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Research Article

Deterministic Analysis of Natural Circulation Events at the Ignalina NPP

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Eight main circulation pumps (MCPs) are employed for the cooling of water forced circulation through the RBMK-1500 reactor at the Ignalina nuclear power plant (NPP). These pumps are joined into groups of four pumps each (three for normal operation and one on standby). In the case of all MCPs trip, the reactor shutdown system is activated due to decrease of coolant flow rate. At the same time, after the pump trip, the coolant to the reactor fuel channels during the first few seconds is supplied by pump coastdown. Later, the reactor is cooled by natural circulation. The main question arises whether this coolant flow rate is sufficient to remove the decay heat from the reactor core. This paper presents the investigation of all MCPs trip events at the Ignalina NPP by employing best estimate code RELAP5 and methodology of uncertainty and sensitivity analysis.

1. INTRODUCTION

The Ignalina nuclear power plant is a twin unit with two RBMK-1500, graphite moderated, boiling water, and multichannel reactors. Unit 1 was permanently shutdown in 2004. A schematic representation of one main circulation circuit (MCC) loop is given in Figure 1. The MCC is divided into two halves: the left and the right loops. The MCPs (5) are joined in groups of four pumps each (three for normal operation and one on standby). The MCPs feed a common pressure header (PH) (8) on each side of the reactor. Each pressure header provides coolant to 20 group distribution headers (GDH) (9), each of which in turn feeds from 38 to 43 fuel channels (11). The coolant flow rate through the individual fuel channel (FC) is regulated by isolation and control valves (ICV) (10), which are mounted in the lower water communication lines. Coolant passing through FCs is boiled and part of the water is evaporated. Steam-water mixture through steam-water communication lines (12) flows to drum separators (DS). The steam, which is separated in the DS, is supplied to turbines through steam lines (13). A detailed description of the Ignalina NPP can be found in [1].

At the Ignalina NPP type CVN-8, MCPs are employed for the forced circulation of cooling water through the RBMK-1500 reactor. These pumps belong to the "wet" stator pump group. The CVN-8 type is a centrifugal, vertical, single-stage pump with a sealed shaft. To increase the rotary inertia in order to prolong the rotation of the shaft in the event the electric motor fails, the massive 0.2 m outside diameter and the 0.195 m thick steel flywheel are mounted on the motor shaft. In the all-pumps-trip case, the coolant, due to high inertia of pump flywheel during the first 40–60 seconds to the reactor fuel channels, is supplied by pumps coastdown. Later, the natural circulation through the core is established. The reactor shutdown system is activated due to the decrease of coolant flow rate. All 211 rods of the control and protection system (CPS) are inserted into the reactor core within approximately 8 seconds. The main question that arises is whether this coolant flow rate is sufficient to remove the decay heat from the reactor core.

Best estimate model of RELAP5 Ignalina NPP RBMK-1500 reactor cooling circuit was developed by Lithuanian Energy Institute (LEI) for the investigation of MCP trip events. This model includes forced circulation circuit, steam lines, and safety systems necessary for transient and accident process analyses. Detailed description of RELAP5 nodalization scheme can be found in [2]. The obtained results were compared with the measurements of Ignalina NPP.

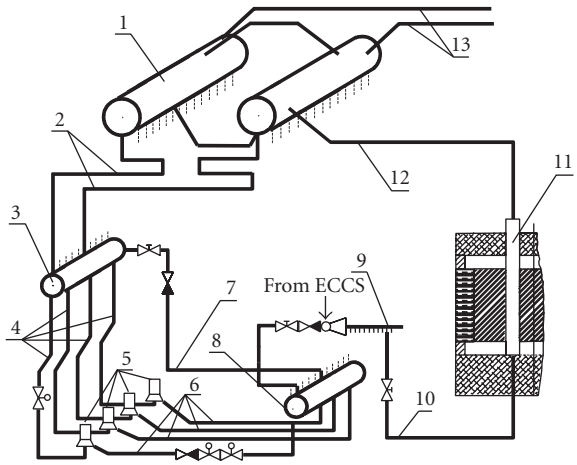

Figure 1: Schematic representation of one loop of the RBMK-1500 MCC: 1-DS, 2-downcomers, 3-MCPs suction header, 4-MCP suction piping, 5-MCPs, 6-MCP discharge piping, 7-bypass line, 8-MCPs pressure header, 9-GDHs, 10-lower water communication line, 11-FC, 12-steam-water communication line, 13-steam lines.

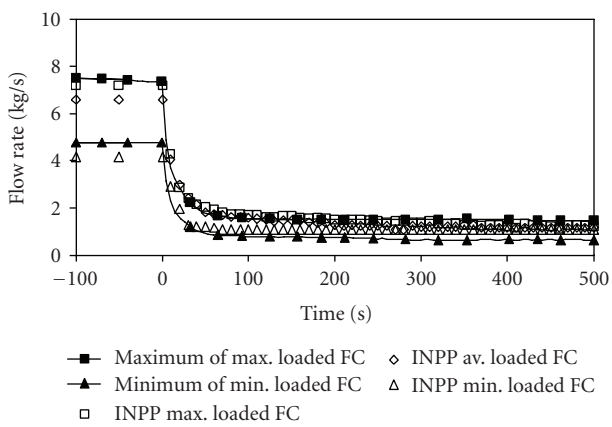

Figure 2: Loss-of-all-MCPs event. Coolant flow rate through individual channels.

