RELAP5/MOD3.2 ANALYSIS OF TRIP OF ONE MCP AT KOZLODUY NPP UNIT 6

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ABSTRACT

This paper discusses the results of the thermal-hydraulic investigations of the trip of one MCP at Unit 6, Kozloduy NPP. This investigation is a process that compares the analytical results obtained by the RELAP5 computer model of the VVER-1000 against the experimental transient data received from the Kozloduy NPP Unit 6. The RELAP5/MOD3.2 computer code has been used to simulate the trip of one MCP in a VVER-1000 Nuclear Power Plant (NPP) model. A model of the Kozloduy Unit 6 has been developed for the systems thermal-hydraulics code RELAP5/MOD3.2 [1]. This model was developed at the Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences (INRNE-BAS), Sofia. The model development and validation has focused on the applicability of RELAP5 to this type of transient. The paper presents a summary of the effort involved in defining a RELAP5 validation benchmark problem based on operational data from Kozloduy NPP and performing the analysis. The transient demonstrates the capability of NPP Unit 6 to reduce reactor power from one level to an other (lower power level) in case of losing one MCP. Reactor power was reduced from 82% to 67% during the transient without any need to initiate a scram. The comparisons between the RELAP5 results and the test data indicate good general agreement. This report was possible through the participation of leading specialists from Kozloduy NPP and with the assistance of Argonne National Laboratory (ANL) and Idaho National Environmental Laboratory (INEL), under the International Nuclear Safety Program (INSP) of the United States Department of Energy.

1. INTRODUCTION

Since experimental facilities are usually scaled down models of real plants, there is an additional need to evaluate accident analysis code performance in actual plant conditions. Usually the plant conditions are not well known, plant transients provide very little data and for safety reasons, the parameters are kept away from limiting conditions where most of the code uncertainties lie. The scenario for the transient Trip of One MCP on Unit 6, Kozloduy NPP, was part of the project: “Safety Analysis Capability Improvement of KNPP in the field of Thermal-Hydraulic Analysis – KNPP-1000/V320 Transient Plant Data for RELAP5/MOD3.2 Model Validation”. The reference power plant for this analysis is Unit 6 at The Kozloduy NPP site. Operational data from Kozloduy NPP are available for the purpose of assessing how the

RELAP5 model compares against plant data. This task has been enveloped in the INSP project for the validation of RELAP5/MOD3.2 for application to VVER-type reactors. Most of the standard problems used in this validation program are based on test data from experimental facilities rather than plant transient measurements. Therefore, the definition of plant-based standard problems is a valuable addition to the validation database.

A model of the Kozloduy Unit 6 was developed for the systems thermal-hydraulics code RELAP5/MOD3.2 [1]. The initial validation of VVER-1000 RELAP5 model was completed and was described in model verification reports [3, 4]. This model was developed at the Institute for Nuclear Research and Nuclear Energy and is applicable to analysis of operational occurrences, abnormal events, and design basis scenarios. The model provides a significant analytical capability for the specialists working in the field of the NPP safety.

The following sections of this report include a description of VVER-1000 power plant, description of the test being studied, a description of the RELAP5/MOD3.2 input model, results, and conclusions.

2. VVER-1000 NUCLEAR POWER PLANT DESCRIPTION

The reference power plant for this analysis is Unit 6 at The Kozloduy NPP site. This plant is a VVER-1000 Model V320 [5, 6, 7] pressurized water reactor that produces 3000 MW thermal power and generates 1000 MW electric power. The basic design of a VVER-1000 plant comprises: a pressurized water reactor of 3000 MW thermal power with 163 hexagonal fuel assemblies in the core, and 10 absorbing rod banks, located in 61 fuel assemblies; four primary loops; and one turbogenerator (1500 rpm) producing 1000 MW of electric power. The reactor vessel has 4 inlet nozzles of ∅ 850 mm and 4 outlet nozzles of ∅ 850 mm to connect to the four primary loops. There are also 4 inlets of ∅ 280 mm for safety injection of boron solution to the upper and lower plena in case of primary loss of coolant. Each loop includes one main circulation pump and a horizontal U-tube steam generator (SG). The behavior of the horizontal SG is very different compared to Western-style vertical SG [5, 6, 7]. For example, the secondary side of the horizontal SG contains much more water and all loss-of-feedwater transients are slower. Steam generators play a very important role in the safe and reliable operation of VVER power plants. They determine the thermal-hydraulic response of the primary coolant system during operational and accident transients. The feedwater (FW) system feeds condensate water into the SG trough the HP Heaters (or their bypass) and controls the SG during normal plant evolutions. The feedwater system includes two turbine-driven FW pumps (FWP), two auxiliary electrically driven FW pumps (AFWP), and ten control valves.

