterministic modelling of a severe accident scenario using the ASTEC code with probabilistic sensitivity analysis performed using the SUNSET (Statistical Uncertainty and Sensitivity Evaluation Tool) statistical tool. The overall objective is to assess the impact of selected uncertain input parameters on the predicted behaviour of key output parameters during a severe accident in the spent fuel pool (SFP) of Unit 4 (simplified) of the Fukushima Daiichi NPP. This approach enhances the credibility of simulation outcomes by accounting the uncertainties of the input parameters and identifying those of them that have the greatest impact on the obtained results. The analytical approach includes certain stages: selection of an accident code; selection of an accident scenario; selection of a statistical tool; selection of uncertainty input parameters; selection of key output parameters; and sensitivity analyses of the code results. These stages of the used methodology are outlined and discussed below. In general, the analysis can be divided into two main parts: the first part is the development of an input data for ASTEC and the performance of a reference calculation, which aims to achieve stable input data that guarantees multiple executions without crashes and the second one is the coupled ASTEC/SUNSET calculation.

ASTEC code. The severe accident code ASTEC [9], is an integral code which aims at simulating a hypothetical severe accident in a nuclear reactor/SFP,

from the initiating event (IE) to the possible radioactive release outside the reactor containment (RC), considering the behaviour of engineering safety systems (ESSs) and procedures used in the severe accident management (SAM). The main areas of the application of the severe accident ASTEC code, are: the source term (ST) determination studies; the probabilistic safety assessment level 2 (PSA2) studies, including the determination of uncertainties; the accident management studies; the analyses of experiments to improve the understanding of the complexity of the severe accident phenomenology [9].

The integral codes, such as the ASTEC code, used for severe accident analysis in Nuclear Power Plants (NPPs), are designed with a balanced combination of detailed and simplified models that represent the key phenomena involved in the accident sequence.

In that case, the model parameters allow to investigate the consequences of the input uncertainty on key results [10]. The ASTEC version 2.2.0.1 code is an integral, has a modular simulation code structure, where each module represents a reactor zone or specific physical phenomena. Modules communicate via a dynamic memory system, exchanging data at macro time steps. ASTEC supports two operating modes: Stand-alone mode – individual modules run independently and coupled mode – multiple modules run sequentially within each macro time step for integrated simulation. In the current evaluation, the coupled mode was used, through activation of the modules: CESAR/ICARE (and ELSA/SOPHAEROS/DOSE/CPA). In this frame, the CESAR [11] module simulates the coolant system thermal hydraulics. The ICARE module simulates the early-phase core degradation processes such as fuel rod heating, ballooning, burst, cladding oxidation, melting, and magma formation.

ASTECv2.2.0.1 SFP model and scenario description. The scenario under simulation in the present investigation is the Loss-Of-Cooling-Accident – a simplified scenario. The ASTEC model of the spent fuel pool used in the present analysis consists of a cylinder, enclosed in a steel liner and concrete. The main ASTEC modelling structures include VESSEL, PRIMARY, and CONTAINM. The VESSEL structure is modelled with four channels and three axial rings. The PRIMARY structure contains three volumes: two volumes are located above the vessel, and one connects the bottom of the vessel to the containment structure. The CONTAINM structure consists of two zones: the SFP-HALL and the ENVIRONMENT. A connection is established between the hall and the environment. The fuel and racks are modelled using the ICARE/CESAR module, with a mesh of 15 axial and 3 radial nodes. The lower plenum ("LOWERPLE"), which is the volume between the bottom of the SFP and the bottom of the fuel assemblies, is connected to the four channels located above it. Fuel assemblies (FAs) are divided axially into: 3 nodes for the unheated lower part, 10 nodes for the heated section, 2 nodes for the unheated upper part. Above the FAs, the region has 10 axial nodes. The rack is split into three radial rings based on FA heat load: Ring 1 –