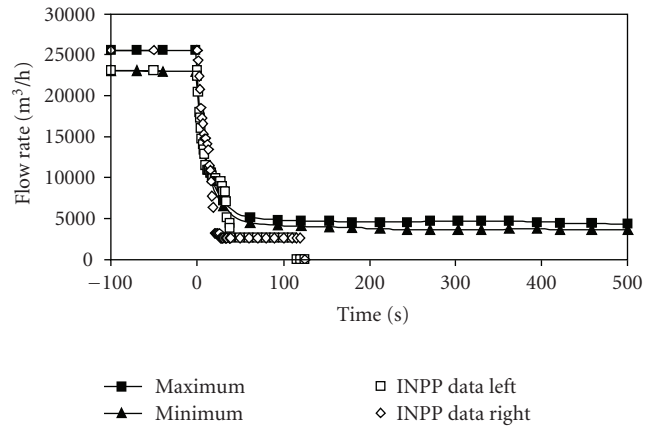

Figure 3: Loss-of-all-MCPs event. Coolant flow rate through one MCC loop.

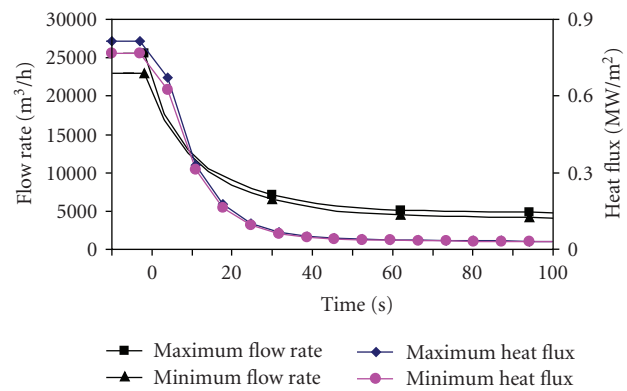

Figure 4: Loss-of-all-MCPs event. Comparison of behaviour of coolant flow rate through one MCC loop and heat flux in maximum loaded fuel channel.

Initial and boundary conditions (coolant pressure, flow rate, feed water temperature, amount of steam for in-house needs, reactor power, and flow energy loss in different MCC components) and RELAP5 code models, assumptions, and correlations may impact the uncertainty of calculation results. The GRS method SUSA 3.5 [3] was used for the sensitivity and uncertainty analysis. The parameters, the initial values of which may have the greatest impact on the simulation results, were used for the analysis on the basis of earlier performed benchmarking calculations. The selection of these parameters is described in [4, 5].

2. BEST-ESTIMATE ANALYSIS OF LOSS-OF-ALL-MCPs EVENT

Loss-of-all-MCPs event occurred at Ignalina NPP on March 26, 1986. During this event, all the six operating MCPs at Ignalina Unit 1 were tripped simultaneously. Before this event, the reactor operated at thermal power level of 4650 mW. In response to multiple pump trips, an emergency protection signal AZ-1 was generated and the reactor was shut down. The MCC flow decreased in response to the MCPs coastdown. Long-term flow was due to natural circulation in the MCC.

RELAP5 analysis results were compared with the plant data. The uncertainty and sensitivity analysis was performed using a two-sided tolerance limit (with 0.95 of probability and 0.95 of confidence); 100 runs were performed.

The agreement of the calculation results, obtained using RELAP5 code with the real plant data, was evaluated using the adequacy standard, presented in the Guideline for performing code validation, and issued by DOE International Nuclear Safety Center [6]. The agreement is judged to be excellent, when the code exhibits no deficiencies in the modelling of a given behaviour; major and minor phenomena and trends are predicted correctly; calculation results are judged to agree closely with the real plant data. The agreement is judged to be reasonable when the code exhibits minor deficiencies, although it provides an acceptable prediction; all major trends and phenomena are correctly

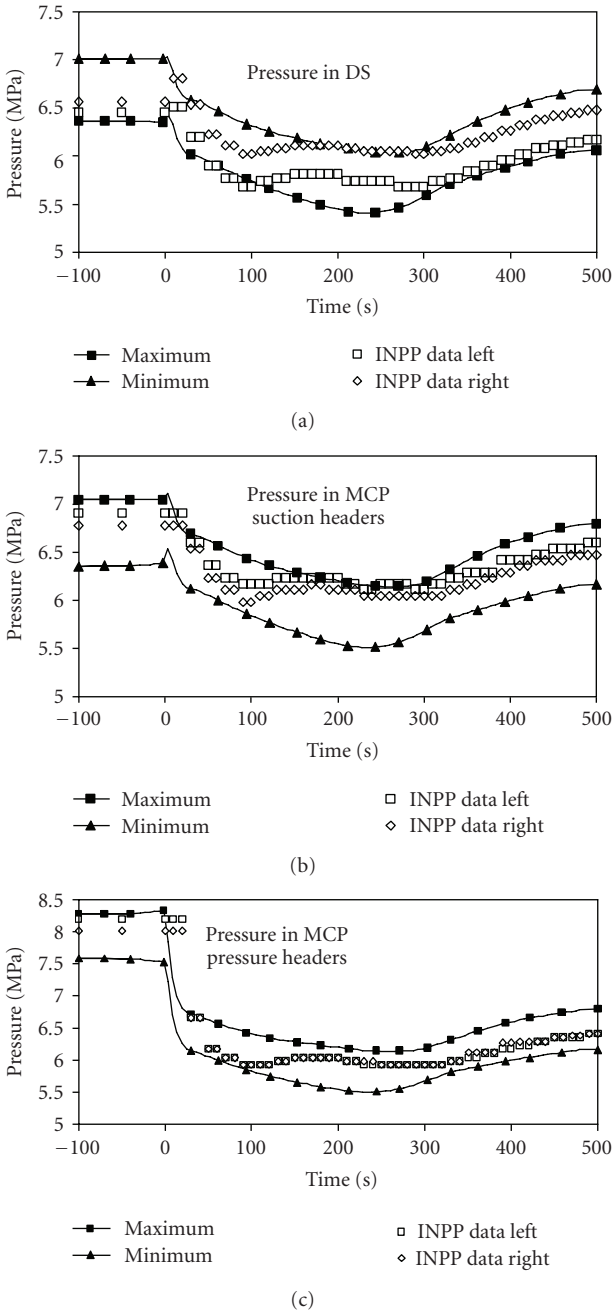

Figure 5: Loss-of-all-MCPs event. Pressure in the MCC.

