Journal of Energy

VOLUME 71 Number 1 | 2022

journal homepage: http://journalofenergy.com/

RELAP5/mod 3.3 Analysis of Natural Circulation Cooldown with One Inactive Loop for Nuclear Power Plant Krško (NEK)

Srđan Špalj, Franc Cizel

Abstract — **The paper presents the RELAP5/mod3.3 analysis of natural circulation cooldown with one inactive loop for Nuclear Power Plant Krško (NEK). The aim of the analysis is to determine the limiting cooldown rates during operator recovery actions to minimize the effect of flow stagnation in inactive loop. Since this is typical asymmetrical transient, the RELAP5/mod3.3 NEK model with split reactor vessel model was developed (models of the reactor vessel and core were axially divided in two parts) and used for this analysis. The several transients of cooldown, with one inactive loop, for different time after shutdown (different decay heat) were performed. The extreme conservative assumptions were applied for the analyses, i.e. the complete loss of feedwater (FW) and auxiliary feedwater (AF), including turbine driven (TD) AF pump, and the cooldown has started after the SG is completely dry (inactive). The analyses show that the cooldown rate shall be significantly reduced, and, based on the results the procedure ES-0.2 "Natural Circulation Cooldown" was modified.**

Keywords — **natural circulation, inactive loop, cooldown rate, RELAP5/mod3.3, Nuclear Power Plant Krško (NEK)**

I. Introduction

If the Reactor Coolant Pumps (RCPs) in a pressurized water nuclear power plant are stopped then a loss of forced reactor coolant flow will occur and the decay heat from the core to reactor coolant and from reactor coolant to the steam generators (SG) will be removed by natural circulation. Natural circulation is a heat removal process where reactor coolant system (RCS) flow is driven by density differences in the RCS fluid between the core and steam generators. If it is not possible to restart the RCPs, then it is required to cooldown and depressurize the system to bring it to injection point of RHR system.

Ideally, all of the reactor coolant system (RCS) loops will be active and participate in the natural circulation cooling process. However, if certain failures occur, one loop may become inactive and that SG would not be available for cooling the RCS. If a natural circulation cooldown is initiated at too high rate using the active SG, the transfer of heat to the inactive loop SG will lag the conditions in the remainder of the RCS, such that the density driving head from the downcomer/core region portion is negated. As the RCS flow in the inactive loop slows down, it can eventually stop or stagnate as a result of this excessive cooldown.

(Corresponding author: Srđan Špalj)
Srđan Špalj and Franc Cizel are with the Krško Nuclear Power Plant (NEK), Krško, Slovenia
(e-mail: srdjan.spalj@nek.si, franc.cizel@nek.si)

The inactive loop flow stagnation during a natural circulation cooldown can delay or prevent cooldown of the inactive loop(s), and extend the time to reach Residual Heat Removal (RHR) System cut-in and cold shutdown conditions. Also, the amount of condensate inventory used (Auxiliary Feedwater – AFW) will increase due to the time delay

Westinghouse document WCAP-16632 [1] provides the results of the analyses performed to determine the limiting cooldown rates and operator recovery actions that should be considered to minimize the impact of flow stagnation in the inactive loops. The results are given for typical Westinghouse plant configuration (4, 3 and 2-loops) with typical Westinghouse steam generators. Direct Work Request DW-04-001 [2] determines and describes the required changes of the EOP procedure ES-0.2 "Natural Circulation Cooldown" [3], which are necessary to prevent stagnant loop flow during natural circulation cooldown.

The purpose of this analysis is to perform specific NEK analysis in order to define the maximum RCS cooldown rates that can be achieved without RCS loop flow stagnation occurring in the inactive loop. The endpoint is to develop specific NEK Figure ES02-1 for ES-0.2 "Natural Circulation Cooldown" [3], with limiting cooldown rates vs. loop ΔT.