548 hottest FAs (1.9 MW), Ring 2 – 783 less hot FAs (0.5 MW), Ring 3 – 204 fresh FAs (0.0 MW). For the analysis, the water level is set to the top of the fuel assemblies. The LOWERPLE structure represents the lower plenum and includes the main supporting plate, which serves as the base for the racks. The initial and boundary conditions used for the simulation of the SFP accident scenario by the ASTEC code are: the collapse water level – 4.5 m; the SFP building pressure – 1 bar; the water temperature – 100 °C; the temperature of the concrete wall of the SF pool – 100 °C; the atmosphere temperature – 80 °C; the atmosphere composition/relative humidity – 100%. The initial water mass in the SFP is assumed as 458 060 kg. The simulation is stopped after ≅130 h (467 840 s) of a transient, when the molten UO_2 is above 3%. In accordance with this criterion, before the coupling ASTEC/SUNSET calculations, the Reference case scenario was carried out in order to achieve the stable ASTEC input desk.

SUNSET statistical tool used in the ASTEC/SUNSET coupling platform. The statistical tool SUNSET [6] is a software for the uncertainty and sensitivity assessment of the ASTEC code results. This type of analysis involves methods and techniques inherent to the statistical tools; in this framework, the SUNSET coupled with ASTEC code as an analytical platform is able to perform such statistical evaluations. The probabilistic method [12] as an available method within the SUNSET tool for the propagation of the input uncertainty is used to perform the uncertainty quantification [13, 14] of the ASTEC code results. This tool performs a probabilistic assessment of the uncertainties. In this case, the uncertainties are modelled through the random variables. The main advantage of probabilistic methods [15] is that they provide a realistic and reasonable evaluation of the uncertainty margins associated with a given result. Furthermore, another advantage of the probabilistic methods is the simplicity of their application in the analyses [16, 17]. Last but not least, there is no limitation regarding the number of the uncertain variables which is accounted in the analyses. In addition, in this analytical framework the sensitivity analyses [18] require to run several times the ASTEC code in order to propagate the information from its input to its output. The SUNSET tool integrates the tools able to perform data analysis. The construction and execution of the SUNSET data deck is carried out by using the SUNSET Graphical User Interface (SUNSET GUI) [6]. Further, the ASTEC/SUNSET coupling calculation consists of four main steps used in the analysis: Step (1) the preparation of the ASTEC runs/data deck; Step (2) the SUNSET Pre-processing; Step (3) the launching the calculations/ASTEC running; Step (4) the SUNSET post-processing – statistical analyses of the obtained results. In practice, the input uncertainty parameters values are simultaneously varied by random sampling according to the type of their PDFs and variation ranges. The Latin Hypercube Sampling (LHS) method is applied. In this way, a set of input parameters is obtained to perform the required number n of ASTEC code runs. Considering the 95% probability and the 95% confidence limits, the

required n-ASTEC code runs were determined based on the Wilks' formula. The Wilks' approach/formula allows to obtain the minimum code runs. In this case for 95%/95% limits, the code runs should be above 93. In this study, it is selected to perform 100 ASTEC runs. The set of input uncertainty parameters used in the ASTEC/SUNSET analysis is given in Table 1.

T a b l e 1

Uncertain input parameters (IUPs)

Name	Short description	Reference value	Range of variation	PDF type
IUP1 (Rho)	Particle mean density, (kg/m^3)	3000	±20%	uniform
IUP2 (R_max)	Particle maximum geometrical radius, (m)	2.E-5	±20%	uniform
IUP3 (R_min)	Particle minimum geometrical radius, (m)	1.E-9	±20%	uniform
IUP4 (VALU)	Thickness for loss of clad integrity, (m)	250.E-6	±20%	uniform
IUP5 (TBEG)	Oxidation: ZROX rubric deals with the zircaloy oxidation by steam or by oxygen, (K)	900	±20%	uniform
IUP6 (EPMX)	Maximum hoop creep until failure cladding	0.40	±20%	uniform
IUP7 (VALU)	Dislocation of cladding, (K)	2300	±10%	uniform

