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Krško NPP Experience with RTD Bypass Elimination

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ABSTRACT

This paper describes Krško experience and problems that had to be resolved with RTD Bypass Elimination project (RTDBE). Following RTD bypass manifold isolation valve leak in 2008, Krško decided to perform RTDBE modification on reactor coolant system narrow range temperature measurement system. The installation was performed during Outage 2013. Soon after the plant returned to power, newly configured measurement channels showed that OPΔT reactor trip was oversensitive to spikes caused by auxiliary relay operation in the cabinets nearby. The solution was to reconfigure OPΔT trip filtering constants to filter out short-term spikes in the signal. After almost full operating cycle of trouble-free operation, RTD failures started occurring on reactor coolant system cold leg, which was caused by the high frequency vibrations (3-5 kHz) induced by reactor coolant pumps. To resolve RTD failures, Krško ordered re-design of the RTDs to add robustness and specific qualification in high-frequency vibration operating environment. Improved RTDs were installed in Outage 2016 and were operating one full cycle with minor deviations.

Keywords: *RTD, RTDBE, high-frequency vibration, reactor coolant pump*

1 INTRODUCTION

Narrow range temperature measurement system of reactor coolant system (RCS) cooling water at Krško, which is used to calculate reactor protection and control signals, was originally implemented by using three flow scoops in the hot legs, bypass piping, isolation and flow regulation valves, and RTD manifolds with directly immersed RTDs (see Figure 1). This mechanically rather complex system addressed hot leg streaming phenomena (see Figure 2) by taking several samples of hot leg water using three scoops with five flow holes each, mixing it hydraulically in the bypass piping and measuring single water temperature in a manifold with two redundant RTDs. Spare RTDs were also installed and wired to protection cabinets in case one of the RTDs would fail. In order to enable RTD replacement without fully depressurizing the primary system, bypass piping was equipped with isolation valves, which acted as a crud trap and became highly radioactive over time, which resulted in high doses for the workers during outage maintenance on the RCS system and components. There were also problems with isolation valves leaking which forced plants to shutdown to replace the valve. These problems motivated most of the similar plants in the world to perform RTD Bypass elimination (RTDBE) project, usually in the early life of the plant. Krško had one of the isolation valves leaking in 2008, and decided to performed RTDBE project, which was done in Outage 2013.

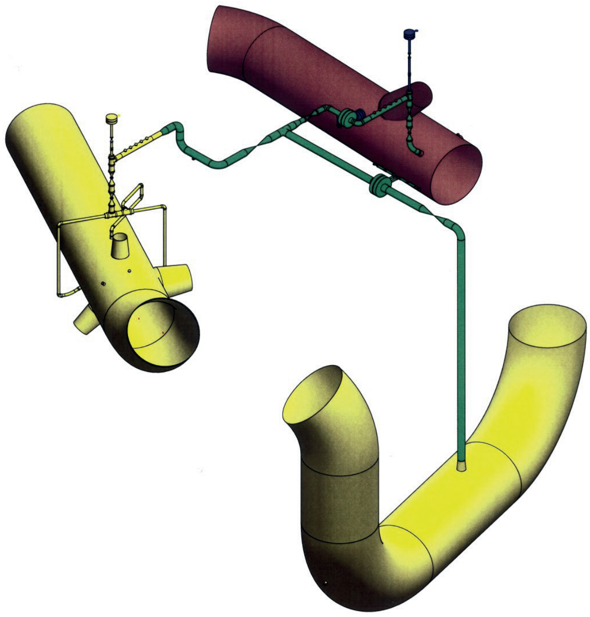

Figure 1: 3-D model of Krško RCS RTD Bypass piping (left: hot leg, right: cold leg, bottom: intermediate leg)

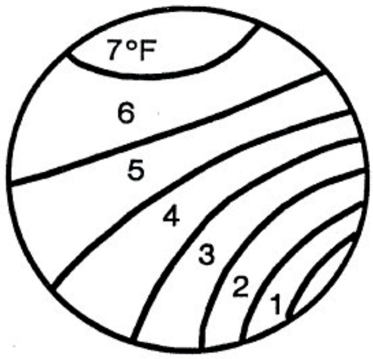

Figure 2: Hot leg streaming – typical pattern

2 DESCRIPTION OF RTD BYPASS ELIMINATION PROJECT

The project generally consisted of existing bypass components removal, installation of new thermowell-mounted RTDs directly into the RCS piping, instrument channel reconfiguration and testing, and revision of the safety analyses.

2.1 Mechanical scope of the project

Mechanical scope of the project was very demanding in terms of high-radiation work environment, radiation shielding installation and limited space. The work consisted of demolition and installation phase. Within the demolition phase, existing bypass piping and components were removed, which became radioactive waste. They were placed in containers and transported outside of the reactor building. Table 1 provides overview of radwaste amounts [1].

