NENE 2019
September 9–12
PORTOROŽ
SLOVENIA
28th International Conference Nuclear Energy for New Europe

Constraining Input Uncertainty Sources of PSA by Sensitivity Analysis Using FFTBM-SM

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ABSTRACT

There are multiple sources of uncertainties in the probabilistic safety assessment (PSA) of initiating events (e.g. station blackout). The most influential sources of uncertainty in deterministic studies should be identified and reduced before integration within the PSA. The purpose of this study is therefore to propose and demonstrate the fast Fourier transform based method by signal mirroring (FFTBM-SM) for judging the impact of given parameter uncertainty in deterministic safety analysis on plant response. The plant parameters and corresponding uncertainties are classified into two main categories, external and internal parameters. The proposed method is applied on the station blackout (SBO) event of the two-loop pressurized water reactor (PWR). This is done with the utilization of the RELAP5/MOD3.3 Patch 04 computer code simulations of the SBO scenarios. Obtained results demonstrate that larger source of uncertainties are external (i.e. operator actions) than internal parameters. Therefore, in the context of deterministic calculations in support of the PSA priority should be made on sources of uncertainties from external parameters, followed by sources of uncertainties from internal parameters.

1 INTRODUCTION

There are multiple sources of uncertainties in the probabilistic safety assessment (PSA) of initiating events (e.g. station blackout). Some input parameters for PSA are based on results of the deterministic calculations to support PSA. This paper proposes a new approach for identification of the most influential sources of uncertainty for the PSA. Prioritization for reducing them can be done accordingly so that uncertainty coming from deterministic modelling results can be constrained before integration within the PSA. The parameters are classified into two groups, external and internal, as described in Section 2.2. The uncertainties of the external parameters and internal parameters affect the progression of the event. They are not related to the deterministic code uncertainties or code input parameter uncertainties (i.e. initial and boundary conditions). Deterministic code uncertainties are assessed (based on previous studies, e.g. [1]) to have smaller impact on the scenario progression and obtained results than external parameters and internal parameters identified in study [2]. Therefore only assessment of the external and internal parameters uncertainties influence on the Station

Blackout (SBO) scenario progression is demonstrated. First fast Fourier transform based method by signal mirroring (FFTBM-SM), used for sensitivity analysis of deterministic calculations, and SBO scenarios selected for demonstration are described. Then the results of sensitivity analysis using FFTBM-SM, showing influence of uncertain parameter variation on thermal-hydraulic PWR response is presented for the selected scenarios, which calculations have been performed in the frame of the previous study [3]. Main conclusions of the study are provided.

2 METHODS USED

The assessment of the impact of the main parameters uncertainties on the scenario progression is done with the utilization of the sensitivity analysis. The FFTBM-SM has first been used for sensitivity analysis of deterministic calculations [4]. The calculated results of scenario with input parameter variation(s) were compared to calculated results of reference scenario in which reference values of input parameters were used. FFTBM-SM figures of merit have been used to judge the similarity of two scenarios [4]. In this study the external and internal parameters identified in [2], based on study presented in publication [3], have been used in sensitivity analysis to show the influence of parameters uncertainty.

2.1 Description of FFTBM-SM

Nomenclature		F_{ref}	reference signal
$\lvert\tilde{F}_{ref}(f_n)\rvert$	reference signal amplitude at frequency	N_{var}	number of the variables analysed
$\lvert\tilde{\Delta}F(f_n)\rvert$	difference signal amplitude at frequency	$\Delta F(t)$	difference signal
f_n	n-th frequency	N	number of points
AA_m	average amplitude	$(AA_m)_i$	average amplitude for the *i*-th variable
AA_{m-tot}	total average amplitude – total accuracy	$(w_f)_i$	weighting factors for the *i*-th analysed variable
F_{com}	compared signal		as defined in [4]

The original fast Fourier transform based method (FFTBM) was developed to quantify the accuracy of thermalhydraulic code calculations [5] versus results from the corresponding experiments. Later an improved version of FFTBM by signal mirroring (FFTBM-SM) has been developed, in which the signals are symmetrized. In the following brief description of FFTBM-SM is given. For more information on the original and the improved version of FFTBM the reader can refer to [4].