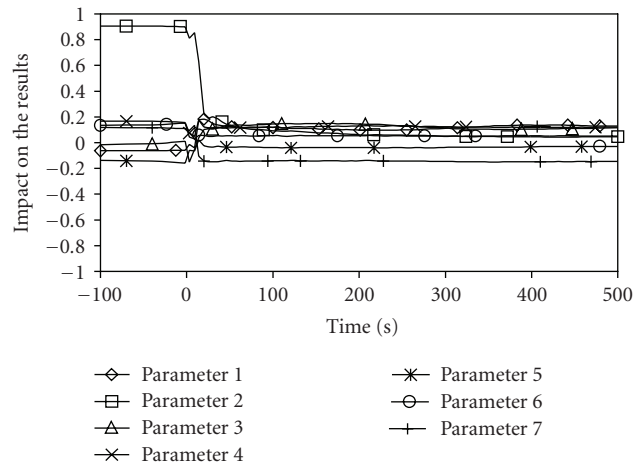

Figure 6: Loss-of-all-MCPs event. The impact of parameters no.1–7 on the coolant flow rate through one MCC loop. The numbering of parameters is the same as in Table 1.

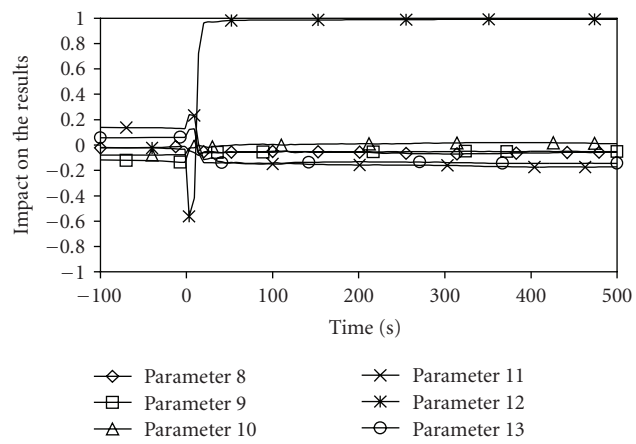

Figure 7: Loss-of-all-MCPs event. The impact of parameters no.8–13 on the coolant flow rate through one MCC loop. The numbering of parameters is the same as in Table 1.

predicted, but differences between the calculation and data are greater than deemed acceptable for excellent agreement. According to the standard, both excellent and reasonable agreements of the calculation results and the real plant data are considered as being acceptable.

Data of the flow rate in twelve individual channels during natural circulation regime were available and are presented in Figure 2. For the comparison of calculated and measured flow rates, calculated maximum flow rate through maximum loaded FC and calculated minimum flow rate through minimum loaded FC were used. These calculated flow rates represent the whole interval (from minimal up to maximal) of flow rates through the core channels. The calculated maximum flow rate through maximum loaded FC, the calculated minimum flow rate through minimum loaded FC, and real plant data showed reasonable agreement. Coolant flow rate through one MCC loop is presented in Figure 3. As it is seen from the figure, measured values are available only in a limited range, and become equal to 0 after approximately 115 seconds from the beginning of the accident. The comparison of measured coolant flow rate through the fuel channels and through one MCC loop at the flow $< 7000\,\mathrm{m}^3/\mathrm{h}$ shows that the last measures are unreliable. This is because the throttling devices, which are not designed for the measurement of low coolant, are employed. The flow rates show a coastdown associated with the loss of forced circulation by the MCPs. The coastdown continues during the first 40 seconds from the beginning of the transient. Later, a natural circulation of the coolant was established at a flow rate equal to approximately 15% of the initial flow.

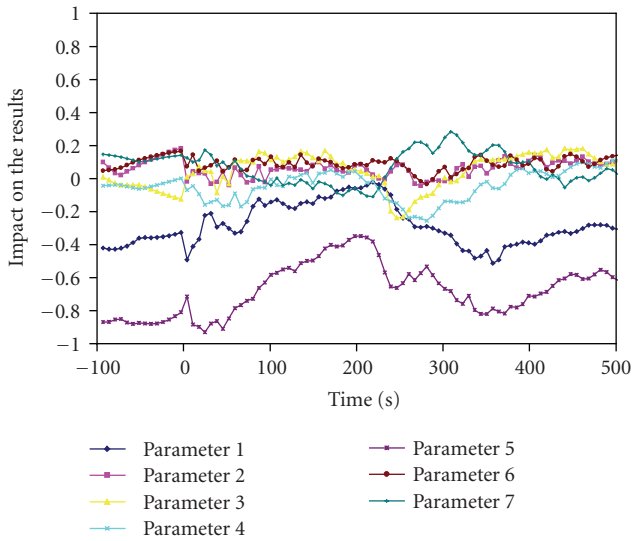

Figure 8: Loss-of-all-MCPs event. The impact of parameters no.1–7 on the CHFR. The numbering of parameters is the same as in Table 1.