Table 1: Overview of radwaste

Waste type	Amount [pieces]	Volume [m3]
Reflective metal insulation	120	7
Snubbers and supports	54	1.7
Piping	N/A	1.7
Valves	26	1.7

Installation phase of the mechanical scope consisted of six new thermowells installed in each hot leg, two thermowells installed in each cold leg, welding of cap on the intermediate leg piping, and new reflective metal insulation installation. For hot legs, three thermowells were placed inside exiting scoops, which were left inside the pipe. Three new holes had to be drilled at 60° to the scoops (see Figure 3). Since drilling into RCS piping represents Foreign Material Exclusion (FME) issue because of the metal residue, pipes were first drilled to about 90% of the pipe wall thickness with standard drilling bits, and the last 10% was drilled using Electrical Discharge Machining EDM technique. With EDM, only metal droplets less than 20 µm in diameter [2] may remain in the RCS, and they have been proven not to adversely affect nuclear fuel cladding.

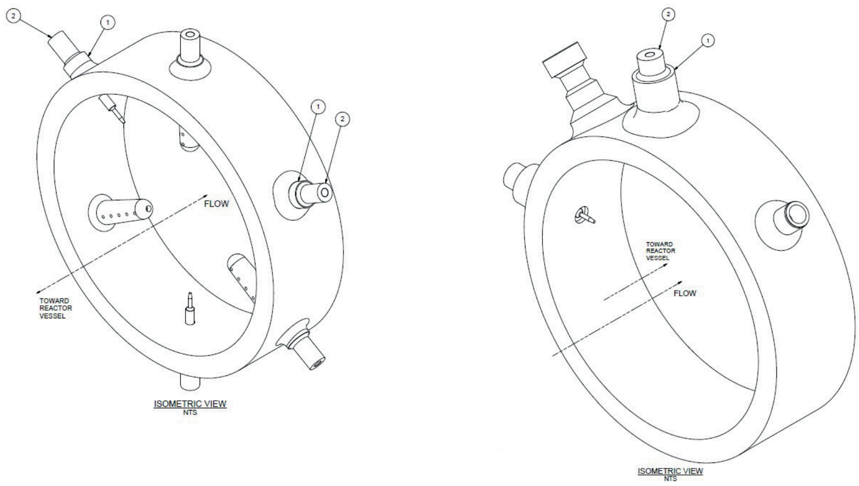

Figure 3: Isometric view of hot leg RTDs installation (left) and cold leg RTDs installation (right)

For cold leg thermowell installation, Krško used NPP Vandellos experience [3], where multiple RTD failures occurred in the cold leg due to flow-induced vibrations of the thermowell in the cold legs. This problem was resolved by removing thermowell outwards by 1 inch, which reduced vibrations, and the plant did not report any more RTD failures since. Identical design was used at Krško.

2.2 I&C scope of the project

Krško reactor protection system consists of 4 independent measurement channels for each critical parameter, which means that 2 independent narrow range temperature channels had to be installed per RCS loop. To address the hot leg streaming phenomena, 3 RTDs were used per hot leg per channel, with second channel also having 3 RTDs in the same hot leg which were 60° apart (see Figure 3). Each channel then averaged 3 RTDs to obtain single Thot-average signal, as shown on

Figure 4. In order to exploit six-point measurement in each hot leg, but with channel independency rule, a bias circuitry was installed, which enabled correction of Thot-average to the average of six RTDs. Once set the bias is a fixed value (it is not connected to other protection channel) and is checked periodically by manual calculation, and reset if necessary. It is also reactor-power dependent (using ΔT signal), so that it does not give false offset when the reactor is shut down.

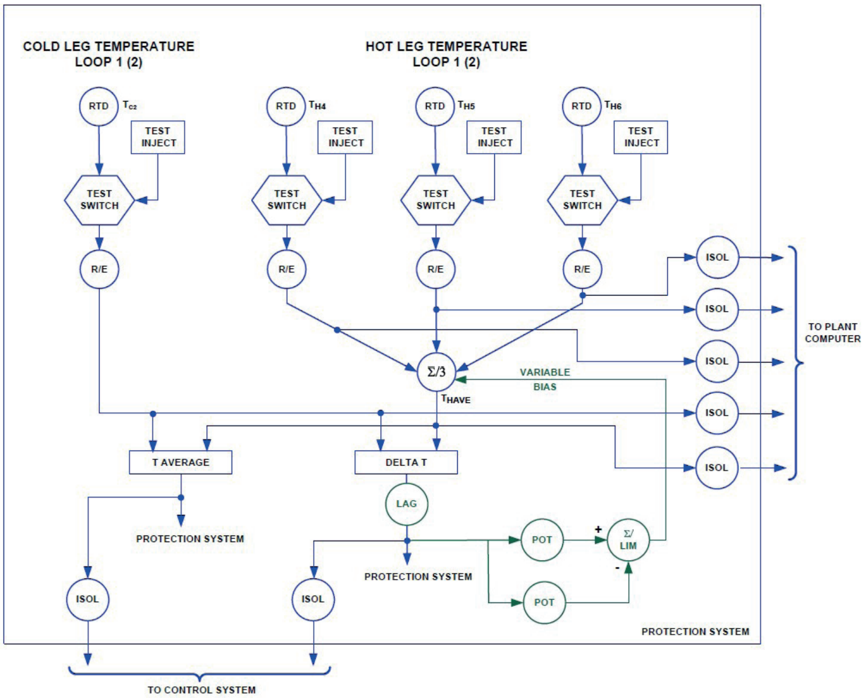

Figure 4: Thot-average and bias signal diagram

Streaming phenomena in cold legs is only marginal due to good mixing of RCS coolant by the reactor coolant pump (RCP) impeller, so 1 RTD per measurement channel was installed.

