International Conference
Nuclear Energy for Central Europe 2003
Portorož, Slovenia, September 8-11, 2003
http://www.drustvo-js.si/port2003

RELAP5/MOD 3.3 Analysis of Reactor Coolant Pump Trip Event at NPP Krško

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ABSTRACT

In the paper the results of the RELAP5/MOD 3.3 analysis of the Reactor Coolant Pump (RCP) Trip event at NPP Krško are presented. The event was initiated by an operator action aimed to prevent the RCP 2 bearing damage. The action consisted of a power reduction, that lasted for 50 minutes, followed by a reactor and a subsequent RCP 2 trip when the reactor power was reduced to 28 %. Two minutes after reactor trip, the Main Steam Isolation Valves (MSIV) were isolated and the steam dump flow was closed. On the secondary side the Steam Generator (SG) pressure rose until SG 1 Safety Valve (SV) 1 opened. The realistic RELAP5/MOD 3.3 analysis has been performed in order to model the particular plant behavior caused by operator actions. The comparison of the RELAP5/MOD 3.3 results with the measurement for the power reduction transient has shown small differences for the major parameters (nuclear power, average temperature, secondary pressure). The main trends and physical phenomena following the RCP Trip event were well reproduced in the analysis. The parameters that have the major influence on transient results have been identified. In the paper the influence of SG 1 relief and SV valves on transient results was investigated more closely.

1 INTRODUCTION

The RCP Trip event at NPP Krško began on 24.02. 2002. at night when the shift crew decided to reduce the power because the temperature increase of the upper radial bearing of the RCP 2 had been noticed. After about 50 minutes as the bearing temperature reading still was high, it was decided to trip the reactor and the RCP 2. At the time of reactor trip, reactor power was equal to 28 %. After manual reactor trip and RCP 2 trip had been completed, there was the noise in the control room. It was concluded that an unexpected steam leak on the secondary side occurred. Therefore, the MSIV isolation was carried out. As a consequence of MSIV isolation, the steam dump flow was terminated. Following the steam dump flow isolation, the only available heat removal from the secondary side was by means of SG relief and safety valves. About 300 sec after reactor and RCP 2 trip, the SG 1 safety valve opened. After stabilizing the plant at no-load conditions, the detailed analysis of the RCP Trip event had found the failure in the indication of the RCP radial bearing temperature detector.

The standard RELAP5/MOD 3.3 nodalization for NPP Krško developed at Faculty of Electrical Engineering and Computing (FER) was used in the analysis. A comprehensive NPP Krško model with all major control systems has been developed. It represents protection, monitoring and simplified control systems used only during steady state initialization, as well as main plant control systems. The realistic boundary and initial conditions obtained from the event report and Process Instrumentation System (PIS) records were assumed in the analysis. The RELAP5/MOD 3.3 analysis was subdivided into two parts:

- Calculation of the initial conditions of the event, i.e., the power reduction: 100 % - 28 %. The power reduction was initiated by turbine power change, i.e., the steam mass flow reduction in the same time period, as indicated in the PIS data. The most important control systems to perform the power change are the automatic Rod control system that maintains the programmed average temperature and the SG level control system, which regulates the main feedwater valve position so that sufficient feedwater flows into the steam generator to maintain the level at a reference value.
- Calculation of RCP Trip event transient. In the analysis the major assumptions were based on the realistic transient conditions (e.g., steam dump flow, auxiliary feedwater flow, specific SG 1 SV 1 behavior). The transient was simulated for 1500 sec.

The aims of the presented work are threefold:

1. The realistic RELAP5/MOD 3.3 analysis of the plant event has been performed. The obtained differences between measured and calculated values for the power reduction: 100 % - 28 % were demanded to lie within the acceptance criteria so that the liable initial conditions for RCP Trip event analysis were obtained.
2. The analysis was aimed to determine the major trends following the RCP Trip event, e.g., reactor and turbine trip, the asymmetrical power distribution in the SGs following the RCP 2 trip, the secondary side pressure and level trends and its influence on the overall plant behavior.
3. In the plant event analysis it was evident that because of the complexity of the event scenario, as well as of the interference between inherent plant behavior and operator actions, an additional parametric study analysis would have to be performed. Therefore, the basis for the sensitivity study analysis has been created. The parameters that have the major influence on transient results have been identified, e.g., inherent plant behavior parameters (decay heat, heat transfer conditions in the SGs, etc.) as well as various parameters influenced by balance of plant actions (automatic as well as operator actions). In this work the influence of SG 1 relief and safety valves behavior on transient results was investigated.

