International Conference
Nuclear Energy in Central Europe 2001
Hoteli Bernardin, Portorož, Slovenia, September 10-13, 2001
www: http://www.drustvo-js.si/port2001/ e-mail: PORT2001@ijs.si
tel.:+ 386 1 588 5247, + 386 1 588 5311 fax:+ 386 1 561 2335
Nuclear Society of Slovenia, PORT2001, Jamova 39, SI-1000 Ljubljana, Slovenia

BENCHMARK ANALYSIS OF THREE MAIN CIRCULATION PUMP SEQUENTIAL TRIP EVENT AT IGNALINA NPP

Eugenijus Uspuras, Algirdas Kaliatka, Rolandas Urbonas
Lithuanian Energy Institute
Laboratory of Nuclear Installation Safety
Breslaujos 3, LT-3035 Kaunas, Lithuania
eugeniju@isag.lei.lt, algis@isag.lei.lt, rolandas@isag.lei.lt

ABSTRACT

The Ignalina Nuclear Power Plant is a twin-unit with two RBMK-1500 reactors. The primary circuit consists of two symmetrical loops. Eight Main Circulation Pumps (MCPs) at the Ignalina NPP are employed for the coolant water forced circulation through the reactor core. The MCPs are joined in groups of four pumps for each loop (three for normal operation and one on standby).

This paper presents the benchmark analysis of three main circulation pump sequential trip event at RBMK-1500 using RELAP5 code. During this event all three MCPs in one circulation loop at Unit 2 Ignalina NPP were tripped one after another, because of inadvertent activation of the fire protection system. The comparison of calculated and measured parameters led us to establish realistic thermal hydraulic characteristics of different main circulation circuit components and to verify the model of drum separators pressure and water level controllers.

1 INTRODUCTION

The RBMK-1500 is graphite moderated, boiling water, multichannel reactor. Several important design features of RBMK-1500 are unique and extremely complex with respect to western reactors [1]. The Main Circulation Circuit (MCC) is divided into two halves –left and right loops. For the cooling water forced circulation through the RBMK-1500 reactor at the Ignalina NPP eight MCPs are employed. The MCPs are joined in groups of four pumps each (three for normal operation and one on standby). In the one pump trip case, the check valve in this pump outlet closes and throughput through operating pumps increases. In the case of all MCPs trip, the coolant in the reactor during the first few seconds is supplied by pumps coastdown due to high inertia of pumps flywheel. Later the natural circulation through the core is established. The MCPs feed common pressure headers on each side of the reactor. Each pressure header provides coolant to 20 Group Distribution Headers (GDH), each of which in turn feeds from 38 to 43 pressure tubes.

The state of the art code RELAP5 was originally designed for Pressurized Water Reactors. Because of unique RBMK design, the application of this code to RBMK-1500 encountered several problems. The paper deals with the development of proper Ignalina NPP RELAP5 model and investigation of MCPs trip events. A successful best estimate RELAP5 model of the Ignalina NPP has been developed. This model includes the reactor circulation circuit, reactor control systems and plant safety systems required for transient analysis. Calculations performed with Ignalina NPP RELAP5 model agree favorably with the plant data. The developed RELAP5 model is proper and can be used for the plant analysis.

2 THE RELAP5 MODEL

The RELAP5 system thermal-hydraulic code has been adapted to model the RBMK type reactors and used since 1989. The state-of-the-art RELAP5/MOD3 code originally was designed for Pressurized Water Reactors [2]. In the USA licensing practice RELAP5 code is used mainly for transients and small break Loss Of Coolant Accidents (LOCA) analysis. An extended verification program was conducted for this code. The free exchange of code user experience and other information have resulted in wide employing of RELAP5. The application of RELAP5 code to RBMK would benefit from a wider involvement of experts from different countries in this process. This paper deals with benchmark calculations using MCP trips, which occurred at Ignalina NPP.