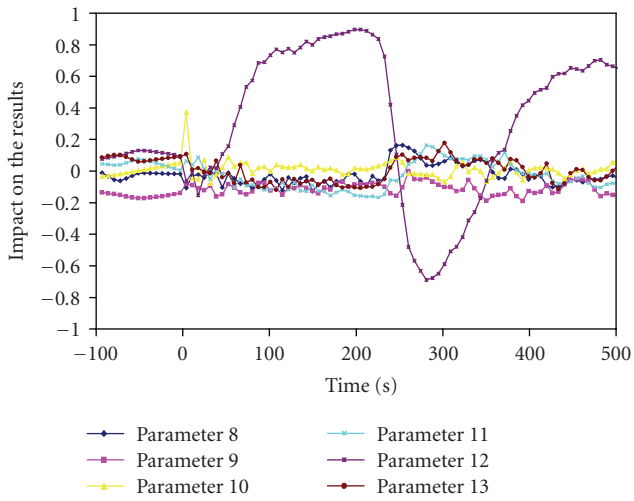

Figure 9: Loss-of-all-MCPs event. The impact of parameters no.8–13 on the CHFR. The numbering of parameters is the same as in Table 1.

After reactor shutdown, the reactor is reliably cooled by natural circulation because heat flux decreases faster than coolant flow rate due to pumps coastdown (see Figure 4).

Figure 5 shows pressure in the MCC. Pressure in the pressure header decreases immediately after MCP trip because the MCP head is decreasing. During the first seconds, before the reactor shutdown, the coolant flow rate decrease through the core causes the short-term increase of steam generation. The increase of steam generation causes the short-term pressure increase in the DS. Steam generation in the core decreases and pressure in the MCC also decreases after the reactor shutdown. The reloading process of turbines is starting immediately after the reactor shutdown. When the turbine control valves are closed, the pressure starts to increase again.

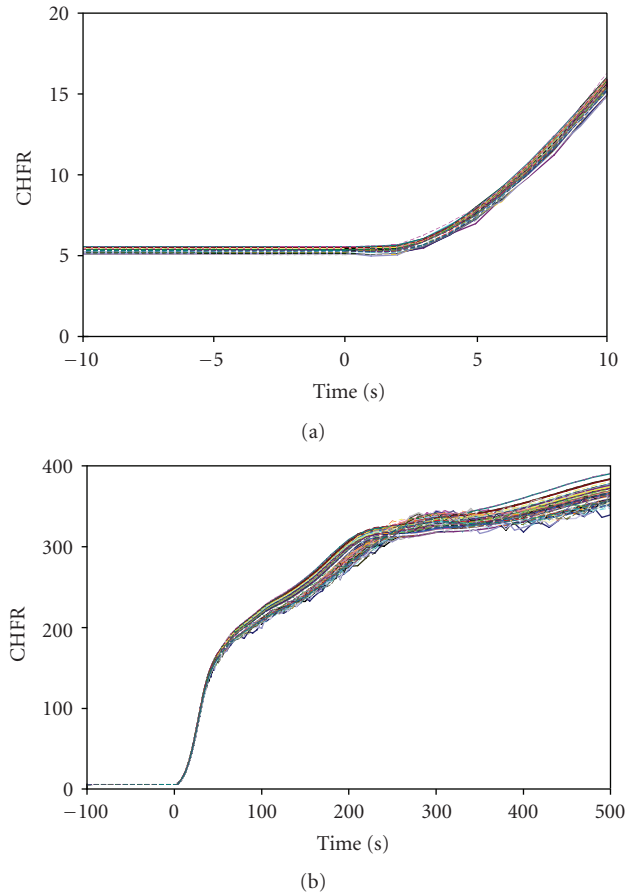

Figure 10: Loss-of-all-MCPs event. CHFR in case of all MCPs trip.

Furthest pressure changes depend on the amount of removed steam for in-house needs. As could be seen from the presented comparison, pressure losses in different parts of the MCC are predicted correctly using the developed model.

Uncertainty and sensitivity analyses were performed for the following.

(i) Coolant flow rate through one MCC loop—one of the important technological parameters which allows identifying the existence of natural circulation.

(ii) Calculated critical heat flux ratio (CHFR) from the side of fuel assembly to coolant. CHFR is defined as a relationship between the calculated critical and real heat transfer fluxes. If critical heat flux ratio is greater than one, no critical heat flux will be observed in any fuel channel segment, and drying of FC will not occur.

Parameters, which may impact the calculation results, are presented in Table 1. Selected RELAP5 code parameters are varied in the area where two-phase flow conditions might occur: in the vertical section before the heated channels, in the heated channels, above the heated channels, and in the steam water communications. The areas with single-phase conditions are excluded due to the fact that these parameters do not have impact on the results in such region. Additionally, one parameter, which might impact the coolant flow regime

