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Analysis of Manual Reactor Trip of NEK NPP in APROS Computer Code

Tadeja Polach, Dejan Slovenc, Jure Jazbinšek
ZEL-EN d.o.o., Vrbina 18,
8270 Krško, Slovenia
tadeja.polach@zel-en.si, dejan.slovenc@zel.en.si, jure.jazbinsek@zel-en.si

Ivica Bašić
APoSS d.o.o, Repovec 23b,
49210 Zabok, Croatia
basic.ivica@kr.t-com.hr

Luka Štrubelj
GEN energija d.o.o, Vrbina 17,
8270 Krško, Slovenia
luka.strubelj@gen-energija.si

ABSTRACT

The Slovenian Krško Nuclear Power Plant (NEK) model was built in using APROS - Advanced PROcess Simulation environment. The basis for the this model was the RELAP5/MOD3.3 Engineering Handbook, the model was updated to the 26th cycle and also includes the upflow conversion modification.

A detailed model nodalisation was created for each system and every system was separately validated. The current model covers the primary circuit with the core kinetics model, the secondary circuit and their control systems. The steady state of the APROS NEK model already having been validated, the plan now is to validate the model for some transients and design basis accidents. In this article the plant behaviour after the manual reactor trip is analysed in detail. Two scenarios of the manual reactor trip transient are performed, where either the Main Steam Isolation Valve (MSIV) closes after 60s – case A, or remains open – case B.

After the manual reactor trip from the 100% power, the control system signal actuations and their times were followed and then the responses of different affected systems were being observed. All those recorded values were then compared with the identical transient performed on the similar NEK model with the RELAP5/MOD3.3 system code. This procedure allowed to bring the current APROS NEK model one step forward towards being assured to have accurate calculations.

Keywords: *APROS 6, NEK, reactor trip, point kinetics, steam dump, PORV*

1 INTRODUCTION

The Krško Nuclear Power Plant – NEK in Slovenia has a two loop Westinghouse PWR nuclear steam supply system with 1994 MW thermal output power. A model of the primary circuit with a reactor core and the secondary circuit was built using the Advanced PROcess Simulation environment – APROS [1].

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Up to the present time the APROS model of primary and secondary circuit have been verified in the steady state. Beforehand also singular systems have been validated, as separate plant system tests have been performed comparing the APROS model response to the set of plan surveillance tests – for example steam dump (SD) control actuation, Reactor Coolant Pump (RCP) coastdown curve, pressurizer (PRZ) pressure and level control, accumulator full flow test, high/low pressure safety injection (SI) recirculation and full flow test, etc.

The aim of work presented in this paper is to perform the manual reactor trip from the 100% power, analyze the results and evaluate them by comparison to the similar transient made in the RELAP5/MOD3.3. As the long-term goal is to validate the APROS NEK model, comparing its simulation results with already existing NEK analyses performed in the past with RELAP5 code and reanalysis of on-site transients that occurred at NEK in the past.

APROS, developed by the Research Centre VTT and Fortum Engineering in Finland, is a program package that allows making the dynamical simulations for engineering purposes. The tool is suitable for modelling and simulation of the dynamics of a process plant during all phases of its life span from predesign to training and model supported operation and control, for small simple models and full scope simulators. The data used for the model specification is inserted through the graphical diagrams. With the help of a graphical interface and use of a selection of process components i.e. basic building blocks, the system can be built. These building blocks have different graphical symbols representing the tank, valve, heat structure, etc. and can then be spatially discretized into several volumes for simulation purposes [2].

The RELAP5 data of the trip were obtained from the RELAP5/MOD3.3, a transient analysis code for complex thermal-hydraulic system and it was also used for the analysis of the manual reactor trip [3]. The NEK RELAP5 model represents the updated model to the state of the 26th cycle. It is updated in accordance to Resistance Temperature Detector Bypass Elimination (RTDBE) project and therefore are also updated the systems that are affected by RTDBE: the NR temperature measurement, OTΔT (over temperature Δ temperature) and OPΔT (over power Δ temperature) protection functions, compensated low steam line pressure lead-lag time constants, and Steam Dump System, were updated and changed in accordance with RTDBE project [3].

2 APROS MODEL DESCRIPTION

The current APROS NEK model built in APROS 6.04 version currently consists of 52 diagrams describing the processes of the primary and secondary coolant and the point kinetics model of the reactor core. With the changes and updates done in NEK also the already validated APROS NEK model of the 23rd cycle was brought up-to-date to reflect those changes. Therefore the RDTBE project required changes were entered into the model according to the NEK RELAP5\MOD3.3 Post-RTDBE Nodalization Notebook [4]. Additionally the upflow conversion of the Reactor Pressure Vessel was added, the modification that was introduced to NEK in the 28th cycle. The steady state of this new updated model was used as the initial condition. And for the case of this simulation the part of the secondary system was isolated and the turbine was set as a boundary of the model.

2.1 Boundary conditions

With the intention to minimize the CPU calculation times, part of the secondary system was isolated and the boundary of the simulated system was set to be the turbine. The turbine boundary condition in APROS was simply represented by two points (Figure 1), where the boundary pressure (p = 60.5 bar) and temperature (T=275.9°C) were set.

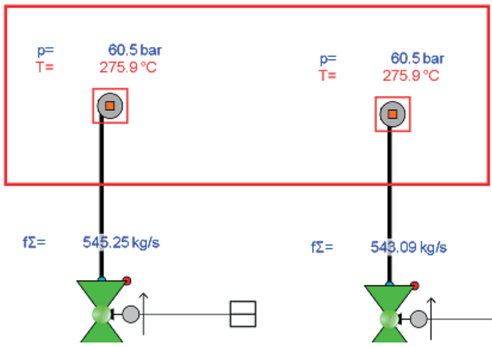

Figure 1: The boundary condition of the Reactor Trip model is set via 2 points in APROS representing the turbine.

