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OPTIMIZATION OF OPDT PROTECTION FOR OVERCOOLING ACCIDENTS

SUMMARY

Overcooling accidents are typically resulting in power increase due to negative moderator feedback. There are more protection set points responsible for terminating power increase. OPDT protection set point is typically protection from exceeding fuel centre line temperature due to reactivity and power increase. It is important to actuate reactor trip signal early enough, but to be able to filter out events where actuation is not necessary. Different concepts of coolant temperature compensation as part of OPDT set point protection were studied for decrease of feedwater temperature accident and for small main steam line breaks from full power for NPP Krško. Computer code RELAP5/mod 3.3 was used in calculation. The influence of different assumptions in accident description as well as nuclear core characteristics were described.

Key words: OPDT protection, overcooling accident, RCS temperature measurement, RELAP5, RTD bypass

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1. INTRODUCTION

The accidents that manifest in the overcooling of the primary side are typically caused by a failure on the secondary side that lead to an increased heat removal in the steam generators. In the presence of the negative moderator reactivity coefficient, the excessive cooling of the primary side leads to an increase of nuclear power. The temperature increase in reactor vessel which is a measure of the core heat power will increase whereas the cold leg temperature decreases due to increased heat removal. The coolant temperature decrease leads also to an increase of coolant density and outsurge from the pressurizer. The primary pressure will decrease and Safety Injection (SI) signal may be actuated. As a consequence of the nuclear power increase in combination with a pressure decrease, overcooling accidents (with no protective functions) can result in fuel temperature increase and departure from nuclear boiling (DNB) which can ultimately lead to fuel damage. The necessary protection against the overcooling accidents is provided by reactor trip that will reduce the core power to decay heat and the fuel temperature to no load values. The second protective action consists of the stopping the excessive heat extraction from the primary side and depends on the initial event (feedwater malfunction or excessive steam load). The reactor protection system will actuate the reactor trip on any of the following trip signals: a) Power range high neutron flux, b) Overpower ΔT (OPΔT), c) Overtemperature ΔT (OTΔT), d) Low pressurizer pressure, e) SI or f) Turbine trip signal. The OPΔT and OTΔT reactor trip functions are intended to provide fuel integrity protection during the overcooling accidents such as feedwater system malfunction or excessive steam load increase as well as during a number of overpower and overtemperature events (e.g., rod withdrawal at power and uncontrolled boron dilution).

The measured narrow range (NR) temperature signals are used in plant protection system (the setpoints for OPΔT and OTΔT reactor trip), as well as in a number of plant control systems (automatic rod control system, steam dump, pressurizer level control). During the 2013 outage the NPP Krško has undergone the Resistance Temperature Detector Bypass Elimination (RTDBE) project to improve operation and maintenance. The Resistance Temperature Detectors (RTD) bypass manifold system for the NR temperature measurement has been removed and the fast–response thermowell (TW) RTDs were embedded in the thermowell structure as a part of the primary loop wall. The response time of TW RTDs is slower due to thermal inertia of the additional metal mass attached to the RTD than the response time of the directly immersed RTDs. On the other hand, for TWs, there is no delay due to loop transport or thermal lag. The RCS temperature measurement response time is accounted for in reactor protection system set points as well as in plant control system settings. The OPΔT protection function has been modified as part of RTDBE. In the old pre-RTDBE implementation the compensated measured temperature difference ΔT was calculated by applying the lead-lag on measured temperature difference. In the new implementation, different compensations were applied for the measured hot and cold leg temperature. For overcooling accidents the OPΔT trip protects the core due to the increasing compensated measured temperature difference ΔT whereas the OPΔT trip set point does not change from its steady state value. The safety concern for the overcooling accidents is that after RTDBE the response time of the OPΔT may increase thus decreasing the margin to DNB.

Two overcooling accidents for NPP Krško were analyzed using RELAP5/mod 3.3 for NPP Krško: 1. Feedwater Malfunction-Decrease in Feedwater Temperature (FM DFT) and 2. Hot Full Power Main Steam Line Break (HFP MSLB). In the analyses different concepts for coolant temperature compensation in OPΔT protection set point were studied and the adequacy of the protection functions were investigated.

2. CALCULATION MODEL FOR NPP KRŠKO

The RELAP5/mod 3.3 nodalization for NPP Krško, Figure 1, developed at Faculty of Electrical Engineering and Computing (FER) was used for transient analysis, [1] and [2]. The plant model has been updated taking into account the RTDBE project realized during the plant 2013 outage. The explicit RTD bypass manifold system for the NR Reactor Coolant System (RCS) temperature measurement was removed and it was replaced with compensated temperature signals that were modelled to take into account the thermowell structure's thermal lag. RELAP5 model consists of 481 thermal-hydraulic volumes, 518 junctions, 378 heat structures with 2107 mesh points, 733 control variables and 197 variable and 221 logical trips. It includes major modifications related to the Krško modernization project as well as RTDBE project; e.g., the model of the replacement steam generator (RSG) based on data provided by the RSG designer (Siemens), power uprate, removal of the guide tubes plugs inside the core as well as changes to the protection and plant control systems. The RELAP5 model contains the models of the NPP Krško monitoring as well as protection and control systems, e.g., the detailed models of Safety Injection (SI) system, Main feedwater (MFW) and Auxiliary feedwater (AFW) system as well as of control systems (automatic rod control, pressurizer pressure and level control, steam dump control with realistic representation of steam dump valves and steam generator level control).

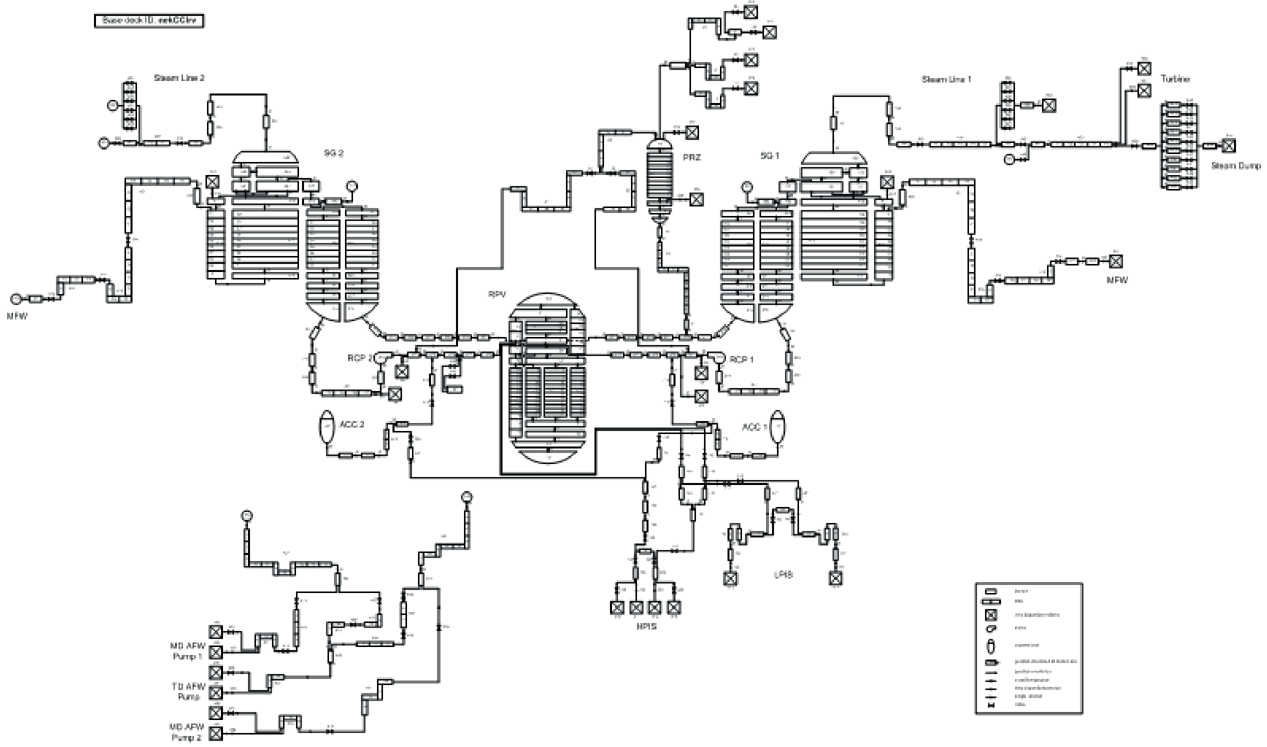

Figure 1. RELAP5/mod 3.3 nodalization scheme for NPP Krško

2.1 Reactor Trip Protection Functions during Overcooling Accidents

The OTΔT and OPΔT protection functions are schematically presented in Figure 2 (Old configuration before RTDBE) and in Figure 3 (New plant configuration after RTDBE).

