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# Uncertainty Evaluation for a Postulated Severe Accident Scenario at a VVER1000 NPP Using ASTEC-SUNSET

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This study presents the main results from an uncertainty evaluation performed for a postulated severe accident scenario - a Station Blackout (SBO) in a Nuclear Power Plant (NPP) equipped with a VVER1000 reactor. The primary aim of this investigation was to quantify uncertainties in code predictions and, additionally, to perform a sensitivity analysis of key output variables. The analysis was conducted using the ASTEC severe accident simulation code, integrated with the SUNSET uncertainty quantification tool, forming a comprehensive analytical platform. A total of eight input parameters were considered, with the focus placed on evaluating the uncertainty in ten fission products (FP) as output variables predicted by ASTEC. The statistical framework provided by SUNSET, which uses Wilks' formula, guided the determination of the required number of simulations and enabled the assessment of how input uncertainties influence output variability. The study details the analytical process, including the ASTEC-SUNSET coupling methodology, and presents key findings from the uncertainty analysis. The results demonstrate the effectiveness of the integrated approach in identifying the most influential input parameters and characterising the range of predicted fission products. These findings contribute to enhancing the robustness of uncertainty quantification practices in nuclear safety analysis and support ongoing safety evaluations for VVER1000 reactors.

*Keywords*: Uncertainty, fission product, severe accident, VVER1000, ASTEC-SUNSET.

## 1. Introduction

Severe accident scenarios in nuclear power plants, although characterized by low probability, are associated with potentially high consequence outcomes that require in-depth analysis and comprehensive safety evaluation (Groudev et al., 2014; Stefanova et al., 2015). Traditionally, deterministic simulations have been the cornerstone of severe accident research, providing insight into accident progression. However, the inherent uncertainties associated with model parameters (Brumm et al., 2025) limit the adequacy of purely deterministic approaches for a complete characterization of possible accident evolutions. In recent years, the integration of uncertainty quantification (UQ) and sensitivity analysis (SA) methodologies (Herranz et al., 2025; Coindreau et al., 2023) into severe accident assessments has gained increasing importance (IAEA, 2023). These statistical frameworks enable a systematic treatment of input variability and facilitate the evaluation of its influence on the calculation outputs. Furthermore, additional sensitivity analyses allow the identification of dominant input parameters contributing to the uncertainty of the output data, thus providing a more robust basis for nuclear safety assessment. In this regard, the present study uses an analytical approach that combines deterministic and probabilistic methodologies for the analysis of a VVER1000 Station Blackout (SBO) scenario in the absence of operator actions. The analysis employs the ASTEC v3.1.1 severe accident simulation code (Chatelard P, and L. Laborde, 2023) in conjunction with the SUNSET statistical tool. The methodology used (Petrova et al., 2022; Groudev et al., 2023) is structured into two main stages: (1) a base case deterministic simulation of the SBO sequence to establish a baseline representation of accident progression, and (2) a probabilistic analysis involving Monte Carlo sampling (through the LHS technique) of uncertain input parameters, followed by statistical characterization of the resulting outputs. The objective of this study is to quantify the uncertainty associated with predicted fission products selected as Figures Of Merits (FOM) and to identify the input parameters exerting the greatest influence on these outcomes. This enables a more comprehensive understanding of the accidental scenario and associated model parameter uncertainties and its possible effects on the code prediction results. Furthermore, the applied methodology (Petrova et al., 2025) demonstrates the effective integration of advanced statistical techniques within existing severe accident analysis frameworks.

## 2. Methodology

This study employs a two-stage evaluation methodology to analyse severe accident progression and assess uncertainties associated with given input parameters. The overall approach integrates deterministic simulations using the ASTEC severe accident code with probabilistic uncertainty analyses performed via the SUNSET 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 NPP with VVER1000. 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 comprehensive uncertainty (and sensitivity) evaluation process includes: an accident code selection; an accidental scenario selection; a statistical tool selection; selection of input uncertainty parameters (UPs); selection of key output parameters/FOMs; multiple ASTEC code runs and statistical analyses: uncertainty and sensitivity analyses of the ASTEC code results for the FOMs. These stages of the evaluation methodology employed are outlined and discussed below in the text. In general, the analysis can be divided into two main parts: the first part is the development of an input data block for ASTEC and the performance of a Base case calculation, which aims to achieve a stable input data block that guarantees multiple executions and the second one, is the coupled ASTEC-SUNSET calculation.