Other main boundary conditions for the simulation of the transient were identical as in the RELAP5 model and are listed in Table 1 below.

Table 1: Main boundary conditions for the analysis [3].

Boundary condition	RELAP5 Value	APROS value	Comment
Letdown flow	3.7 kg/s	3. 7 kg/s (valve initially at 80%).	assumed constant flow until isolation
Letdown closing time for isolation	5 s	5 s	
Charging	270°C	270°C	assumed constant temperature
FW	219.35°C	219.4°C	assumed constant temperature
FW isolation valves	5 s	5 s	closing time
AFW	38°C	38°C	assumed constant temperature
SG SV	3 s	3 s	closing time
SG PORV	RELAP5 servo valve model	3 s	closing time
SG MSIV	3 s	3 s	closing time
Turbine valve	0.1 s	0.1 s	closing time
Secondary heat losses	neglected	neglected	

2.2 Initial conditions

The initial conditions of the transient simulation are the steady state values of the updated APROS NEK model of the 26th cycle including the upflow conversion of the RPV. To obtain these values, the model was left to run for several hours. And the values calculated with the APROS model were compared to NEK reference data and RELAP5 calculations, for 26th cycle in both cases. The results of the new steady state and the NEK reference data and RELAP5 found in the NEK RELAP5/MOD3.3 Post-RTDBE Steady State Qualification Report [5] were compared are presented below in Table 2.

Table 2: Comparison of NEK reference data and RELAP5 and APROS calculated values [5]. The below listed APROS values were also used as initial conditions of the transient simulation.

	Unit	NEK cycle 26	RELAP5	APROS
1. Pressure	MPa			
pressurizer		15.513	15.513	15.51
steam generator·		6.281	6.278/6.289	6.39
accumulator		4.93	4.93	4.93
2. Fluid Temperature	°C			
cold leg		285.6	286.37/286.14	286.83
hot leg		324.4	323.63/323.63	324.3

feedwater		219.45	219.55	219
3. Mass Flow	kg/s			
core		8966.9	9040.7	8867.6
cold leg		4694.7	4721.1/4720.1	4691.2/4693.5
main steam line		544.5	540.9/544.7	545.4/542.8
DC-UP bypass (2%)		187.8	184.94	200.67
DC-UH bypass (0.5%)		28.2	29	28.75
buffle-barrel flow (1.25%)		117.4	116.8	109.23
RCCA guide tubes (2%)		187.8	186.4	178.43
4. Liquid level	%			
pressurizer		55.7	55.8	54.09
SG narrow range		69.3	69.3/69.3	69.3/69.3
5. Fluid Mass	t			
primary system		-	131.27	132
SG (secondary)		47	49.1/49	
6. Power	MW	1994	1994	1994
core		1000	996.6/1003.1	997.6/1002.4
steam generator		15.513	15.513	15.51

3 GENERAL DESCRIPTION OF THE REACTOR TRIP TRANSIENT

To better validate our APROS NEK model, the same trip scenario made in RELAP5 model was also performed in APROS NEK model. The main events of the manual reactor trip form the 100% power were the following.

At manual signal for the reactor trip all rods fall into the core, the turbine trip is initiated and steam flow to the turbine stops abruptly. The loss of steam flow results in a rapid rise in secondary system temperature and pressure, therefore the SD is almost immediately initiated, it operates in the T_{avg} mode. The automatic SD system releases the excess steam generation, therefore the reactor coolant temperatures and pressure have no significant increase, while the SD and PRZ pressure control system are functioning. When the LO-T_{avg} temperature is met, it is followed by the isolation of the FW system via the Main Feedwater Isolation Valve closure, afterwards the Auxiliary Feedwater system (AFW) is started ensuring the adequate residual and decay heat removal capability. It operates in cycles keeping the steam generator (SG) level between 60% and 70%. There is no RCP trip [3]. In the later times two different scenarios are evaluated.

In case A there is a MSIV closure after 60 s, done as operator action and thus the SD valves that release the excess steam from the secondary system are cut-off and the task of lowering the main steam line pressure falls to the steam generator pressure operated relief valves (SG PORVs).

In case B the MSIV remains open and the SD valves continue in operation lowering pressure in the main steam line. And in both cases the simulation was left to run for 5000s.

The actuation of the above mentioned events is governed by the list of signals that are listed below in Table 3 and are the same in the RELAP5 and APROS NEK model.

Table 3: Delays of main protection signals and actions [3].

Event	Action	Setpoint	Delay [s]
REACTOR TRIP	manual		0
TURBINE TRIP	reactor trip		0
FW ISOLATION	LO-T_{avg} + R_x trip	295.6°C	0
Closure time for FW FIV			5
SL ISOLATION	manual		60
AF INJECTION	FW isolation signal		0
AF injection added delay			5

4 REACTOR TRIP CALCULATION IN APROS

The process diagrams in the APROS environment simulate the thermal-hydraulic variables of all the elements within one system that have been subdivided into volumes. The flow through the primary and secondary system is calculated using a six-equation flow model based on conservation equations of mass, momentum and energy for two phases. The core is modelled with the point kinetics model and the decay heat calculation was based on the ANS-79 decay curve, as in the RELAP5 model. The time step control had the maximum step size at the beginning of the transient 0.01s, 0.05s from 10 s and 0.1 s after 1000 s.