At the plant, the set point for OPΔT trip is continuously calculated by solving the following equation:

$$OP\Delta T_{setpo\,\mathrm{int}} = \Delta T_0\left[K_4 - K_5\left(\frac{\tau_3 s}{1+\tau_3 s}\right)\left(\frac{1}{1+\tau_7 s}\right)T_{avg} - K_6\left(T_{avg}\left(\frac{1}{1+\tau_7 s}\right) - T_{avgref}\right)\right] \qquad (1)$$

Where:

$OP\Delta T_{setpo\,\mathrm{int}}$ - Overpower ΔT set point

ΔT_0 - Indicated ΔT at nominal thermal power

T_{avg}, T_{avgref} - Measured and indicated loop average temperature at nominal thermal power

K_4 - Set point bias

K_5, K_6 - Constants that depend on dynamic behaviour of the measured T_{avg}

τ_3 - Time constant (s) of dynamic signal compensator (impulse)

τ_7 - Time constant (s) in the measured T_{avg} lag compensator

s - Laplace transform variable (s^{-1})

$OP\Delta T_{setpoint}$ is limited to the value calculated at nominal T_{avg} (T_{avgref})

The calculated $OP\Delta T_{setpoint}$ is compared with two sets of loop temperature difference measurements (ΔT) per loop. The OPΔT reactor trip function will trip the reactor on coincidence of two out of four signals satisfying the condition below:

$$OP\Delta T_{setpoint} \leq \Delta T \tag{2}$$

In the old plant configuration (before RTDBE, Figure 2) the lead-lag compensation was applied after measured temperature difference ΔT was formed. For the current post-RTDBE plant configuration, the measured compensated ΔT for the OPΔT protection function is calculated by subtracting the compensated T_{cold} signal from the compensated T_{hot} signal. The hot leg temperature is compensated by a lag element in order to suppress the oscillations in the hot leg measurement due to hot leg streaming (lag element, time constant=τ_8 in Figure 3). The compensation of the cold leg temperature that has a rather uniform distribution across the pipe is directed to fulfil the efficiency of the OPΔT protection function for overcooling accidents. Among the available options, the lead-lag compensation (with greater lead time constant) as well as the lag compensation was considered. The lead-lag element for T_{cold} has shown to be very sensitive to the outside electromagnetic disturbances thus leading to unnecessary reactor trips.

Finally, at the plant, the measured compensated ΔT will be calculated using the following equation:

$$\Delta T = T_{hot}\frac{1}{1+\tau_8 s} - T_{cold}\frac{1}{1+\tau_5 s} \tag{3}$$

where $\tau_5 < \tau_8$. Thus, the increase of the compensated measured ΔT is accelerated for overcooling accidents since the cold leg temperature decreases due to excessive heat removal in steam generators. Due to the fact that $OP\Delta T_{setpoint}$ is limited to the value at nominal power since the RCS average temperature decreases during the overcooling accidents, the OPΔT trip may be actuated due to increasing measured temperature difference (ΔT), Eqs. (2) and (3).