To add some redundancy in case of RTD failure, dual RTD units were used (Weed/Ultra electronics model N9004, see Figure 5), with two platinum coils inside each RTD assembly, as shown on Figure 6, and both wired individually to the protection cabinets. New thermowell-mounted RTDs have guaranteed response time of 4 seconds [4], with additional 1 second allowed in the safety analyses for conservatism and maintenance flexibility [5].

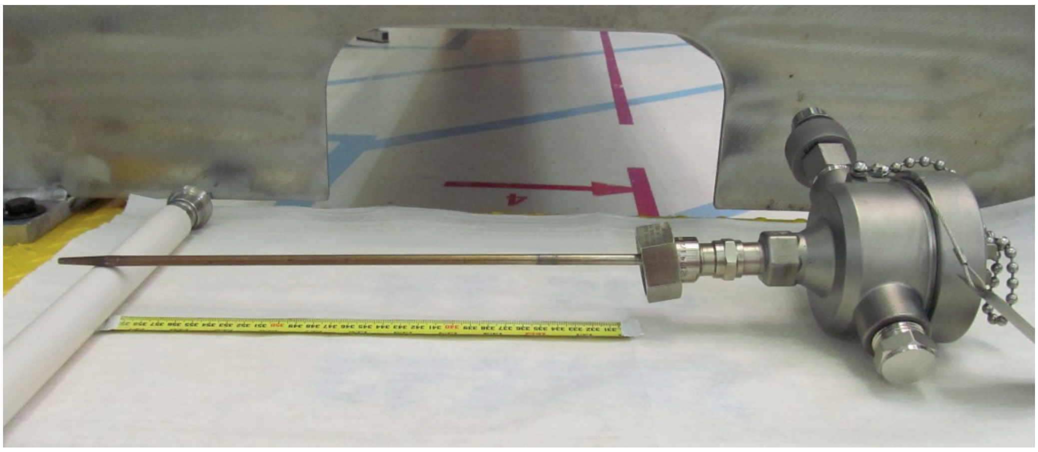

Figure 5: Weed/Ultra Electronics RTD model N9004

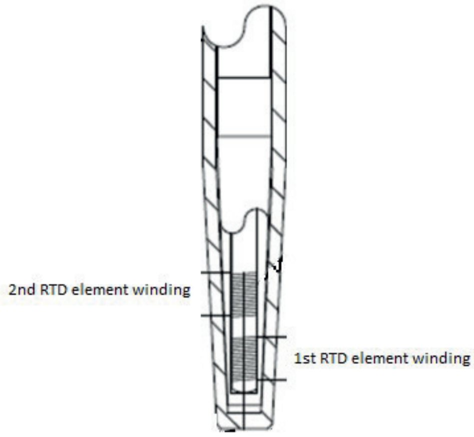

Figure 6: Dual RTD configuration

The biggest concerns for the post-RTDBE plant operation were hot leg streaming distribution and margin to OPΔT/OTΔT turbine runback and trip.

Hot leg streaming phenomena occurs due to imperfect mixing of the RCS coolant after it exits fuel elements' channels with temperature differences of more than 30°C. Because of that, temperature distribution in the hot legs has layers with significant temperature differences, so point temperature measurements inherently contain uncertainties that had to be evaluated for (primarily) RCS flow calculation. Originally, hot leg streaming data from Vandellos Unit 2 (3-loop) and Beznau Unit 2 (2-loop) plants were used to asses Krško streaming [6], but the adequacy of those plants as references for Krško was questionable. This phenomenon was considered to be more pronounced on 2-loop plants with reactor power uprate performed and with low load leakage pattern, which is the situation at Krško. In order to estimate streaming magnitude, Krško-specific CFD simulation was performed with ANSYS thermo-hydraulic code [7], which then served for input data for streaming uncertainty calculation. As power operation after the RTDBE showed, results from the simulation were very conservative in estimating more than 13°C temperature difference between highest and lowest RTD reading, which are typically 6°C to 8°C and quite stable, see Figure 7.

