Impact of Selected Long-Term Operation Improvements Relevant to the Pressurized Thermal Shock in PWR

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ABSTRACT

The impact of six different long-term operation (LTO) improvements relevant to the pressurized thermal shock (PTS) phenomena in a pressurized-water reactor (PWR) was investigated. Four LTO improvements are connected with the change in parameters of the reactor safety systems: a heating of water in high-pressure injection (HPI) tanks, a heating of water in accumulators, a heating of water in low-pressure injection (LPI) tanks, and a decreasing the accumulator pressure. The remaining two LTO improvements are related to human factors, and they are each modelled as operator actions: a reduction of high-pressure injection system (HPIS) flow by the operator and a different secondary-side cooldown rate.

The thermohydraulic (TH) impact of the LTO improvements was studied with the RELAP5/Mod3.3 computer code with emphasis on the reactor pressure vessel that is vulnerable to the PTS. The two-dimensional nodalization is applied to the reactor downcomer section to enable modelling of asymmetric cooldown of the reactor pressure vessel (RPV). The sequence selected as relevant for PTS analysis is the small-break loss-of-coolant accident (SB-LOCA) with a 50-cm^2 break in the hot leg (HL) and coincident with a loss of offsite power. The studied plant used in the analysis is based on a 1300 MW four-loop PWR German design. Analyses show that the most promising results for the SB-LOCA are obtained for the heating of water in HPI tanks and the reduction of HPIS flow by the operator.

This work is a part of the larger benchmark performed in the Work Package 2 of the project Advanced PTS Analysis for LTO (APAL), which is a Euratom-funded research and training programme.

This work is focused on the TH effects of the LTO improvements. Additional deterministic and probabilistic fracture-mechanics benchmarks will be performed in the APAL project to quantify the effect of selected LTO improvements on final fracture-mechanics results.

Keywords: *pressurized thermal shock, PTS, long-term operation improvement, thermal-hydraulic analysis, RELAP5.*

1 INTRODUCTION

In the EU, most of nuclear power plants (NPPs) are in the second half of their designed lifetime, and their lifetime extensions are an important consideration for the European Union countries. Pressurised thermal shock (PTS) is one of the most limiting safety issues for long-term operation (LTO). PTS can occur during number of postulated accident scenarios, including loss-of-coolant accidents (LOCAs). During LTO upgrades, the owners and plant operators that know the plant design and its limitations can introduce LTO improvements in order to reduce the impact of a potential PTS. One of the goals of the APAL project is to propose such LTO improvements and assess their impact on PTS. To verify safe operation of NPPs going through LTO upgrades, advanced PTS assessment methods are utilized, which are applied in the APAL project. The studies in the project are focused on a reactor pressure vessel (RPV), which is one of the most important and non- replaceable elements in water-cooled reactors of non-boiling type. Significant stresses that arise in the RPV due to thermal shock can lead to the initiation of cracks and their propagation. Therefore, detailed assessment of stresses arising in the RPV metal and analysis of fracture mechanics are required. This work is focused on the TH effects of the LTO improvements.

2 REACTOR MODEL AND CALCULATION CODE

The simulated plant used in the analysis is based on a 1300-MWe four-loop PWR of German design (KWU-1300) and specifications of ICAS T2 [1]. A model of KWU-1300 was prepared for the APAL project, and the nodalization of the RPV is presented in Figure 1. In order to better model the phenomena connected to a PTS during the studied transient, the reactor downcomer (DC) was modelled by eight parallel channels (RELAP5 ANNULUS components) connected by cross-flow junctions. All four loops are modelled individually (only the nodalization of Loop 1 and Loop 4 is shown in Figure 2 and Figure 3). Modelling of steam generators (SG), emergency core cooling systems (ECCS) including high-pressure injection system (HPIS), low-pressure injection system (LPIS) and accumulators, is also depicted in Figure 2 and Figure 3. The total number of hydraulic volumes used in the model is 470.

The transient under investigation in this study is ICAS T2 transient [1]. The transient is the small-break LOCA (SB-LOCA) with a 50-cm^2 break in a HL and coincident with a loss of offsite power.

The RELAP5/MOD3.3/Patch05 computer code [3] was used for system thermal-hydraulic calculation of the ICAS T2 SB-LOCA. The RELAP5 code is based on a nonhomogeneous and nonequilibrium model for the two-phase system that is solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. The RELAP5 code was developed for best-estimate transient simulation of light-water reactor coolant systems during postulated accidents. The code is able to model the coupled behaviour of the reactor coolant system and the core for LOCAs and operational transients, such as anticipated transient without scram, loss of offsite power, loss of feedwater, and loss of flow. A generic modelling approach is used that permits simulating a variety of thermal-hydraulic systems. The control system and secondary-side system components are included to permit modelling of plant controls, turbines, condensers, and secondary-side feedwater systems (FWS).