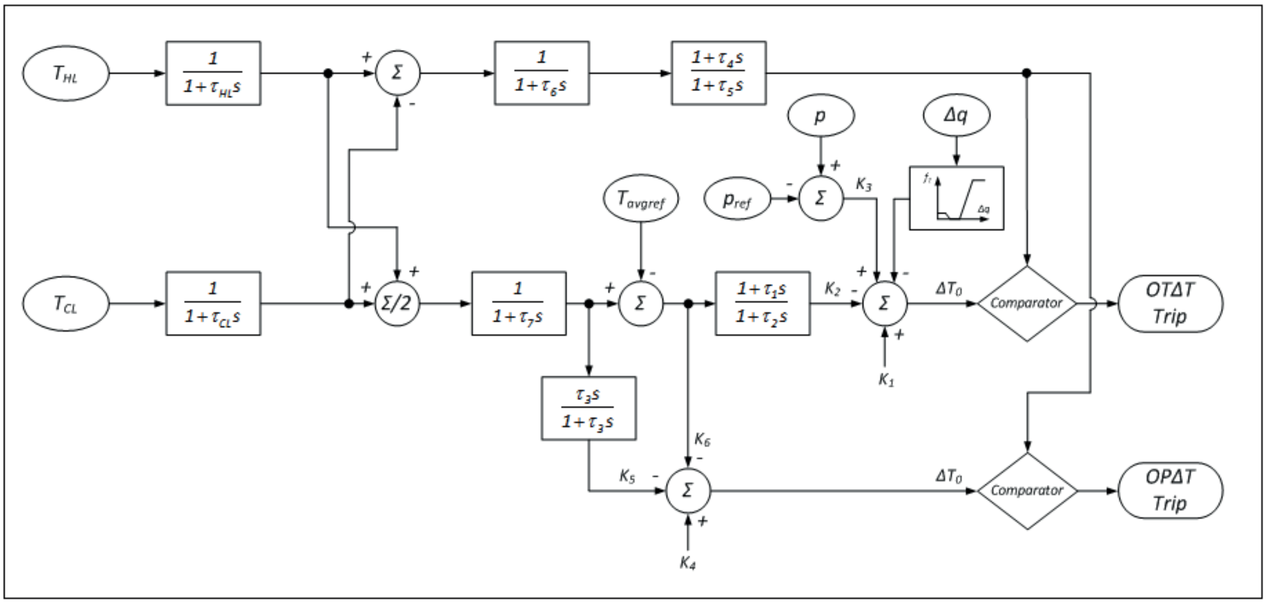

Figure 2. Old (before RTDBE) OTΔT/OPΔT control block scheme

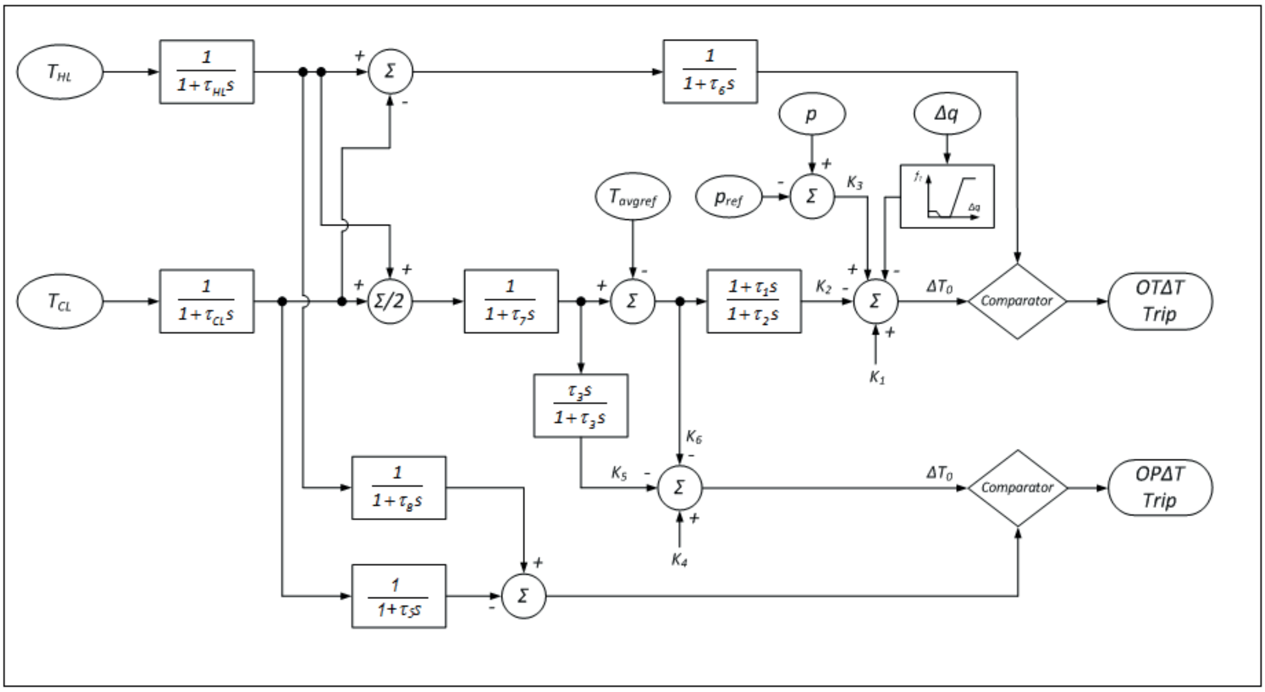

Figure 3. New (post-RTDBE) OTΔT/OPΔT control block scheme

3. ANALYSIS OF OVERCOOLING ACCIDENTS FOR OPΔT OPTIMIZATION

The typical overcooling accidents that are used for an assessment of the efficiency of OPΔT protection function are the Feedwater Malfunction – Decrease in Feedwater Temperature (FM DFT) and the Hot Full Power Main Steam Line Break (HFP MSLB). Both accidents were analyzed using RELAP5/mod 3.3 code. In order to make an assessment of the adequacy of the OPΔT protection, sensitivity study calculations were performed with different concepts for coolant temperature measurement and OPΔT set point calculation. For the base case best-estimate calculation the current post-RTDBE NPP Krško configuration, cycle 26, and with the cold leg temperature compensation with lag element (time constant=2 s) in measured ΔT signal was used. The End of Cycle (EOC) conditions with maximum negative moderator temperature reactivity coefficient were assumed. The power range high neutron flux trip was not credited in the analysis. Steam line pressure signal for steam line isolation and safety injection is compensated by lead-lag element introduced along with RTDBE with lead and lag time constant equal to 48 s and 8 seconds, respectively.

3.1 Analysis of Feedwater System Malfunction – Decrease in FW Temperature (FM DFT)

The accident is simulated by a step decrease in the feed water temperature from the initial full power (492.7 K) to a minimum credible value (414.55 K). There are a number of events that can cause the feedwater temperature decrease, e.g., the opening of the feedwater heater bypass valve, a spurious trip of the heater drain pumps, or the break of steam flow to the high pressure heaters. The results for the base case best-estimate calculation with the lag element (time constant=2 s) for the cold leg temperature compensation in OPΔT function are presented in Figure 4 through Figure 7. As a consequence of feedwater temperature decrease and the fact that the flow to the turbine remained constant, the heat transferred in the steam generators will increase and the coolant temperature on the primary side will decrease, Figure 4 and Figure 5. In the presence of negative moderator reactivity coefficient, decrease in moderator temperature will result in an increase in core power and fuel temperature increase. The Doppler reactivity coefficient is negative and it will reduce the total reactivity due to fuel temperature increase, Figure 6. If the automatic control system is in operation, decrease in coolant temperature may cause control rod withdrawal in an attempt to maintain the average coolant temperature at its programmed value. This may cause a further increase of nuclear power and fuel temperature. The decrease in coolant temperature will result in coolant density increase, causing the outsurge from the pressurizer and the subsequent decrease in the primary pressure. The necessary protection against the FM DFT accident is provided by reactor trip that will reduce the core power to decay heat and the fuel temperature to no load values. Further, the feedwater that causes the cooldown on the primary side will be isolated on either the low average RCS temperature in combination with reactor trip or by safety injection signal that may be actuated due to low pressurizer pressure. The reactor trip can be actuated on either of the following signals: Power range high neutron flux, OPΔT or OTΔT, Low pressurizer pressure and Turbine trip (on High-high SG water level). The OPΔT provides the specific protection against two major concerns during FM DFT, i.e. the high neutron flux and low DNB ratio (DNBR). Both the nuclear power increase and the DNB are managed by the measured compensated temperature difference, whereas the OPΔT set point is limited to its steady state value since the average temperature decreases in the transient. In our case, the OPDT trip trips the reactor (44.3 s after transient begin) before the temperature error in the Automatic rod control system increased above the value for control rod movement, Figure 6 and Figure 7. In order to estimate the influence of different RCS temperature measurement concepts and OPΔT set point calculation the sensitivity study calculations have been performed. Five groups of FM DFT cases have been analyzed:

1. RTDBE base case best-estimate calculation, OPΔT cold leg temperature compensation: lag (time constant=2 s). Two cases have been analyzed:
   a) dft_be_00_auto (Automatic rod control system active) and
   b) dft_be_00_manual (Automatic rod control system not active)
2. RTDBE best-estimate calculation, OPΔT cold leg temperature compensation: lag (time constant=7 s). The aim of the sensitivity calculation is to estimate the influence of cold leg temperature lag time constant. Two cases have been analyzed:
   a) dft_be_01_auto (Automatic rod control system active) and
   b) dft_be_01_manual (Automatic rod control system not active)
3. RTDBE best-estimate calculation, OPΔT cold leg temperature lead-lag compensation with lead and lag time constants equal to 30 s and 10 s, respectively. Only the case with automatic rod control system not active was analyzed: dft_be_02_manual.
4. RTDBE conservative calculation with the assumptions from the referent literature, e.g., ref. [5]: 1) The Safety Analysis Limit (SAL) for OPΔT set point calculation with K_4=1.15 instead of 1.08, 2) Conservative moderator (maximum) and Doppler (minimum) reactivity feedback coefficients, 3) Turbine trip on reactor trip not credited, 4) Maximum feed water flow (feedwater flow=steam flow until feedwater isolation), 5) The minimum initial SG mass (10% less than nominal), 6) The maximum initial RCS average temperature (580.55 K) and 7) The feed water temperature decreases instantaneously at the very entrance of the steam generator (without delay from feedwater header). OPΔT cold leg temperature compensation lag time constant=2 s. Two cases have been analyzed:
   a) dft_sal_auto (Automatic rod control system active) and
   b) dft_sal_manual (Automatic rod control system not active)
5. RTD best-estimate calculation. The case represents the configuration before the RTDBE modification, i.e., with RTD bypass. Two cases have been analyzed:
   a) dft_rtd_auto (Automatic rod control system active) and
   b) dft_rtd_manual (Automatic rod control system not active)