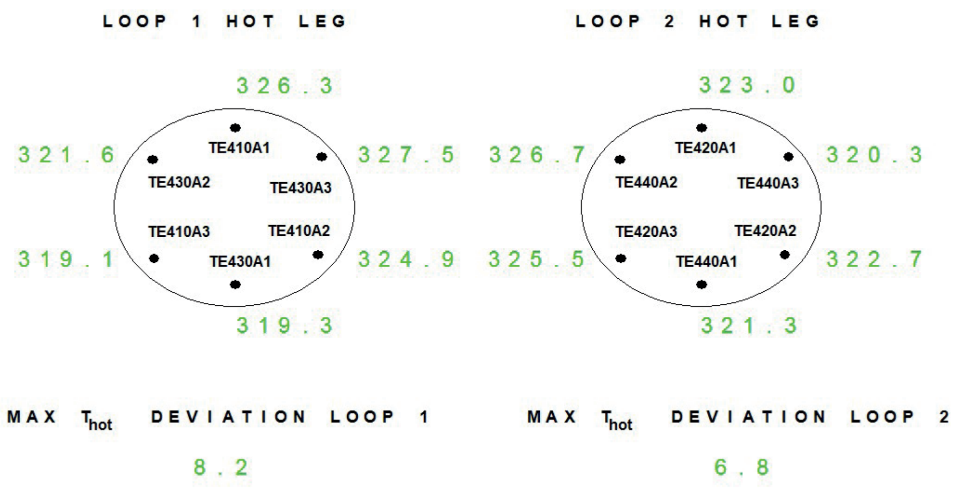

Figure 7: Typical RTD measurements with the plant at full power

Direct RCS coolant temperature measurement after the RTDBE modification was expected to result in increased fluctuations of Thot and possible rod control movement or even OPΔT/OTΔT runback/reactor trip. The designer proposed adding lag filter to Thot signal and lead/lag filter to Tcold signal, as implemented on Tihange Unit 2 plant [6]. Placing the lead/lag on Tcold preserves or even increases the efficiency of the protection for secondary accidents, while suppressing hot leg fluctuations. The resulting OPΔT/OTΔT trip function diagram can be seen on Figure 8.

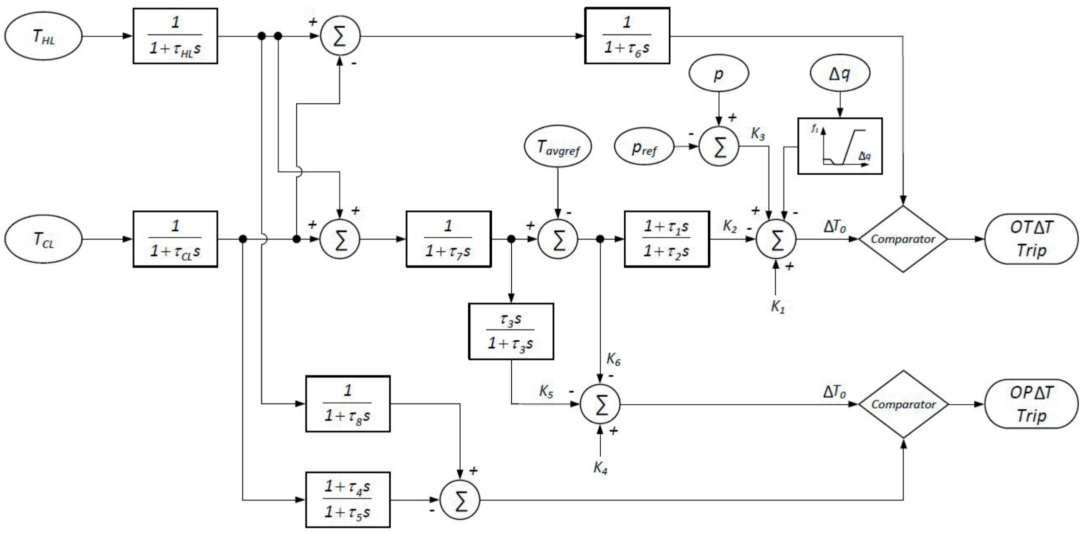

Figure 8: OPΔT/OTΔT trip function diagram

The OTΔT trip calculation expression was changed as follows:

$$\text{Delta T}\left(\frac{1}{1+t_6 S}\right) \le \text{Delta T}_0 \left\{ K_1 - K_2\left(\frac{1+t_1 S}{1+t_2 S}\right)\left[T_{avg}\left(\frac{1}{1+t_7 S}\right) - T^0_{avg}\right] + K_3(p - p_0) - f_1(\text{Delta q}) \right\} \quad (1)$$

The OPΔT trip calculation expression was changed as follows:

$$\text{Delta T}_{OP} = T_{hot}\frac{1}{1+t_8 S} - T_{cold}\frac{1+t_4 S}{1+t_5 S}$$

$$\le \text{Delta T}_0 \left\{ K_4 - K_5\left(\frac{t_3 S}{1+t_3 S}\right)\left(\frac{1}{1+t_7 S}\right)T_{avg} - K_6\left[T_{avg}\left(\frac{1}{1+t_7 S}\right) - T^0_{avg}\right]\right\} \quad (2)$$