The list of selected ASTEC output parameters, i.e., the Figures of Merit (FOMs), is provided according to their numbering in the Reference case: FOM1: Xenon (Xe) released into the environment, [% of ii]; FOM2: Caesium (Cs) released into the environment, [% of ii]; FOM3: Ruthenium (Ru) released into the environment, [% of ii]; FOM4: Strontium (Sr) released into the environment, [% of ii]; FOM5: Xenon (Xe) released from the fuel, [% of ii]; FOM6 Caesium (Cs) released from the fuel, [% of ii]; FOM7: Ruthenium (Ru) released from the fuel, [% of ii]; FOM8: Strontium (Sr) released from the fuel, [% of ii]; FOM9: Iodine (I) released into the environment, [% of ii]; FOM10: Iodine (I) released from the fuel, [% of ii].

Results and discussion. ***Results from reference case simulation.*** In the beginning of the ASTEC/SUNSET analyses, it is important to obtain the stable ASTEC code input deck used as a base for the preparation of the SUNSET data deck. To this end, ASTEC code simulation of the selected scenario was carried out, considering 3% UO_2 melting as a criterion for the determination of the end of the simulation, as previously noted. The evaluation of the maximum fuel temperatures for the three rings (Fig. 1a) is carried out. The temperature of ring 1/the hottest FAs increases and leads to the fuel melting. The temperatures of the FAs in rings 2 and 3 are below 1000 K. The hydrogen production (Fig. 1b) as a result from the oxidation of zirconium claddings is rapidly increasing at 95 h of the simulation, when the maximum fuel temperature is reached. Further, the increasing of the temperature in the hottest FAs leads to the boiling of the water

in the spent fuel pool and this causes the changes of the atmosphere composition in the containment, where about 100% steam prevails. This may be a result of dislocation of molten materials into the water, producing the steam that oxidizes the zircaloy and steel. At the same time, the water mass, respectively the water level decreases as results of these phenomena. The cladding failure and the gap releases occur at 97 h. The evaluation of the fission products (specifically Caesium/Cs and Iodine/I) release versus simulation time as a % of initial inventory is presented in Fig. 1c and d. In such figures, the rapid increase of the fission products releases is observed.