2 RELAP5/MOD 3.3 CALCULATION OF THE INITIAL CONDITIONS FOR THE REACTOR COOLANT PUMP TRIP EVENT

In the analysis the model of plant nodalization for the NPP Krško developed for RELAP5/MOD 3.3 code was used, [3] and [4]. The RELAP5 model has 469 volumes and 497 junctions. The total number of heat structures is 378 with total number of mesh points of 2107. The developed RELAP5/MOD 3.3 input data set contains the models of the NPP Krško monitoring as well as protection and control systems. The RELAP5/MOD 3.3 analysis of RCP Trip event was subdivided into two parts: 1) Calculation of the initial conditions for the event analysis, i.e. calculation of power reduction: 100%-28% and 2) RCP Trip event analysis.

The initial conditions for the event were obtained as a result of power reduction: 100%-28% calculation. For the power reduction transient scenario as well as for main feedwater temperature, the realistic plant data obtained from PIS data, [5], were assumed. The power reduction transient lasted for approximately 50 minutes (3020 sec). It was initiated on the secondary side by a reduction of turbine steam flow. There are two control systems that automatically adjust the plant parameters following the turbine power change. The automatic Rod control system maintains the programmed average temperature by inserting reactivity in the core and the SG level control system regulates the main feedwater valve position so that sufficient feedwater flows into SG to maintain the level at a reference value. The results of the power reduction transient are presented in Figure 1 to Figure 4. Following the turbine steam mass flow reduction, Figure 1, the SG secondary pressure increased, Figure 2, while the set point for the RCS average temperature decreased according to coolant average temperature program linearly as the turbine power decreased. Following the control rod insertion according to the control rod speed program, the RCS average temperature, Figure 3, as well as nuclear power, Figure 4, decreased. Calculated initial conditions for the RCP trip event at the end of power reduction: 100%-28% transient are summarized in Table 1. A very good agreement between the calculated and measured values at time = 3020 sec (nuclear power = 28 %) was obtained.

Table 1: Initial conditions for Reactor Coolant Pump Trip Event at NPP Krško

Parameter	**Unit**	**Measurement time = 3020 s**	**RELAP5 time = 3020 s**
Pressurizer pressure	MPa	15.5	15.5
Steam generator pressure	MPa	7.27/7.3	7.347/7.347
Cold leg temperature	K	564.02/563.65	564.87/564.88
Hot leg temperature	K	575.55/576.0	575.88/575.88
RCS average temperature	K	569.79/569.65	570.4/570.4
Feedwater temperature	K	452.25/451.05	453.5/452.8
Feedwater mass flow	kg/s	160.06/158.81	154.6/155
Main steam line mass flow	kg/s	109.8/125.8	136.5/136.5
Pressurizer level	%	36.6	41.8
Steam generator narrow range level	%	69.9/69.5	68.5/68.5
Reactor core power	MW (%)	558.32 (28 %)	561.82 (28.18 %)