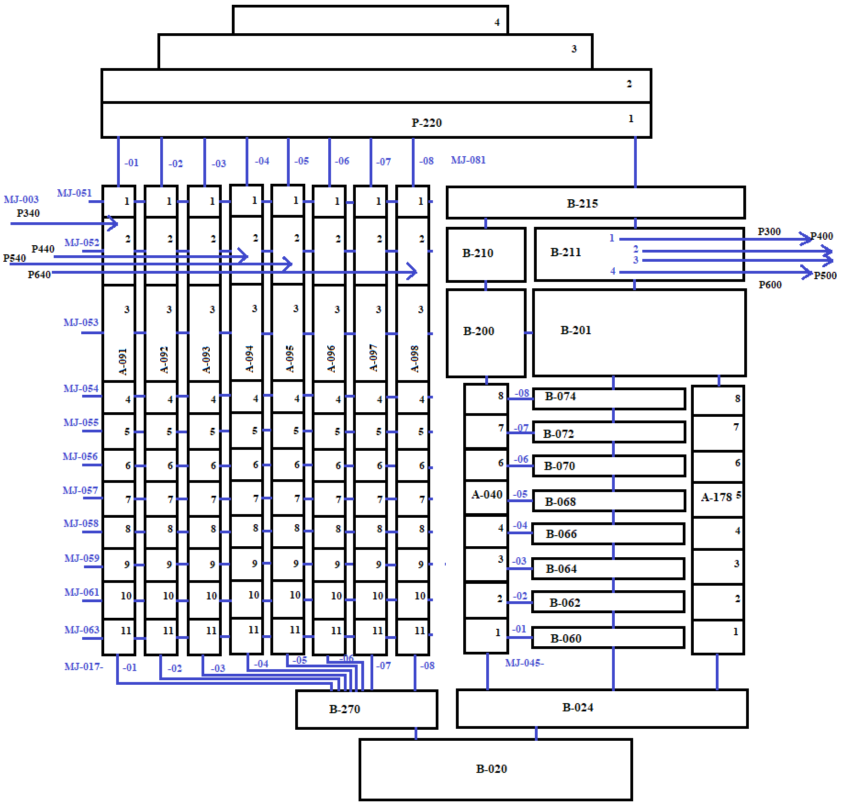


Figure 1: Nodalization of RPV [1]

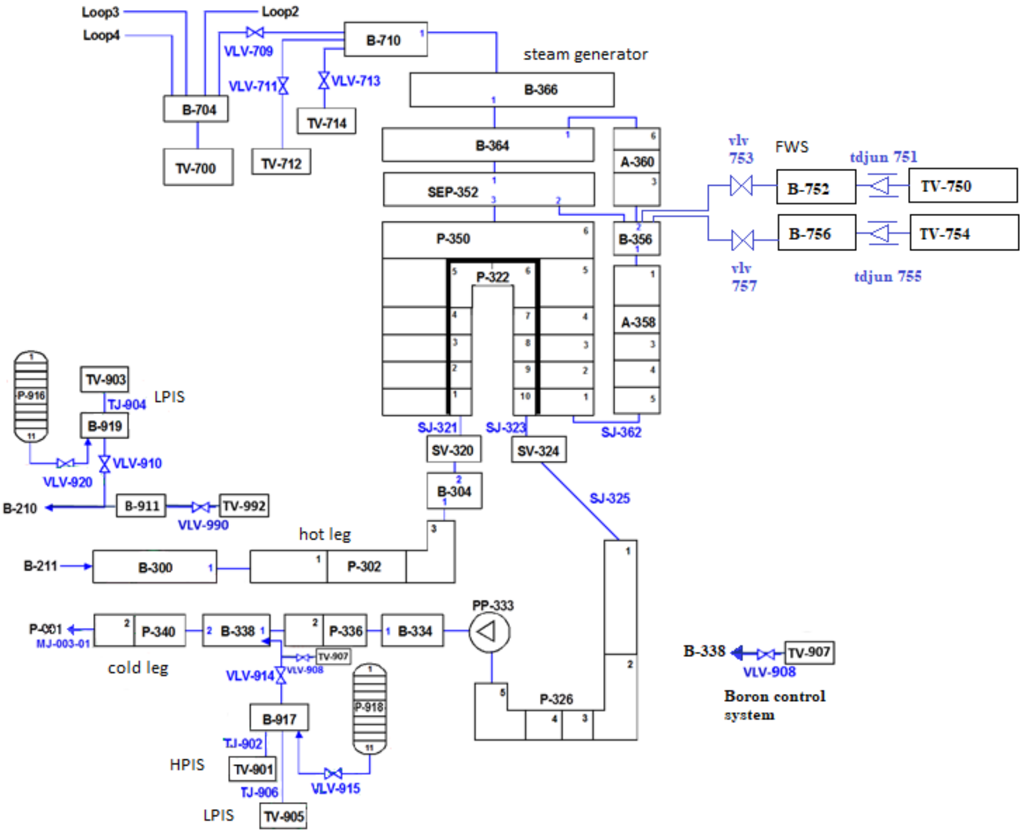


Figure 2: Nodalization of Loop 1 [1]