The Westinghouse method [1] for determining limiting cooldown rate cannot be applied to NEK with adequate confidence, so the specific analysis is needed. The analysis was performed using RELAP5/mod3.3 computer code [4]. The first step of the analysis is the development of NEK RELAP5/mod3.3 model with split reactor vessel because the natural circulation cooldown with one inactive loop is an asymmetrical transient. The split vessel model is not limited to the mentioned transient, but, with or without simple modifications, it can be used for the variety of asymmetrical transients.

The split reactor vessel model development required remodeling of the reactor downcomer, lower plenum, core, core bypass, Rod Control Cluster Assembly (RCCA) guide tubes and part of the upper plenum as well as the corresponding heat structures and control variables [5], [6]. The guidelines for mixing in lower and upper plenum is taken from SSR-NEK-AADB "Krško Accident Analysis Database" [7]. Accordingly, the ratio of mixing in lower plenum is 0,7:0,3. It was assumed that there is no mixing in upper plenum in order to elevate the temperature difference in hot legs and possibility of flow stagnation in the inactive loop (this is specific for natural circulation analysis with one inactive loop).

First, the steady state calculation was done and the results were compared to the case with standard vessel nodalization in order to confirm the correctness of model. Next, the analysis of natural circulation cooldown with one inactive loop was performed and, finally, Figure ES02-1 for ES-0.2 [3], with limiting cooldown rates vs. loop ΔT was developed.

II. Analysis and Results

2.1. Evaluation of Applicability of WCAP-16632 [1] to NEK

The results for the analyses of natural circulation with inactive SG are given for typical Westinghouse plant configuration (4, 3 and 2-loops) with typical Westinghouse steam generators. Specifically, this WCAP discusses the sensitivity analyses that were performed to identify the following important factors in determining a limiting cooldown rate to prevent flow stagnation:

1) number of RCS loops

2) active loop ΔT at the start of the cooldown

3) elevation of the top of the steam generator U-tubes with respect to the hot leg centerline

The maximum cooldown rate is dependent on the decay heat level of the core (based on time after trip) and the elevation from the bottom of the SG plenum to the top of the U-tube bend. The maximum allowable cooldown rate decreases as the SG elevation increases. Similarly, the maximum cooldown rate decreases as the decay heat level decreases.

For NEK this process would be straightforward if NEK SGs are those of the standard Westinghouse type. But, since NEK SGs are quite different, this method cannot be used with confidence since the method is based on similarity. NEK SG is rather high (distance from the HL centerline to the top of U-tubes is 14.77 m) and, in addition, ΔT vs. decay heat is different than in presented Westinghouse plants what can be seen from Table 1(ΔT depends on decay heat level and flow rate, i.e., flow resistances in the loops).

Table I

Active loop ΔT vs. Decay Heat (Comparison of typical Westinghouse 2-loop and NEK (RELAP5 calculation), values are approximate

Decay Heat	Westinghouse 2-loop	NEK (RELAP5 calculation)
Q (MW)	DT (°C)	DT (°C)
20	23	16,4
15	-	14,1
10	9,4	11,0
5	5,6	-

Accordingly, it can be concluded that the proposed Westinghouse method for determining limiting cooldown rate cannot be applied to NEK with adequate confidence, therefore the specific analysis is needed. The analysis is performed using RELAP5/mod3.3 computer code and it is presented below

2.2 Development of RELAP5/mod3.3 Split Reactor Vessel Model for NEK

The basis for the split reactor vessel model development is already existing NEK RELAP5/mod3.3 model, used for safety analyses and NEK Full Scope Simulator verification, and described in the NEK RELAP5/mod3.3 Nodalization Notebook [5] and Steady State Qualification Report [6].