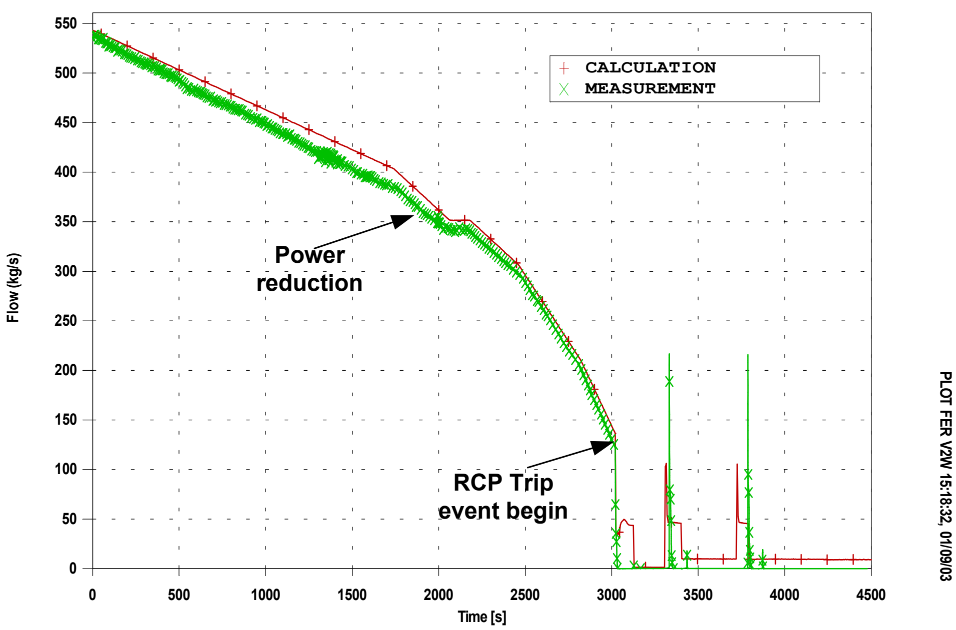

Figure 1: SG 1 steam mass flow, power reduction (0-3020 sec), RCP Trip event CASE 3 (3020-4500 sec)

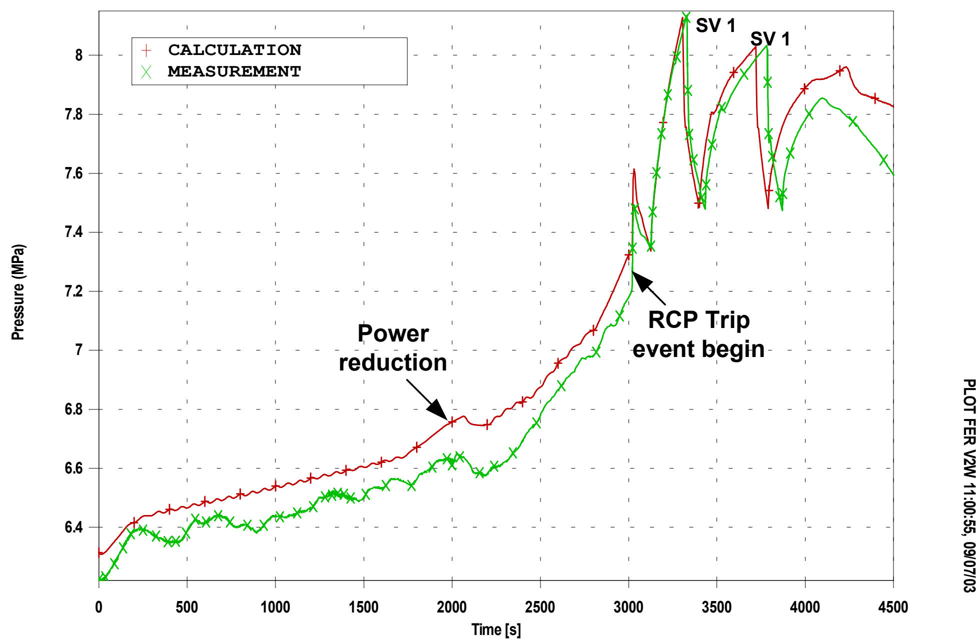

Figure 2**:** SG 1 secondary pressure, power reduction (0-3020 sec), RCP Trip event CASE 3 (3020-4500 sec), SV 1 – SG 1 SV 1 opening