The APROS NEK model had all the values of its steady state at 100% power saved as the initial conditions, which are described in the chapters before. Then the simulation queue file was included which started the simulation with the manual reactor trip signal actuation and stopped it after 5000s, inside also the changes of the maximum step size during transient were set, and in case A it actuated the MSIV closure.

The reactor trip signal actuated the rod drop signal, the turbine trip signal and one of the FW isolation required signals (Figure 2).

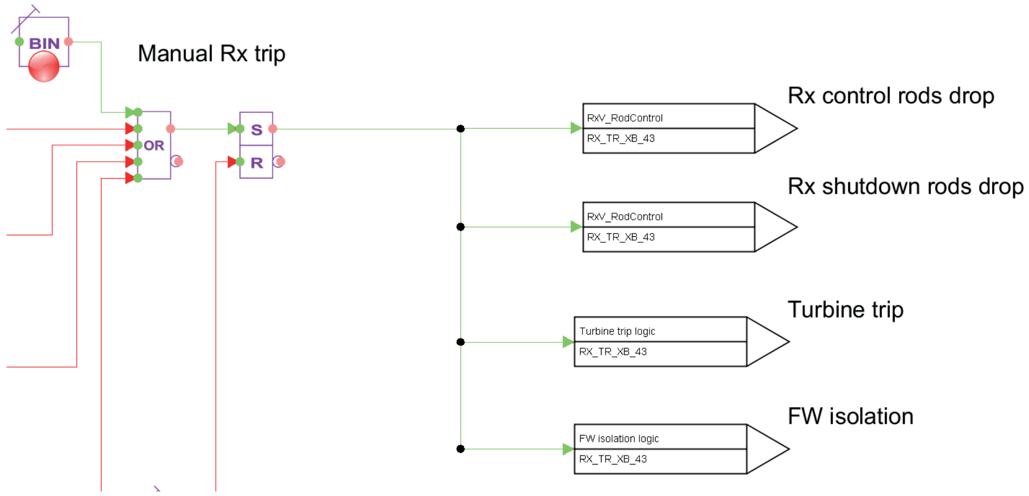

Figure 2: The Manual Reactor Trip in APROS actuation the rod drop signal, the turbine trip signal and one of the two required signals for FW isolation.

The rod drop in the core shuts-off the core kinetics calculation and the decay heat calculation is activated (Figure 3).

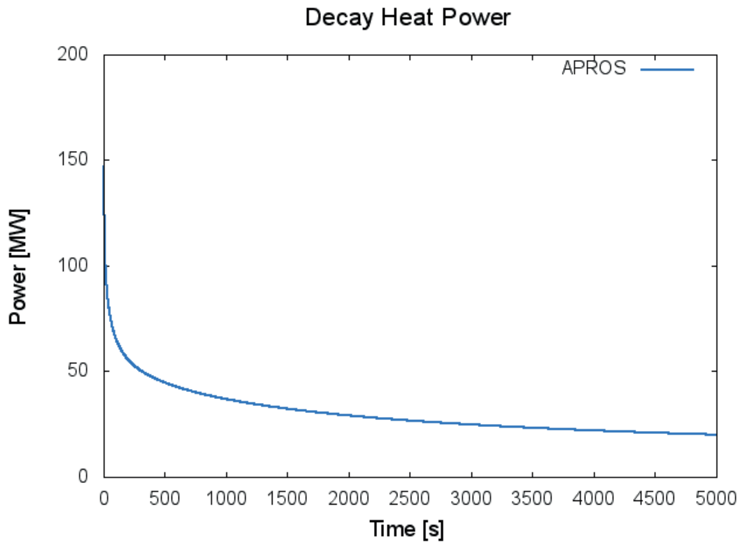

Figure 3: The decay heat curve calculated in APROS during the Reactor Trip transient.

The tubine trip actuates the closure of the turbine stop valve, which has 0.1s closing time, thus the turbine trip happens 0.1s after the Reactor Trip signal. The turbine trip signal also actuates the opening of the bank A and bank B of the SD that try to lower the T_{avg} to the T_{noload} (T=291.67°C) value by releasing steam to the condenser.

By releasing steam T_{avg} starts to decrease and when it reaches the LO- T_{avg} temperature (295.6°C), the second condition for the FW isolation is fulfilled and the FW isolation valve closes. Then with the delay of 5s the AFW motor pumps start and the AFW is used as secondary coolant. But as there is no exit for the steam after the turbine trip, the pressure starts increasing.

Case A – pressure rises until the PORV opening setpoint is reached and the PORV opens lowering the pressure. The steam pressure of the secondary circuit is therefore determined by the SG PORV opening and the on/off functioning of the AFW and that operation also maintains the SG level between 60% and 70%. And in case B the SD valves open when the T_{avg} temperature goes above T_{noload}. The long term goal of both scenarios is to remove the decay heat from the core.

5 ANALYSIS AND RESULT EVALUATION

The two scenarios, case A and case B were left to run in APROS and the calculated variables were sampled every second. All the relevant parameters were compared to RELAP5 results of the simulation, except those that did not change at all during the transient as the system did not start.

At the beginning of the transient the values calculated in APROS are very similar to those in RELAP5. The FW isolation happens 3 seconds later than in RELAP and the peak flow rate value is approximately 100 kg/s higher. Afterwards throughout the time of the transient the FW system remains isolated and the AFW system takes over regulating the SG level and cooling the core (Figure 4). The time sequence of the main events in the first minute was the same for case A and B, their comparison with RELAP5 is presented in Table 4.