The task required remodelling of the reactor downcomer, lower plenum, core, core bypass, RCCA guide tubes and part of the upper plenum as well as the corresponding heat structures and control variables. This is done by vertically dividing the existing RELAP5 control volumes of reactor pressure vessel in two equal parts. The junctions are also modified in the same way with additional adjustment of flow loss coefficients to match exact bypass flow values. Also, the corresponding heat structures are equally divided. The control variables that calculate mass, level and heat losses in the vessel and power in the core are modified. The model of the reactor kinetics was adjusted to the split vessel model in order to correctly analyse the transients for which the neutron kinetics behaviour is essential. The rest of the model, including control and protection system, remained the same as described [5] and [6].

The modelling approach without horizontal cross-flow connections between separated volumes inside reactor vessel was chosen to maximize the effect of asymmetrical transients. The guidelines for mixing in lower and upper plenum is taken from SSR-NEK-AADB "Krško Accident Analysis Database" [7]. Accordingly, the ratio of mixing in lower plenum is 0,7:0,3. Specifically, for analysis of natural circulation with one inactive loop, it was assumed that there is no mixing in upper plenum in order to elevate the temperature difference in hot legs and possibility of flow stagnation in the inactive loop.

The differences between standard vessel nodalization and split vessel nodalization are shown on Figure 1.

2.3 Evaluation of the Steady State Calculation

The steady state calculation was performed with NEK RELAP model with split Reactor Pressure Vessel (RPV) using the same assumptions and steady state criteria from [6] and the results show almost no differences compared to the case with standard vessel nodalization. The correctness of the steady state can be seen in Table 2 where comparison between NEK reference data and the calculated values for standard and split RPV model are shown.

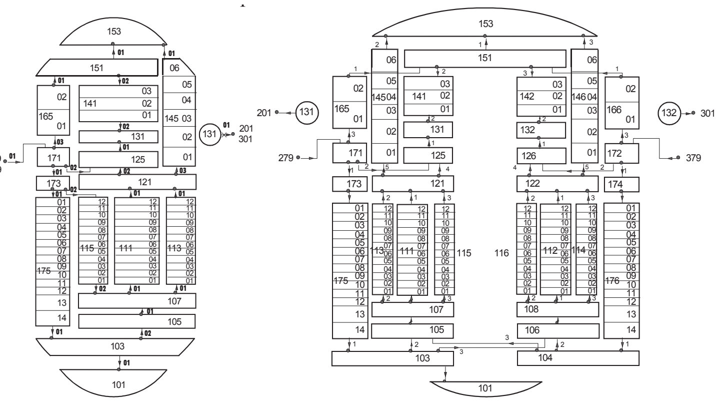

Fig. 1: RELAP5 Nodalization of NEK reactor vessel – standard and split vessel model

Table II

Comparison Between NEK Reference Data and Results of the Steady State Calculation for Standard and Split RPV Model

		NEK	RELAP5	
Parameter	**Unit**	**reference**	**Standard RPV model**	**Split RPV model**
1. Pressure	MPa			
Pressurizer		15.513	15.513	15.513
Steam generator		6.281	6.45/6.43	6.45/6.42
2. Fluid Temperature	K			
cold leg		558.75	559.65/559.46	559.45/559.44
Hot leg		597.55	596.92/596.92	596.94/596.90
3. Mass Flow	kg/s			
Core		8966.9	9034.3	4515.0/4515.1 (9030.1)
cold legs		4694.7	4718.0/4716.4	4717.8/4716.6
main steam lines		544.5	541.4/544.5	541.7/544.4
DC-UP bypass (2%)		187.8	184.8	93.8/93.8 (187.6)
DC-UH bypass (0.3%)		28.2	29.0	14.1/14.1 (28.2)
Buffle-barrel flow (1.25%)		117.4	116.8	58.1/58.1 (116.2)
RCCA guide tubes (2%)		187.8	186.3	94.2/94.2 (188.4)
4. Liquid level	%			
Pressurizer		55.7	55.8	55.8
Steam generator narrow range		69.3	69.3/69.3	69.3/69.3
5. Fluid Mass	t			
Primary system		-	131.2	131.3
Steam generator (secondary)		47.0	49.1/49.0	49.1/49.0
6. Pressure Drop	kPa			
reactor		290.0	297.1	297.3
core		171.0	174.4	174.5
Steam generator (primary)		234.0	211.0	210.6
RCS piping		39.4	38.6	38.5
7. Power	MW			
Core		1994.0	1994.0	1994.0
Steam generator		1000.0	996.6/1002.5	997.2/1002.3