2.3 Revised analyses of record

Following analyses of record had to be updated because of the new RCS coolant temperature measurement system and OPΔT/OTΔT reactor protection changes [8]:

- Revised Thermal Design Procedure Uncertainty Analysis
- Integrated Core Design
- Margin to DNB
- Containment Response to Steamline Break
- Increase in Heat Removal by the Secondary System
- Reactivity and Power Distribution Anomalies
- Decrease in Reactor Coolant Inventory
- Radiological Consequences

- RCL Branch Nozzle Analysis
- Class 1 Lines Reconciliation Analysis Summary

2.4 Post-installation testing

After all the installation works were completed complex testing of all components were performed per Site Acceptance Tests Program [9]. These include new temperature channels calibration, calibration of channels affected by rack card relocation, response time measurements of all branches of new temperature channels, RTDs response time testing, RTDs cross-calibration, deltaT and bias calibrations at power, and RCS flow calculation.

3 PLANT TRIP ON OPΔT

As the plant was performing an initial power increase after the outage, at about 90% power, the reactor tripped on OPΔT protection signal. By looking at the trends on the plant computer (as shown on Figure 9 and Figure 10), it could be seen that all temperature signals coming from the field had downward spike. Lag filters filtered out these spikes for the Thot signal, but strong lead/lag filters amplified the spike on Tcold signal, which resulted in large spikes on ΔT signal, so that it went above the OPΔT trip setpoint on 2 out of 4 channels. Reactor operator on shift noted that the trip coincided with reactor makeup water selector switch operation, which was known to sometimes cause irregularities on control equipment, but plant did not have any record of spikes or any irregularities in reactor protection instrumentation. With reactor tripped, the troubleshooting team was able to reconstruct the spikes of varying amplitude on resistance-to-voltage cards (NRA cards) whenever the reactor makeup water selector switch was operated. The cause for that was determined to be operation of up to 12 auxiliary relays that are located in auxiliary relay racks nearby temperature channels. The relays are powered by 118 VAC power source. Since relays did not have any surge protection, whenever a relay was energized or de-energized, voltage spikes of sometimes more than 1000 volts occurred (see Figure 11), which emitted electro-magnetic (EM) pulse. EM pulse is believed to be picked-up by the interconnecting cables and transferred from auxiliary relay racks to reactor protection cabinets, where temperature channel cards were located. Since NRA cards operate with relatively small field signals of about 300 mV, which is then amplified with large gains, they were most susceptible to picking up the EM pulse.