For the calculation of the differences between two signals, reference signal F_{ref} and the difference signal $\Delta F(t)$ are needed. The difference signal in the time domain is defined as $\Delta F(t) = F_{ref} - F_{com}$. The similarity of the signals is based on the amplitudes of the discrete experimental and difference signals obtained by fast Fourier transform FFT (frequency domain) at frequencies f_n, where n=0,1,...,2^m and m is the exponent defining the number of points $N=2^{m+1}$ (where m=8, 9, 10, 11; this gives minimum 512 and maximum 4096 point). The average amplitude AA_m is defined as:

$$AA_m = \sum_{n=0}^{2^m} \lvert\tilde{\Delta}F(f_n)\rvert / \sum_{n=0}^{2^m} \lvert\tilde{F}_{ref}(f_n)\rvert \quad (1)$$

The AA_m factor is a figure of merit for similarity of the signals. The larger the sensitivity is the larger is the difference between the signals, normally resulting in a larger AA_m value. The overall picture of the accuracy (using FFTBM-SM) for a given code calculation is obtained by defining average performance indices that is the total average amplitude AA_{m-tot}:

$$AA_{m-tot} = \sum_{i=1}^{N_{var}} (AA_m)_i (w_f)_i \text{ with } \sum_{i=1}^{N_{var}} (w_f)_i = 1 \quad (2)$$

The first figure of merit AA_m tells how the single input parameter variation (or combination of input parameter variations) influences the output variable. The second figure of merit is AA_{m-tot}, which tells how the deterministic calculation (considering several output variables – flows, pressures, temperatures, levels etc.) is sensitive to input parameter variation. The figures of merit are such that they accumulate the discrepancies during time. Typically 20 to 25 variables are used. In this study 21 variables were used (see Table 2). The selection of variables for FFTBM-SM sensitivity analysis considered findings from study [7], presenting application of original FFTBM to station blackout scenario.

2.2 Sources of uncertainty

For the purposes of this study the parameters and corresponding input uncertainties for PSA are divided in external and internal parameters, following study in [2]. The external parameters are all those parameters characterizing/affecting the progression of the event that are not related to the status of the primary and secondary system of the PWR: (a) time delay between loss of offsite power (LOOP) and extended SBO; (b) time delays between the extended SBO start and start of the pump injections to steam generators (SGs). The internal parameters include all parameters that characterise the state of the primary and secondary system: (a) types of reactor coolant system (RCS) loss scenarios (existence of normal system leakage, seal and letdown loss of coolant accident (LOCA)); (b) primary system depressurization strategy.

2.3 Scenarios selected for demonstration

For assessment of the external and internal parameters uncertainties influence on the SBO scenario progression the calculated cases presented in Table 1, which have been performed in the frame of study presented in publication [3], are used. External parameter demonstration case is a), while internal parameter demonstration cases are b) to d) in Table 1.

Table 1: Selected cases for sensitivity analysis

Parameter	Reference calculation	Compared calculations
a) Sensitivity of SBO to emergency diesel generator (EDG) operation time	S_LOCA_3	S_LOCA_3_noEDG
b) Sensitivity of SBO to RCS loss type – restoration of cooling after 5h	NO_LOSS_5	N_LOSS_5 S_LOCA_5 SL_LOCA_5
c) Sensitivity of SBO to RCS loss type – restoration of cooling after 3h	NO_LOSS_3	N_LOSS_3 S_LOCA_3 SL_LOCA_3
d) Sensitivity of SBO to depressurization with delay 0.5 h	SL_LOCA_5	SLD_LOCA_5

The above SBO scenarios used have been calculated by RELAP5/MOD3.3 Patch 04 computer code. The label XX_YYYY_Z for scenarios has the following meaning: XX is loss type of RCS mass inventory (NO means no loss, N means normal leakage, S means seal LOCA, SL means reactor coolant pump seal LOCA and loss of coolant through the letdown relief valve, SLD means SL with depressurization (D) of the primary side through the secondary side to 1.57 MPa, started 30 minutes after SBO occurrence), YYYY has code LOSS or LOCA to distinguish leakages from loss of coolant accident, while Z denotes time delays (in hours) between the extended SBO start and start of the pump injections to SGs (restoration of cooling Z hours after SBO initiation). In all cases EDG is running 1 h after LOOP except in case with "noEDG".