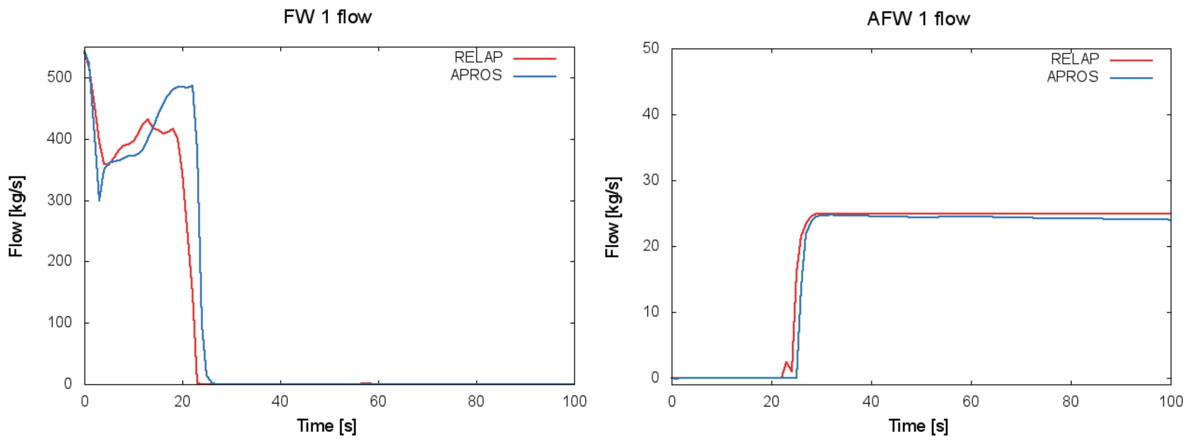

Figure 4: The comparison of the FW and AFW flow the first 100s of the transient.

Table 4: Comparison of the time sequence of main events.

Event	Time of event [s]			Comment
	RELAP5 case A	RELAP5 case B	APROS case A&B	
Reactor trip	0	0	0	
Turbine trip	0.06	0.03	0.1	on reactor trip
Main FW closure	17.91	17.87	21	LO-1 T_{avg} and reactor trip
AFW flow enabled	22.91	22.89	26	5 s delay after Main FW closure
AFW cycling on level enabled	32.91	32.91	36	10 s delay after AFW enabled
MSIV 1(2) isolation	60.09	/	60	60 s after turbine trip signal (case A only)

As stated in the previous paragraph the primary goal during this transient is the cooling of the core, which was successfully achieved in both cases (Figure 5).

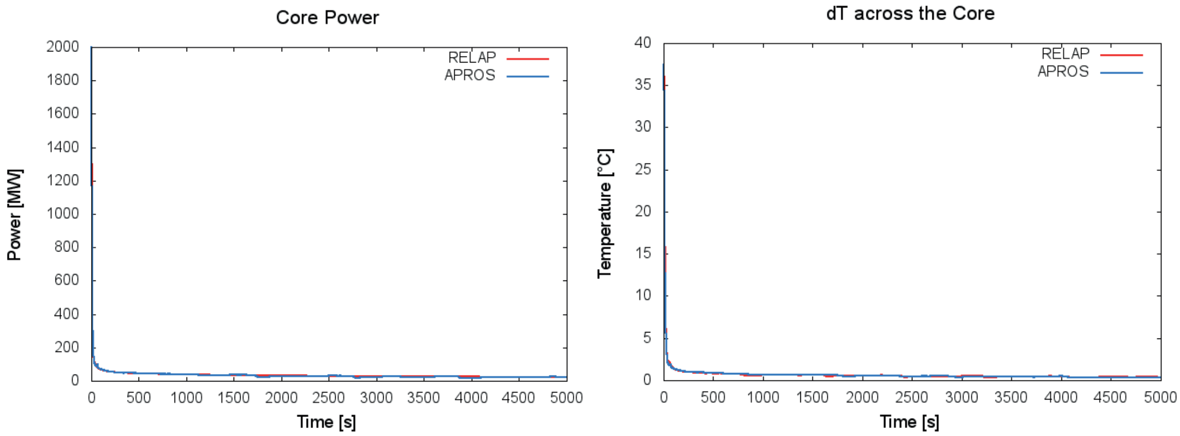

Figure 5: RELAP5 and APROS comparison of core power and dT across the core during the transient.

5.1 Case A analysis

After the MSIV closure the SD system is cut-off form the MS and the regulation of the pressure in MS is taken over by the SG PORVs. Just after the MSIV closure, the pressure of steam exiting from the SGs rises rapidly there is an earlier opening of the PORVs as the setpoint pressure 79.17 bar is reached already after approximately 350s, which is approximately 600s earlier than expected considering the RELAP5 results (Figure 6 left). This more rapid pressure rise at the beginning is because of the different condensation correlation calculation model used in APROS, where the Nusselt theory was chosen, contrarily in RELAP5 the maximum Nusselt and Shah is used. In total during the 5000s seconds of the transient the SG PORVs open 5 times as they do in RELAP5 simulation, but at the first opening the PORVs are open for a shorter period than in the later 4 times, and also the flow rate the first time is lower than the four later times (Figure 6 right).