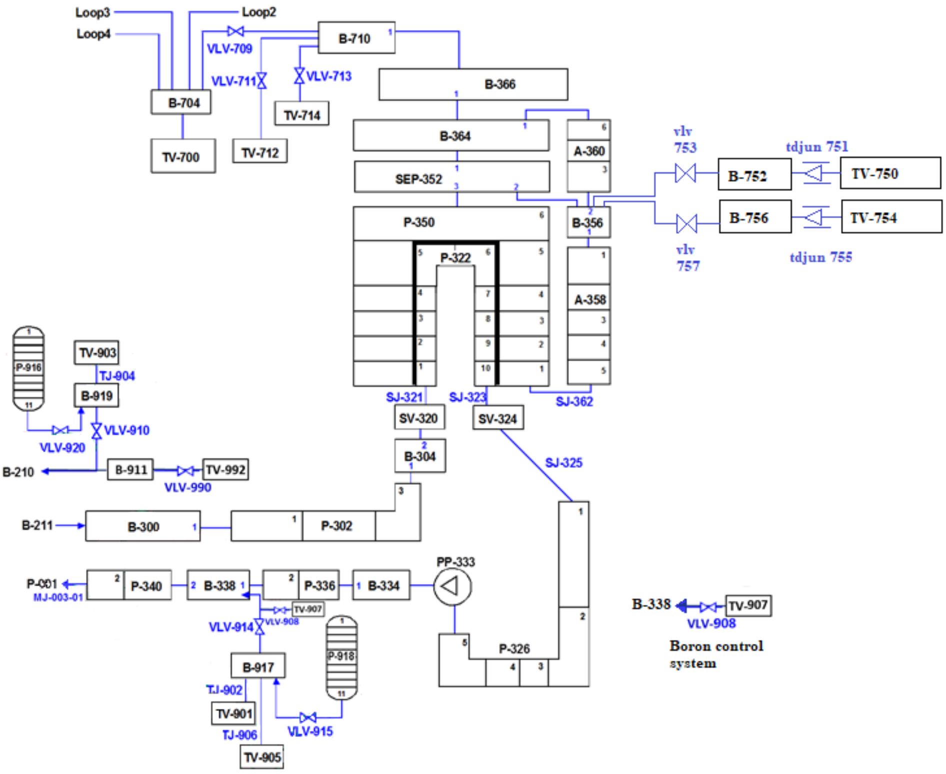


Figure 3: Nodalization of Loop 4 with a pressuriser [1]

3 LTO IMPROVEMENTS AND RESULTS OF CALCULATIONS

The LTO improvements can be of various kinds, and in this study six of them were investigated. Four LTO improvements are related to application of various parameters of the reactor safety systems: a heating of water in high-pressure injection (HPI) tanks, a heating of water in accumulators, a heating of water in low-pressure injection (LPI) tanks and a decreasing the accumulator pressure. The remaining two LTO improvements are related to human factors and they are modelled as different operator actions: a reduction of HPIS flow by the operator and a different secondary-side cooldown rate.

The areas that are prone to the initiation of cracks and their propagation are the locations of circumferential welds in the beltline region of the RPV, which are presented in Figure 4. The parameters that contribute the most to the crack development in the RPV during a PTS are pressure, the inner temperature of the RPV wall and heat transfer coefficient, which are shown in Figure 5, Figure 6, and Figure 7, respectively. In particular, the pressure, the inner temperature of the RPV wall and heat transfer coefficient are presented only for one weld location, i.e. 2.638 m below the centre line of cold leg No. 2.