In study [3] the extended station blackout mitigation strategy for a two-loop pressurized water reactor (PWR) has been studied using RELAP5/MOD3.3 best estimate thermalhydraulic system code. During extended SBO are available passive systems such as safety relief valves both on primary and secondary side of PWR, steam generator (SG) relief valves, which can be manually operated (it means that operator actions are needed) and accumulators for safety injection of into RCS. Turbine-driven auxiliary feedwater (TD-AFW) system for feeding steam generators is also assumed unavailable after extended SBO start due to control and instrumentation loss (direct current (DC) electric loss), needed for TD-AFW valve control. Time needed for recovery of DC power and by this TD-AFW system depends on the operators (external parameter restoration of cooling). More details on the SBO scenario description is given in [3].

3 RESULTS OF SENSITIVITY ANALYSIS

In demonstration cases from Table 1 the sensitivity to EDG operation time (external parameter; case a)), RCS loss type (internal parameter loss flow; cases b) and c)) and use of depressurization strategy (internal parameter start of depressurization; case d)) are presented.

3.1 Case a): Sensitivity of SBO to the EDG operation time

In sensitivity analysis the influence of failure to start EDGs at LOOP initiation (scenario 'S_LOCA_3_noEDG') is analysed. Time trends of important variables are shown in Figure 1 (the red lines show the transient progression times). Figure 1(a) shows that in scenario 'S_LOCA_3_noEDG' pressure starts to increase above PRZ relief valves setpoint when steam generator water covering U-tubes boils off (see SG mass in Figure 1(d) and heat transfer from primary to secondary side is terminated around 4300 s. Shortly after the PRZ relief valves opened, discharging of RCS inventory occurred (see discharged mass in Figure 1(c)). Due to discharged RCS inventory the core starts to uncover after 6500 s, resulting in core heatup after 8000 s (see Figure 1(b)) and calculation stop. It is evident that without any recovery action to restore injection into primary system the heatup would continue, finally resulting in core damage.