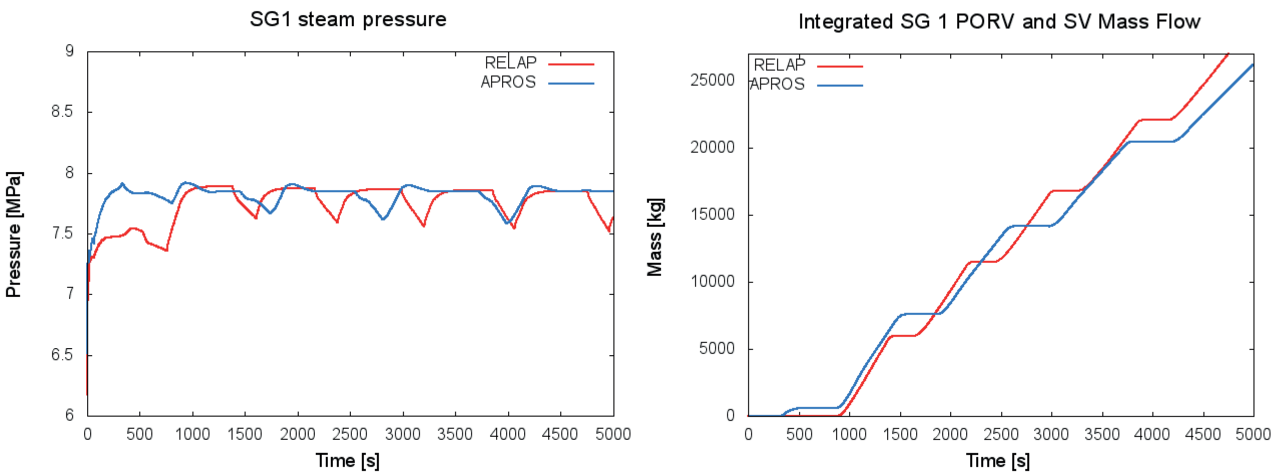

Figure 6: The comparison of the calculated values of the steam pressure exiting the SG 1 (left) and of the cumulative mass of the steam exiting through the SG 1 PORV (right).

In consequence of this different rate of pressure change there is also a different variation of the level change in the SGs instead of five 70% to 60% level drops as result in RELAP5, there are only four in APROS. Therefore there the times, at which the SG level drops to 60% and the AFW is activated, are different than in RELAP5. Additionally the AF pumps have been modelled including the heat-volume flow curve, therefore while they operate their flow rate is not constant (Figure 7).

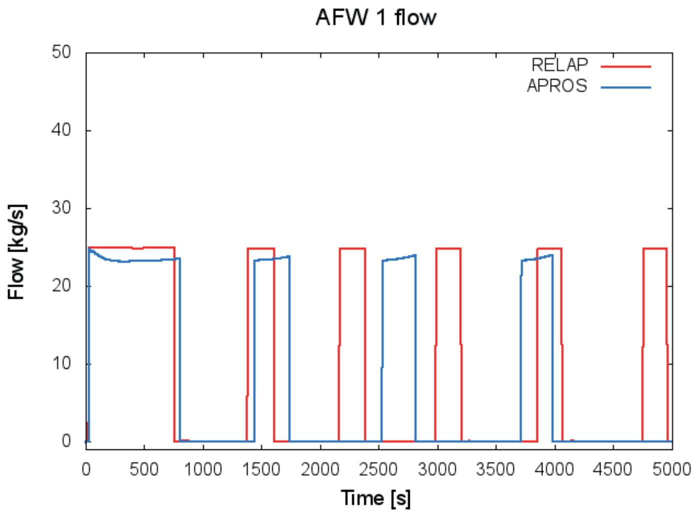

Figure 7: The comparison of the calculated values of the loop 1 AFW into the SG.

Due to this different rate of PORV opening and AFW cycling also other variables are phase-shifted, nevertheless their responses are similar to RELAP5's, as for example the heat flow through the SG. There the thermal heat transfer from the primary to the secondary circuit through the SG U-tubes is the very similar to RELAP5 results the first 20s, between the 20s and 60s the heat transfer in APROS is approximately 20 MW lower than in RELAP, most probably due to effect of a different condensation correlation type used in the models (Figure 8 left). Later during transient the thermal heat transfer is very similar, but there is also visible the phase difference (Figure 8 right).

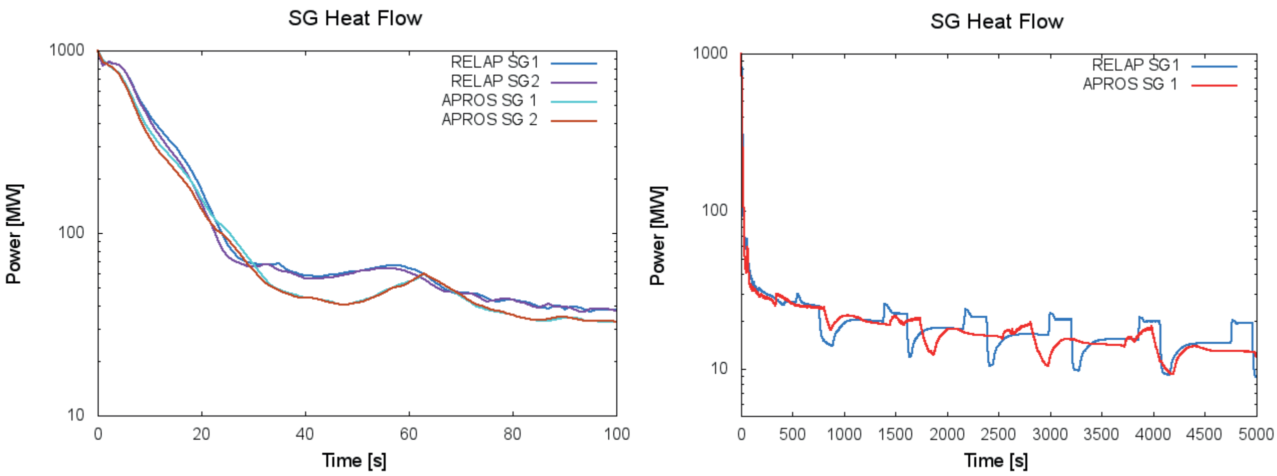

Figure 8: The comparison of the calculated heat flow through the SG U-tubes the first 100s of the transient (left) and throughout the transient (right).