Reactor control and protection system consists of the following subsystems: Control rods and driver; reactor power controller (ARM); reactor power limitation controller (ROM); reactor scram subsystem; warning protection and fast load coastdown subsystems.

ARM-5C has two modes of operation:

Mode T: Power control based on constant secondary pressure in the range 10-110% of the nominal reactor power.

Mode N: Maintains constant neutron flux density in the range 8-110% of the nominal reactor power, using AKNP (automated control of neutron flux system) signal.

ARM-5C operates together with the electro-hydraulic turbine control system (EHSR).

Power restriction controller (ROM-2M) decreases reactor power to a pre-defined value in the following cases:

- -Tripping of 1 out of 4 RCP - to 67% of nominal;
- -Tripping of 2 non- neighbouring RCP - to 50% of nominal;
- -Tripping of 2 neighbouring RCP - to 40% of nominal;
- -Tripping of 1 out of 2 main FW pumps - to50%;
- -Tripping of 2 out of 2 main FW pumps - to 6%;
- -Grid frequency less than 49Hz - 10% below the current power;
- -Closing of 2 out of 4 turbine stop valves-to 40%;
- -Opening of KAG-24 - to 40%;
- -Opening of BB-440 - to 40%.

In all these cases ARM-5C is switched off. The power decrease is performed by inserting the operational group into the core with operational velocity.

3. DESCRIPTION OF THE TRANSIENT TRIP OF ONE MCP AT KNPP, UNIT #6

The test considered in this report can be categorized as a class of transients resulting from power plant equipment failure and perturbing the coolant flow rate through the reactor core. The model development and validation has focused on the applicability of RELAP5 to this type of transient. In general, the reason for the failure of the main coolant pumps (MCPs) could be electrical – loss of electrical power. The experiment and the RELAP5 analysis have assumed that the MCP failure is due to the loss of electrical power.

The transient demonstrates the capability of NPP Unit 6 to reduce reactor power from one level to an other (lower power level) in case of losing one MCP. Reactor power was reduced from 82% to 67% during the transient without any need to initiate a scram. During the transient primary side pressure has been controlled by the Make up system and by the Pressurizer heaters. Secondary side feed water controllers reduce feed water flow rates corresponding to the new reactor power level.

One of the four main circulation pumps was tripped and the power level was reduced from 82% [2460 MW] to 67% [2010 MW]. In base-load mode of NPP unit operation the Reactor Power Controller (RPC) operates in “T” mode (secondary circuit pressure stabilization). During the transient, a signal from Reactor Power Limitation Controller (RPLC) generates a warning protection-1 (WP-1) signal, the RPC automatically switches to “N” operation mode (neutron power stabilization), and the RPC is disconnected from operating the control rods (CR) and drives. Rod Bank #10 inserted from position 296 cm to 263 cm of the core height in 28 sec at the normal operational speed of 2 cm/s. WP-1 is a type of emergency action of the control rods: downward movement of the control rods bank by bank, starting with the “control bank”, normally Rod bank #10. When the initiating signal is cleared, rod movement stops.

Changes of the RPC modes of operation automatically lead to corresponding changes in the Electro-Hydraulic Turbine Controller (EHTC) mode and reduces turbine power corresponding to the reduction in thermal power of reactor.

When the WP-1 signal is cleared, the RPC continues to work in "N" mode and maintains the neutron power level reached at that time (67% power) and switching to controlling the control rods.

During the transient, the plant staff did not interact with the operation of the automatic control system. The response of the primary and secondary side control system did not reach the reactor scram setpoint. Transients indicated that the steam dump to condenser facility (BRU-K), steam dump atmosphere (BRU-A), and spray system from the cold leg piping are not active.

The initial steady state conditions of important plant parameters at 82% power, before starting the test, are shown in Table 1.