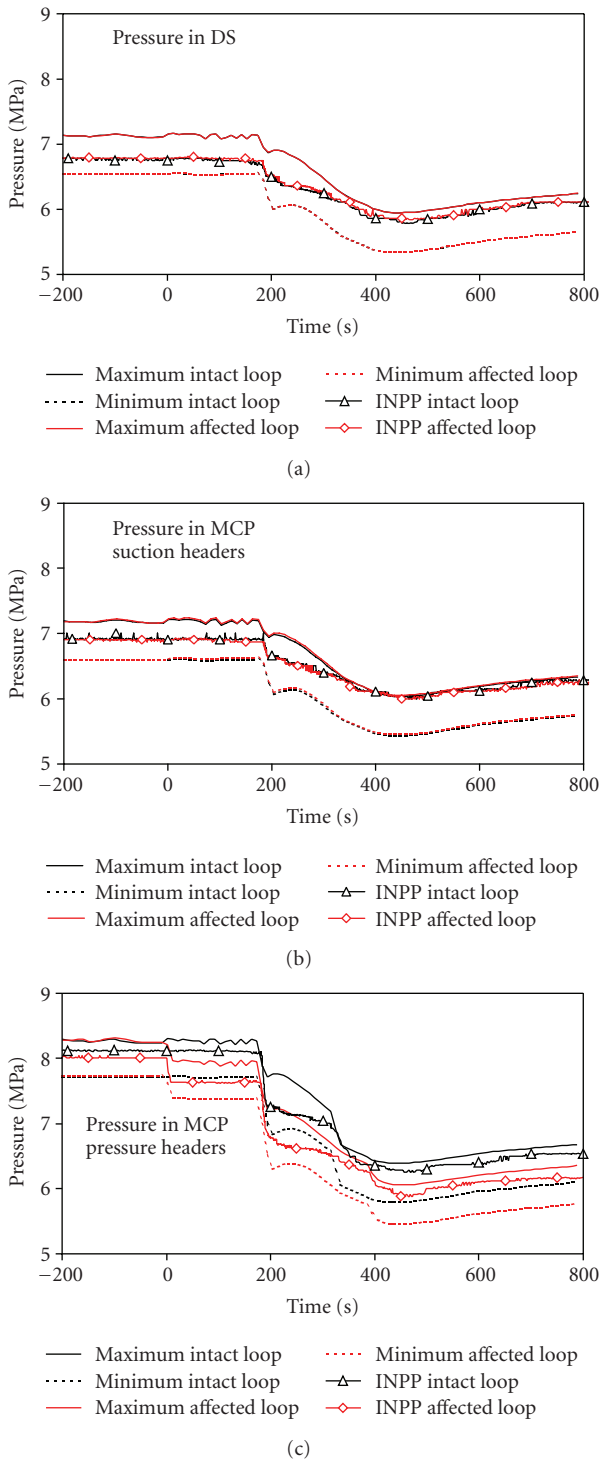

Figure 11: Three MCPs sequential trip. Pressure in the MCC.

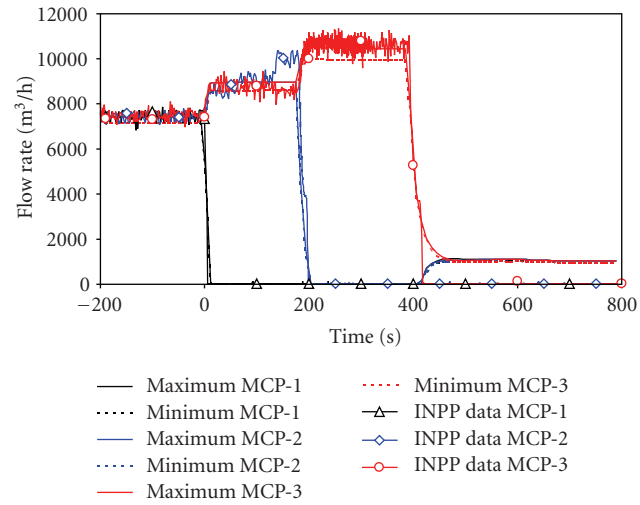

Figure 12: Three MCPs sequential trip. MCPs throughput in the affected MCC loop.

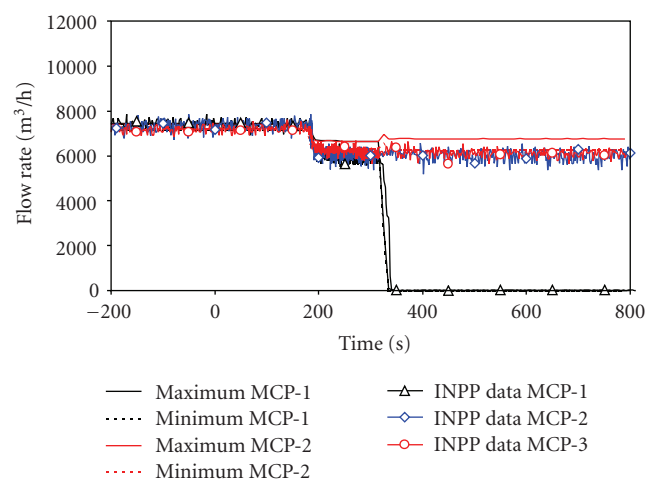

Figure 13: Three MCPs sequential trip. MCPs throughput in the intact MCC loop.

in the reactor fuel channels, was selected—the 13th position of ICV, what affects coolant flow rate through fuel channels.

Results of the sensitivity analysis are presented using plots with the parameters impact on the results. Higher absolute value of impact on the results means higher parameter influence on the result. The positive impact means that when the higher value of the parameter is selected, the higher coolant flow rate is obtained; the negative impact means that when the higher value of the parameter is selected, the lower coolant flow rate in the affected MCC loop is obtained.

The performed analysis shows that the selection of homogeneous or nonhomogeneous models (see Figures 6, 7, 9, and 10) has the largest impact on the calculation results. Homogeneous model selection is a nonphysical conservative assumption and it is not recommended for best estimate codes.