The results for the FM-DFT analysis for the sensitivity study are summarized in Table I. For an assessment of fuel integrity the maximum nuclear power and the maximum core heat power were observed. The comparison of the two base cases (after and before RTDBE- cases 1 and 5) shows the slower response of the OPΔT protection function for the new post-RTDBE than for the old pre-RTDBE configuration and correspondingly the higher maximum core heat power for the former case. For the post-RTDBE the OPΔT trip is actuated 4.1 s later than for the pre-RTDBE and the maximum values for the core heat power for the post-RTDBE and pre-RTDBE are equal to 109.5% and 107.69%, respectively. The sensitivity study calculation for the post-RTDBE configuration has shown a relatively small difference between the two lag compensations (2 s and 7 s); i.e., the maximum values for heat power are equal to 109.5% and 111.9%, respectively. The case 3 has resulted in a considerably faster reactor trip and the maximum core heat power was only slightly above the nominal value (103.4%). However, as already mentioned, the lead-lag compensation for T_{cold} will not be used because under normal operational conditions it causes unnecessary reactor trips. In general, for best-estimate cases the transient was terminated before the temperature error in the Automatic rod control system rose above the value to start the control rod movement. For the conservative calculation (Case 4) the resulting temperature error was even negative due to significant increase of nuclear power and the control rods were inserted into the core thus reducing the nuclear power. A very good agreement between RELAP5 analysis (case 4) and referent literature (ref. [5]) was obtained. The maximum core heat power in RELAP5 analysis and in ref. [5] were obtained for the case with manual rod control (117.8% and 118.6%).

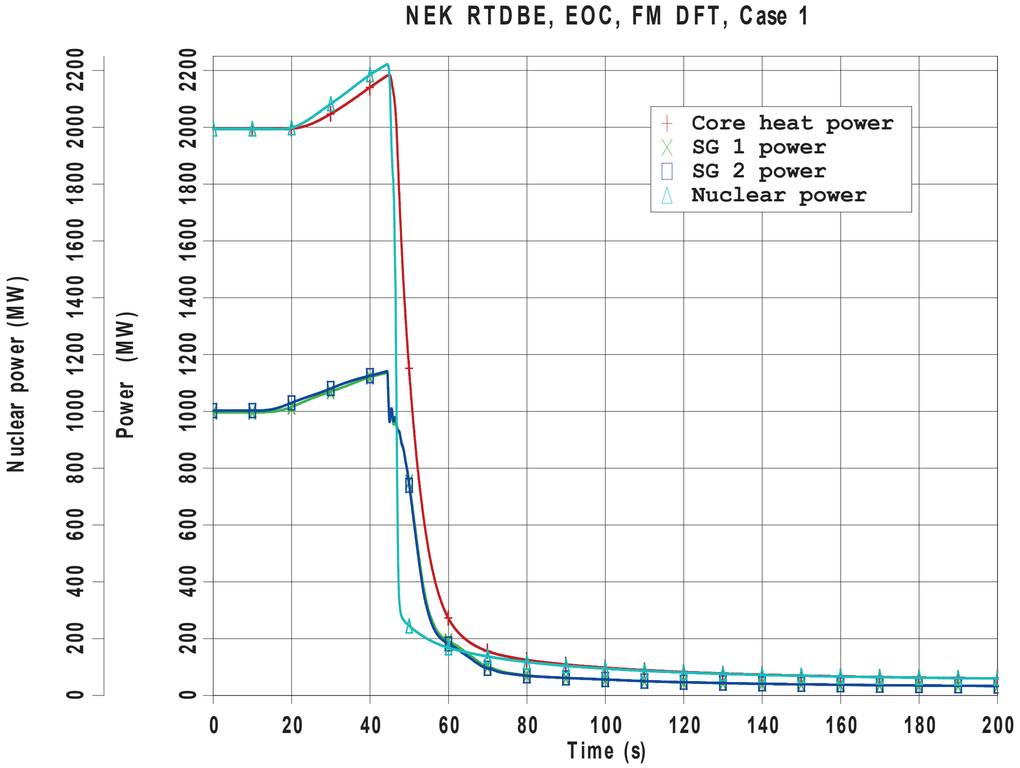

Figure 4. FM DFT analysis, base case, Nuclear and core heat power and power transferred in SGs

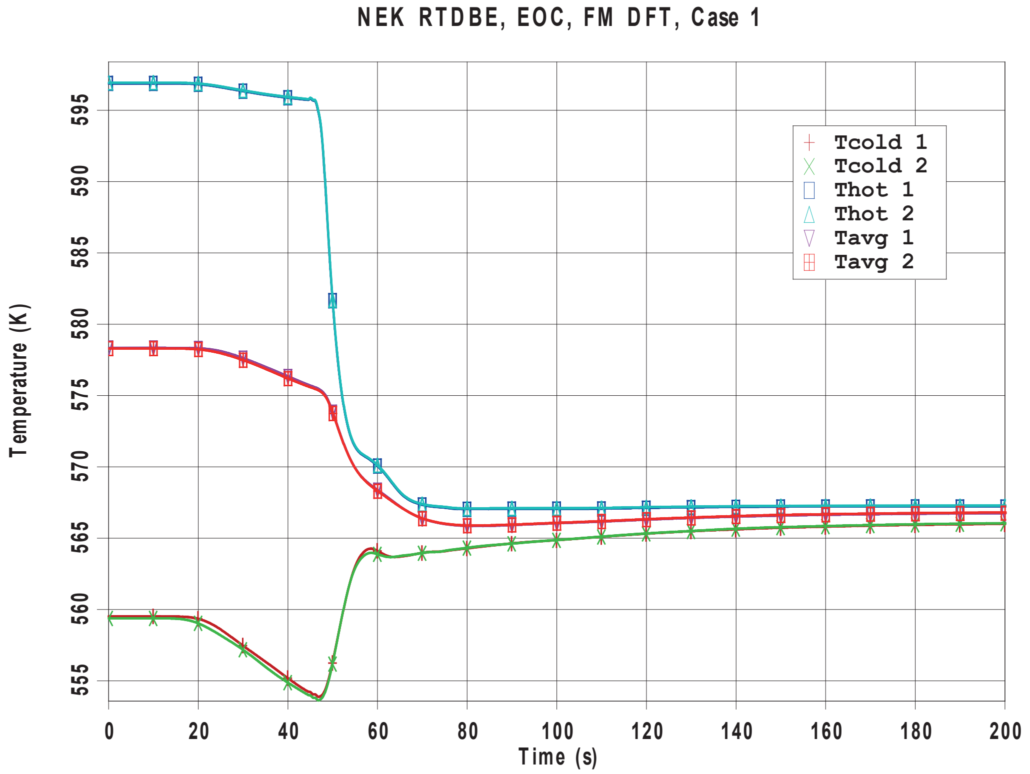

Figure 5. FM DFT analysis, base case, RCS loop temperature and RCS average temperature