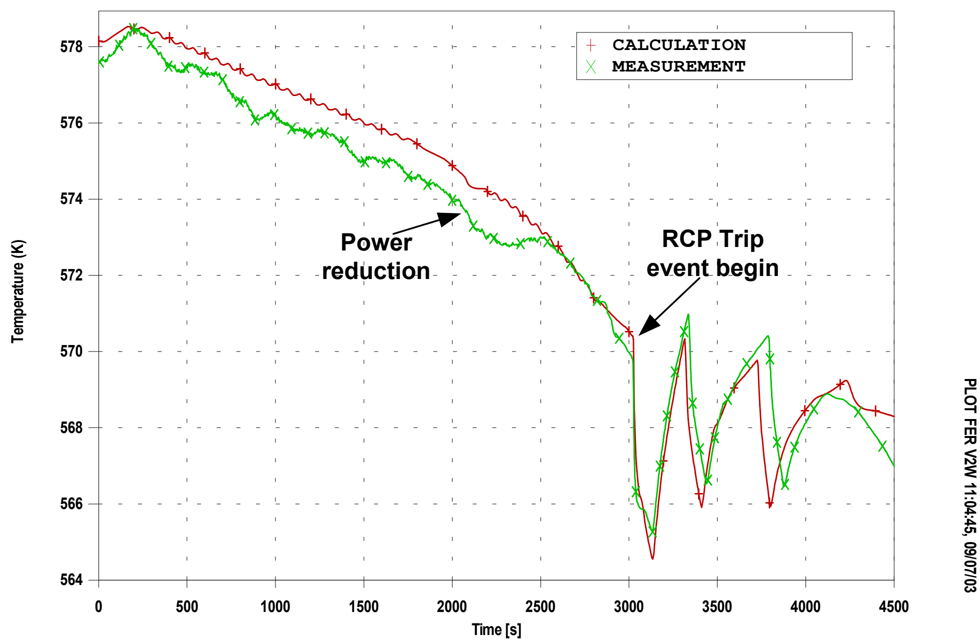

Figure 3**:** Average temperature (loop 1), power reduction (0-3020 sec), RCP Trip event CASE 3 (3020-4500 sec)

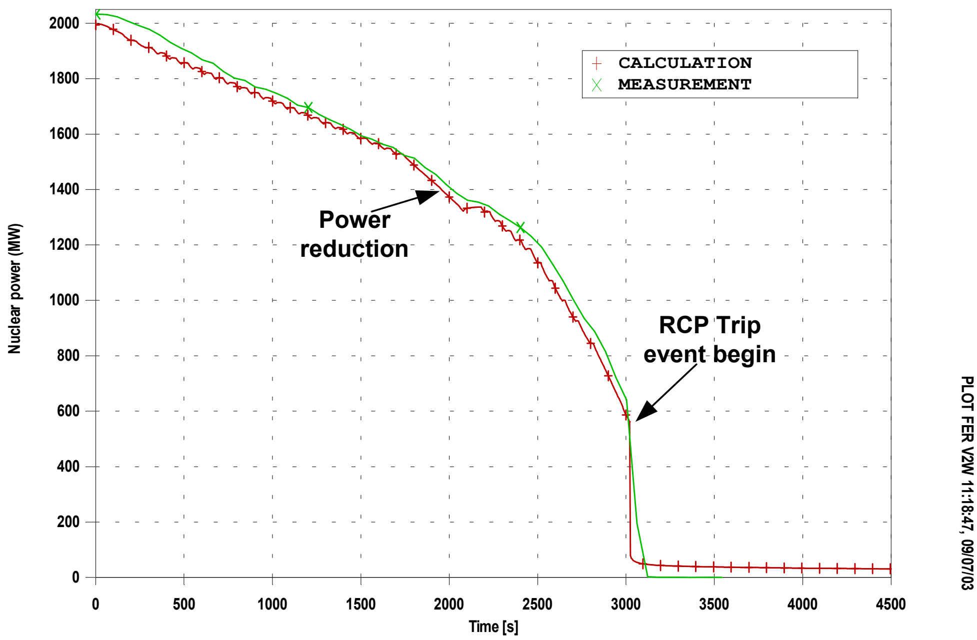

Figure 4: Nuclear power, power reduction (0-3020 sec), RCP Trip event CASE 3 (3020-4500 sec)