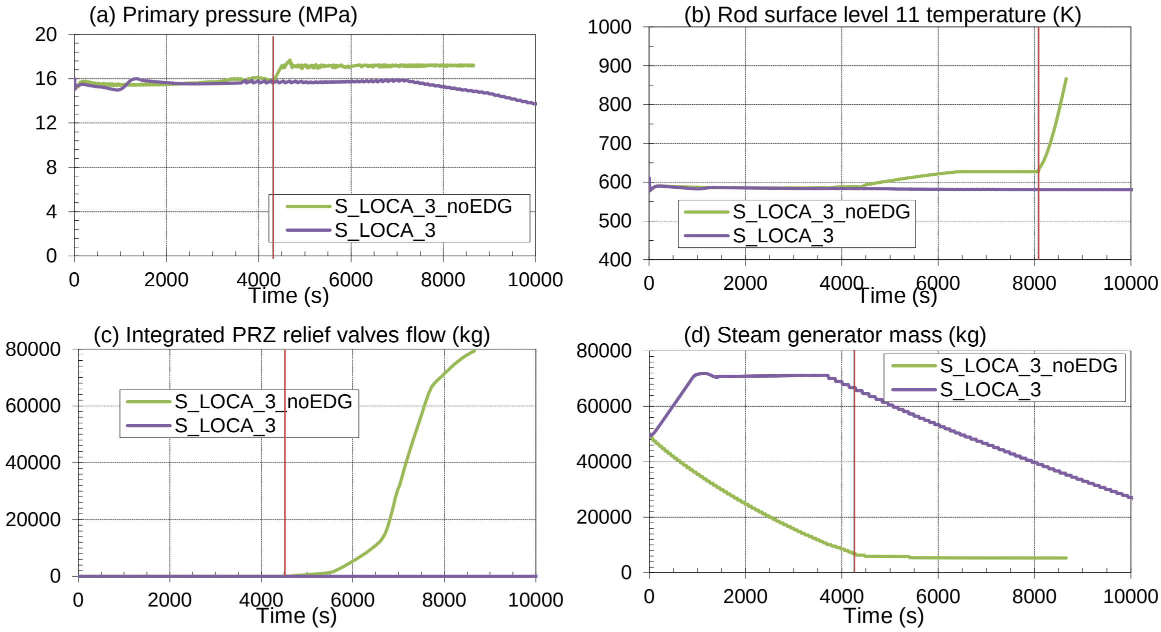

Figure 1: Time trends of important variables for scenario with different EDG operation time after LOOP occurrence and with 3 h operator action delay to recover cooling

From Figure 2 it can be seen that external parameter uncertainty influences the primary pressure and calculation from the very beginning due to the difference on the secondary side (in case of 'S_LOCA_3_noEDG' steam generators are emptying, while in case of 'S_LOCA_3' are filling – see Figure 1(f)). When SGs are full at 1000 s, the filling is terminated, therefore $AA_{m\text{-}tot}$ decreases. Once steam generators boil off at around 4300 s, there is again increase in figure of merit measure $AA_{m\text{-}tot}$ and the differences are present till the end time 8600 s, which is used in sensitivity analysis.

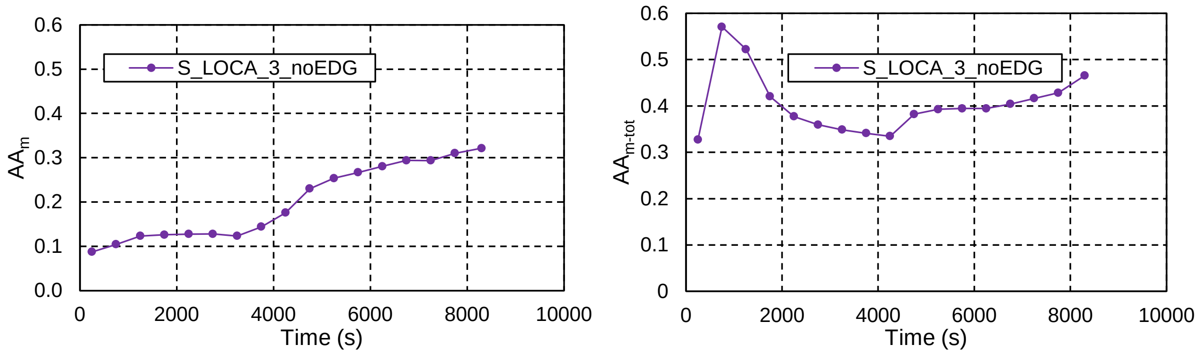

Figure 2: Sensitivity as function of increasing time intervals starting at 0 s till 8600 s for scenario with failure of EGD start: (a) AA_m for primary pressure; (b) $AA_{m\text{-}tot}$ for calculation

The calculated scenarios can be later refined regarding their uncertainties by performing best estimate plus uncertainty (BEPU) analysis. In BEPU analysis the code calculation uncertainty is quantified due to model uncertainties and uncertain initial and boundary conditions. This can further constrain the uncertainties, but this requires significant computational resources. It should be also emphasized that just the use of more accurate system thermalhydraulic code (e.g. RELAP5) significantly reduces the uncertainties in calculated results comparing to best estimate severe accident codes. Typically, for PSA calculations the BEPU analysis was not been used in the past.

3.2 Cases b) and c): Sensitivity of SBO to RCS loss type

Two cases are considered regarding restoration of cooling (external parameter), after 5 h and 3 h, respectively. In Figure 3 time trends of rod surface temperature are shown.