### 2.1. *ASTEC v3.1.1 short overview, model and scenario description*

Developed by IRSN, the Accident Source Term Evaluation Code (ASTEC) is designed to simulate the full progression of a severe accident in a nuclear facility, from the Initiating Event (IE) to the potential release of Radioactive Elements (REs) beyond the containment boundary. ASTEC supports a wide range of applications, including the determination of Source Term (ST), Level 2 Probabilistic Safety Assessment (L2 PSA) studies, Accident Management (AM) analyses, and the interpretation and physical analysis of experimental data aimed at improving the understanding of severe accident phenomenology. The code is based on a modular architecture, in which individual modules represent specific facility (reactor) regions or model particular physical processes occurring during severe accident conditions. In this regard, the ASTEC version 3.1.1 generic input deck employed in the present work includes the following computational modules: CESAR, ICARE/with ELSA, SOPHAEROS, RUPUICUV/CORIUM, MEDICIS, DOSE, and CPA, which are coupled to provide an integrated and comprehensive simulation of the severe accident scenario. The reactor vessel (RV) structures are modelled with the ICARE module, which includes reactor core, baffle, the cylindrical part of the barrel, vessel cylindrical part, fuel assembly supports and vessel lower head. The primary four loops have been modelled in two ASTEC loops: one single loop and the other (three) loops are represented in a common loop. Each one of ASTEC primary loops is modelled by seven volumes and eight junctions, representing the hot leg, the Steam Generator (SG) hot collector, the SG tubes, the SG cold collector, the cold leg (presented by three parts) and the Main Coolant Pump (MCP). The Pressurizer with three relief valves and surge line is also modelled. The reactor core is divided in axial and radial direction (twenty nodes in axial direction and five rings in radial direction, including baffle and barrel). The Upper plenum is modelled by two volumes ‘UPPLE1’ and ‘UPPLE2’. The Downcomer and lower plenum are also modelled. The bypass coolant path is organized with the thermal-hydraulic components of the ICARE module. The FRAGLOWE structure is used for corium fragmentation during slump into the lower plenum. For rupture of lower head is used RUPTURE structure with three options/criteria CRIT TEMPERAT, CRIT FUSION and CRIT MECHANIC. The scenario under simulation in the present investigation is the SBO without considering the operator actions. The end time of the simulation is 20 000 s.

### 2.2. *The statistical tool SUNSET used in the coupling platform ASTEC-SUNSET*

The statistical software SUNSET is a tool for the uncertainty (and sensitivity) assessment of the ASTEC code results. SUNSET involves methods and techniques inherent to the statistical tools. The probabilistic method as an available method within the SUNSET tool for the propagation of the input uncertainty is applied to perform the uncertainty quantification of the ASTEC code results. This tool performs a probabilistic assessment of the uncertainties (Mascari et al., 2024). In this case, the uncertainties are modelled trough the random variables. The main advantage of probabilistic methods is that they provide a realistic and reasonable evaluation of the uncertainty margins associated with a given result. Further, the other advantage of the probabilistic methods is the simplicity of their application in the analyses. And also, but not least, there are no limitation regarding the number of the uncertain variables which is accounted in the analyses. In addition, in this analytical framework the uncertainty and sensitivity analyses 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 Graphical User Interface (the so-called SUNSET GUI). Further, the ASTEC-SUNSET coupling calculation comprises of four main steps used in the analysis consist of the main procedures for performing the ASTEC-SUNSET coupled analyses: 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 varies by random sampling according the type of theirs PDFs and variation ranges. The Latin Hypercube Sampling (LHS) method is applied. As a result, sets of input parameters are obtained to perform the required number n of ASTEC code runs. Considering the 95% probability and the 95% confidence limits (IAEA, 2008), the required n-ASTEC code runs were determined based on the Wilks’ formula (Wilks S., 1941). 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 the presented work, we chose to perform 100 ASTEC runs, of which 98 were successful and 2 failed, which were removed. The statistical analyses were performed considering data from 98 runs. The set of uncertainty input parameters used in the present ASTEC-SUNSET analysis is given in Table 1.