3 RELAP5/MOD 3.3 CALCULATION OF REACTOR COOLANT PUMP TRIP EVENT

Results of the RELAP5/MOD 3.3 calculations of the RCP 2 Trip event are graphically presented in Figure 1 through Figure 7. The main events and characteristic phenomena are summarized in Table 2. The transient was initiated at time=3020 sec by the sequence of the following events: reactor trip, turbine trip and RCP 2 trip. Following the RCP 2 trip, a part of the cold leg flow from the unaffected loop (1) bypassed reactor core and flew to the cold leg of the affected loop (2) so that flow in that loop reversed. Hence, the imbalance in the transferred heat on the SG secondary side between the two loops was established. Thereby, the major part of the heat produced in the core was transferred in the SG 1. Following reactor trip, nuclear power was quickly reduced, Figure 4. The average temperature, Figure 3, dropped quickly to the value for the Low Tavg & Reactor trip signal, which actuates main feedwater isolation. Owing to steam dump flow, which is determined by steam dump control – turbine trip mode, the secondary pressure was reduced following turbine trip, Figure 2. However, because of MSIV isolation, Table 2, the steam dump flow was terminated and the SG pressure increased. Following the MSIV isolation, the only means of heat removal to the secondary side was by SG relief and safety valves. The analysis of the measured data has suggested that the SG 1 relief valve did not open at the set point pressure. Also, a nonstandard behavior of SG 1 SV 1 was observed. A very late start of the Auxiliary Feedwater (AFW) flow and consequently a low SG 1 level, Figure 7, could be observed in the measurement. In order to describe the phenomena obtained in the real event, three RELAP5/MOD 3.3 analyses were performed:

1) CASE 1: SG 1 relief valve and SVs were operating as expected.
2) CASE 2: SG 1 relief valve was not operating. The SG 1 SV 1 was closing at the closing pressure of SG relief valve. In the pressure range: (SG SV 1 closing pressure,

SG PORV closing pressure) the SG SV 1 area was assumed to be equal to SG relief valve area. After first time opening the SG 1 SV 1 opening set point was lowered.

3) CASE 3: The same assumptions as for the CASE 2 were taken with the exception that SG 1 SV 1 did not close completely, so that it remained 8 % open after closing signal.

In the analysis it was assumed that AFW flow started at a time point when SG 1 pressure exceeded 7.8 MPa and either the SG 1 relief valve (CASE 1) or SV 1 (CASE 2, CASE 3) were closed after first time opening. Following that time point, the AFW flow obtained from the measurement including flow measurement error was assumed. The steam mass flow through the SG 1 relief and SV 1 and the resulting SG 1 pressure for the analyzed cases are presented in Figure 6 and Figure 5, respectively. In the CASE 1 only SG 1 relief valve opened, while SV 1 did not open at all. In the time period (3020, 4020) sec, SG 1 relief valve opened six times in the CASE 1, Figure 6, while in the real event, Figure 2, only the opening of the SG 1 SV 1 valve (two times) has been reported. The results for secondary pressure for the CASE 1 indicate that SG relief valve prevents the pressure increase above the opening set point. Hence, it was concluded that in the real event the SG 1 relief valve did not open. Furthermore, a particular behavior of the SG 1 SV 1 valve was modeled, different from the set point in order to obtain the SG 1 secondary pressure match with measurement, Figure 2. For the CASE 2, the SG 1 secondary pressure was well reproduced till the SG 1 SV 1 first time closing, Figure 5 and Figure 2. However, in the observed time period (3020, 4020) sec, the SG 1 SV 1 valve opened four times in the CASE 2 which is different from measurement (two times). To realistically describe the event, the CASE 3 has been analyzed. In this case, after SG 1 SV 1 closing signal a residual flow (9.4 kg/s) remained, Figure 6, i.e., it was assumed that SG 1 SV 1 did not close completely. The average temperature (loop 1) trend, Figure 3, followed the SG 1 SV 1 behavior, Figure 5. Together with the heat removal through the SG 1 relief or SV 1 valve, the SG secondary side behavior was determined by the AFW flow. The role of the AFW flow is twofold. First, the spray-type injection of the cold AFW water efficiently reduces the SG pressure due to the steam condensation on water droplets. Secondly, the AFW flow recovers the SG level and thus the heat sink is preserved. In this event, the AFW 1 flow was actuated first when SG 1 level was quite low (30 %) and still decreasing because of steam removal through the SG 1 relief or SV 1 valve, Figure 7. Moreover, the measured AFW flow was much less than nominal (25 kg/s), so that measured SG 1 level fell to 15 % at the end of simulation. Coincident with the SG 1 SV 1 valve opening intervals, the SG 1 level increased, due to buoyancy driven water droplets rise, Figure 6 and Figure 7. For the CASE 3, a very good agreement with the measurement for the SG 1 pressure, Figure 2, average temperature, Figure 3, as well as SG 1 level, Figure 7, was obtained. The AFW flow influenced the SG 1 secondary pressure significantly at the very beginning of the injection when the AFW flow was greater than 14 kg/s and after time = 4000 sec. At that time point, a significantly less core decay heat is produced (about 11 % less than at time = 3500 sec) which also contributes to the slower secondary pressure rise. After time = 4200 sec a steeper decrease of the SG 1 pressure and the lower SG 1 level in the measurement than in the calculation was obtained. The obtained results suggest that in the real event an additional steam release following that point took place, which was not considered in the calculation.