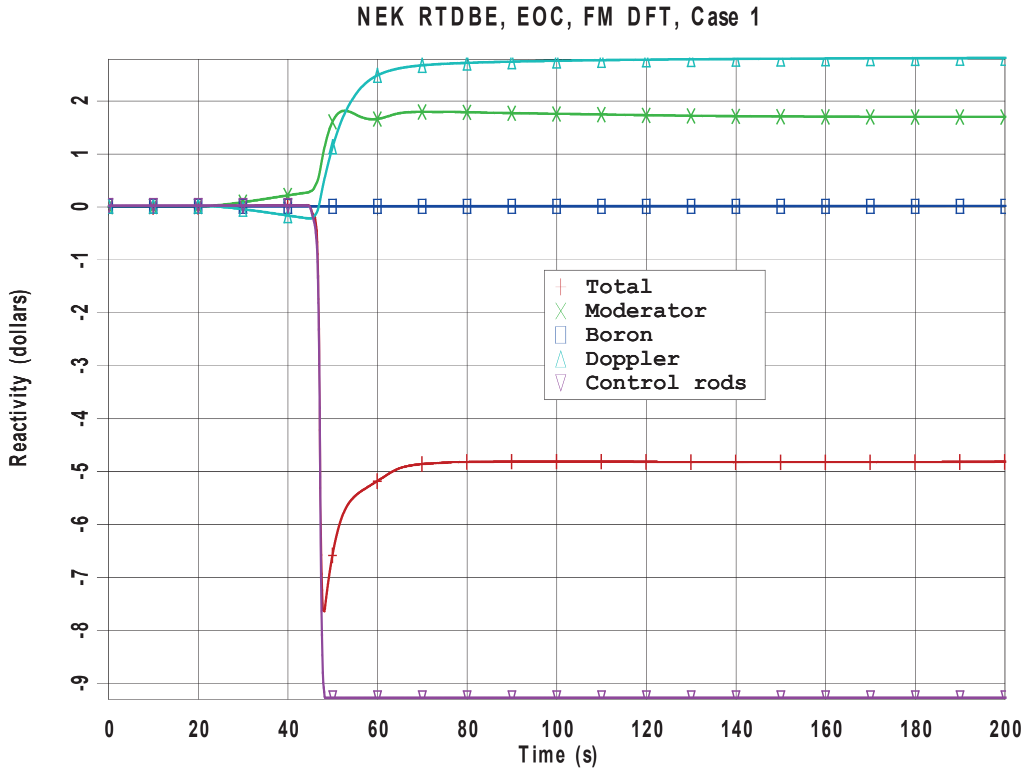

Figure 6. FM DFT analysis, base case, Reactivity

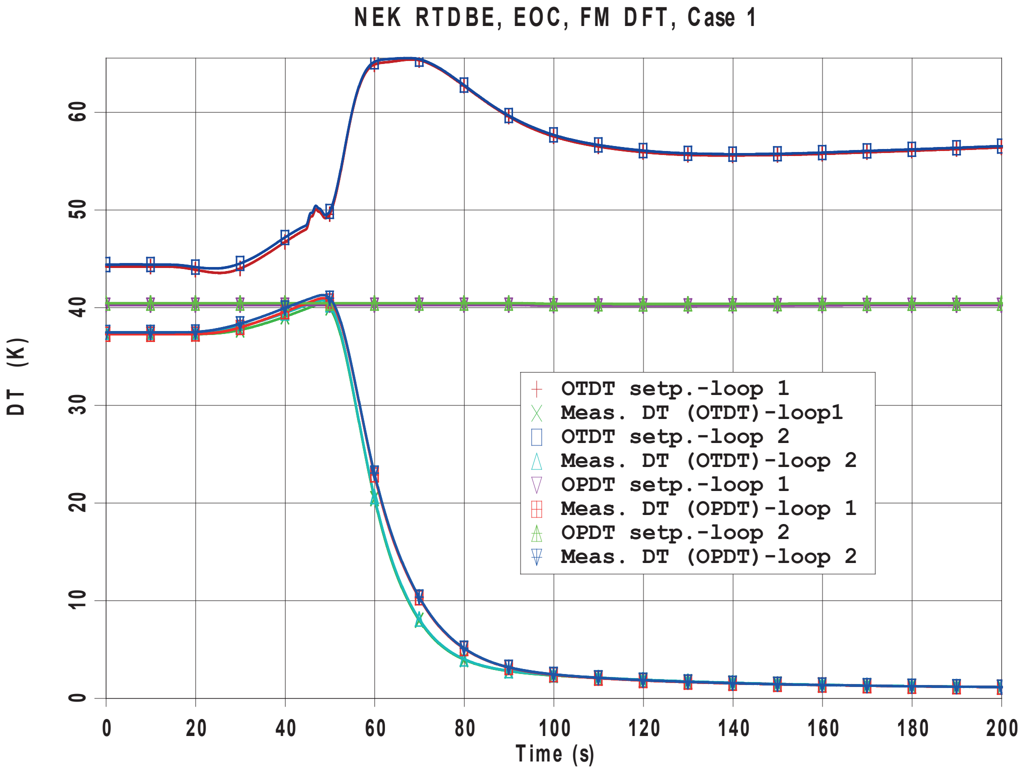

Figure 7. FM DFT analysis, base case, OPΔT and OTΔT set points

3.2 Analysis of Hot Full Power Main Steam Line Break (HFP MSLB)

Steam line break can result from a rupture of the main steam piping or branch steam piping. Depending on the location of the break the steam flow from one or both steam generators will increase. In the analysis it was conservatively assumed that the break is located upstream of the main steam isolation valve in the steam line 2 (loop without pressurizer). Further, it was assumed that the flow to the turbine remained constant and equal to the steady state value, Figure 8. The steam flow of both steam generators therefore increase and the extracted heat from the primary system increases thus resulting in a decrease of temperatures on the primary side. In the presence of the negative moderator reactivity feedback the nuclear power and the fuel temperature will increase. The combination of increased heat production on one side and the decreased margin to DNB due to lower primary pressure may lead to fuel damage if the heat production in the core is not stopped. For larger breaks, the low steam line pressure signal will actuate the safety injection signal that will actuate reactor trip. For smaller breaks the OPΔT protection may be required to trip the reactor. Similarly to the FM DFT, the OPΔT trip provides the protection for this transient due to increased compensated measured temperature increase in reactor vessel whereas the set point will not change. The same conservative assumptions as for the FM DFT accident were used in the analysis, i.e., the end of cycle when the moderator reactivity coefficient has the maximum negative value. The results for the secondary pressure and compensated steam line pressure for two break areas leading to OPΔT trip (0.0221 m²) and to SI (0.0222 m²) are shown in Figure 9. For 0.0222 m² break, the main steam line isolation is actuated together with the safety injection. From that point onward, the pressure of the two steam generators decouple after steam line isolation. For the 0.0221 m² break, the two steam generators continue to discharge its inventory through the break after reactor and turbine trip as it is also illustrated in Figure 8.

Table I. RELAP5 results for FM DFT accident

Case	Time of reactor trip (OPΔT)	Max. nuclear power (%)	Max. core heat power (%)
1. Base case best-estimate, cold leg temp. compensation (OPΔT): lag (2 s)			
a) dft_be_00_auto (Automatic rod control)	44.3 s	111.4% (44.3 s)	109.5% (44.9 s)
b) dft_be_00_manual (Manual rod control)	44.3 s	111.4% (44.3 s)	109.5% (44.9 s)
2. Base case, cold leg temperature compensation (OPΔT): lag (7 s)			
a) dft_be_01_auto (Automatic rod control)	50.34 s	113.49% (50.3 s)	111.86% (50.8 s)
b) dft_be_01_manual (Manual rod control)	50.34 s	113.49% (50.3 s)	111.86% (50.8 s)
3. Base case, cold leg temperature compensation (OPΔT): lead-lag (30s, 10 s)			
dft_be_02_manual (Manual rod control)	31.62 s	105.17% (31.4 s)	103.4% (31.8 s)
4. Conservative calculation, ref. [5], cold leg temp. compensation (OPΔT): lag (2 s)			
a) dft_sal_auto (Automatic rod control)	48.32 s; (43.8 s, ref. [5])	117.95% (48.3 s)	117.04% (48.4 s); (118.1% (44.2 s), ref. [5])
b) dft_sal_manual (Manual rod control)	45.3 s; (33.1 s, ref. [5])	118.44% (45.2 s)	117.8% (45.0 s); (118.6% (33.5 s), ref. [5])
5. Best-estimate calculation for configuration before RTDBE			
a) dft_rtd_auto (Automatic rod control)	40.22 s	110.13% (40.2 s)	107.69% (40.4 s)
b) dft_rtd_manual (Manual rod control)	40.24 s	109.7% (40.2 s)	107.64% (40.9 s)

Similarly to the previous analysis for FM DFT, a number of sensitivity study calculations were performed to assess the effectiveness of protective functions. Seven groups of HFP MSLB analyses have been performed:

1. RTDBE base case best-estimate calculation, OPΔT cold leg temperature compensation: lag (time constant=2 s). Four cases have been analyzed:
   a) mslb_be_00_notrip (the largest break where no reactor trip signal is actuated)
   b) mslb_be_00_first_trip (the smallest break where reactor trip signal is actuated)

c) mslb_be_00_opdt (the largest break where the safety injection signal is not actuated, the OPΔT signal trips the reactor)

d) mslb_be_00_si (the smallest break where the safety injection signal actuates reactor trip)

2. RTDBE base case best-estimate calculation, OPΔT cold leg temperature compensation: lag (time constant=2 s). Steam line pressure signal for steam line isolation and safety injection was compensated by lead-lag element as for the pre-RTDBE with lead and lag time constant equal to 50 s and 5 seconds, respectively. The aim of the analysis is to evaluate the influence of the new RTDBE OPΔT protection as well as of steam line pressure compensation on transient results. Two cases have been analyzed:

a) mslb_be_00_opdt_1 (the largest break where the safety injection signal is not actuated, the OPΔT signal trips the reactor).

b) mslb_be_00_si_1 (the smallest break where the safety injection signal actuates reactor trip).

3. RTDBE best-estimate calculation, OPΔT cold leg temperature compensation: lag (time constant=7 s). The aim of the sensitivity calculation is to estimate the influence of cold leg temperature lag time constant. Four cases have been analyzed:

a) mslb_be_01_notrip (the largest break where no reactor trip signal is actuated)

b) mslb_be_01_first_trip (the smallest break where reactor trip signal is actuated)

c) mslb_be_01_opdt (the largest break where the safety injection signal is not actuated, the OPΔT signal trips the reactor)

d) mslb_be_01_si (the smallest break where the safety injection signal actuates reactor trip)

4. RTDBE best-estimate calculation, OPΔT cold leg temperature lead-lag compensation with lead and lag time constants equal to 30 s and 10 s, respectively. Three cases have been analyzed:

a) mslb_be_02_notrip (the largest break where no reactor trip signal is actuated

b) mslb_be_02_opdt (the largest break where the safety injection signal is not actuated, the OPΔT signal trips the reactor)

c) mslb_be_02_si (the smallest break where the safety injection signal actuates reactor trip)

5. RTDBE conservative calculation with the assumptions from the referent literature, e.g., ref. [6]: 1) The SAL limit for OPΔT set point calculation with K_4=1.15 instead of 1.08, 2) OPΔT trip actuation if the set point is reached in both loops, 3) Conservative moderator (maximum) and Doppler (minimum) reactivity feedback coefficients, 4) Feed water flow =steam flow until feed water isolation and 5) The maximum initial RCS average temperature (580.55 K). OPΔT cold leg temperature compensation lag time constant=2 s. Three cases have been analyzed:

a) mslb_sal_notrip (the largest break where no reactor trip signal is actuated)

b) mslb_sal_opdt (the largest break where the safety injection signal is not actuated, the OPΔT signal trips the reactor)

c) mslb_sal_si (the smallest break where the safety injection signal actuates reactor trip)

6. RTD best-estimate calculation. The case represents the configuration before the RTDBE modification, i.e., with RTD bypass. Low steam line pressure signal for steam line isolation and safety injection was compensated by the pre-RTDBE lead-

lag element with lead and lag time constant equal to 50 s and 5 seconds, respectively. Four cases have been analyzed:

a) mslb_rtd_notrip (the largest break where no reactor trip signal is actuated)
b) mslb_rtd_first_trip (the smallest break where reactor trip signal is actuated)
c) mslb_rtd_opdt (the largest break where the safety injection signal is not actuated, the OPΔT signal trips the reactor).
d) mslb_rtd_si (the smallest break where the safety injection signal actuates reactor trip).

7. RTD best-estimate calculation. The case represents the configuration before the RTDBE modification, i.e., with RTD bypass. Steam line pressure signal for steam line isolation and safety injection was compensated by the post-RTDBE lead-lag element with lead and lag time constant equal to 48 s and 8 seconds, respectively. Two cases have been analyzed:

a) mslb_rtd_opdt_1 (the largest break where the safety injection signal is not actuated, the OPΔT signal trips the reactor).
b) mslb_rtd_si_1 (the smallest break where the safety injection signal actuates reactor trip).

The results for the maximum nuclear and maximum core heat power are summarized in Table II. The comparison of the two base case calculations for the new and old configuration (Cases 1 and 2 and Cases 6 and 7) has shown the influence of both the change in OPΔT set point and the change of the low steam line pressure set point for safety injection actuation. In the pre-RTDBE original configuration the SI signal on low steam line pressure was more sensitive and it was actuated for smaller break size (0.0186 m^2) than for the new RTDBE configuration (0.0222 m^2). Among the base case best estimate cases (Case 1 and Case 6) the earliest reactor trip for the smallest break for SI actuation was actuated for the pre-RTDBE and consequently the maximum core heat power (102.14%) was the minimum for these two groups. For the largest break for the OPΔT calculation (base case) post-RTDBE (Case 1c-0.0221 m^2) the larger maximum core heat power (109.02%) than for the corresponding pre-RTDBE case (107.13% , Case 6c-0.0185 m^2) was obtained. On one side, for larger breaks more adverse conditions on the primary side result before reactor trip than for the smaller break areas. Secondly, the OPΔT response for the post-RTDBE is slower for the post than for the pre-RTDBE configuration. The sensitivity analysis for the post-RTDBE and steam line compensation as for pre-RTDBE (Case 2a) and for the same break area as for the corresponding pre-RTDBE case (Case 6c) has shown that the post-RTDBE OPΔT function is slower than the pre-RTDBE OPΔT function (5.65 s later response). The resulting difference for the maximum heat flux between these two cases (108.63% and 107.13%) is slightly less than between the cases 1c and 6c due to smaller break size in the former case. However, the obtained differences for the maximum heat flux between these two base cases are small (less than 2%). A smaller difference for the response time of the OPΔT function (4.77 s) between the post and pre-RTDBE was obtained for larger break area (0.0221 m^2) when comparing the base post-RTDBE case (1c) with the pre-RTDBE sensitivity case 7a. Again, the difference for the maximum heat power between these two cases is rather small (1.65%). The similar results were obtained for the FM-DFT analysis, e.g., by comparing the cases

1a and 5a (Table I) the post-RTDBE has a slower response (4.1 s) than the pre-RTDBE and correspondingly the higher maximum core heat power (1.8%).

For the post-RTDBE with the pre-RTDBE steam line compensation (Case 2) the similar results as for the base case pre-RTDBE were obtained for the smallest break area for SI actuation (Case 2b; reactor trip at time=10.21 s due to SI signal resulting in a low maximum core heat power=101.87%). The calculated differences for the maximum core heat power between the base case post-RTDBE and the base case pre-RTDBE are small for both groups of break areas leading to either OPΔT trip or to the trip due to SI. The results for the core heat power are presented in Figure 10. For the RTDBE Case 3 (cold leg temperature lag compensation time constant=7 s) the maximum core heat power was larger (110.76%) than for the base case 1 (109.02%) since the OPΔT trip was actuated later. Similarly to the FM DFT analysis, for the Case 4 (lead-lag compensation) a fast response for the OPΔT trip has resulted in a considerably smaller maximum core heat power (103.5%) than for the base case. The largest break area for which no trip is actuated is almost identical for all the analyzed best-estimate cases (0.0085 m^2 for the Case 4 and 0.0088 m^2 for the rest of the cases). The maximum core heat power for that break area has stabilized at approx. 107.63% that corresponds to the value at which the total removed power on the secondary side (turbine and break) are equal to the elevated core power. The smallest break area for which the OPΔT trip is actuated was equal to 0.0089 m^2 for both the base pre and post-RTDBE calculations (cases 1b and 6b). As expected from the previous discussion, the OPΔT trip was actuated earlier for the pre-RTDBE than for the post-RTDBE case (172.15 s vs. 190.8 s). However, for this limiting small break, the maximum core heat power is close to the no-trip case and it was equal for both cases (107.7%). For conservative calculation, a good agreement between RELAP5 analysis and referent literature (ref. [6]) was obtained. The similar values for the maximum core heat power for RELAP5 analysis and ref. [6] were obtained (123.21% and 122.1%) and for the slightly larger break area for RELAP5 calculation (0.03198 m^2 vs. 0.0307 m^2). For the maximum core heat power greater than 118% detailed nuclear analysis is performed (not presented here) in order to demonstrate that the limiting acceptance criteria are met. The nuclear analysis presented in ref. [6] has shown that the minimum margin to minimum DNBR is greater than 9%.