Table 1. List of the input uncertain parameters: reference values and ranges of variation

| Par # | IUPs description | Ref. value | Ranges |
|---|---|---|---|
| 1 | **Rho**/Particle mean density, (kg/m$^3$) | 3000 | ±20 % |
| 2 | **R_max** (Particle maximum geometrical radius, (m) | 2E-5 | ±20 % |
| 3 | **R_min**/Particle minimum geometrical radius, (m) | 1E-9 | ±20 % |
| 4 | **VALU**/Thickness for loss of clad integrity, (m) | 250E-6 | ±20 % |
| 5 | **TBEG**/Oxidation: ZROX rubric deals with the zircaloy oxidation by steam or by oxygen, (K) | 900 | ±20 % |
| 6 | **EPMX**/Maximum hoop creep until failure cladding) | 0.40 | ±20 % |
| 7 | **VALU**/Dislocation of cladding, (K) | 2300 | ±10 % |
| 8 | **Lambda**/Particle mean thermal conductivity,(J/m/K) | 3.5 | ±10 % |

The selected output uncertain parameters/FOMs used in the analysis are listed in Table 2.

Table 2. List of the selected output uncertain parameters/as FOMs.

| FOM # | Description & Dimension |
|---|---|
| 1 | Release of iodine from the fuel, % ii |
| 2 | Release of caesium from the fuel, % ii |
| 3 | Total aerosols (I, Cs, Mo, Rb, Sr) in containment, g |
| 4 | Amount of gaseous iodine in the containment's atmosphere, g |
| 5 | Amount of suspended iodine in the containment's atmosphere, g |
| 6 | Total deposited iodine in the containment, g |
| 7 | Total FP (I) to Environment, g |
| 8 | Amount of suspended Cs in the containment's atmosphere, g |
| 9 | Total deposited Cs in the containment, g |
| 10 | Total FP (Cs) to environment, g (assuming only allowed design unsealing) |

## 3. Results and discussions

As a noted in the beginning, the first stage of the overall ASTEC-SUNSET analysis is the Base case simulation, serving not only as a base of the complete Uncertainty/and Sensitivity Analysis (Un/SAs), but also as a first important stage necessary to achieve the stable ASTEC input desk that predetermined success of the overall evaluation process. Considering the accuracy of the Base case input deck, the SUNSET data deck was prepared for the actual analysis. For this purpose, ASTEC code simulation of the selected scenario was carried out, considering 20 000s as the end of the simulation.

### 3.1. *Base case simulation results for FOMs (up to 20 000s)*

The first part of the overall ASTEC-SUNSET analysis was the Base case study. This formed the important necessary stage for preparing the SUNSET data deck. For this purpose, ASTEC code simulation of the selected scenario was carried out, considering 20 000s as the end of the simulation. Among the various initiating events, a Station Blackout (SBO) represents one of the most challenging and safety relevant scenarios, as it involves the complete loss off-site and on-site alternating current power, potentially leading to core degradation and fission product (FP) release. After the initiation of a SBO scenario without operator actions (unmitigated scenario), all four MCPs tripped at 0.0 s. As a result of the loss of 3 of the 4 MCPs, the signal for reactor SCRAM at 0.0 s is generated and the reactor trips with a delay of 1.0 s. The turbine stops valve (TSV) is tripped off and isolated the turbine in 2.0 s after reactor SCRAM. The main feed water stopped and disconnected at 6.0 s. The isolation of the turbo generator leads to an increase in the pressure in the secondary side. It is assumed that all Steam dump valves to the atmosphere (BRU-As) were failed. This is because they are electrically driven (by battery). Because of the SBO and loss of vacuum, all Steam dump valves to the condenser (BRU-Ks) are also unavailable. In the absence of active heat removal, decay heat is removed initially through natural circulation and secondary site heat losses. As the secondary side inventory is depleted and feedwater injection is unavailable, heat removal through the steam generators gradually degrades, leading to a progressive heat up of the primary system. The primary system pressure evolution, coolant inventory depletion, and core uncover occur as the accident progresses. The scenario assumes no operator intervention, where the accident is expected to evolve toward core degradation, as a result of fuel heat up (Fig. 1), hydrogen generation (Fig.2), cladding oxidation, and the release of fission products from the fuel matrix (Figs.3&4) into the reactor coolant system and containment. The results obtained for all output variables/FOMs are given in Table 3.