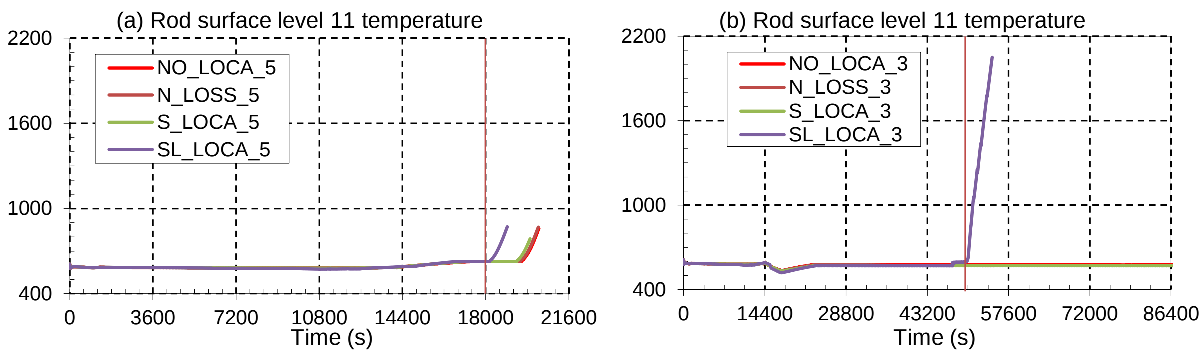

Figure 3: Time trends of rod surface temperature: (a) 5 h operator action delay to recover cooling, (b) 3 h operator action delay to recover cooling.

It can be seen that operator action delay of 5 h to recover cooling is not successful in core heatup prevention in first 24 h, while delay of 3 h prevents core heatup for ‘N_LOSS_3’ and ‘S_LOCA_3’ cases in first 24 hours. In case with seal LOCA and letdown loss (‘SL_LOCA_3’) the core heatup is unavoidable due to RCS mass loss. Time trends of other variables are provided in reference [3].

The results of sensitivity analysis to RCS loss type are shown in Table 2. Larger value of AA_m means larger influence of input parameter. The most important (3 to 6) parameters for each case scenario are marked with red colour in each column.

Table 2 Sensitivity of whole transient to RCS loss type (restoration of cooling after 5 h and 3 h)

No.	Variable	AA_m for time interval 0 - 18900 s			AA_m for time interval 0 – 54000 s		
		N_LOSS_5	S_LOCA_5	SL_LOCA_5	N_LOSS_3	S_LOCA_3	SL_LOCA_3
1	Primary pressure	0.227	0.580	0.806	0.298	0.427	0.644
2	Core collapsed liquid level	0.120	0.182	0.807	0.382	0.516	1.674
3	Primary mass	0.045	0.130	0.350	0.116	0.298	0.917
4	Steam generator no. 1 mass	0.046	0.057	0.131	0.079	0.096	0.131
5	Steam generator no. 2 mass	0.023	0.048	0.111	0.085	0.093	0.119
6	Integrated pressurizer relief valves flow	0.126	0.313	0.608	0.830	1.000	1.000
7	Integrated accumulator flow	0.000	0.000	0.000	0.000	1.000	1.000
8	Rod surface level 11 temperature	0.007	0.014	0.345	0.036	0.053	2.016
9	Steam generator no. 1 pressure	0.333	0.357	0.471	0.331	0.350	0.467
10	Steam generator no. 1 wide range level	0.104	0.141	0.265	0.151	0.165	0.213
11	Steam generator no. 2 pressure	0.201	0.346	0.469	0.279	0.364	0.444
12	Steam generator no. 2 wide range level	0.065	0.113	0.264	0.161	0.161	0.217
13	Steam generator no. 1 valves discharge	0.049	0.059	0.131	0.198	0.111	0.156
14	Steam generator no. 2 valves discharge	0.025	0.050	0.109	0.200	0.090	0.142
15	Cold leg no. 1 liquid temperature	0.012	0.020	0.153	0.035	0.053	0.445
16	Cold leg no. 2 liquid temperature	0.007	0.018	0.126	0.033	0.057	0.244
17	Hot leg no. 1 liquid temperature	0.006	0.012	0.033	0.037	0.052	0.091
18	Hot leg no. 2 liquid temperature	0.006	0.012	0.034	0.035	0.052	0.092
19	Cold leg no. 1 flow	0.081	0.107	0.262	0.576	0.622	0.353
20	Cold leg no. 2 flow	0.126	0.124	0.296	0.629	0.576	0.367
21	Pressurizer level	0.454	0.962	0.892	0.301	0.686	1.104
	Total	0.074	0.137	0.268	0.160	0.242	0.527