Because of unique design, the application of this code to RBMK-1500 encountered several problems. The RELAP5 nodalization for the Ignalina NPP have been developed. Key features of this model are the following:

- Both loops of the MCC are represented. Flow paths within a loop are modeled by either one or more passes. In turn, a core pass model uses one or more equivalent fuel channels. The equivalent fuel channels are an abstract that conserves the heat generated in a group of real channels, as well as hydraulic properties of this group. They are modeled by multiple axial and radial meshing for heat structures.
- Heat transfer among the equivalent fuel channels is approximated by means of heat exchange through the graphite moderator gaps to the reactor cavity gas circuit.
- Steam paths that remove the vapor from steam separators are represented explicitly, including steam lines, steam relief valves, etc.
- Feed water system and the Emergency Core Cooling System (ECCS) are represented explicitly.

The RELAP5 nodalization scheme is presented in the Figure 1.

The model consists of two loops. The left loop model consists of one equivalent core pass. All downcomers are represented by a single equivalent pipe (2), further subdivided into a number of control volumes. The pump suction header (3) and the pump pressure header (8) are represented as branch objects. Three operating MCPs are represented by one equivalent element (5) with check and throttling-regulating valves. The pumps are characterized by pump impeller angular speed and coolant flow rate through the pump. In the RELAP5 pump model the four-quadrant characteristics are expressed by so-called homologous curves [3]. The throttling-regulating valves are used for coolant flow rate regulation through the core. These valves are modeled by employing “servo valve” [2] elements. The normalized flow area versus normalized stem position is described in the RELAP5 model. The stand-by MCP is not modeled. The bypass line (7) between the pump suction header and the pump pressure header is modeled with the manual valves closed. This is in agreement with a modification recently performed at the Ignalina NPP. All fuel channels of this left core pas are represented by an equivalent channel (12) operating at average power and coolant flow. Compared to the model for the left loop, in the right loop, the loop section between the pressure header and the Drum Separator (DS) is represented in a more detailed manner. The MCP system is modeled in more detail also (it is modeled with three equivalent pumps). The right loop model consists of two equivalent core passes. One core pass represents one GDH. Fuel channels from this GDH are represented by three equivalent channels of three power levels (a single channel with maximum power level, a single channel with minimum power level and 41 channels with average power level). For the core power of 4200 MW_{th}, the channel average power is assumed to be 2.53 MW_{th}, the maximum channel power is 3.75 MW_{th} and minimum channel power is 0.88 MW_{th} [4]. The other core pass represents the other 19 GDHs. The channels of this pass are simulated by an equivalent fuel channel of average power. The steam separated in the separators is directed to turbines via steam lines (15). Two Turbine Control Valves (TCV) organize steam supply to the turbines. The control of these valves was modeled by “servo valve” [2] elements based on algorithm of steam pressure regulators used at Ignalina NPP, when one turbine operates in a power maintenance regime, and other – in pressure maintenance in DS regime. There are four Steam Discharge Valves (SDV-C) in each loop of the MCC to direct the steam to the condensers of the turbines. The pressure of the steam is also controlled, and peaks of pressure are eliminated by two high pressure steam loops (one for each MCC loop). One Steam Discharge Valve to Accident Confinement System (SDV-A) and six Main Safety Valves (MSV), which are connected to high pressure steam loop, discharge the steam to pressure suppression pool of the Accident Confinement System (ACS) tower. The model also takes into consideration steam mass flow rate through the Steam Discharge Valve to the deaerator for in-house needs (SDV-D). All models of steam discharge valves are connected to the “time dependent” elements, which define boundary conditions in turbine condensers or ACS pressure suppression pool.