Table 3. Base case analysis results for all 10FOMs

| FOM # | Base case (20000s) |
|---|---|
| 1 | 80.64 |
| 2 | 81.29 |
| 3 | 9350.72 |
| 4 | 30.41 |
| 5 | 1807.49 |
| 6 | 83.47 |
| 7 | 0.04 |
| 8 | 7026.99 |
| 9 | 269.05 |
| 10 | 0.14 |

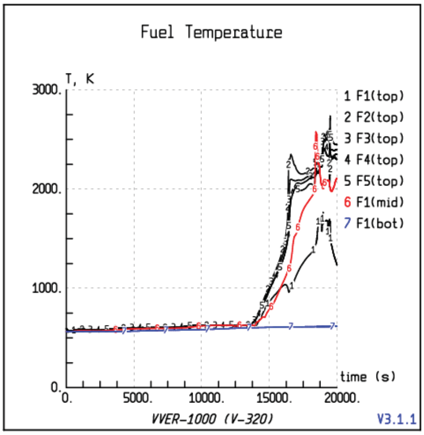

Fig. 1. Base case - Fuel temperature computation

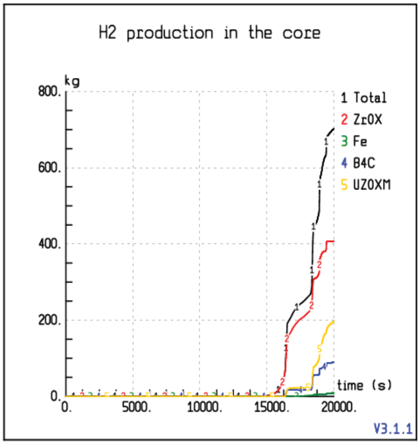

Fig. 2. Base case - Total mass of H2 produced

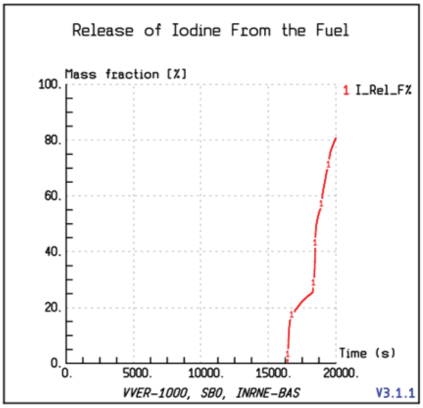

Fig. 3. Base case – FOM1

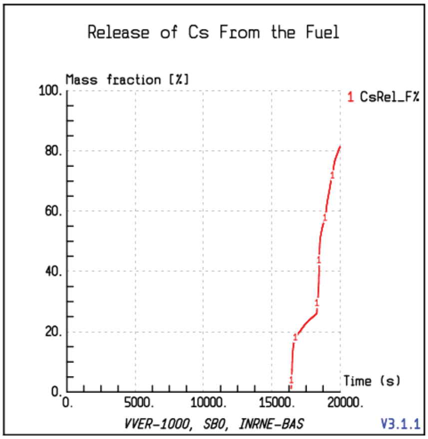

Fig. 4. Base case – FOM2

Considering the Base case results (at 20 000s), presented in this section (Table 3), the coupling ASTEC-SUNSET calculation was 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 SBO accident are presented and discussed in the next part of the present document.