At the beginning of the transient the T_{avg} was being lowered by the SD system and during that time the APROS calculated T_{avg} and consequently T_{hot} and T_{cold} are very similar to the respective RELAP5 results (Figure 9 left), but in later times when the PORVs take over the cooling there is discrepancy due to the phase difference explained above. The T_{avg} the temperature peaks are at approximately 295.5°C in APROS and a degree higher in RELAP5, and in both they decrease for about 0.5°C throughout the transient (Figure 9 right).

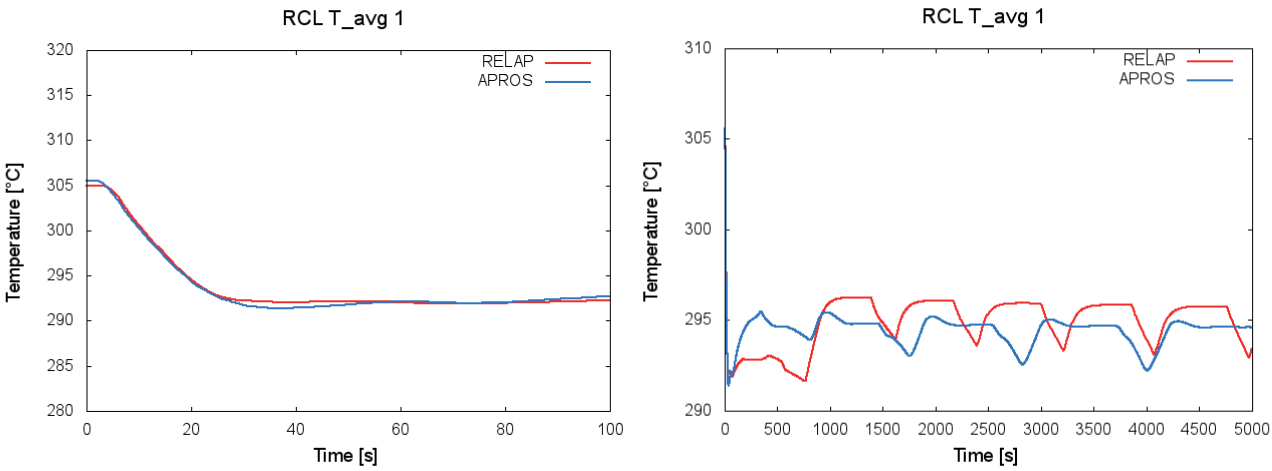

Figure 9: The comparison of the calculated T_{avg} value the first 100s of the transient (left) and throughout the transient (right).

The PRZ pressure peaks a little later than in RELAP5 and the PRZ level recuperates some time later than in RELAP5 (Figure 10 left and right), probably because of the some longer response times in regulation. Therefore we have a higher charging flow in APROS than in RELAP5, the letdown flows are fixed in both models.

The pressurizer heaters (Figure 11 left) and sprays (Figure 11 right) have similar responses in APROS as in RELAP but the spray peaks are much lower in APROS than in RELAP and the phase of the responses is shifted because of the reason described above. The RCS flow in APROS is very similar to that in RELAP, but again there is the same phase shift.

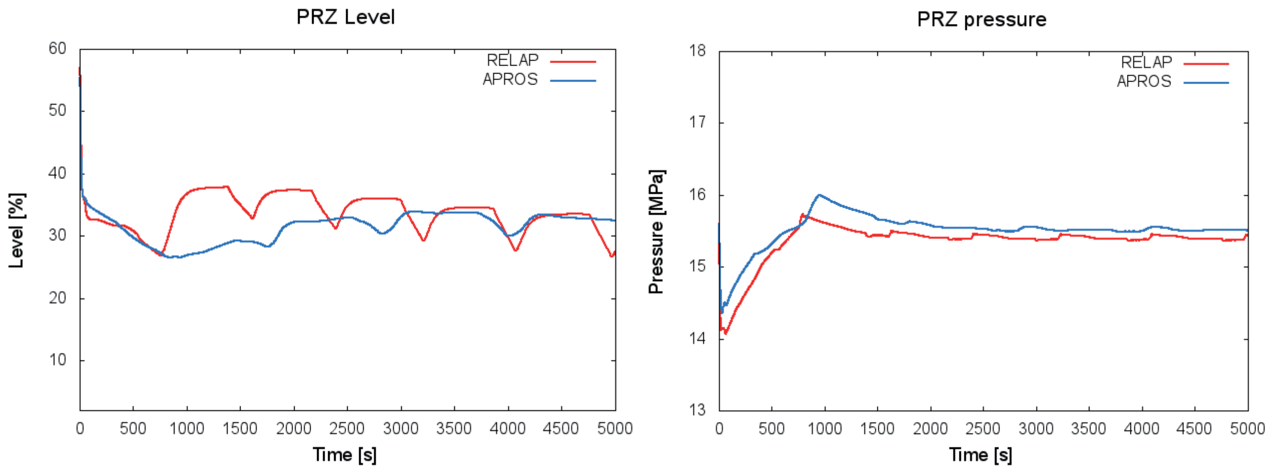

Figure 10: The comparison of the calculated PRZ level (left) and PRZ pressure (right).