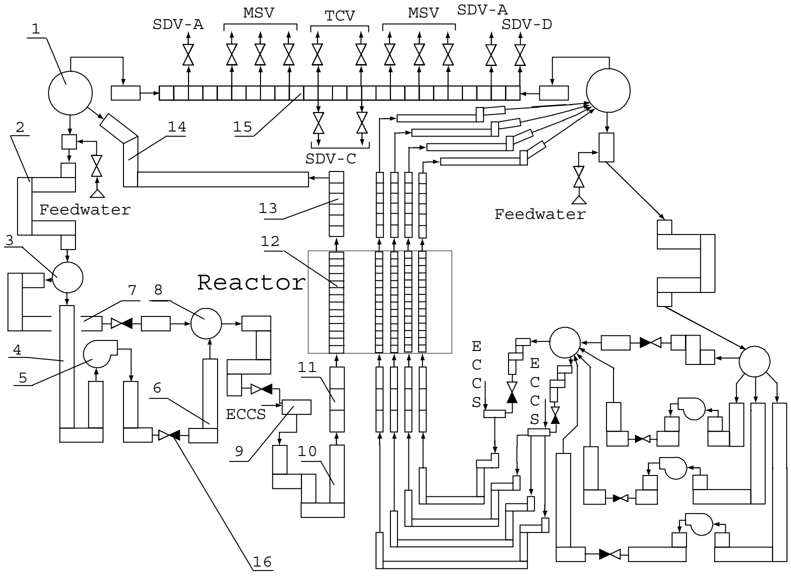

Figure 1: RELAP5 Ignalina NPP model nodalization scheme: 1 - DS, 2 - downcomers, 3 - MCP Suction Header (SH), 4 - MCP suction piping, 5 - MCPs, 6 - MCP discharge piping, 7 - bypass line, 8 - MCP Pressure Header (PH), 9 - GDHs, 10 - lower water communication line, 11 - reactor core inlet piping, 12 - reactor core piping, 13 - reactor core outlet piping, 14 - Steam-Water Communication (SWC) line, 15 - steam line, 16 - check valve

The feed water injection into the DS is simulated explicitly using RELAP5 “pipe”, “junction”, “volume” and “pump” elements. The nodalisation scheme of the feed water system is not presented in this paper. The feed water from the deaerators (in which the available amount of water is 480 m^3) is supplied to the MCC by Main Feed Water Pumps (MFWP). There are seven MFWPs. During normal conditions one pump is in stand-by and one pump can be out of service due to maintenance. The capacity of one MFWP is about 400 kg/s.

In the RELAP5 model of the Ignalina NPP the core is represented by a number of equivalent channels. Heat structures of the equivalent fuel channel simulate only the active region in the reactor core (top and bottom reflectors are not modeled). The fuel element is modeled with an equivalent four radial node model. One of these radial nodes is for the fuel pellet, one for the gap region and two for the cladding. The vertical bundle option is used in heat structure description of fuel assembly with 18 fuel elements. The fuel channel and the graphite stack are modeled with an equivalent six radial node model. Two of these radial nodes are for the fuel channel wall, one for the gap and graphite rings region and three for the graphite blocks. Fuel element, fuel channel, graphite rings and graphite blocks are modeled with 14 axial segments, 0.5 m in length each. The square graphite stack is represented by an equivalent cylindrical volume. Energy deposition in the graphite is calculated as a fixed fraction (4.15%) of the fission power plus a fixed fraction (11.12%) of the decay power. This largely represents the gamma-ray energy deposition in the graphite. The net result is that at full power approximately 5% of the total energy is deposited in the graphite.

3 MODELLING OF MCP TRIPS EVENT

This event took place on August 23, 2000. In this case, three MCPs at Ignalina NPP Unit 2 were tripped one after another. Before the accident the reactor operated at 2300 MW thermal power level. Six MCPs were in operation, each provided a coolant flow of 7300 m^3/h (21900 m^3/h for each loop of the MCC).