Table 2: Time table of main events for the RCP Trip event

Event	CASE 1 Time (sec)	CASE 2 Time (sec)	CASE 3 Time (sec)	Measurement Time (sec)
Reactor trip, turbine trip	**3020**	**3020**	**3020**	**3020**
RCP 2 trip	**3023**	**3023**	**3023**	**3023**
MSIV isolation	**3125**	**3125**	**3125**	**3125**
Main feedwater isolation	**3029**	**3029**	**3029**	**not available**
AFW start	**3329**	**3440**	**3467**	**3521**
SG 1 relief valve opens for the 1st time	**3235**	**-**	**-**	**-**
SG 1 SV 1 opens for the 1st time	**-**	**3310**	**3310**	**3330**
SG 1 SV 1 opens for the 2nd time	**-**	**3525**	**3725**	**3781**

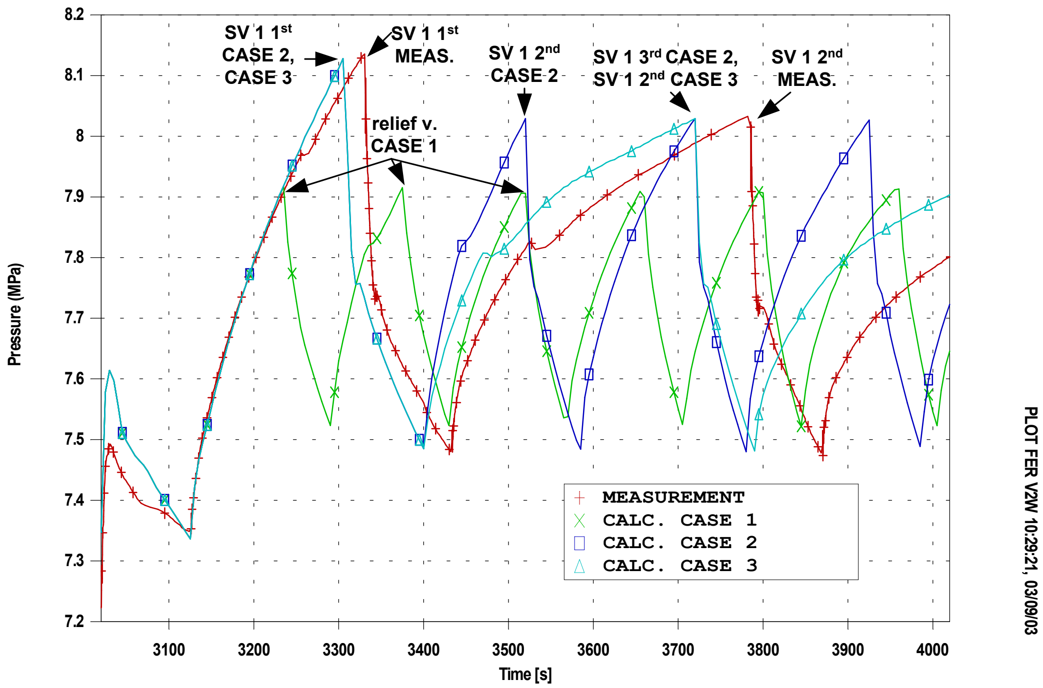

Figure 5: SG 1 pressure, RCP Trip event calculation (CASE 1, CASE 2, CASE 3)

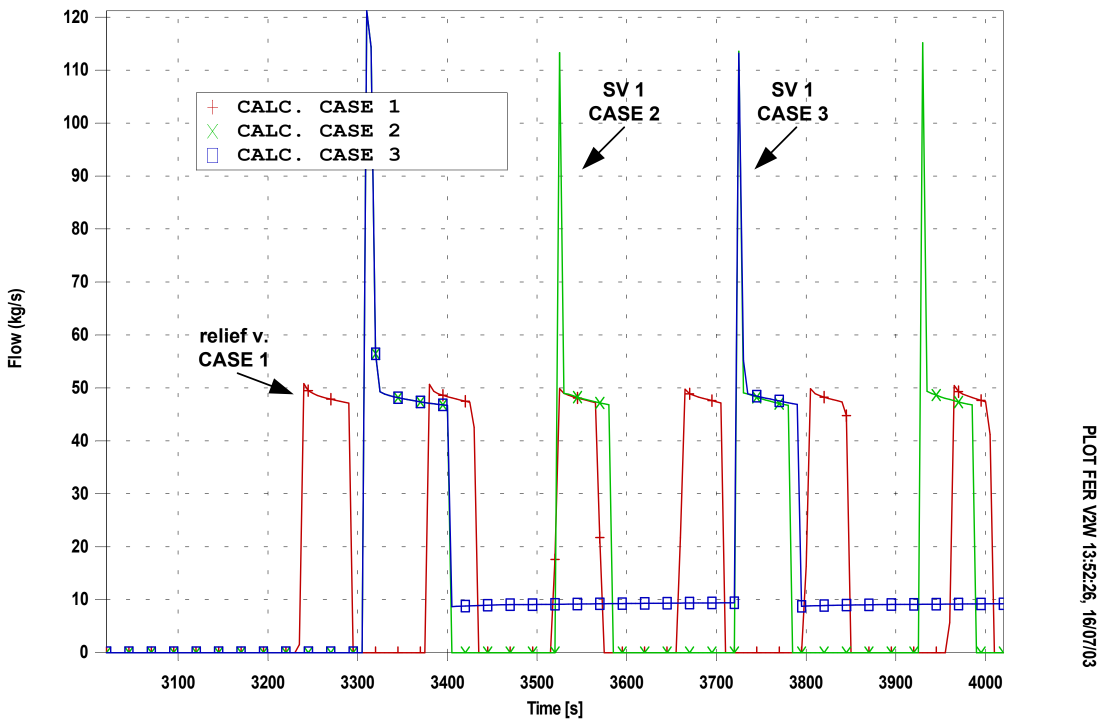

Figure 6: SG 1 relief and safety valve 1 flow, RCP Trip event calculation (CASE 1, CASE 2, CASE 3)