Table 1. Initial conditions at 82% reactor power (Equilibrium conditions before initiation of the plant event)

Parameters	Sensor posit.	Value
Reactor Power, MW	N_{RP}	2460
Electrical power, MW	N_{TG}	820
Primary Side Pressure, кgf/cm^2	YC10P20	161.2
MSH Pressure, кgf/cm^2	RC12P03	60.93
Reactor vessel pressure difference, кgf/cm^2		3.984
Pumps Heads кgf/cm^2		
RCP#1		6.21
RCP#2		6.2
RCP#3		6.1
RCP#4		6.25
Flow Rate in loops, t/h:		
Loop #1;		16060
Loop #2		15840
Loop #3		15620
Loop #4		16120
Cold Legs Temperature, ^{o}C:		
Cold Leg#1 Temperature	YA12-T24	284.8
Cold Leg#2 Temperature	YA22-T24	284.7
Cold Leg#3 Temperature	YA32-T24	285.1
Cold Leg#4 Temperature	YA42-T24	284.6
Hot Legs Temperature, ^{o}C:		
Hot Leg#1 Temperature	YA11-T24	310.6
Hot Leg#2 Temperature	YA21-T24	310.1

Hot Leg#3 Temperature Hot Leg#4 Temperature	YA31-T24 YA41-T24	311.3 310.2
Temperature Under the Reactor Vessel Cover, ^{o}C	YC00T01	320.0
Steam Temperature in the Pressurizer, ^{o}C	YP10T01	344.2
Pressurizer vessel temperature, ^{o}C	YP10T05	343.0
SG Water Level, cm	YB10-40L11/19	210/245
SG Pressure, кgf/cm^2	YB10-40P10	62
Control rods level, cm		296

All plant systems are available during the transient

Temperature of Main feed water was accepted to be equal to 220.0 ^{o}C.

The section below is the scenario that was followed at the NPP - Kozloduy Unit #6 and it was used in the RELAP5 calculations:

The basic scenario is as follows:

Initial conditions: Reactor Power - 82 % N

1) Trip of MCP #3

2) Switching on RPLC and decreasing of Reactor Power from 82 % to 67%.

3) Switches off RPLC

A more detailed scenario of the main events during the performance of the test is shown in Table 2.

Table 2. List of events for trip of one main coolant pump at KNPP

Time	Events
00:00:00 hr (22:13:16 hr)	Switching off MCP#3 (6YD30D01)
00:00:00 hr	RPLC switched on
00:00:28 hr	RPLC switched off
00:00:28 hr	Conrol group #10 elevation – 251.0 cm
00:00:30 hr	Cold leg #3 Temperature YA32 –283.3^{o}
00:00:38 hr	Stabilization of reactor pressure difference - 2.382 kgf/cm^2
00:00:38 hr	MCP Head #1 (YD10D01) – 5.12 kgf/cm^2 MCP Head #2 (YD20D01) – 4.96 kgf/cm^2

	MCP Head #4 (YD40D01) – 5.17 kgf/cm^2
00:00:38 hr	Reactor Power N_{RP} 2073 MW
00: 00:38 hr	Primary Side Pressure - 160.2 кgf/cm^2
00:00:42 hr	Pump Head of MCP #3 - YD30D01- 1.9 кfg/cm^2
00:00:50 hr	**Cold legs Temperature:** Loop #1 YA12 –285.7 ^{o}C Loop #2 YA22 –285.7 ^{o}C Loop #3 YA32 –283.3 ^{o}C Loop #4 YA42 –285.3 ^{o}C **Hot legs Temperature:** Loop #1 YA11 –312.2 ^{o}C Loop #2 YA21 –310.6 ^{o}C Loop #3 YA31 –303.8 ^{o}C Loop #4 YA41 –311.2 ^{o}C
00:01:03 hr	Control group #10 elevation - 263 cm
00:01:12 hr	**Cold legs Temperature, ^{o}C** Loop #1 YA12 –286.5 ^{o}C Loop #2 YA22 –284.2 ^{o}C Loop #3 YA32 –284.3 ^{o}C Loop #4 YA42 –286.1 ^{o}C **Hot legsTemperatures, ^{o}C** Loop #1 YA11 –313.3 ^{o}C Loop #2 YA21 –307.0 ^{o}C Loop #3 YA31 –284.6 ^{o}C Loop #4 YA41 –312.2 ^{o}C
00:01:34 hr	Stabilization of Reactor Power at level 2041 MW
00:03:00 hr	Hot leg #3 Temperature (YA31) –276.8 ^{o}C
00:15:00 hr	END of transient

4. RELAP5/MOD3.2 MODEL

The Baseline input deck for VVER-1000/V320 Kozloduy Nuclear Power Plant Unit 6 was developed by the INRNE-BAS. The initial validation of the Kozloduy VVER-1000 RELAP5 model was completed and was described in verification reports [4]. The model was developed for analysis of operational occurrences, abnormal events, and design basis scenarios. The model provides a significant analytical capability for the specialists working in the field of the NPP safety. Data and information for the modeling of these systems and components were obtained from the Kozloduy documentation and from the power plant staff.