The parameter-dependent sensitivity analysis shows that initial plant conditions (coolant flow rate, pressure in the DS, feed water temperature, and reactor power) and ICV position have only insignificant influence on coolant flow rate through the pumps (natural circulation regime) (see Figures 6 and 7).

Reactor core is reliably cooled because the CHFR is greater than 1 in all 100 calculations (see Figure 10).

Table 1: Parameters which may impact the uncertainty of calculation results in case of all MCPs trip.

No.	Parameter	Width of parameter distribution Min.	Max.	Value of the parameter in the basic case calculation	Mean deviation and error[%]	Probability distribution	Explanation
			Initial conditions				
Par. 1	Pressure in DS, Pa	$6.35 \cdot 10^6$	$7.035 \cdot 10^6$	$6.70 \cdot 10^6$	$1.675 \cdot 10^5$ [5%]	Normal	Measurement error
Par. 2	Coolant flow rate through single MCP, m^3/h	7938	8262	8100	81 [2%]	Normal	Measurement error
Par. 3	Feed water temperature, K	458.52	467.78	463.15	2.32 [1%]	Normal	Measurement error
Par. 4	Coefficients which define steam flow rate to the in-house needs header	0.98	1.02	1.0	0.01 [2%]	Normal	Measurement error
Par. 5	Reactor thermal power, W	$4.510 \cdot 10^9$	$4.790 \cdot 10^9$	$4.650 \cdot 10^9$	$7.0 \cdot 10^7$ [3%]	Normal	Measurement error
			Modelling parameters in the core				
Par. 6	Water packing	0 (on)	1 (off)	1 (off)	—	Nonparametric	Model assumption
Par. 7	Stratification	0 (on)	1 (off)	0 (on)	—	Nonparametric	Model assumption
Par. 8	PV term	0 (off)	1	0 (off)	—	Nonparametric	Model assumption
Par. 9	CCFL	0 (off)	1 (on)	0 (off)	—	Nonparametric	Model assumption
Par. 10	Thermal front tracking	0 (off)	1 (on)	0 (off)	—	Nonparametric	Model assumption
Par. 11	Mixture level tracking	0 (off)	1 (on)	1 (on)	—	Nonparametric	Model assumption
Par. 12	Nonhomogeneous	0 (nonhomogeneous model)	1 (homogeneous model)	0 (nonhomogeneous model)	—	Nonparametric	Model assumption
			Flow energy loss				
Par. 13	Coefficients which define ICV position	0.9	1.1	1.0	0.05 [10%]	Normal	Model assumption

The parameter-dependent sensitivity analysis (see Figures 8 and 9) shows that reactor thermal power (Par. 5) and pressure in DS (Par. 1) have the greatest impact on the reactor cooling conditions if the selection of homogeneous or nonhomogeneous models is not taken into account.

Thus, the performed uncertainty and sensitivity analysis shows that in presented all MCPs trip case, reactor core is reliably cooled due to natural circulation regime.

3. BEST-ESTIMATE ANALYSIS OF SEQUENTIAL MCP TRIP

A three-MCPs sequential trip event occurred at the Ignalina NPP on August 23, 2000. Before this event, the reactor operated at 2300 mW thermal power level. At 11 : 17, due to the short circuit into the control cable, fire-prevention signal of Ignalina NPP was activated by mistake. This caused the fire-prevention pump to provide a foam mixture into the MCPs compartments of one MCC loop. The foam was found on the cabinets of MCP electric motors control. The short circuit protections were activated. At 11 : 23, the first MCP was switched off. As the core thermal power was less than 2860 mW, AZ-4 signal was not generated. Still after three minutes, the second MCP of the same MCC loop was switched off. According to two MCPs trip in one loop of the MCC, AZ-1 signal was generated. According to this signal, all CPS rods were inserted within 12–14 seconds, and the reactor was shut down. Approximately 20 seconds after AZ-1 initiation, the steam supply for turbine was suspended. At 11 : 29, the last operating MCP in the affected loop of the MCC was switched off. In order to decrease flow rate differences in both loops, operators stopped one pump in intact loop of the MCC.