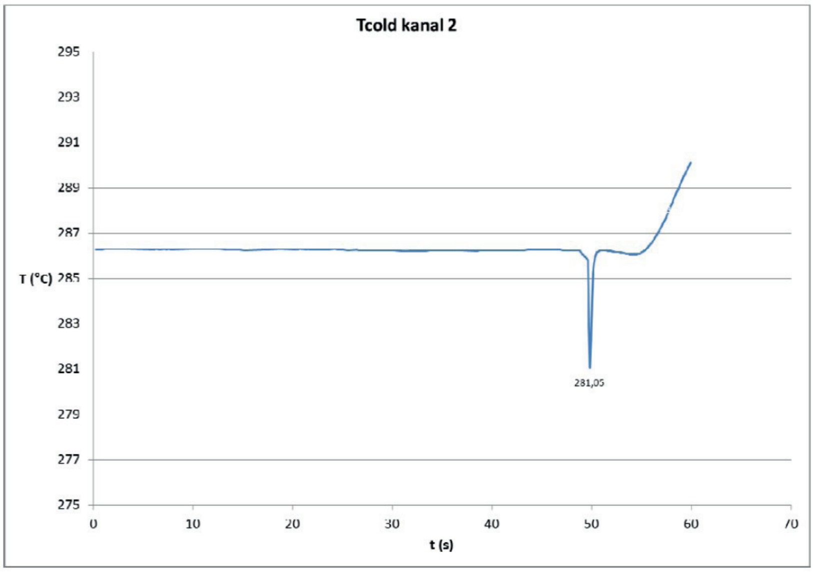

Figure 9: Plant computer trend for protection channel 2 Tcold

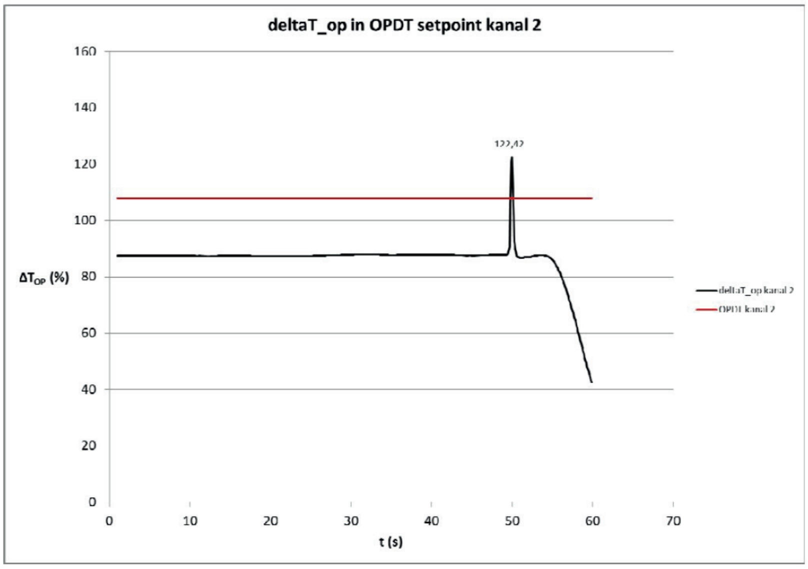

Figure 10: Plant computer trend for ΔT signal for OPΔT reactor trip (black) and OPΔT setpoint (red) for protection channel 2

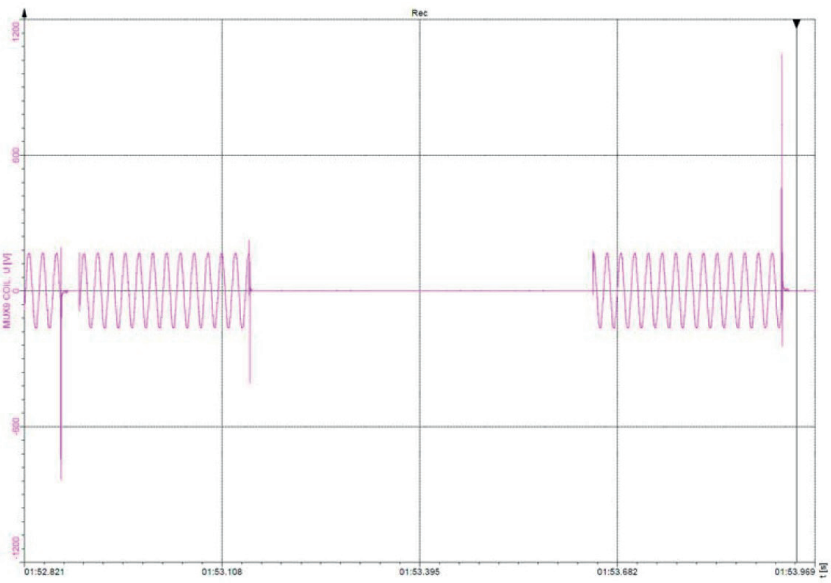

Figure 11: Voltage spikes on auxiliary relay coils

The root cause analysis was performed which identified four contributing causes for the trip: the EM pulse generation by the auxiliary relays, the transfer path for the pulses, the NRA cards input stage susceptibility to EM noise, and OPΔT protection reconfiguration that made the channel vulnerable to short-term spikes in field signal. In order to prevent such events in the future, three contributing causes were addressed and resolved or mitigated. It was judged that resolution of EM noise transfer to protection cabinets would require significant effort without further improvement to temperature channels noise immunity, and possibly creating new problems.

The EM pulse generation was greatly reduced by installation of the surge protectors an all affected relays, which limit the voltage spikes on the relay coils to 200 volts. These are passive metal oxide varistors, which do not require any maintenance.

It is believed that the EM spike transmission is through interconnecting cables (cables can generally act as an antenna) from auxiliary relay racks to protection cabinets, where the pulse can be re-emitted and picked up again by RTD field cables in the protection cabinets. The NRA card supplier modified the card design to include a filter in order to mitigate card output variations due to short-term input signal disturbances. This card design upgrade now normally comes with the NRA card available on the market.

The most complex contributing cause to address was OPΔT protection change that would remain efficient for the mitigation of design accidents and not be over-sensitive to short-term signal disturbances. A sensitivity study [10] was performed where a series of Tcold lead/lag or lag-only filters were compared with magnitude of the Tcold signal disturbance they can filter out without generating a trip signal, and compared with the departure from nucleate boiling ration (DNBR) they still attain (as a measure of reactor protection efficiency). This showed that the implemented aggressive Tcold lead/lag filtering was very conservative and that DNBR margin remains with lag filter on the Tcold signal, while it offered maximum disturbance rejection. Based on this conclusion, Tcold lead/lag filter was replaced with lag-only filter.