The model was defined to include all major systems of the Kozloduy NPP Unit 6, namely reactor core, reactor vessel, main coolant pumps (MCP), steam generator (SG), steam generator steam line and main steam header (MSH), emergency protection system, pressure control system of the primary circuit, makeup system, safety injection system, steam dumping devices (BRU-K, BRU-A, SG and pressurizer safety valves), and main feedwater system.

In the RELAP5 model of the VVER-1000, the primary system has been modeled using four coolant loops representing the four reactor loops. The RELAP5 model configuration provides a detailed representation of the primary, secondary, and safety systems. The reactor core region is represented by a hot and average heated flow paths and a core bypass channel. The reactor vessel model includes a downcomer, lower plenum, and outlet plenum. The pressurizer (PRZ) system includes heaters, spray, and pressurizer relief capability. The safety system representation includes the accumulators, high and low pressure injection systems, and the reactor scram system. The model of the make up and blowdown systems includes the associated control systems.

The scenario that was followed at the NPP - Kozloduy Unit #6 during the transient was simulated in the RELAP5 calculations (See Table 2). Before running the transient calculations the RELAP5 VVER-1000/V320 input model was stabilized at 82 % power. All model parameters have been stabilized very close to the levels recorded at the plant, as shown in Table 1. After establishing steady state conditions with the RELAP5 input model at 82% reactor power, the transient calculation was started.

The following parameters (available from plant data collected during the transient) were compared between plant measurements and RELAP5 code calculations:

- Primary and secondary side pressure;
- Temperatures in hot and cold leg #3
- Temperatures in hot and cold leg #1;
- MCP #3 pressure difference;
- Delta P of reactor vessel;
- Flow rates of loops (Loop #1 and Loop #3);

5. RESULTS AND DISCUSSION

Integrated plant event results obtained from actual power plant provide important data for analytical model validation. The plant event and the RELAP5 analysis have assumed that the MCP failure is due to the loss of electrical power. During the transient Pressurizer heaters and Make up /Let down system , will work automatically to support the primary side pressure.

The sequence of events described in section 3 was modeled with the RELAP5 code and the VVER-1000 input model for Kozloduy NPP Unit 6. The model development and validation has focused on the applicability of RELAP5/MOD3.2 to this type of transient. As the overall results show, RELAP5 predicted the plant behavior correctly.

The most important parameter behaviors are shown in **Figures 1** to **6**. The calculation was performed up to 400 sec of transient time. The interesting event here is the reverse flow in one of the loops (the damaged one). Before running the investigated transient event the RELAP5 model was run with the real plant equilibrium conditions to establish steady state conditions at 82 % power (shown in Section 3, **Table 1**).

The initial values of main parameters could be seen in Figures 1. through 6. at time 0.0 sec.

All SGs water level was accepted to be 2.45 m.

Initial values of inlet and outlet reactor vessel temperatures are the same as in the plant.

In RELAP5 model inlet temperature was established to 558.0 K and outlet temperature – 584.0 K (see **Table 1**. for plant data).

Another RELAP5 initial parameter that has a small difference from plant data is reactor pressure difference. In the model it was used the value of 0.38 MPa while the plant value is 0.39 MPa. The reason to use 0.38 MPa in the model instead of 0.39 MPa is that in Baseline model it was used 0.38 MPa (see **Table 1**. and **Figure 5**.).

All other parameters have been stabilized at the levels equal to the measured plant parameters.

The transient calculations are compared with the plant event data in **Figure 1**. through **Figure 6.** One of the important parameters is the pressure in the primary and in the secondary circuit, since this parameter is input to many reactor control systems in primary and secondary side.