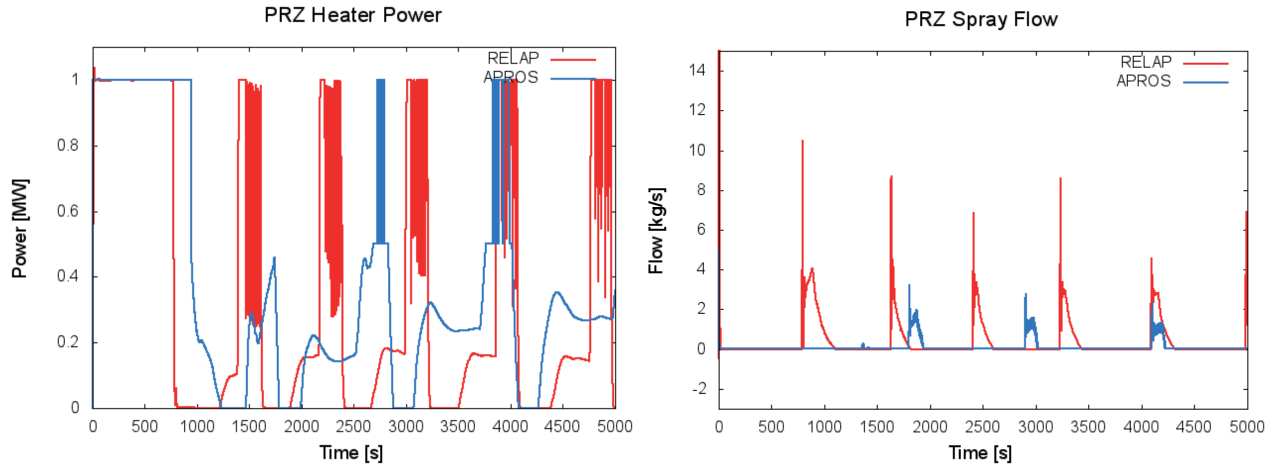

Figure 11: The comparison of the calculated PRZ heater power (left) and PRZ spray flow (right).

5.2 Case B analysis

In case B even after 60 s of the transient the SD system remains in operation and continues to release steam always, when T_{avg} is above T_{noload} in order to lower it (Figure 12 left). In case A and case B the SD opens 3s after the Turbine trip signal. SD flow peaks 4s after the reactor trip in both APROS and RELAP5, only in APROS it is approximately 100 kg/s lower, however it lowers the T_{avg} sufficiently, afterwards in both environments there are a few ripples that continue lowering the temperature, which in APROS are a bit higher than RELAP5. The cyclic operation of SD in APROS starts approximately 75s later than in the RELAP5 model. Most likely because of the reason stated earlier. The SD open cycles in APROS are longer than in RELAP5, but there are only 4 of them, in contrary there are 5 RELAP5 and they have slightly higher flow rates, less than 4 kg/s.

As the oscillations of the SD valves are directly linked to the T_{avg}, there are 5 shorter oscillations of T_{avg} in RELAP5 and 4 longer in APROS. The oscillation peak in RELAP5 is at 292.2°C and decreases for 0.2°C during the transient. In APROS T_{avg} peaks 0.3°C lower and decreases for less than 0.1°C during transient (Figure 12 right).

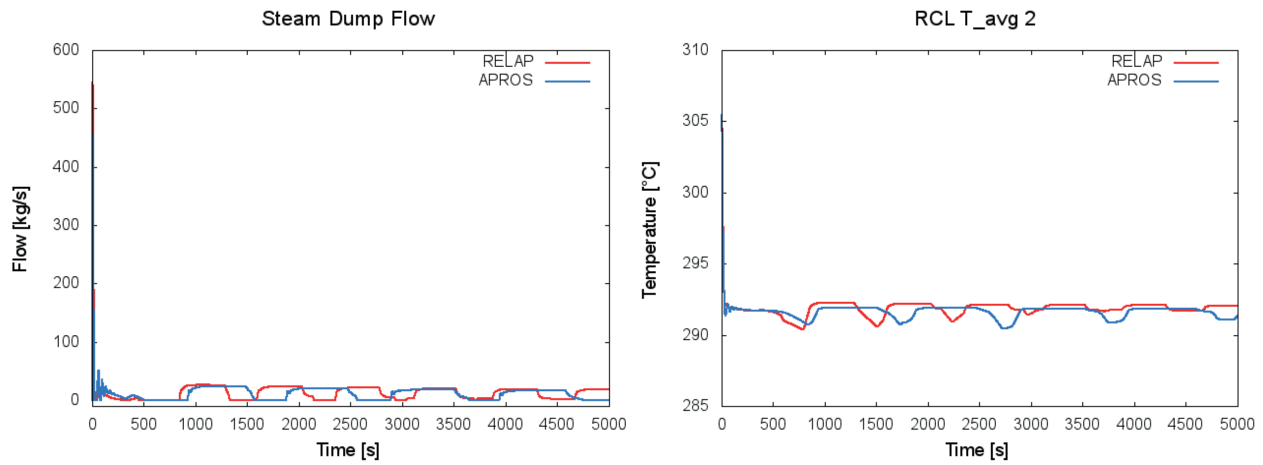

Figure 12: The comparison of the calculated SD flow (left), T_{avg} (right).

The steam pressure in the steam generator is in APROS calculations approximately 1 bar higher than in RELAP5, again here most likely because of the different condensation correlation calculation (Figure 13). The same oscillation pattern of that is given by the SD operation can be

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seen also in the responses of other variables as in case B they are governed by the SD and AFW cycling. As for example, the heat flow through U-tubes is presented on Figure 14.