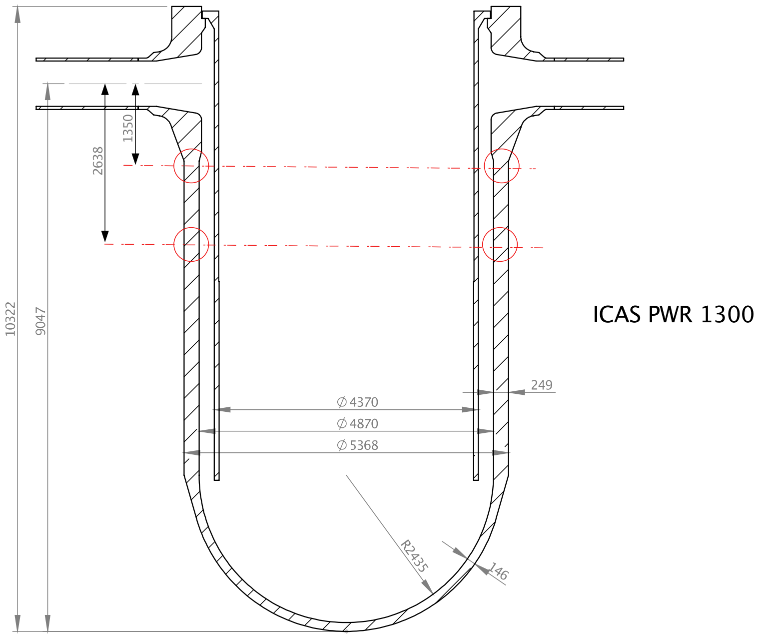


Figure 4: Location of the welds (indicated by the red lines and circles) in RPV [1]

The heating of the water in the HPI tanks was simulated by increasing the injection temperature from the reference value of 15°C to 45 °C. Comparative plots for the important parameters described above are provided in part a) of Figure 5 through Figure 7. The calculations show that the increased injection temperature shown in part a) of Figure 6 resulted in a higher RPV inner surface temperature during the entire transient, and part a) of Figure 7 shows slightly higher heat transfer coefficient at the end of the transient. The proposed LTO improvement affected the break flow and liquid levels until the initiation of the accumulators (around 2790 s). The LTO improvement could potentially be beneficial from a PTS perspective.

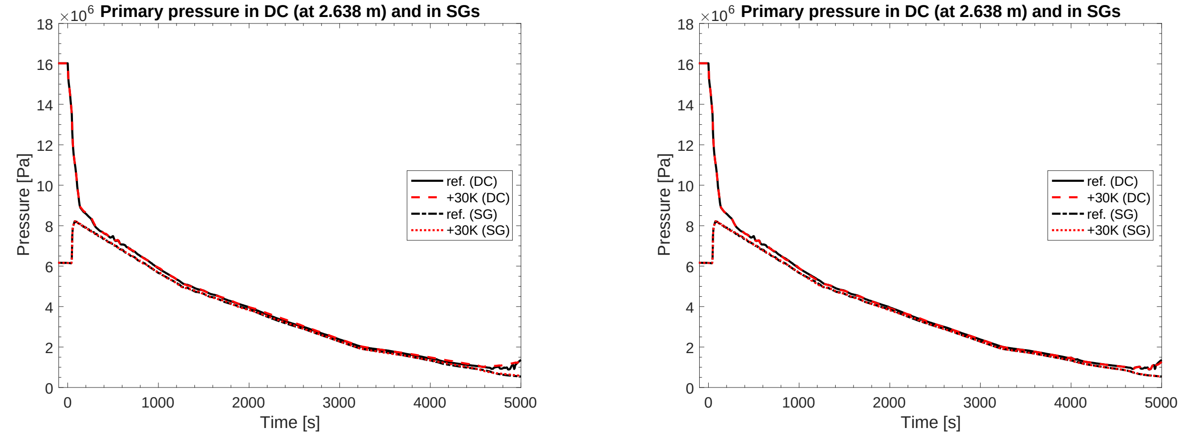
The heating of the water in the accumulators was simulated by increasing the injected water temperature from the reference value of 20 °C to 50 °C. Comparative plots for same important parameters are provided in part b) of Figure 5 through Figure 7. The calculations show that only after the initiation of the accumulators (around 2790 s) can the differences in the parameters (around 2790 s) be observed. The LTO improvement resulted in the slightly higher RPV inner surface temperature after the beginning of the flow from the accumulators, as shown in part b) of Figure 6. Almost no changes of the heat transfer coefficient were observed in part b) of Figure 7. The LTO improvement provides no significant benefit from a PTS perspective.

The heating of the water in the LPI tanks was simulated by increasing the injection temperature from the reference value of 15 °C to 45 °C. Comparative plots for the important parameters are provided in part c) of Figure 5 through Figure 7. The injection of water from LPI tanks began at around 4550 s, which is very late in the transient. The calculations show in part c) of Figure 6 that there is insignificant impact on RPV inner surface temperature and heat transfer coefficient through the end of transient at 5000 s, as shown in part c) of Figure 7. The LTO improvement provides no benefit from a PTS perspective.