The total accuracy $AA_{m\text{-}tot}$ for selected cases of restoration of cooling 5 h of SBO initiation show that scenarios in general are rather similar and that selected loss types are moderately influential to extended SBO scenario progression. The reason for this is compensating effect. In case of larger RCS inventory loss the primary pressure drops more and by this delays its increase to pressurizer safety relief valve opening setpoint. By this release of RCS inventory through the pressurizer safety relief valves is delayed. The heatup in time interval 0 – 18900 s (in FFTBM-SM the maximum time interval used is the end time of shortest signal) occurs only for 'SL_LOCA_5'. Figure 3(a) shows that heatup occurs with some small delay also in 'N_LOSS_5' and 'S_LOCA_5' scenarios. This means that all three scenarios from the point of PSA are qualitatively similar, ultimately resulting in core damage.

The results of sensitivity analysis for selected cases of restoration of cooling 3 h of SBO initiation show that in such scenario the SBO is more sensitive to loss type. The sensitivity analysis was done till 54000 s due to core heatup resulting in code calculation termination (no models for core melt) in 'SL_LOCA_3' scenario. Figure 4 shows how total accuracy AA_m changes over time, starting at zero time. The loss flow in 'SL_LOCA_Z' scenarios (where Z is 3 and 5 for case b) and c), respectively) impacted at 3600 s when letdown loss is assumed. At 7200 s the seal LOCA is assumed, therefore also 'N_LOSS_Z' and 'S_LOCA_Z' are influenced by loss flow. Another significant change is when PRZ relief valves start to discharge the RCS inventory. The last significant change is in 'SL_LOCA_Z' scenarios, when core heatup occurred. The trends of total average amplitude $AA_{m\text{-}tot}$ for calculated cases are rather similar after 7200 s from the start of the event.

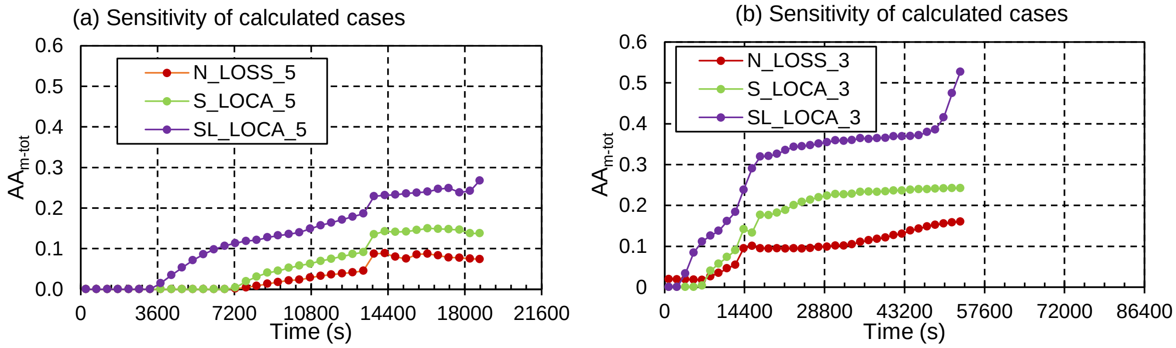

Figure 4: Code calculation sensitivity ($AA_{m\text{-}tot}$) as function of increasing time intervals: (a) restoration of cooling after 5 h; (b) restoration of cooling after 3 h.