The event occurred due short circuit into the control cable, fire-prevention signal of Ignalina NPP was activated by mistake. This caused that fire-prevention pump provided foam mixture into the MCP compartments of one MCC loop. Foam was found on the cabinets of MCP electric motors control. Because of the short circuit protections were activated, first MCP was switched off after approximately 6 minutes. If reactor operates at the nominal power level, AZ-4 signal would be generated due to one MCP trip. According this signal the CPS rods would be slowly inserted into reactor core. Reactor power would be decreased at the velocity of 2% per second down to 60% of the maximum design power. However, because the initial core power was less than 2860 MW_{th}, AZ-4 signal was not generated. 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 shutdown. During the first 15 seconds reactor power decreased down to 3% of initial power level. Further on power decreased significantly slower, and after 15 minutes decay heat still was 2% of initial power level. After reactor power decrease the amount of steam generated in the core decreased also. To avoid very sharp pressure drop in the MCC after reactor scram initiation, the steam supply for turbine was suspended during approximately 20 seconds by reactor protection system. Water level controllers controlled the feed-water supply to maintain necessary water level in DS. After next 6 minutes the last operating MCP in affected loop of the MCC was switched off. During all these listed events the operator did not take any action and only supervised the right operation of automatic safety systems. Later, in order to decrease flow rate differences in both loops, operators stopped one pump in intact loop of the MCC.

Analysis of the above-described transient, employing the RELAP5 model, was performed. Before transient analysis using RELAP5 model the steady-state condition was reached. The heat release in the reactor core was assumed according Ignalina NPP data. Appropriate feedwater and generated steam amounts were modeled in such a way, that necessary pressures in the elements of MCC were settled. The calculated initial (before first MCP trip) pressure distribution in the MCC is compared to measured pressure in Figure 2. In abscise axis of the graphic the MCC elements were marked, and in ordinate axis – the pressure in these elements. The marking FC1 means core inlet, and FC2 – core outlet. As it is seen from the presented picture, the pressures in the DS, suction and pressure headers are only measured values. Unfortunately, important parameters such as pressure drop in the core, pressure in lower water communication pipes and maximum pressure in the MCP outlet are not measured in the Ignalina NPP.