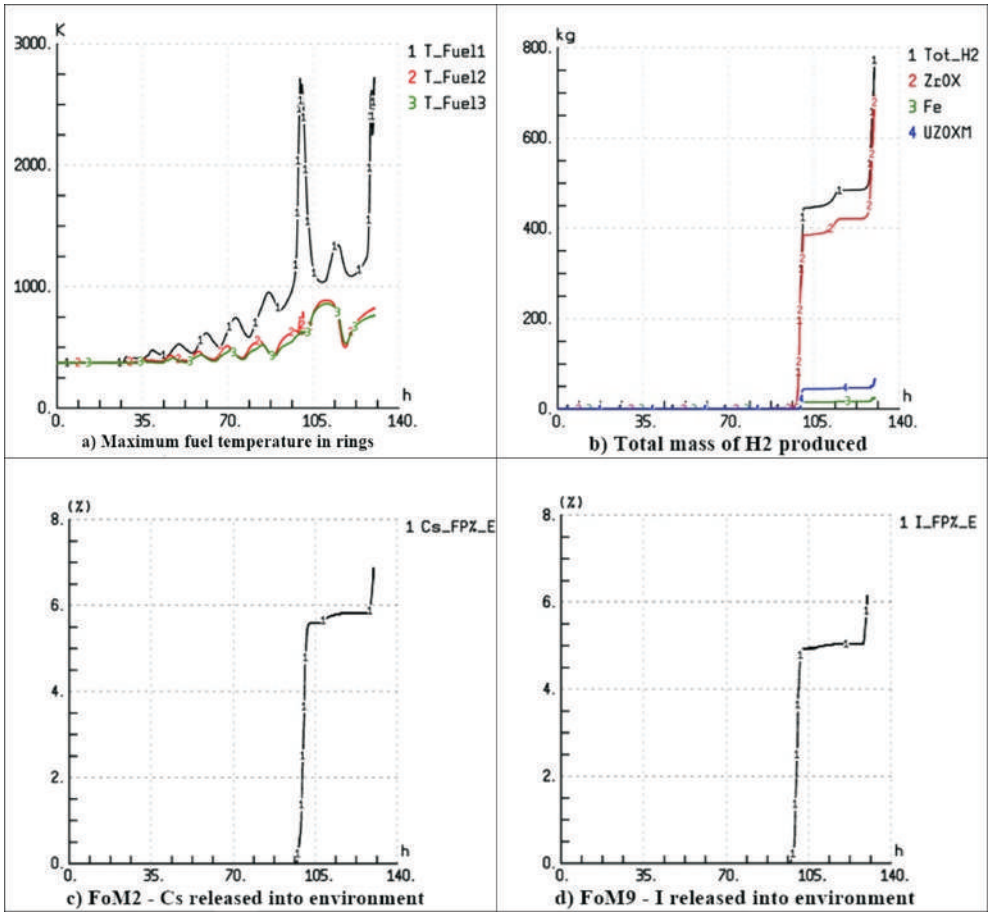

Fig. 1. Reference case results: a) Maximum fuel temperature in rings [K]; b) Total mass of H_2 produced [kg]; c) FoM2 – Cs released into environment, [% ii]; d) FoM9 – I released into environment, [% ii]

Considering the Reference case results, presented in this section, the coupling ASTEC/SUNSET calculations were done. A part of the generated results from the last step of the overall ASTEC/SUNSET evaluation process, i.e. statistical

analyses of the ASTEC severe accident code results issued by the simulation of the SFP accident are presented and discussed in the next part of the present study.

Results from ASTEC/SUNSET coupling simulations. The analysis presented herein was conducted with the ASTEC/SUNSET coupling. In this frame, the sources of uncertainties are modelled in SUNSET tool, which generates a random sample for each uncertain variable. It was chosen to sample 7 uncertain variables using a random 100 sample size. SUNSET generates 100 combinations of values for the 7 variables, which are read as input variables by ASTEC code. In this way, the SUNSET tool launches 100 ASTEC sessions, and then extracts the 100 computed values for each of the selected 10 output variables, denoted as FOMs. The general process for carrying out the sensitivity analysis using the ASTEC/SUNSET consists of four steps presented earlier in the text. Step 1 and Step 2, consist of the preparation of the ASTEC data deck to be able to exchange the data with the statistical tool SUNSET and also pre-processing (the number of input variables, their ranges and PDFs; the output variables selection). Step 3 consists of the 100 ASTEC code runs, executed in 100 different directories created by the SUNSET and containing the doncal files. The last Step 4 (after the calculations) consists of post processing of the obtained results. The SUNSET GUI is used to carry out all four steps briefly described above. In the analysis is used the uniform PDFs type for the selected input parameters (see Table 1).

Sensitivity analysis results. The main results obtained from the sensitivity analyses performed for the selected ASTEC output parameters as figures of merit are presented. The emphasis in the work on the results and further discussion is given on the two important radiological FPs, namely Caesium (FOM2) and Iodine (FOM9), other data is provided for illustration of the discussion. The sensitivity analysis is a technique, used to obtain the relationship between two sets of the variables – the input uncertain parameters (X) and selected output parameters (Y) as figures of merit. The Pearson correlation coefficients are used as a measure of the relationship between input uncertain parameters and the FOMs. From statistical point of view, the values of the correlation coefficient range between –1 and +1. The value 0 means that the values of X (IUPs) and Y (FOMs) are independent, the value +1 means that the values of X (IUP) and Y (FOM) are identical (positive correlation), and the value –1 means that the values of X (IUP) and Y (IUP) vary in inverse order (negative correlation). Considering this, there are positive correlations between inputs and outputs, except the correlations between IUP4 and FOMs (Fig. 2a).