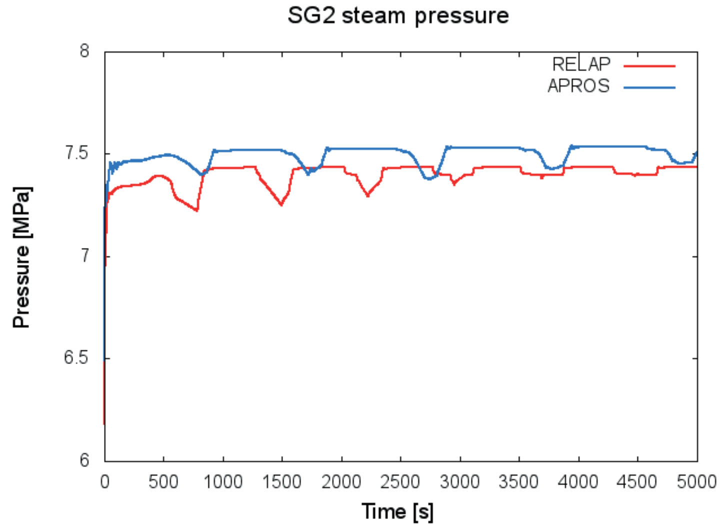

Figure 13: The comparison of the calculated steam pressure exiting the SG 2.

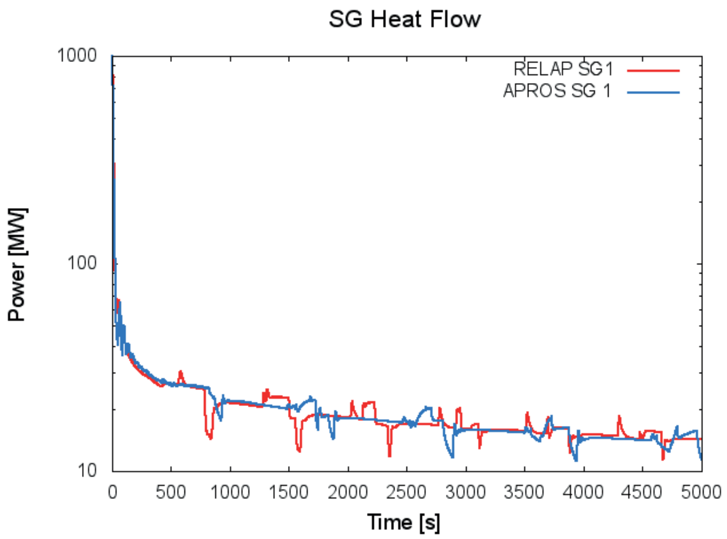

Figure 14: The comparison of the calculated heat flow through the SG U-tubes.

The PRZ level in case B (Figure 15 left) is higher in APROS calculations, but this is most likely due to the slightly higher spray flow rate throughout the transient (Figure 15 right).

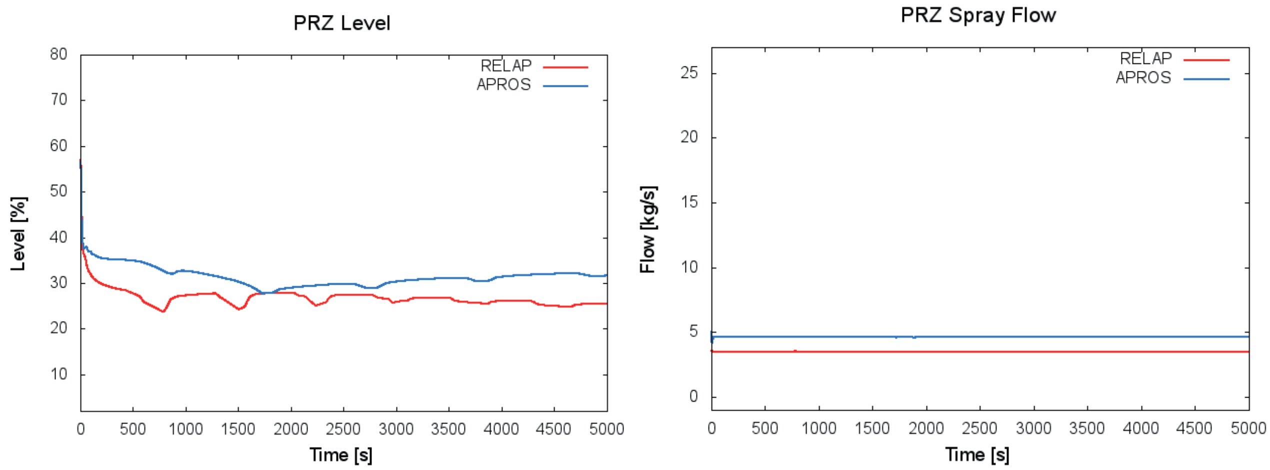

Figure 15: The comparison of the calculated PRZ level (left), PRZ spray flow (right).

6 CONCLUSION

In this Reactor Trip transient simulation two scenarios were analysed in order to observe the response of the SD valves and the SG PORVs. The APROS NEK simulations results were compared to the calculations obtained running the same transient on the RELAP5 model, as this model has already been validated. This analysis showed a satisfactory behaviour of our model. Many differences that arose were also expected as APROS and RELAP5 used different calculation methods. Nevertheless further transient analyses are planned, in order to validate different systems responses that have been incorporated into a wide-ranging model. Then further on, the model behaviour is to be compared to real plant responses. In the immediate future the APROS NEK model will be imported into the new version of APROS 6.05, and will therefore benefit of the more advanced programming options.

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