### 3.2. *Results from ASTEC-SUNSET analysis*

The analysis presented herein was conducted with the ASTEC-SUNSET coupling. In this frame, the sources of uncertainties are modelled in SUNSET tool, which generate a random sample for each uncertain variable. We choose to sample 8 uncertain variables using a random 100 sample size, SUNSET generates 100 combinations of values for the 8 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 carry out the uncertainty and sensitivity analysis using the ASTEC-SUNSET consists of two main stages and several steps presented earlier into the text. The 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). The next, the 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, we use the uniform PDFs type for the all selected input parameters (see Table 1).

### 3.2.1 *Uncertainty analysis results*

The following Table 4 summarize the statistical data analysis issued from the uncertainty analyses. This table gives the information about the average values, the standard deviations, the min, the max values for the ten output variables /selected FOMs. The SUNSET tool allows to perform the statistical analyses for the minimum, maximum and last values of the output parameters. The present work is performed using the last values/scalar values of the outputs (in our case at 20000s).

Table 4. Uncertainty analysis results for all 10FOMs

| FOM # | average | std | min | max |
|---|---|---|---|---|
| **1** | 77.36 | 3.61 | 65.93 | 82.74 |
| **2** | 78.12 | 3.48 | 67.07 | 83.32 |
| **3** | 21356.7 | 9591.58 | 6638.81 | 48515.1 |
| **4** | 17.15 | 17.64 | 1.47e-7 | 102.11 |
| **5** | 2675.71 | 577.96 | 1250.3 | 4649.97 |
| **6** | 154.63 | 59.20 | 32.56 | 242.37 |
| **7** | 0.08 | 0.03 | 0.01 | 0.12 |
| **8** | 17452.77 | 8613.10 | 5010.24 | 42626.5 |
| **9** | 1006.29 | 638.50 | 133.33 | 2814.17 |
| **10** | 0.50 | 0.33 | 0.05 | 1.44 |

According the obtained results from uncertainty analysis for FOM1: Release of Iodine from the Fuel (% ii), its average value is 77.36, standard deviation is 3.61, min/max values respectively are 65.93 and 82.74. The Base case analysis value for FOM1 is 80.64 (% ii), (see Table 3). It is within the calculated uncertainty band (min/max values of the FOM1). Accordingly, the calculated values for all 10 FOMs (Table 3) fall within the limit defined by the min. and max. calculated value for each output parameter/FOM.

### 3.2.2 *Sensitivity analysis results*

The main results obtained from the sensitivity analyses performed for the selected set of ten ASTEC output parameters as figures of merit are presented. The emphasis in the presentation of the results and the discussion is on the first two FOMs, respectively the release of I and Cs from the fuel. Furthermore, for both FOMs we observe a strong correlation with the IUP7. Also, for those of the FOMs that Correlation Coefficients (CCs) values are below -0.2/+0.2, we assume a weak correlation. The Pearson (Fig. 5) and Spearman (Fig. 6) correlation coefficients were used to present the sensitivity analysis results. We observe that the most influential parameters are IUP4, IUP5 and IUP7. Other input uncertain parameters have a negligible influence on the outputs. For FOM1 (Fig. 7), the most influential parameter and positive correlation is observed for IUP7 (VALU/Dislocation of cladding, (K)). This means that with increasing of the IUP7, the value of the output parameter FOM1 (Fig. 7.) increases too. This observation is the valid and for the FOM2 (Fig. 8.). In contrast to the positive correlation observed for FOM 1 and FOM2, a mostly negative correlation is observed for FOM3 and FOM8 regarding all IUPs, and further, the most influential parameter on FOM3, FOM8 is IUP4 (VALU/Thickness for loss of clad integrity, (m)).