Figure 1 presents the measured primary and secondary pressure during the experiment and the calculated by REALP5 primary and secondary pressure. As shown, the calculated secondary side pressure are almost identical to the measured secondary pressure. In comparison of RELAP5 calculated primary side pressure with plant data there is a small difference. While in the plant data there is no changes during the transient, in RELAP5 calculated primary pressure there is a small increasing of pressure for the first 30 sec. and decreasing of pressure for the next 30 sec. Maximum pressure of 16.10 MPa was reached at 30.sec. Due to work of Make up/ Let down system primary side pressure was stabilized at level 16.0 MPa after first 120.0 sec. for both cases calculated and measured. In **Figure 1**. there are presented plant data for every 4 sec. for the first two minutes from the beginning of transient.

The most interesting parameters for investigated event are behavior of coolant temperature and behavior of flow rates in different loops. The comparison of hot and cold leg #3 temperature is presented in **Figure 2**. As it was mentioned above initial values of these parameters are the same for both cases – calculated and measured. But, while hot leg #3 temperature in the end of transient is the same for calculated and measured , for cold leg # 3 RELAP5 calculated temperature in the end of transient is 2 degrees higher compared to plant data. This difference is acceptable based on the accuracy of measurement. In RELAP5 calculations there is an increasing of hot leg # 3 temperature at approximately 30.0 sec. It could be explained with the accuracy of measurements. Decreasing of hot leg temperature becomes faster in recorded plant data compared with RELAP5 calculation between 30.0 sec. and 50.0 sec. and later for next 50.0 sec. decreasing of hot leg temperature becomes faster in RELAP5 calculation (see **Figure 2.**). Nevertheless, from **Figure 2.** it is seen that the calculation closely follows the results obtained from the plant event.

Comparison of hot and cold leg #1 temperatures is shown in **Figure 3**. Cold leg temperature closely follows the results obtained from the plant event except for the first 50 sec, where Calculated results are 2.0 –3.0 degrees higher. So if we compare RELAP5 calculated results with plant data there is a small difference of 2-3 degrees. This value is comparable to the different values of the different measured hot legs.

The results from the experiment and RELAP5 calculations for main coolant pump pressure difference are compared in **Figure 4**. Decreasing of RELAP5 calculated MCP pressure difference is faster in first 50 sec. In RELAP5 calculation this value became 2 bars at 30 sec, while in experiment data this parameter became 2 bars at 45 sec. Later in the transient there is no big difference (see **Figure 4**.).

Figure 5 provides comparison of Reactor Vessel Pressure Difference. As it is shown in this figure, there is also a good agreement between the plant data and the RELAP5 calculation.

Comparison of flow rates in Loop #1 and Loop #3 (tripped loop) are shown in **Figure 6**. In both cases is indicated reverse flow rate. The flow rates of tripped loop and RELAP5 calculated results decreases rapidly in the first minute of the transient. The flow rates of intact loops increase in the same time.