2.4 RELAP5/mod3.3 Analysis of Natural Circulation Cooldown with One Inactive Loop

Since it is assumed that the heat transfer to one steam generator is not possible, this transient can be classified as the typical asymmetric transient. The detection of the flow stagnation in the inactive loop is based on the difference between hot leg temperature decrease rate. For that reason, this transient was analysed using modified NEK RELAP5 model with split vessel, as discussed in the chapters above. It was assumed that there is no mixing in upper plenum in order to elevate the temperature difference in hot legs and possibility of flow stagnation in the inactive loop. Based on the evaluation of the WCAP-16632 [1] it is supposed that the inactive SG will become completely dry, which is the most restrictive assumption.

The analysed transient assumed complete loss of feedwater and the unavailability of auxiliary feedwater in SG1, and, after a certain period the entire SG1 inventory is lost meaning that the SG1 is inactive. The following figures (Figure 2 to Figure 4) present the decay heat, the temperatures of the hot and cold legs and the mass flow rates in the loops for the analysis where the cooldown is not started. The analysis was done with control of pressure and level on primary and secondary side in order to stabilize the transient behaviour. On the contrary, the cycling of the SG PORVs/Steam Dump would result in oscillation of the parameters (pressure, temperature) around the value presented herein. The differences of hot leg temperatures and loops mass flow rates clearly indicate the effect of the inactive SG. Table 3 summarizes the results for distinct decay heat values.

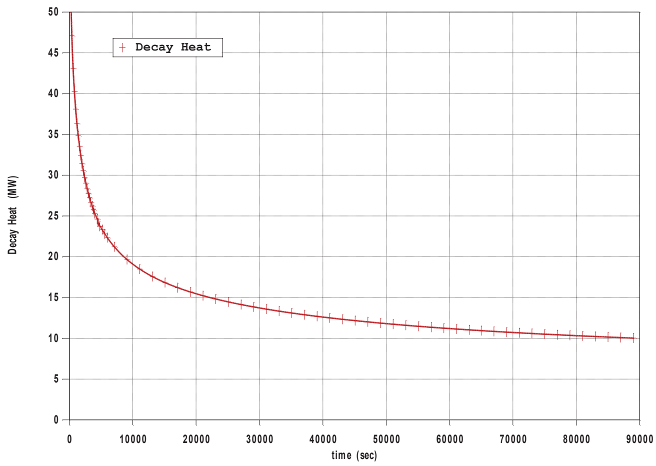

Fig. 2: Decay heat

Table III

Active loop DT vs. Decay Heat (RELAP5 calculation)

Q (MW)	DT (ºC)	Time (seconds)	Time(hours)
20	16,4	8500	2,4
17,6	15,6	13000	3,6
15	14,1	22200	6,2
10	11,0	89000	24,7

Srđan Špalj, Franc Cizel, RELAP5/mod3.3 Analysis of Natural Circulation Cooldown with One Inactive Loop for Nuclear Power Plant Krško (NEK), Journal of Energy, vol. 71 Number 1 (2022), 34–39
https://doi.org/10.37798/2022711409