3.3 Case d): Sensitivity of SBO to start of depressurization

When steam generators are boiled off around 10000 s, the primary side start to repressurize due to decay heat and primary pressure reaches pressurizer (PRZ) relief valves opening setpoint (see Figure 5(a)). Therefore in less than 30 minutes the core heatup occurred. To be successful in preventing core heatup the cooling of core through the secondary side should be restored in approximately 4 h or earlier by delivering makeup water to steam generators. Namely, with boiling off the steam generators mass the primary and secondary side pressure are decoupled, therefore primary side could not follow the secondary side pressure. Both analysed scenarios ended with core heatup due to RCS mass loss through PRZ relief valves.

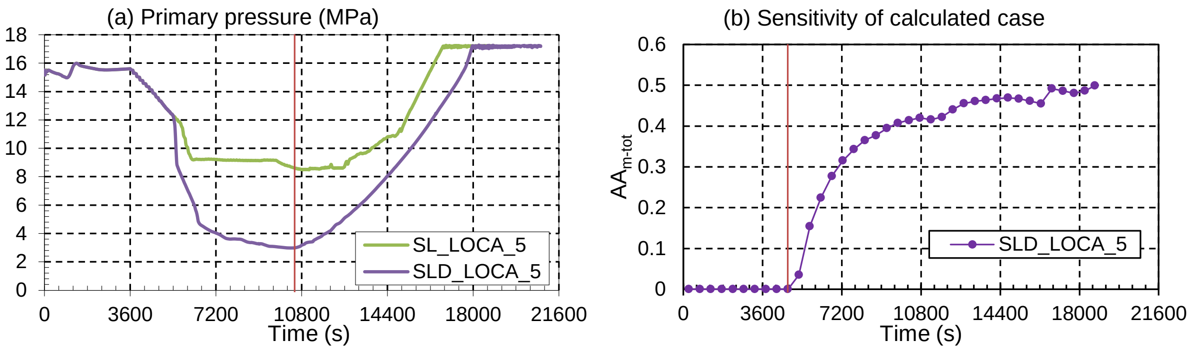

Figure 5: (a) Primary pressure trend; (b) Code calculation sensitivity ($AA_{m\text{-}tot}$) as function of increasing time intervals.

Figure 5(b) shows that the results are rather sensitive to the operator action related to depressurization of RCS. Nevertheless, due to large loss of RCS inventory and emptied steam generators the core melt is unavoidable without liquid injection into RCS. Early steam generator water makeup would provide cooling of the core, and prevent repressurization of RCS. This would at the same time terminate the letdown loss (when RCS pressure is below 4.2 MPa) and by this significantly reduce the RCS inventory loss.

4 CONCLUSIONS

The demonstration of FFTBM-SM for sensitivity analysis and evaluation of the scenarios similarities is presented. Quantitative sensitivity analysis gives measures, which can be used to evaluate parameters uncertainties impact on the obtained results of the deterministic analysis. Obtained results demonstrate that both external (i.e. operator actions) and internal parameters may be source of large uncertainties. The operator actions provide strategies to restore the electric power and with that the function of core cooling and by this preventing the core damage. Such strategies largely influence the accident progression, much more than internal parameters. The calculated scenarios could be later refined regarding their uncertainties by performing the best estimate plus uncertainty (BEPU) analysis.

Obtained results show that external parameters uncertainties used in probabilistic safety assessment could be only partly constrained, if no support deterministic calculations are made. Therefore, the deterministic calculations should be performed in parallel to PSA event tree build-up to provide the information such as possible operator actions and available time for restoring safety functions.

The modelling of the station blackout event in other models/tools (for example Bayesian belief network) is expected to include identified important parameters. In case of modelling of operator/human actions, the human failure probability for these actions can be assessed and included in the study.

ACKNOWLEDGMENTS

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0026) and the European Union's Horizon 2020 research and innovation programme project New Approach to Reactor Safety ImprovementS - NARSIS under grant agreement No. 755439.

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