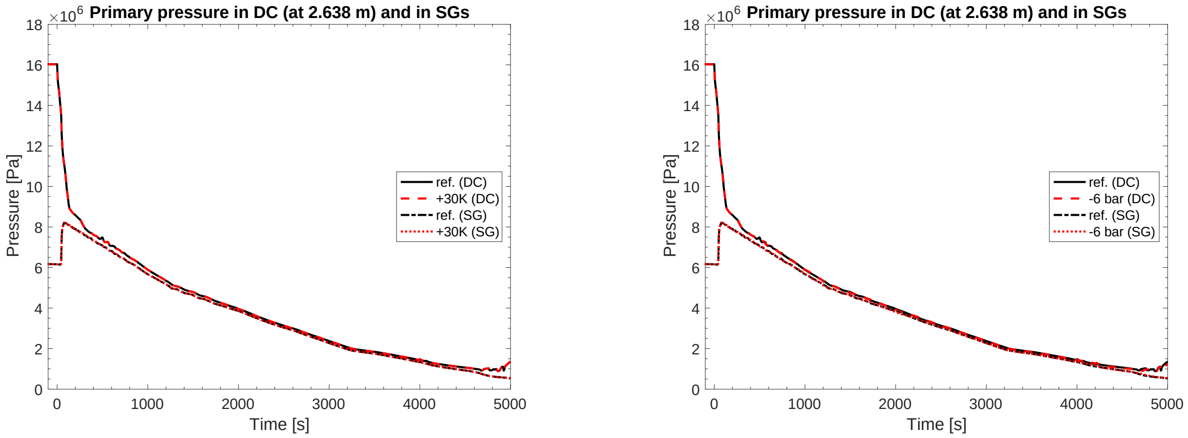
The reduction of the accumulator pressure was simulated by decreasing the accumulator pressure from the reference value of 26 bar to 20 bar. Comparative plots for the important parameters are provided in part d) of Figure 5 through Figure 7. The calculations show in part d) of Figure 6 that the decrease of the accumulator pressure slightly increased the RPV inner surface temperature due to the fact that the accumulator injection was postponed from 2790 s until 3160 s and, additionally, due to the fact that lower amount of water was injected. Almost no changes of the heat transfer coefficient in part d) of Figure 7 were observed. This LTO improvement provided no significant benefit from a PTS perspective.

The reduction of HPIS flow by the operator was simulated by switching off one of the two operating HPIS pumps 1800 s after the initiation of the break. Comparative plots for the important quantities are provided in part e) of Figure 5 through Figure 7. The calculations show in part e) of Figure 6 that the reduction of HPI injection, and therefore less injected cold water to the RCS, resulted in a higher RPV inner surface temperature starting at 1800 s. Additionally, after 2000 s the higher heat transfer coefficient is also observed in part e) of Figure 7. The studied LTO improvement could potentially be beneficial from a PTS perspective.

a) heating of water in HPI tanks b) heating of water in accumulators



c) heating of water in LPI tanks d) decreasing the accumulator pressure



e) reduction of HPIS flow by the operator f) different secondary side cooldown rate

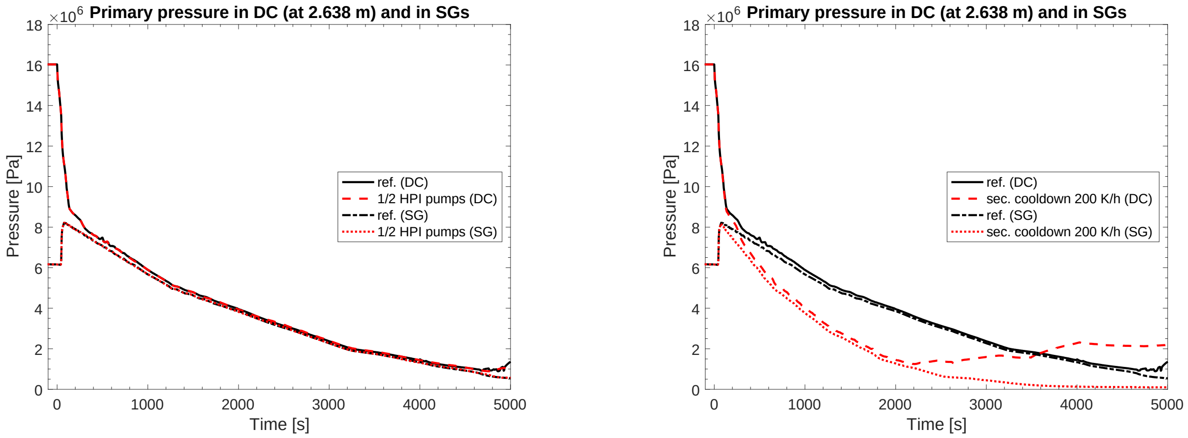
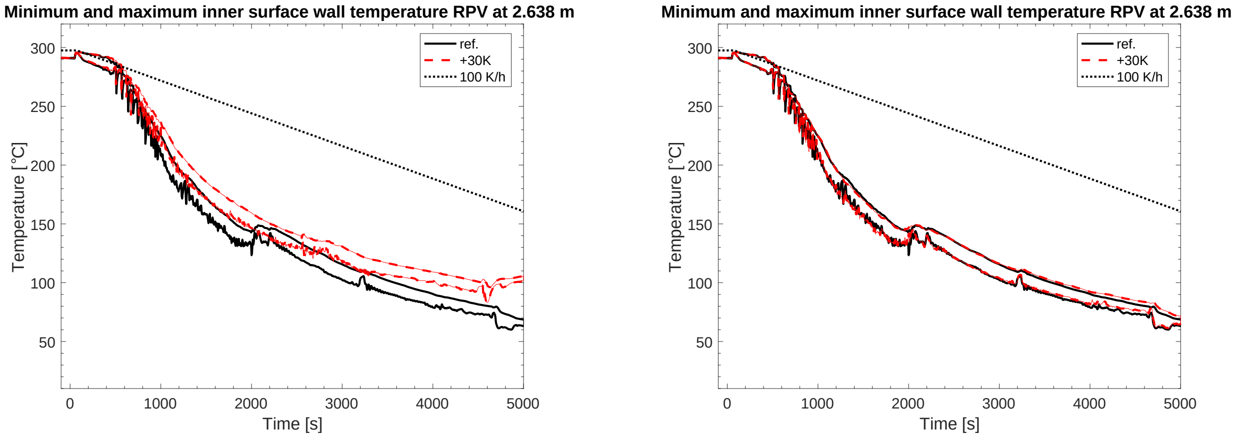