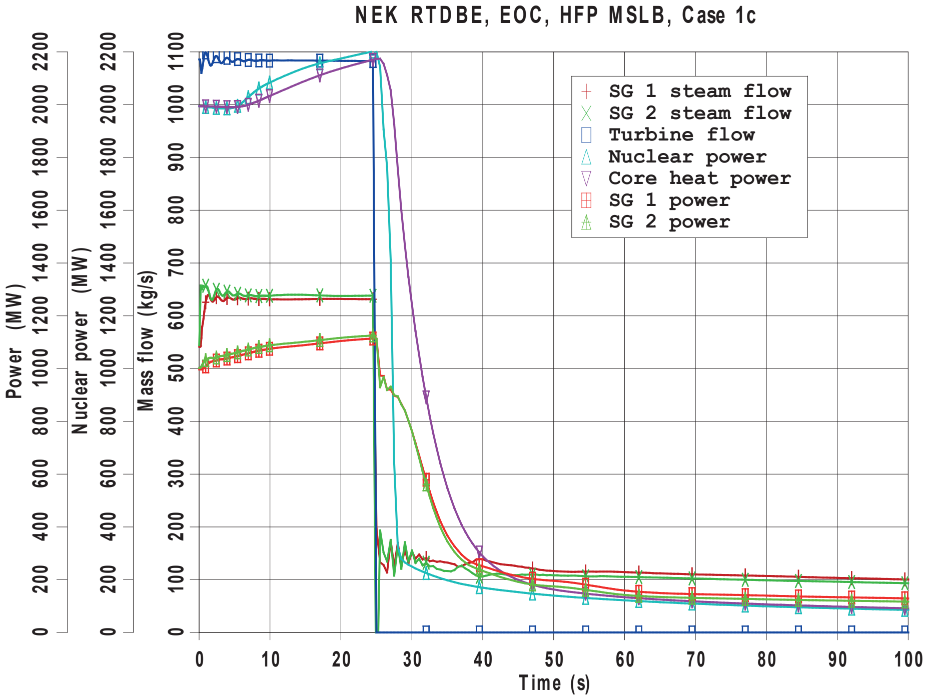

Figure 8. HFP MSLB analysis, base case, Case 1c (0.0221m² break), Steam flow, nuclear power, core heat power and power transferred in SGs

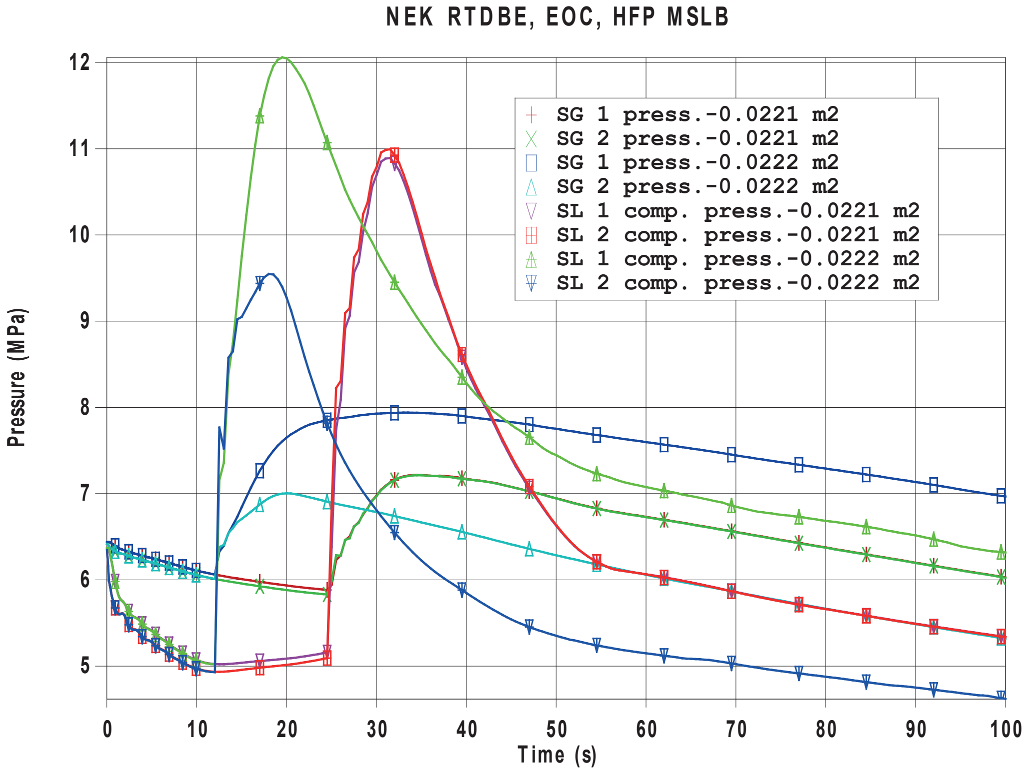

Figure 9. HFP MSLB analysis, secondary pressure and compensated steam line pressure signal, sensitivity calculations for RTDBE (Case 1c vs. Case 1d)