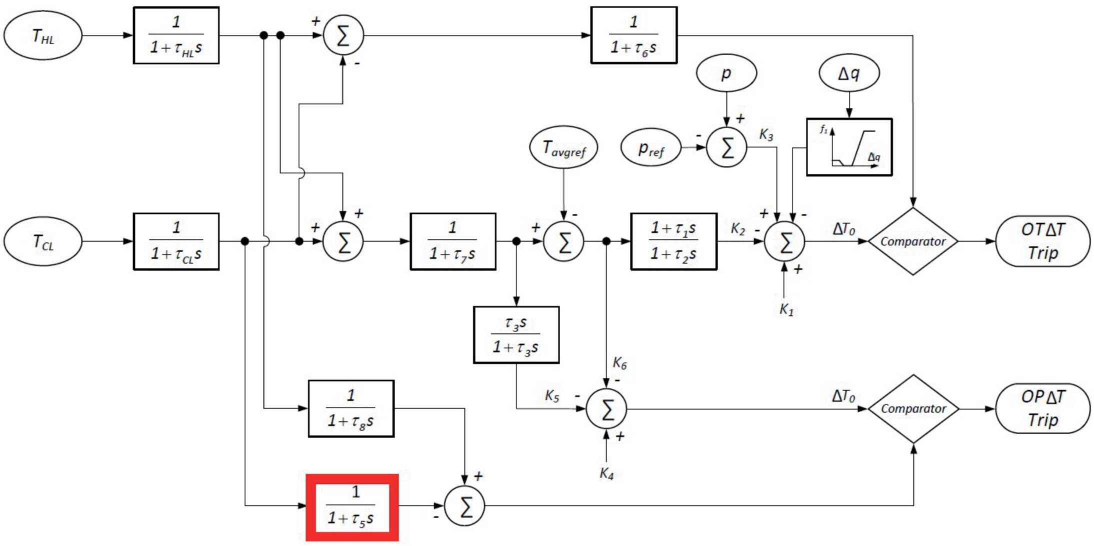

Figure 12: OPΔT/OTΔT trip function diagram after Tcold filter change (in red)

The time constant reduction on Thot signal lag filter did not make significant impact to DNBR for affected accident analyses, so it remained unchanged to keep the filtering capacity of possible Thot fluctuations (Thot indications have been very steady since RTDBE). Accident analyses in which OPΔT is actually actuated were impacted and had to be repeated. Those are Hot Full Power Steam Line Break and Decrease in Feedwater Temperature.

Tcold filter change also affected trip response time, which had to be re-calculated and measured again on each protection channel as an acceptance test.

4 COLD LEG RTD FAILURES

After about 17 months of stable operation of temperature channels, one of the cold leg RTDs indication started drifting upwards. The troubleshooting team checked all channel components that could cause the rise in the indication and narrowed it down to actual resistance coming from the RTD and connecting wires (including wire splices). One of the possible causes for this behaviour was assumed to be platinum wire cracks due to vibratory load, but not much testing was possible with the plant at power due to neutron radiation, noise and heat at the RTD location. Ultimately the RTD failed open completely, so the plant used spare RTD in the dual-RTD unit, and continued operation until nearing outage.

In Outage 2015 the vibration levels were measured at and near the RTDs with readily available equipment, finding significant levels of high-frequency vibrations within 3-5 kHz [11], which were also measured on and believed to originate from reactor coolant pumps (RCP). Failed RTD was removed from the thermowell and significant rub marks were observed on several places on RTD sheath (see Figure 14), which supported the assumptions about vibratory environment. The plant conservatively decided to replace all four cold leg RTDs in outage 2015 with spares. The failed RTD unit was shipped to the manufacturer for examination and determination of root cause for the failure. After one cycle of operation in a neutron flux environment the RTD was slightly activated so the manufacturer was only able to perform visual and x-ray examination, because he did not have means to contain radioactive debris that would form with destructive examination. Nevertheless, the cause for the RTD failure was clearly visible as platinum lead wire breaks on the x-ray shots (see Figure 13). The causes for the break however could only be assumed.