Figure 5: Comparisons of pressure in the DC at 2.638 m below the CL-2 axis and the secondary side pressure for the selected LTO improvements

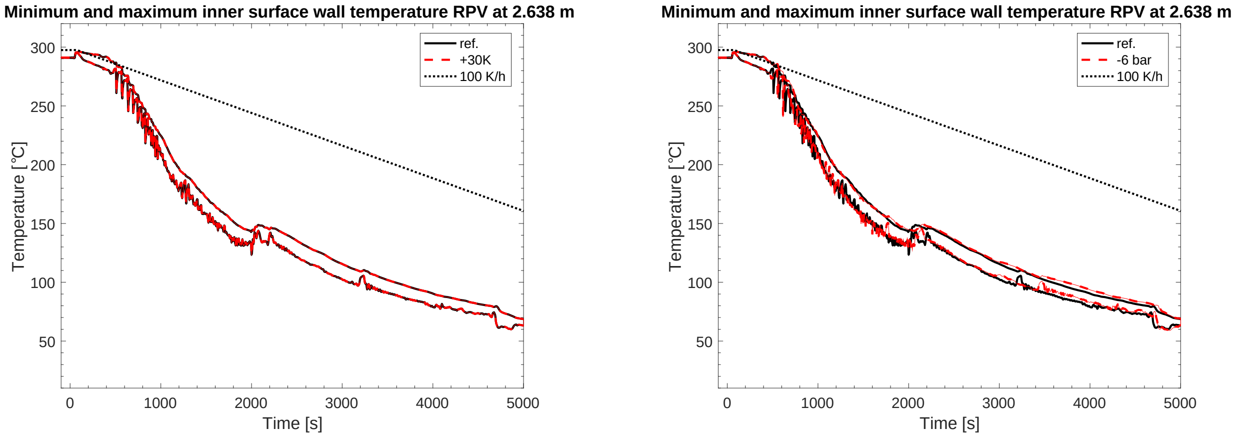
a) heating of water in HPI tanks

b) heating of water in accumulators



c) heating of water in LPI tanks

d) decreasing the accumulator pressure



e) reduction of HPIS flow by the operator

f) different secondary side cooldown rate

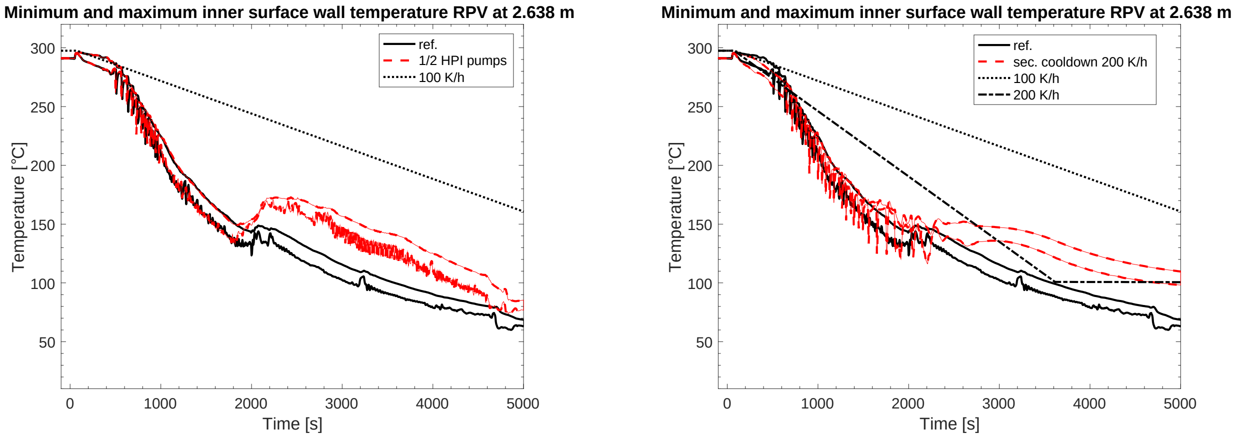
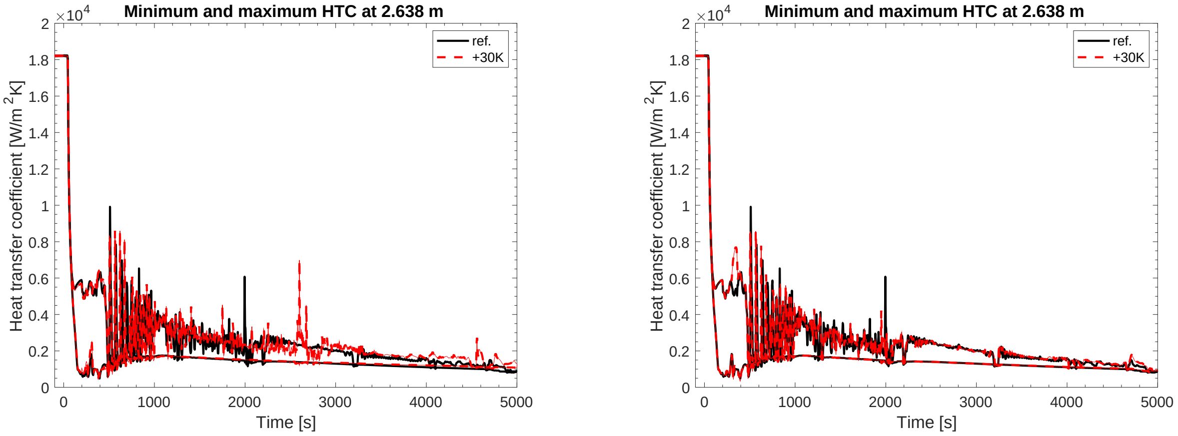


Figure 6: Comparisons of RPV inner surface temperature range (minimum to maximum) at 2.638 m below the CL axis for the selected LTO improvements

The increase of the secondary-side cooldown rate by the operator was simulated by increasing the cooldown of the secondary side from 100 K/h to 200 K/h. Comparative plots for important quantities of interest are provided in part f) of Figure 5 through Figure 7. The calculations show in part f) of Figure 5 that the increase of the secondary side cooldown rate resulted in a faster depressurization of the primary and the secondary side. The 200 K/h curve becomes flat at 3540 s. At this time, the secondary-side pressure in the SGs reaches 1 bar and for that pressure, the saturation temperature is around 100 °C. Due to the faster depressurization, the reduced time-integrated break flow and the increased time-integrated ECCS injection flow was observed up to around 4500 s. The proposed LTO improvement resulted in the increase of the RPV inner surface temperature in the DC after 2000 s, as shown in part f) of Figure 6. This LTO improvement could potentially be beneficial from a perspective of higher RPV inner surface temperature and faster pressure drop in DC. However, after 2000 s a higher heat transfer coefficient is also observed in part f) of Figure 7, which could be a detriment. The overall benefit of this LTO improvement needs to be verified by the structural analysis.