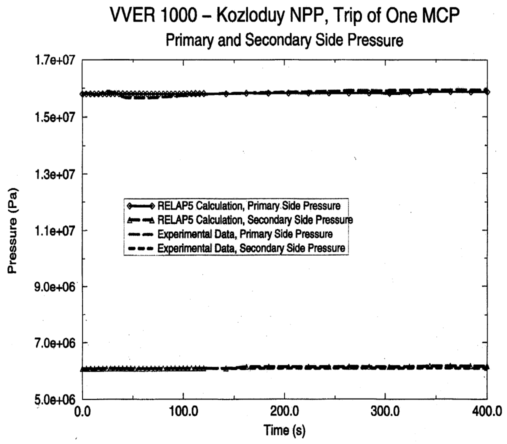

Fig.1 Comparison of Primary and Secondary Side Pressure

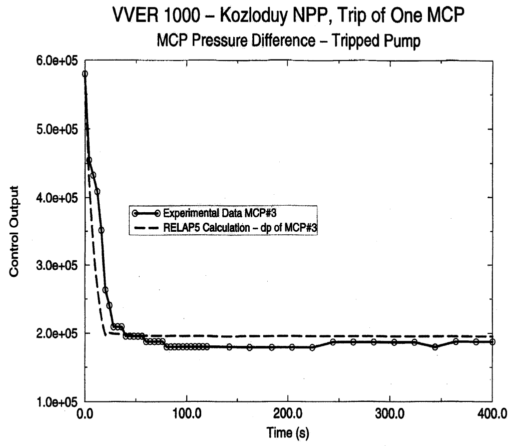

Fig. 4 Comparison of MCP Pressure Difference for Tripped Loop

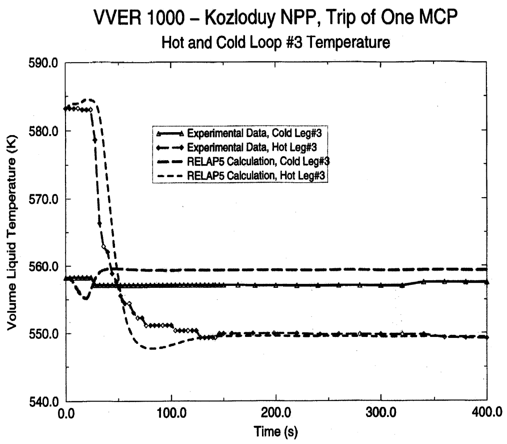

Fig.2 Comparison of Hot and Cold Leg Temperatures of Loop #3

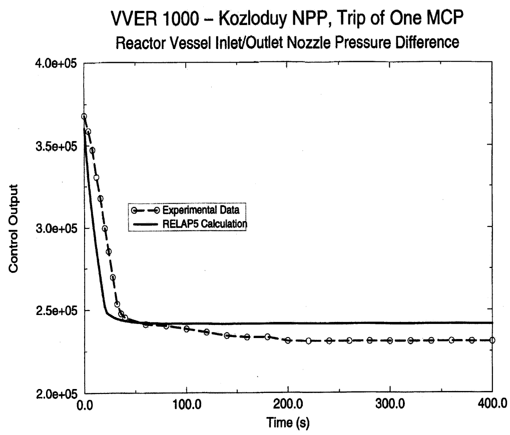

Fig. 5 Comparison of Reactor Vessel Pressure Difference

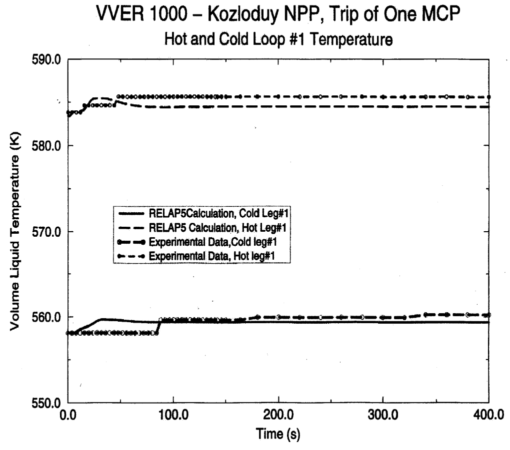

Fig.3 Comparison of Hot and Cold Leg Temperatures of Loop #1

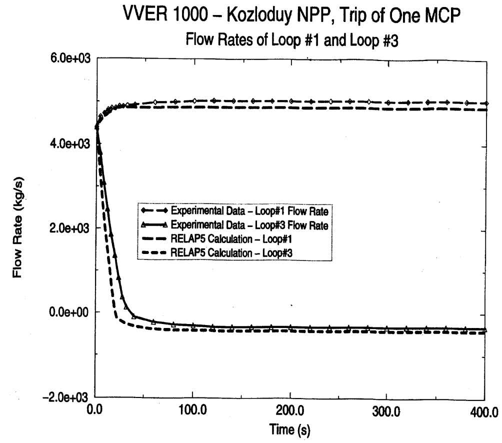

Fig. 6 Comparison of Flow Rates of Loop #1 and Loop #3

6. CONCLUSIONS

In general the comparisons indicate good agreement between the RELAP5 results and the experimental data for the investigation of trip of one MCP on Unit 6, KNPP. Test facilities are frequently scaled down models of the actual power plant; the scaling can increase the uncertainty of the results of the test facility relative to the reactor performance. In this benchmark based on Kozloduy NPP the scaling is not a factor. The results provide an integrated evaluation of the complete RELAP5 VVER-1000 model. The comparisons indicate that RELAP5 predicts the test results very well.

The RELAP5 model developed for the transient analysis of VVER-1000 nuclear power plants has been used to accurately predict the results obtained during the trip of one MCP test performed at the Kozloduy NPP (Unit 6). These results are an important part of the validation of the RELAP5 model developed for Kozloduy NPP. The overall conclusion is that RELAP5/MOD3.2 is adequate to simulate the transient phenomena occurring in a VVER-1000 for this type of transient MCP failure conditions.

7. REFERENCES

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