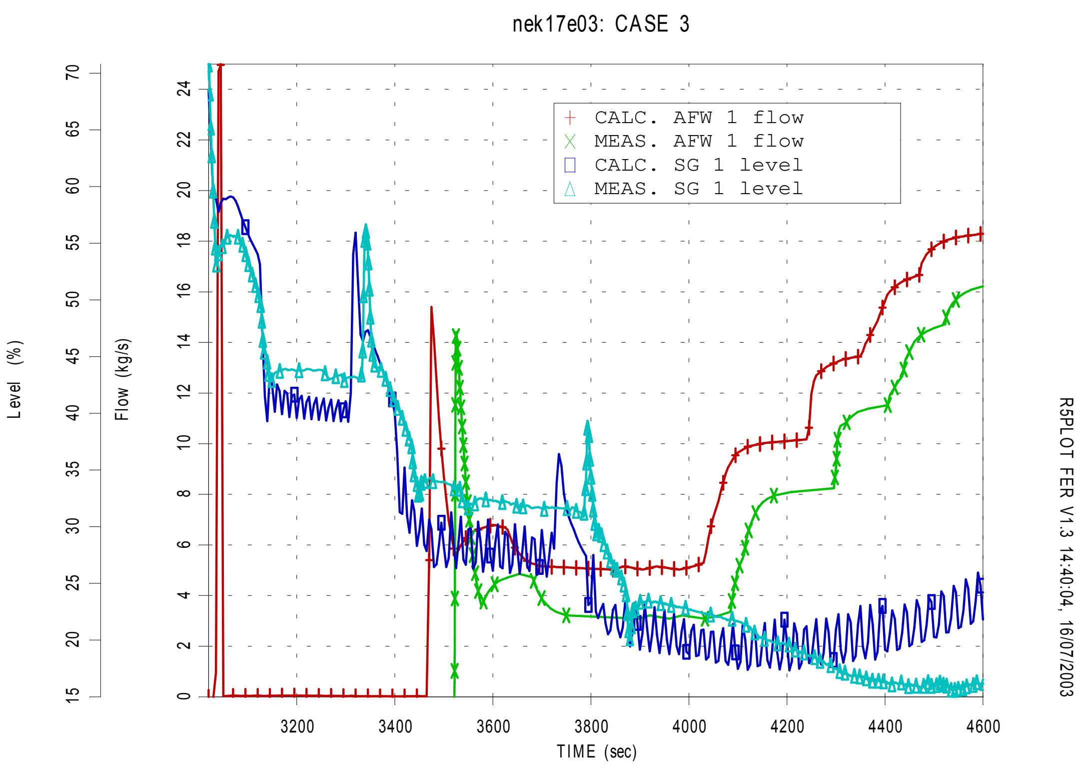

Figure 7: SG 1 AFW flow and SG 1 narrow range level, RCP Trip event calculation (CASE 3)

4 CONCLUSION

The RELAP5/MOD 3.3 analysis of the RCP Trip event at NPP Krško was performed. In the analysis the realistic boundary and initial conditions were assumed. The analysis was subdivided into two parts:

- Calculation of the initial conditions for the RCP Trip event, i.e., the power reduction: 100 % - 28 % during the first 50 minutes of the simulation. The analysed power reduction transient made demands on proper modelling of all control systems in the plant. The obtained differences between measured and calculated values are well within the acceptance criteria.
- Calculation of the RCP Trip event. The realistic plant behaviour influenced by operator actions has been taken into account in the analysis. All major trends following the RCP Trip event were well predicted by the model. During the simulation the two major effects on transient results were identified: the SG 1 relief or SV 1 open/close behaviour and AFW flow actuation. Three sensitivity study analyses (CASE 1, CASE 2 and CASE 3) were aimed to investigate the influence of SG 1 relief and SV 1 flow on transient results. The comparison of the cases CASE 1 and CASE 2 with measurement has suggested that in the real event the SG 1 relief valve did not open. In the CASE 2 the particular SG 1 SV 1 valve behaviour influenced by the operator actions was assumed. In the CASE 3 it was assumed that in addition to the particular SG 1 SV 1 valve behaviour the residual valve flow remained (8 % valve opening). Thus, for the CASE 3 the major characteristics of the real transient have been reproduced, e.g., the results for SG pressure, SG level, average temperature, etc.

The presented RELAP5/MOD 3.3 analysis has demonstrated the appropriateness of the developed NPP Krško nodalization with models of the plant control systems for use in the realistic transient simulation.

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