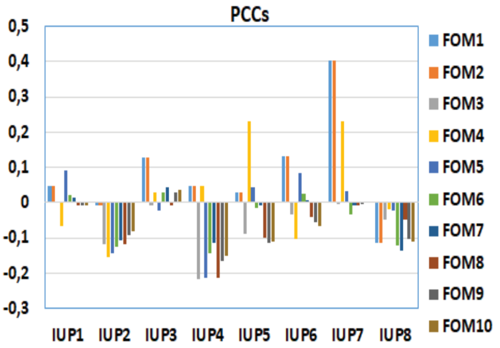

Fig. 5. Pearson correlation coefficients (PCCs) for FOM1 ÷ FOM10

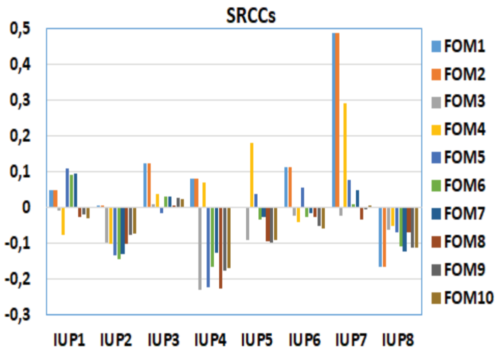

Fig. 6. Spearman rank correlation coefficients (SRCCs) for FOM1 ÷ FOM10

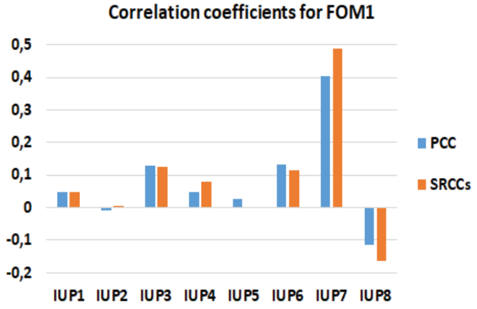

Fig. 7. Correlation coefficients (PCC&SRCCs) for FOM1

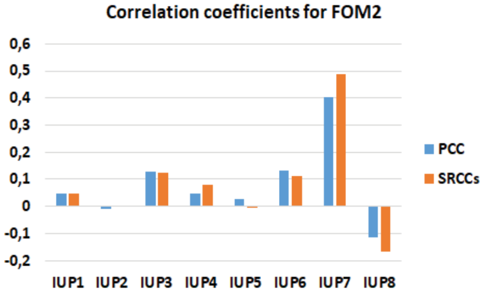

Fig. 8. Correlation coefficients (PCC&SRCCs) for FOM2

Figures 5-8. Sensitivity analysis results: Pearson and Spearman correlation coefficients for the last value of the FOMs (at the end of the simulation, 20 000s).

In Fig. 5, the Pearson Correlation Coefficient (PCC) between each output parameters/FOMs and the input uncertain parameters is shown. The PCC measures the linear relationship between considered input/output variables; the most influential input parameters on the FOMs are the VALU/thickness for loss of clad integrity/IUP4; TBEG/Oxidation: ZROX rubric deals with the zircaloy oxidation by steam or by oxygen/IUP5; and the VALU/Dislocation of cladding/IUP7. In the Figures 7-8, Correlation coefficients (PCCs and SRCCs) are given for the first two FOMs, considering that the SRCC gives the strength of the monotonic relationship between input/output variables. Considering the results, we observe that CCs (and both) are below -0.2/+0.2 for the FOM6; FOM7; FOM9 and FOM10 (and IUPs), i.e a weak correlation is observed.

## 4. Conclusions

An uncertainty and complementary sensitivity analysis of the ASTECv3.1.1 code results for a severe accident scenario in a NPP with VVER1000 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 the Wilks' approach/formula. The uncertainty analysis gives the possible range of variation of the output parameters. Further, 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 FPs results (with emphasis on the first two FOMs from correlation analysis) for the simulated VVER1000 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: **FOM7**/VALU/Dislocation of cladding, (K); **FOM4**/VALU/Thickness for loss of clad integrity (m); and **FOM5**/TBEG/Oxidation: ZROX rubric deals with the zircaloy oxidation by steam or by oxygen, (K).

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