Table II. RELAP5 results for HFP MSLB accident

Case	Break area (m^2)	Time of reactor trip	Max. nuclear power (%)	Max. core heat power (%)
1. Base case best-estimate (RTDBE), cold leg temp. compensation (OPΔT): lag (2 s) a) mslb_be_00_notrip	0.0088	-	107.63% (208 s)	107.63% (216 s)
b) mslb_be_00_first_trip	0.0089	190.8 s (OPΔT)	107.7% (190.8 s)	107.7% (190.8 s)
c) mslb_be_00_opdt – last OPΔT	0.0221	24.86 s (OPΔT)	110.41% (24.8 s)	109.02% (25.5 s)
d) mslb_be_00_si	0.0222	12.2 s (on SI)	105.76% (12.2 s)	103.41% (12.8 s)
2. RTDBE, steam line pressure compensation as for before RTDBE a) mslb_be_00_opdt_1 – last OPΔT	0.0186	28.78 s (OPΔT)	109.66% (28.7 s)	108.63% (29.0 s)
b) mslb_be_00_si_1	0.0187	10.21 s (on SI)	103.81% (10.2 s)	101.87% (10.5 s)
3. RTDBE, cold leg temp. compensation (OPΔT): lag (7 s) a) mslb_be_01_notrip	0.0088	-	107.63% (208 s)	107.63% (216 s)
b) mslb_be_01_first_trip	0.0089	194.9 s (OPΔT)	107.7% (194.9 s)	107.7% (195 s)
c) mslb_be_01_opdt – last OPΔT	0.0221	31.59 s (OPΔT)	111.78% (31.5 s)	110.76% (31.8 s)
d) mslb_be_01_si – identical to mslb_be_00_si	*0.0222*	*12.2 s (on SI)*	*105.76% (12.2 s)*	*103.41% (12.8 s)*
4. RTDBE, cold leg temp. compensation (OPΔT): lead-lag (30 s, 10 s) a) mslb_be_02_notrip	0.0085	-	107.38% (200 s)	107.38% (216 s)
b) mslb_be_02_opdt – last OPΔT	0.0221	12.27 s (OPΔT)	105.75% (12.2 s)	103.5% (12.8 s)
c) mslb_be_02_si – identical to mslb_be_00_si	*0.0222*	*12.2 s (on SI)*	*105.76% (1220 s)*	*103.41% (12.8 s)*
5. Conservative calculation, ref. [6], cold leg temp. compensation (OPΔT): lag (2 s) a) mslb_sal_notrip	0.01826; (0.0195, ref. [6]	-	115.78% (100 s)	115.76% (100 s); (116.1% in ref. [6])
b) mslb_sal_opdt – last OPΔT	0.03198; (0.0307,ref. [6])	28.48 s (OPΔT); (27.15 s, ref. [6])	125.77% (28.4 s)	123.21% (28.8 s); (122.1% (27.6 s), ref. [6])
c) mslb_sal_si	0.03199	12.49 s (on SI)	112.92% (12.4 s)	107.68% (13.0 s)
6. Best-estimate calculation for configuration before RTDBE a) mslb_rtd_notrip	0.0088	-	107.64% (208 s)	107.64% (216 s)
b) mslb_rtd_first_trip	0.0089	172.15 s (OPΔT)	107.7% (172 s)	107.7% (172 s)
c) mslb_rtd_opdt – last OPΔT	0.0185	23.13 s (OPΔT)	108.5% (23.1 s)	107.13% (23.4 s)
d) mslb_rtd_si	0.0186	10.72 s (on SI)	104.1% (10.7 s)	102.14% (11.2 s)
7. Best-estimate calculation for configuration before RTDBE, steam line pressure compensation as for RTDBE a) mslb_rtd_opdt_1 - last OPΔT	0.0221	20.09 s (OPΔT)	109.15% (20.0 s)	107.37% (20.5 s)
b) mslb_rtd_si_1	0.0222	12.2 s (on SI)	105.76% (12.0 s)	103.41% (12.8 s)

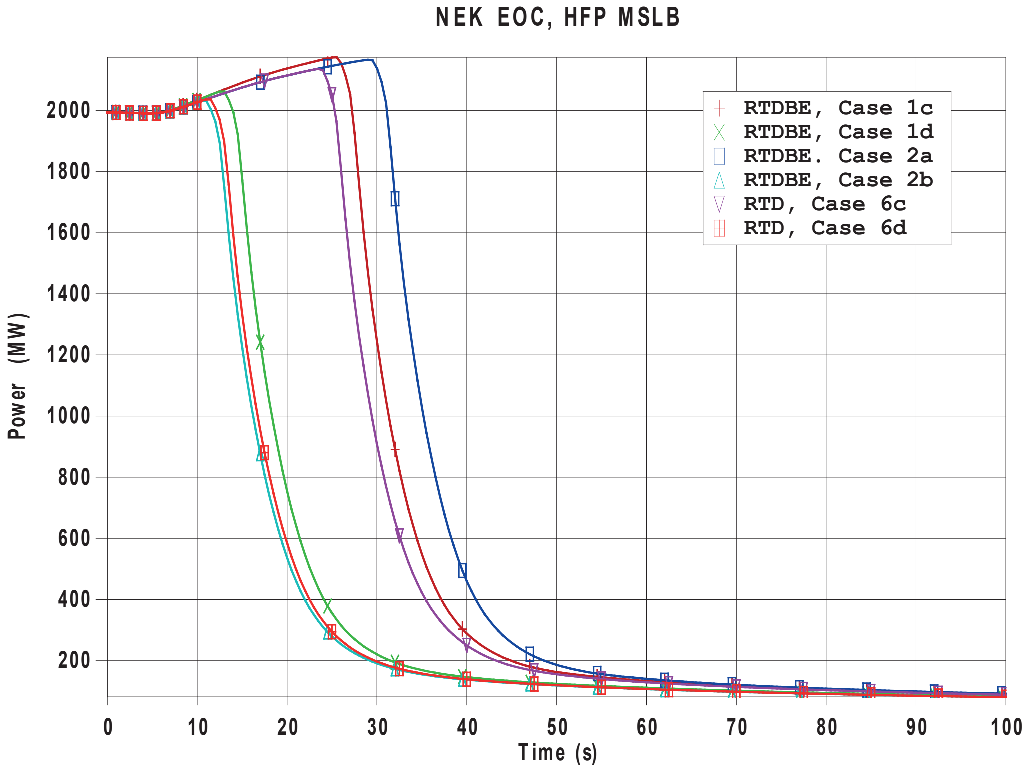

Figure 10. HFP MSLB analysis, core heat power, sensitivity calculations for RTDBE and pre-RTDBE (RTD)

4. CONCLUSION

NPP Krško has changed way of RCS coolant measurement from RTD bypass to thermowell mounted RTDs as part of RTDBE project aimed to improve operation and maintenance. The compensation of the signal representing the coolant temperature increase (ΔT) in reactor vessel for the OPΔT protection function has been modified as part of the RTDBE. In the paper, different concepts for coolant temperature compensation were studied for the decrease of feedwater temperature (FM DFT) and main steam line break at hot full power (HFP MSLB). Following conclusions can be drawn from the performed RELAP5 analyses:

- The cold leg temperature compensation for the base case post-RTDBE configuration (lag compensation, time constant=2 s) results in a delayed response of the OPΔT trip when compared with the pre-RTDBE configuration. However, the obtained differences for the maximum heat power between the post and pre-RTDBE concepts are small (less than 2% for both accidents).
- By increasing the lag compensation for the cold leg temperature from 2 s to 7 s the maximum core heat power for the analyzed accidents would increase by less than (2-3)%.

- The sensitivity calculation with lead-lag compensation for the cold leg temperature with greater lead time constant (30 s vs. lag time constant=10 s) would result in fast response of the OPΔT trip for both accidents and in the considerably lower maximum core heat power than for the pre-RTDBE configuration. That concept has shown to be sensitive to electromagnetic disturbances and it would cause unnecessary reactor trips.
- The analysis for the main steam line break has shown that the change of the steam line pressure compensation has a significant influence on the minimum break size for safety injection actuation. The change of the lead-lag compensation (48 s and 8 s vs. 50 s and 5 s) introduced along with the RTDBE leads to an increase of the minimum break size (0.0222 m^2 vs. 0.0186 m^2 for the pre-RTDBE).
- For both the FM DFT and the HFP MSLB accident similar values for the maximum nuclear power and the maximum core heat power values for the cases where OPΔT signal is actuated were obtained (e.g., the maximum core heat power for the base case post-RTDBE configuration: 109.5% for the FM DFT and 109.02% for the HFP MSLB). The obtained maximum values are acceptable and demonstrate the adequacy of the selected post-RTDBE OPΔT protection concept (cold leg temperature lag compensation, time constant= 2s) to protect the core during overcooling accidents.

5. REFERENCES

[1] NEK RELAP5/MOD 3.3 Post-RTDBE Nodalization Notebook, NEK ESD-TR-02/13, Revision 0, Krško 2013.

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[4] D. Grgić, V. Benčik, S. Šadek, N. Čavlina, “Relap5 Modeling of PWR Reactor RTD Bypass”, Proceedings of the 8th International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids, Dubrovnik, Croatia, 16-20 May 2010.

[5] Krško Modernization-UPR with RTDBE Impacts, Increase in Heat Removal by the Secondary System, SSR-NEK-7.1, Revision 5, March 2014.

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