The correlation analysis carried out using the Pearson's correlation coefficients (as measures) gives information for the main influential parameters. In our analysis, the most influential parameter on the selected fission products is IUP5, denoted as TBEG – the minimum temperature to start zirconium oxidation. Further, the second most influential parameter (IUP7) on the ASTEC code results is $\mathrm{VALU}_{(T,K)}$ – the temperature for cladding dislocation. It should be emphasized

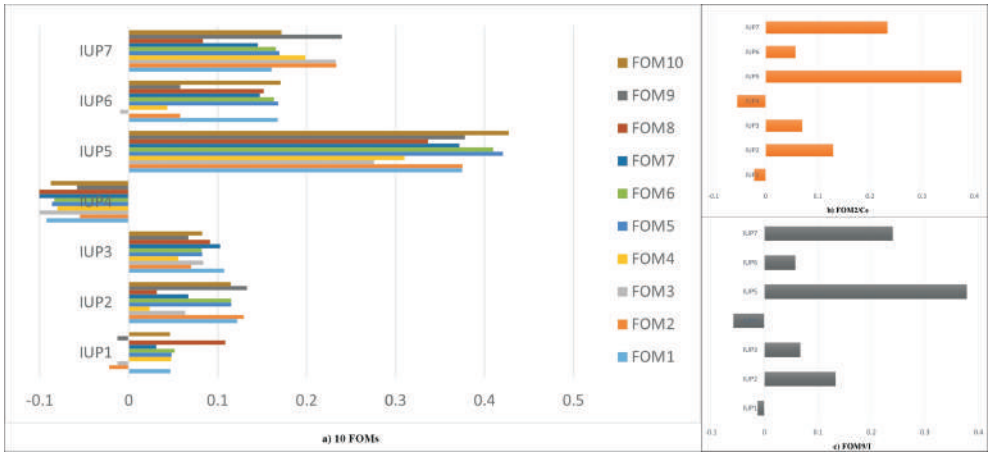

Fig. 2. Sensitivity analysis results: Pearson correlation coefficients for a) 10 FOMs; b) FOM2/Cs released into the environment, [% of ii]; c) FOM9/I released into the environment, [% of ii]

that there is a positive correlation for the most influential parameter/s (TBEG and $\mathrm{VALU}_{(T,K)}$) and FOMs. In this way, an increase in the given IUP leads to the increase in the respective FOM, i.e. the increasing in the IUP5 results in an increase of the fission product releases/FOMs. Also, the other considered IUPs in the analysis have a negligible influence on the FOMs. The Pearson correlation coefficients for FOM2 and FOM9 are presented in Fig. 2b and c, respectively. At the end/last time used for the ASTEC/SUNSET analyses, Cs and I release into the environment is positively correlated with the TBEG (the minimum temperature to start Zr oxidation) – IUP5. Regarding the temperature for cladding dislocation – IUP7, we observe a positive correlation, but smaller compared to that observed for TBEG.

Conclusions. A sensitivity assessment of the ASTECv2.2.0.1 code results for a severe accident scenario in a spent fuel pool is presented. The probabilistic method available in the SUNSET tool for the propagation of input uncertainties is used. This allows the selection of a set of uncertain input parameters without considering the number of ASTEC code runs. The number of ASTEC code runs is determined using Wilks' approach/formula.

The sensitivity analyses performed on the ASTEC/SUNSET calculation platform give the results for the selected fission products as figures of merit for the selected one point of time/as a scalar value – the end time of the simulated sequence. The evaluation of the main important FPs (with emphasis on Cs and I) resulting into the environment from the postulated accident scenario is presented.

The study assesses the impact of input uncertainties on the model outcomes, providing a better view on the code's predictions. Based on the results of the analysis, it can be concluded that the most influential input parameters on the ASTEC

code results are primarily related to the temperature at which Zr oxidation begins (IUP5) and the temperature for cladding dislocation (IUP7).