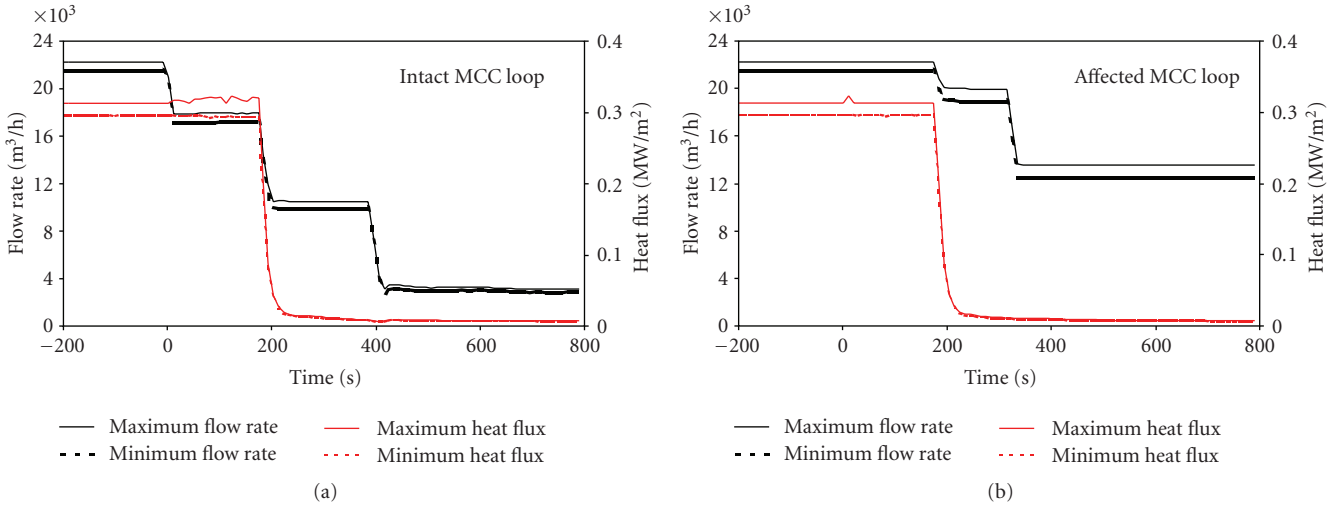

Figure 14: Three MCPs sequential trip. Comparison of behaviour of coolant flow rate through one MCC loop and heat flux in average loaded fuel channel.

Table 2: Parameters which may impact the uncertainty of calculation results in sequential MCPs trip case.

No.	Parameter	Width of parameter distribution Min.	Max.	Value of the parameter in the basic case calculation	Mean deviation and error[%]	Probability distribution	Explanation
			Initial conditions				
Par. 1	Pressure in DS, Pa	$6.517 \cdot 10^6$	$7.203 \cdot 10^6$	$6.86 \cdot 10^6$	$1.715 \cdot 10^5$ [5%]	Normal	Measurement error
Par. 2	Coolant flow rate through single MCP, m^3/h	7154	7446	7300	73 [2%]	Normal	Measurement error
Par. 3	Feed water temperature, K	458.52	467.78	463.15	2.32 [1%]	Normal	Measurement error
Par. 4	Steam flow rate to the in-house needs header, kg/s	81.34	84.66	83	0.83 [2%]	Normal	Measurement error
Par. 5	Reactor thermal power, W	$2.247 \cdot 10^9$	$2.387 \cdot 10^9$	$2.317 \cdot 10^9$	$3.48 \cdot 10^7$ [3%]	Normal	Measurement error
			Modelling parameters in the core				
Par. 6	Water packing	0 (on)	1 (off)	1 (off)	—	Nonparametric	Model assumption
Par. 7	Stratification	0 (on)	1 (off)	0 (on)	—	Nonparametric	Model assumption
Par. 8	PV term	0 (off)	1	0 (off)	—	Nonparametric	Model assumption
Par. 9	CCFL	0 (off)	1 (on)	0 (off)	—	Nonparametric	Model assumption
Par.10	Thermal front tracking	0 (off)	1 (on)	0 (off)	—	Nonparametric	Model assumption
Par.11	Mixture level tracking	0 (off)	1 (on)	1 (on)	—	Nonparametric	Model assumption

Results of the analysis are presented in Figures 11–14. The calculated and measured pressure in the DS, SH, and PH agrees well (see Figure 11). Switching off of one MCP leads to the increase of coolant flow rate through other MCPs of the same loop due to the lower pressure drop in the downstream system caused by cutting off the flow rate of a single pump (see Figure 12). The second MCP of the affected MCC loop was switched off after approximately 180 seconds. Output of the only operating pump increases up to 10500 m^3/h. Approximately 400 seconds after the first MCP was tripped,

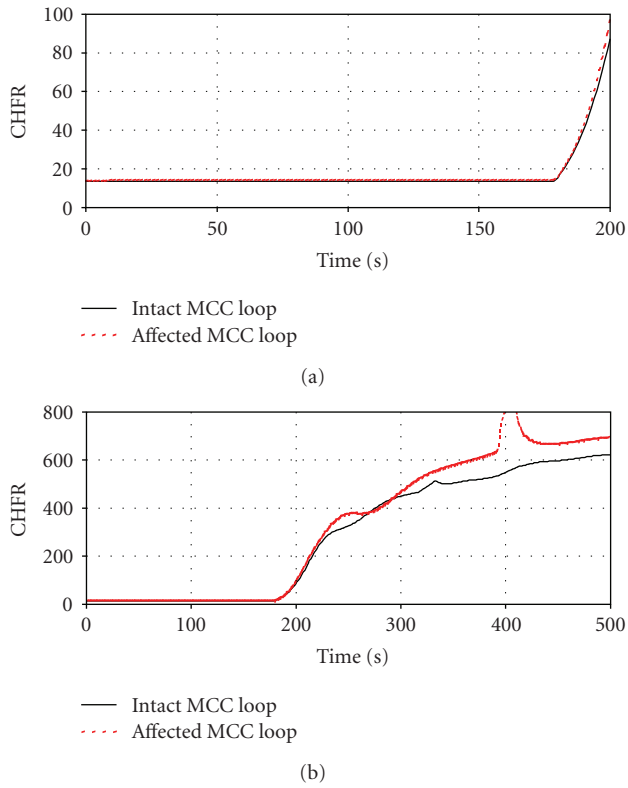

Figure 15: Three MCPs sequential trip. Critical heat flux ratio.