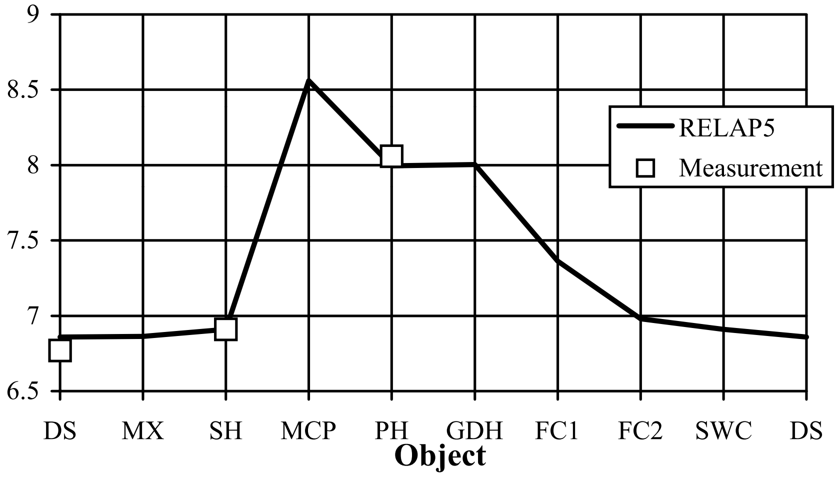

Figure 2: Initial pressure distribution in the MCC

It was assumed in the RELAP5 analysis, that first MCP tripped at the time moment t=0 seconds. The first pump (MCP-1) switch off leads to the increase of coolant flow rate through other MCPs of the same loop (Figure 3). During the operation of three pumps the capacity through each was 7700 m^3/h. Thus, due to one pump switch off the capacity through other two pumps increased up to 8800 m^3/h. Approximately 180 seconds later the second pump (MCP-2) of affected MCC loop was switched off. It led to the activation of reactor emergency protection AZ-1. When heat generation in the core began to decrease that led to decrease of coolant quality and resistance of core. Output of the only operating pump (MCP-3) increased up to 10500 m^3/h. Approximately 400 seconds after the first MCP was tripped, the electrical power supply for electric motor of the last pump (MCP-3) was switched off. RELAP5 calculations showed that after MCP trip, the coolant flow rate through it decreased smoothly due high inertia of flywheel, pump and motor rotors. In about 60 seconds after the last MCP trip, the coolant natural circulation in affected loop of the MCC started. The coolant flow through tripped pumps MCP-1 and MCP-2 was renewed. According RELAP5 calculation, in the case of natural circulation, the coolant flow rate through each MCP was equal approximately 1000 m^3/h (Figure 3). Unfortunately, due to measuring devices insensibility to low coolant flow rates at the Ignalina NPP, the coolant natural circulation was not identified.

Coolant flow rate through MCP of intact loop is presented in the Figure 4. As it is shown in the presented figure, after AZ-1 activation, the coolant flow rate through the MCP of intact loop of MCC decreases. This is due to automatic closure of throttling-regulating valves on MCP outlet. It defends the MCP from the overloading. One circulation pump (MCP-1) switch off 320 seconds after beginning of the accident is marked as “operator action” in Figure 4.

The proper modeling of the DS water level and pressure regulators was confirmed because the calculated and measured pressure in the DS, SH and PH agrees well (Figure 5).