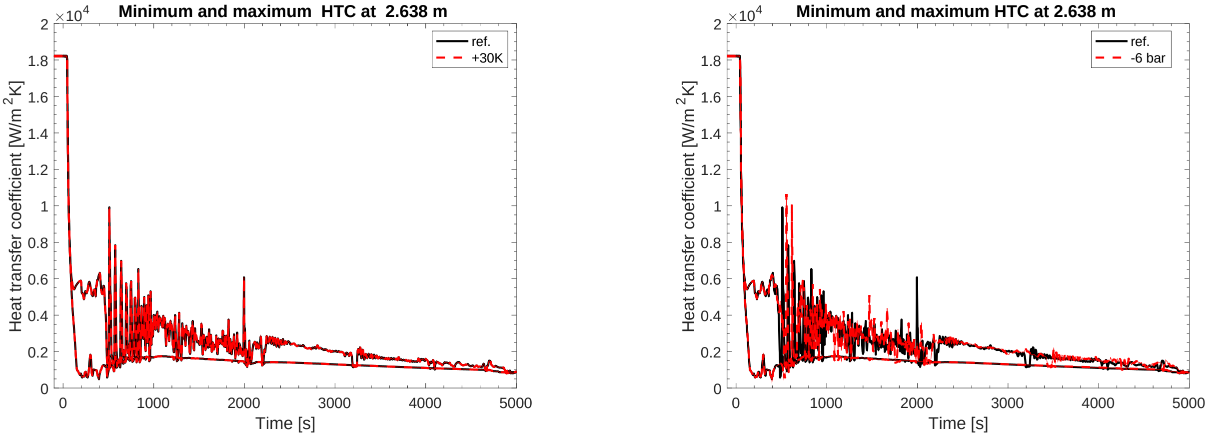
a) heating of water in HPI tanks

b) heating of water in accumulators



c) heating of water in LPI tanks

d) decreasing the accumulator pressure



e) reduction of HPIS flow by the operator

f) different secondary side cooldown rate

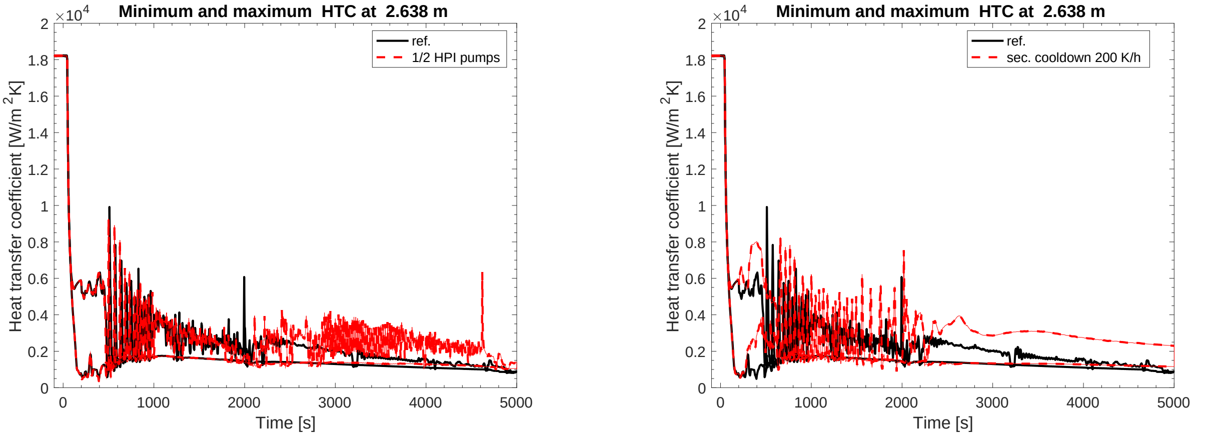


Figure 7: Comparisons of DC heat transfer coefficient (HTC) range (minimum to maximum) at 2.638 m below the CL axis for the selected LTO improvements

4 CONCLUSIONS AND FUTURE WORKS

Of the six potential LTO improvements simulated in this study, only the heating of water in HPI tanks and reduction of HPIS flow by the operator show a clear benefit for the SB-LOCA transient. The impact of heating the water in the accumulator, heating the water in the LPI tanks, and decreasing the accumulator pressure is insignificant on the main parameters that determine the initiation of cracks and their propagation during the SB-LOCA. The remaining LTO improvement, i.e., a different secondary-side cooldown rate, shows an inconclusive outcome that needs further studies. The summary of conclusions for the selected LTO improvements is shown in Table 1.

The impact of the selected LTO improvements will be further studied in the APAL project. Deterministic and probabilistic fracture-mechanics benchmarks will be performed to quantify the effect of selected LTO improvements on final fracture-mechanics results.

Table 1: Summary of conclusions of the studied LTO improvements

LTO IMPROVEMENT		**Conclusion**
Change of the specific parameter of the reactor safety systems	Heating of water in high-pressure injection (HPI) tanks	Potentially beneficial for SB-LOCA
	Heating of water in accumulators	Insignificant benefit for SB-LOCA
	Heating of water in low-pressure injection (LPI) tanks	Insignificant for SB-LOCA
	Decreasing the accumulator pressure	Insignificant benefit for SB-LOCA
Change of operator actions	Reduction of high-pressure injection system (HPIS) flow by the operator	Potentially beneficial for SB-LOCA
	Different secondary side cooldown rate	Inconclusive, needs further analysis for SB-LOCA

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REFERENCES

[1] Comparison Report of RPV Pressurised Thermal Shock International Comparative Assessment Study (PTS ICAS), NEA/CSNI/R(1999)3, 1999.

[2] APAL Project, Results of TH analysis for selected LTO improvements, Deliverable No. 2.1, APAL - Advanced PTS Analysis for LTO, Grant Agreement no. 945253, 2022.

[3] Information Systems Laboratories, Inc., RELAP5/MOD3.3 CODE MANUAL VOLUME I: CODE STRUCTURE, SYSTEM MODELS, AND SOLUTION METHODS, NUREG/CR-5535/Rev P5-Vol I, 2019.