REFERENCES

[1] IAEA (2019) Status and evaluation of Severe Accident Simulation Codes for Water Cooled Reactors, International Atomic Energy Agency, IAEA-TECDOC-1872.

[2] Herranz L. E., S. Beck, V. H. Sánchez-Espinoza et al. (2021) The EC MUSA Project on Management and Uncertainty of Severe Accidents: Main Pillars and Status, Energies, **14**(15), 4473.

[3] Coindreau O., L. E. Herranz, R. Bocanegra et al. (2023) Uncertainty quantification for a severe accident sequence in a SFP in the frame of the H-2020 project MUSA: First outcomes, Annals of Nuclear Energy, **188**, 109796.

[4] Groudev P. P., A. E. Stefanova, M. Manolov (2013) Investigation of dry out of SFP for VVER440/V230 at Kozloduy NPP, Nuclear Engineering and Design, **262**, 285–293.

[5] Kaliatka T. (2018) Modelling of severe accidents in spent fuel pools, analysis of the heat-up of the fuel assemblies in the steam and air environment, Nuclear Engineering and Design, **337**, 341–350.

[6] Chojnacki E., J. Baccou (2013) SUNSET V2.1, Theory Manual and User Guide, IRSN report, IRSN/PSN-RES/SEMIA/2013-00237.

[7] Wilks S. (1941) Determination of simple sizes for setting tolerance limits, Annals of Matematical Statistics, **12**(1), 91–96.

[8] Chatelard P., L. Laborde (2023) ASTEC v2.2 code validation: Illustrative results and main outcomes, Nuclear Engineering and Design, **413**, 112547.

[9] Chailan L., L. Laborde (2021) Overview of the integral code ASTEC v2.2, Rapport no IRSN/2022-00298, BDD-ST SAM-2021-00298.

[10] IAEA (2008) Approaches and Tools for Severe Accident Analysis for Nuclear Power Plants, International Atomic Energy Agency, Safety Report Series No 56.

[11] Zambaux J. A. (2021) ASTEC: CESAR Physical and Numerical Modelling, Rapport no IRSN/2021-00184, BDD-ST SAM-2021-038.

[12] IRSN (2011) SUNSET ASTEC User Guidelines, Quick Guidelines and Test Case Presentation, Rapport CS-SI no M40/21006865, DRAM-SEMIC-2011-100.

[13] Brumm S., E. Gabrielli, V. H. Sanchez Espinoza et al. (2023) Uncertainty quantification for severe-accident reactor modelling: Set-up and first results of the Horizon-2020 project MUSA, Annals of Nuclear Energy, **191**, 109919.

[14] IAEA (2023) IAEA TECDOC SERIES, Advancing the State of the Practice in Uncertainty and Sensitivity Methodologies for Severe Accident Analysis in Water Cooled Reactors of PWR and SMR Types, IAEA-TECDOC-2031.

[15] Mascari F., A. Bersano, G. Agnello et al. (2024) MELCOR-DACOTA coupling for uncertainty analyses in the SNAP environment/architecture, Nuclear Engineering and Design, **421**, 113078.

[16] Petrova P., P. Groudev, P. Vryashkova (2022) BEPU Analyses for the Postulated Loss-of-cooling Accident Scenario in the Spent Fuel Pool at the Fukushima Daiichi Unit 4, C. R. Acad. Bulg. Sci., **75**(7), 959–965.

[17] Groudev P., P. Petrova, P. Vryashkova (2023) Uncertainty Assessment in the Prediction of Selected Fission Products in the Case of a Postulated Severe Accident Scenario at VVER-1000. In: IOP Conference Series: Earth and Environmental Science, **1234**(1), 012015.
[18] Mascari F., A. Bersano, M. Massone et al. (2024) Main outcomes of the Phebus FPT1 uncertainty and sensitivity analysis in the EU-MUSA project, Annals of Nuclear Energy, **196**, 110205.

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