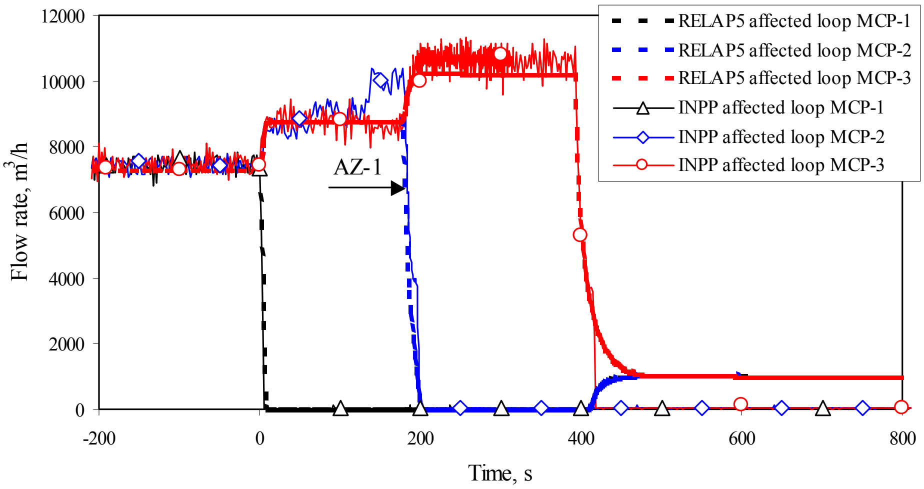

Figure 3: Main circulation pump throughput in the affected MCC loop

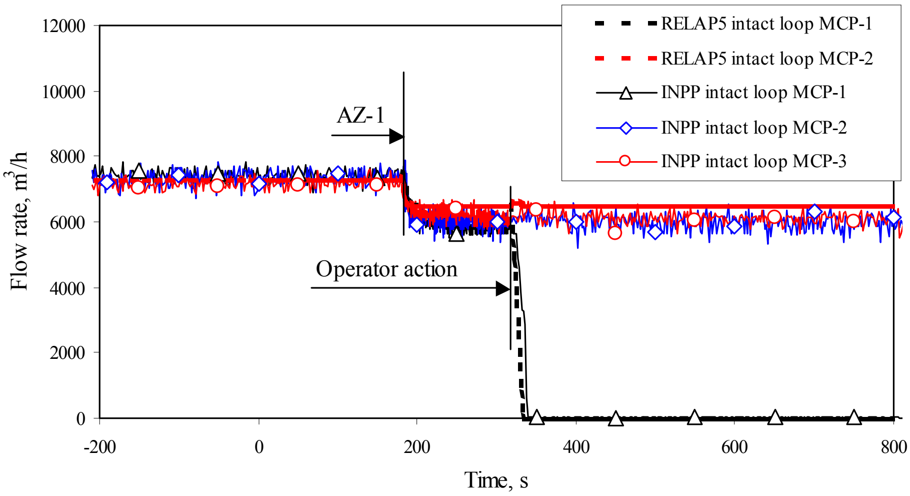

Figure 4: Main circulation pump throughput in the intact MCC loop

After the first MCP switch off, the pressure in the pressure header of affected MCC loop decreased from 8.0 MPa to 7.7 MPa. Pressure in the pressure header of intact MCC loop was not changed at that time. Sharp reactor power decrease after AZ-1 activation led to pressure decrease in all MCC. Sharp pressure drop decreased when the steam supply to turbines terminated after TCV closure (approximately 20 seconds after AZ-1 activation). Further pressure behavior in the DS and suction headers depends from steam supply for in-house needs. According to pressure change in the pressure headers it is possible to identify the moment of last pump (MCP-3) switch off and also operator action, when the one MCP in the intact loop of MCC is switched off.

During the analysis the characteristics (normalized flow area and normalized flow energy loss coefficient versus normalized stem position) of isolation control valves and the MCP throttling regulating valves were established. First of all, these characteristics were adjusted in the manner that calculated initial MCC conditions (pressure in the MCP pressure header and initial coolant flow rate through MCPs during steady state conditions) would