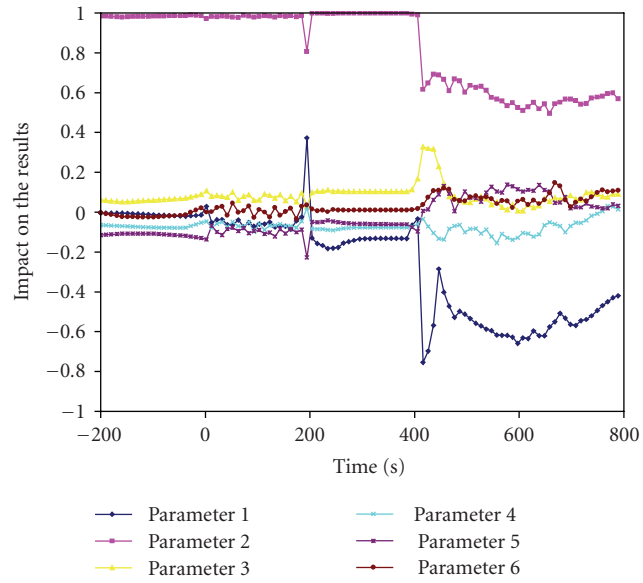

Figure 16: Three MCPs sequential trip. The impact of parameters No.1–No.6 on the coolant flow rate through the affected MCC loop. The numbering of parameters is the same as in Table 2.

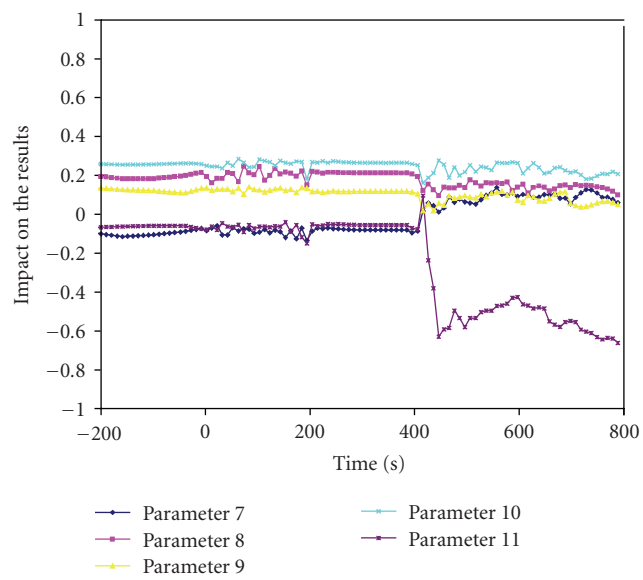

Figure 17: Three MCPs sequential trip. The impact of parameters No.7–No.11 on the coolant flow rate through the affected MCC loop. The numbering of parameters is the same as in Table 2.

the last MCP was switched off. The calculated maximum-minimum values of pressures and coolant flow rates are in reasonable agreement with real plant data (Figures 11–13).

Calculations showed that after MCP trip, the coolant flow rate through it decreases smoothly due to high inertia of flywheel, pump, and motor rotors. In approximately 60 seconds after the last MCP trip, the coolant natural circulation starts in the affected loop of the MCC (see Figure 12). It is necessary to note that coolant flow rate through the first two tripped pumps is also re-established in natural circulation node. Unfortunately, due to insensibility of measuring devices to low coolant flow rates at the Ignalina NPP, the coolant natural circulation was not identified. Coolant flow rate through MCPs of intact loop is presented in Figure 13. In the three-MCPs sequential trip in one MCC loop event, the reactor core is also reliably cooled by natural circulation because heat flux in the core decreases faster than coolant flow rate through the MCPs (see Figure 14), and CHFR is greater than 1 (see Figure 15).

In this case, only coolant flow rate through the affected MCC loop was selected for the uncertainty and sensitivity analysis because CHFR in base case calculations (see Figure 15) is greater than in all MCPs trip case (see Figure 10).

Parameters, which may impact the calculation results, are presented in Table 2. The analysis presented in the previous chapter shows that the selection of the homogeneous model has the biggest impact on the calculation results. However, the homogeneous model is not proper for two-phase flow modelling; it presents too conservative results. Thus, only the nonhomogeneous model was used in the accident analysis described in this chapter.

The performed analysis shows that the initial coolant flow rate through MCP (Par. 2) has the largest positive impact on the calculation results, whereas pressure in DS (Par. 1) has the largest negative impact. Parameter number 11—mixture level tracking model usage (see Figures 16 and17)—has the largest influence in the core. Mixture level tracking model has negative impact on the coolant flow rate in the

affected MCC loop, that is, at the switching off of this model, calculated values of flow rate will be lower.

4. CONCLUSIONS

The uncertainty and sensitivity analysis was performed for the simultaneous trip of all MCPs and sequential trip of three MCPs events.

The performed analysis of all MCPs trip shows that the selection ofthe homogeneous model has the biggest impact on the calculated flow rate through one MCC loop and CHFR. Homogeneous model selection is a nonphysical conservative assumption and it is not recommended for best estimate codes. Calculation results also show that reactor thermal power and pressure in DS have the biggest impact on the reactor cooling conditions.

In the sequential MCPs trip case, initial coolant flow rate through MCP, pressure in DS, and selection of mixture level tracking model have the biggest impact on the reactor cooling conditions. Switch off of the mixture level tracking model decreases the calculated values of flow rate.

Performed benchmark analysis of MCPs trip events showed that the initial reactor thermal power has insignificant influence on cooling conditions during natural circulation regime. Even at an initial maximal thermal power level (loss-of-all-MCPs case in Ignalina NPP), the reactor core is reliably cooled with 0.95 of probability and 0.95 confidence level.

NOMENCLATURE

AZ-1: Emergency protection
AZ-4: Emergency protection
CHFR: Critical heat flux ratio
CPS: Control and protection system
DS: Drum separator
FC: Fuel channel
GDH: Group distribution header
ICV: Isolating and control valve
MCC: Main circulation circuit
MCP: Main circulation pump
NPP: Nuclear power plant
RBMK: Russian acronym for "Channelled Large Power Reactor"

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