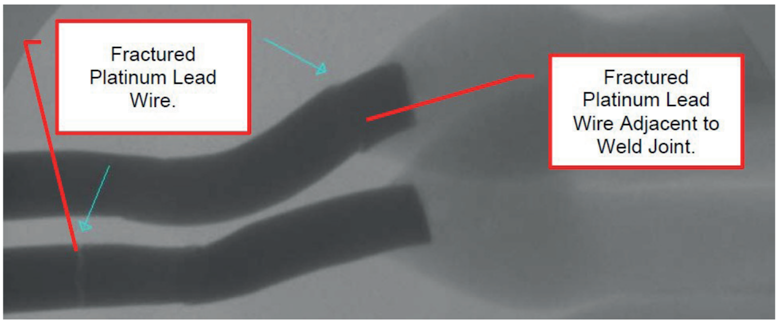

Figure 13: X-ray of RTD platinum lead wire fractures

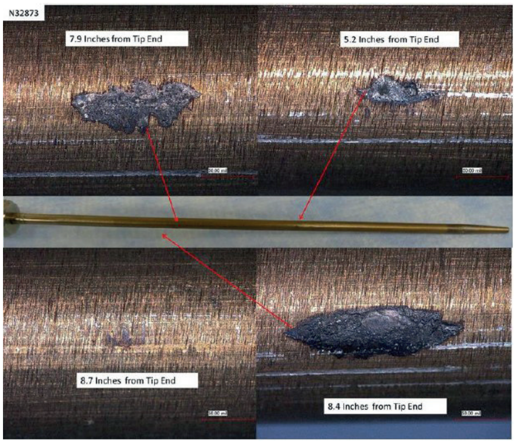

Figure 14: Rub marks on the RTD sheath

Just a few weeks into the following on-line operation, second active RTD failed, followed by failure of a spare unit in dual-RTD (with similar drifting behaviour preceding the failure). The plant resumed power operation since Technical Specifications allow normal plant operation with one failed protection channel in safe (trip) position. This however made the OPΔT and OTΔT reactor trip actuate on 1 out-of 3 coincidence, which significantly decreased the plant operating margin to human errors or equipment failures. Since more information about the vibration environment of the RTDs were needed for the failure root cause determination, the vibration measurement campaign was organized with the RTDBE project contractor and RTD manufacturer. Similar campaign was performed with the same companies involved in order to resolve failures on Vandellos plant, so that experience served as a basis for Krško.

In order to measure vibrations inside thermowell, a special dummy RTD was manufactured which was instrumented with two accelometers in the RTD tip (x and y direction) and two accelometers in the RTD head. The RTD was inserted into the thermowells and the accelometers were wired to the data acquisition station just outside of the RCP cubicles in the reactor building.

Simultaneously RCP vibration data was recorded with second data acquisition system. The measurements started on second RCS loop. Close to completion of second locations of loop 2, the RTD tip broke when extracting the dummy RTD from the thermowell and the measurement campaign was stopped. Since the manufacturer was only able to supply one dummy RTD in the given timeframe, the measurement of vibrations on loop 1 had to be cancelled. It was judged however that vibration level on loop 2 was bounding due to lower vibrations level on RCP no. 1.

The contractor analysed the vibration data and concluded following [12]:

- the RTD sheath has higher resonant modes in 3-5 kHz region
- the measured vibrations in the RTD tip spectre had peaks in the same 3-5 kHz region
- comparison between RTD tip and RCP vibrations proved RCP to be the source of the vibrations
- the vibration data indicates that excitation by flow turbulence is not a large contributor to RTD tip vibrations.

In the meantime, both failed RTD units were shipped to the laboratory capable of performing destructive examination of activated materials. These were most important conclusions of the analysis [13]:

- failed RTD units had insufficient powder potting in the RTD tip region, which resulted in excessive platinum lead wire mechanical loading and failure
- the cross-section of the most of the failed wires showed typical signs of metal fatique.

Based on conclusions from both vibration data and destructive examination analyses, and since RTD dimensions are bounded by the existing thermowells, Krško decided to invest into following:

- redesign of the internals of the RTDs, so that vibratory loading on the critical RTD components would be as low as achievable
- qualification programme for plant-specific high frequency vibration operating environment
- to order the high frequency vibration root cause study from RCP OEM, in order to suggest methods to reduce or eliminate vibrations generation from the pump.

The allowed time for completion of all tasks was Outage 2016, which imposed very demanding schedule for all parties. RTD manufacturer and the RTDBE contractor analysed the possible improvements to the RTD design and manufacturing process within given boundaries and proposed following:

- Instead of pure platinum, a higher strength platinum-rhodium alloy material shall be used for RTD lead wires
- The RTD manufacturing process was revised so that better potting was assured
- RTD tip was slightly redesigned to support better potting.

The same two companies worked together on a qualification programme for improved RTDs. The most important goals of the programme were finding RTD resonant frequency(es) and to simulate 20 years (which was guaranteed RTD lifetime) of operation at that frequency environment without failures. Since this type of qualification was unique in the industry, it was difficult to both contract the laboratory with appropriate capabilities and to execute the programme with confidence in results. The available high-frequency shaking tables had very strict mass limits for equipment under test so manufacturer had to adapt their RTD test setup considerably, reducing the overall mass by the factor of 100. To cover complete frequency spectre recorded at Krško several shakers had to be used, with results on some of them being inconclusive and thus discarded. Eventually with much effort testing was completed, results reviewed and the RTDs were considered to have been qualified to Krško specific high frequency environment.

Concurrently RCP OEM was contracted to perform a root cause analysis for the generation of the high frequency vibrations. Normally vibrations in this spectre do not affect pump operation or behaviour at all and are therefore not even measured, so very little data was available from the industry. For this reason, the analysis was based primarily on the experience and expertise of the author, who used all available information from testing and measurements performed at the plant. The conclusion of this analysis [14] was that the high frequency vibrations are generated due to some sort of acoustic resonant effect in the pumped coolant, excited by the diffuser vane pass harmonics. The possible mitigation actions would be RCP internal design modifications, which were not further considered due to cost and the complexity.

5 CONCLUSION

Following isolation valve leak in 2008, Krško decided to perform RTD Bypass Elimination project. The project was very complex to design and perform, and included significant effort in mechanical, instrumentation and safety analyses area. Although design team resolved many expected negative influences in advance, some plant conditions, that only had minor impact to plant operation before, caused plant trip and major equipment failures during operation of the new system. Krško invested many resources into resolving all the issues and making the new RCS temperature measurement system operate trouble-free.

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