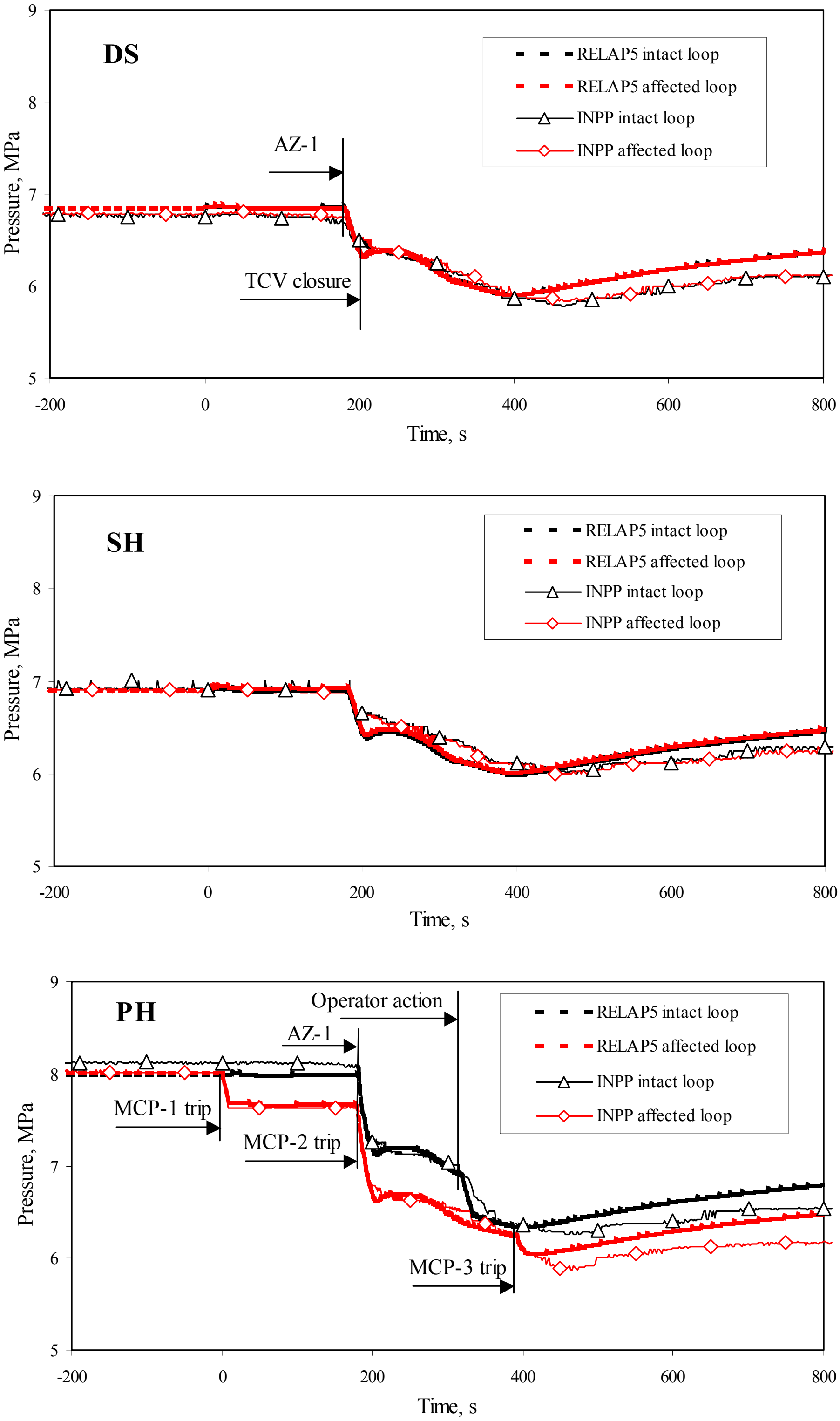

Figure 5: Pressure in the MCC

conform the measured values. Later pressure change in the MCP pressure header and coolant flow rate re-distribution through the pumps were verified for MCPs trip case. Such procedure was repeated several times, while the most universal characteristics were selected, i.e. the best for steady state and transient cases.

4 CONCLUSIONS

A successful best estimate RELAP5 model for the Ignalina NPP has been developed. Benchmark analysis of three MCP sequential trip event was performed. During the analysis the characteristics of isolation control valves and the MCP throttling regulating valves were established. The simulation results were verified against the plant data. Calculation results performed with RELAP5 model compare favorably with the plant data.

NOMENCLATURE

ACS	Accident Confinement System
CPS	Control and Protection System
DS	Drum Separator
ECCS	Emergency Core Cooling System
FC	Fuel Channel
GDH	Group Distribution Header
LOCA	Loss of Coolant Accidents
MCC	Main Circulation Circuit
MCP	Main Circulation Pump
MFWP	Main Feed Water Pump
NPP	Nuclear Power Plant
PH	Pressure header of MCP
RBMK	Russian Acronym for "Channeled Large Power Reactor"
SDV-A	Steam Discharge Valves to Accident Confinement System
SDV-C	Steam Discharge Valves to Turbine Condensers
SDV-D	Steam Discharge Valves to Deaerators and to in-house needs
SH	Suction header of MCP
SWC	Steam-Water Communication
TCV	Turbine Control Valve

SUBSCRIPTS

th	thermal

REFERENCES

[1]] K. Almenas, A. Kaliatka, and E. Uspuras, *Ignalina RBMK-1500. A source Book, extended and updated version*, Lithuanian Energy Institute, 1998, p.121.

[2] The RELAP5 Code Development Team "RELAP5/MOD3 Code Manual". *Volume 1, Code Structure, System Models, and Solution Methods*, NUREG/CR-5535, INEL-95/0174, 1995.

[3] A. Kaliatka, E. Uspuras, "Benchmark analysis of main circulation pump trip events at the Ignalina NPP using RELAP5 code", *Nuclear Engineering and Design 202*, Elsevier Science S. A., 2000, pp. 109-118.

[4] Ignalina NPP Safety Analysis Report. *Volume 3 Task Group 5*, VATTENFALL, 1996.