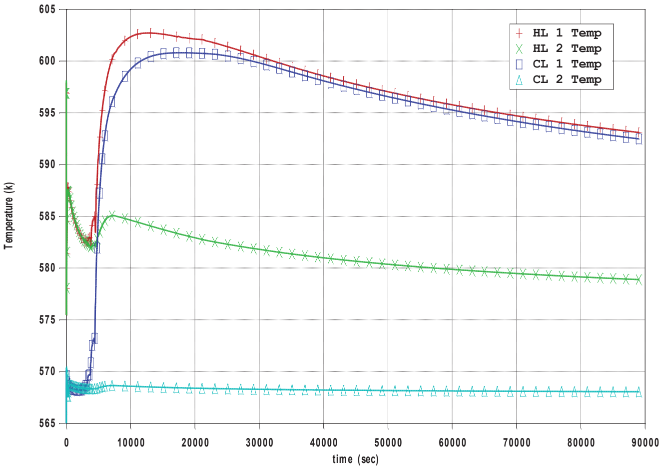

Fig. 3: Hot and cold leg temperatures (cooldown not started)

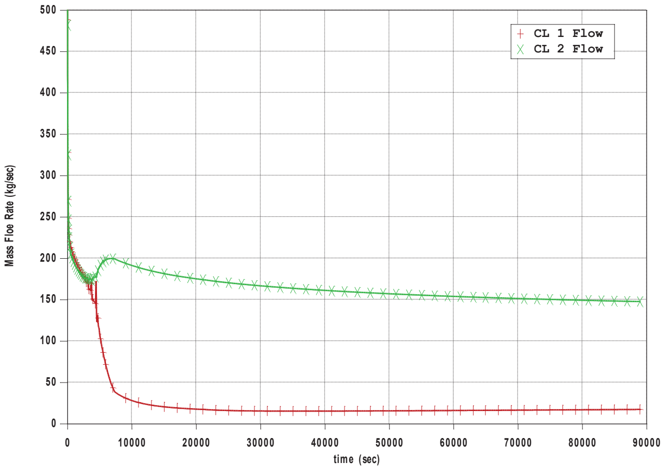

Fig. 4: Cold legs mass flow rates (cooldown not started)

The analysis of cooldown is presented in Figure 5 to Figure 10. It was assumed that the cooldown starts after initial phase of the transient (complete loss of FW and AFW in SG1), when the inactive SG becomes "dry". At time when decay heat is 20 MW the inactive SG is not completely dry, so cooldown is not started at this point. Therefore, the ***cooldown has started at times corresponding to 17.6, 15 and 10 MW decay heat*** (Table 3). The presented results are for limiting cooldown rates when indication of flow stagnation occurs, i.e. when it is determined that the inactive loop T_{hot} is decreasing at the slower rate than the active loop T_{hot}. It shall be noted that the analysis of cooldown is limited to the STEP 6 (beginning from STEP 6) and STEP 7 from the revised ES-0.2 procedure [3], because the STEP 7 is guidance for recovering from stagnant loop by providing the means of heat transfer from inactive loop. During these steps the operator is required to decrease core exit temperature (Figure ES02-1 [3]) to less than 287 °C prior to depressurization. It is questionable if the core exit temperature can be used for determining RCS temperature if there is an inactive loop. Additionally, hot leg temperatures in the loops differs a lot and, since there is almost no flow through inactive loop and cold and hot leg temperatures are almost equal, the inactive loop temperatures are not relevant for RCS temperature determination. According to EOP background documentation [8], the temperature of the active loop can be used when determining RCS temperature. Therefore, it is assumed that the cooldown for these steps ends when the active loop hot leg temperature reaches the temperature of 287 °C (560 K). After the depressurization to 137 kp/cm^2 the cooldown can be continued during STEPS 12 and 13 and it is limited according to the Figure ES02-1 at the same manner as in the STEP7.

The results shows rather restrictive cooldown rates (Figure 5, Figure 7 and Figure 9) what is caused by the extreme conservative assumptions (complete loss of FW and AFW including TD AF pump) and, to some extent, by the physical characteristics of NEK steam generator. The results are summarized in Table 4, from which the required figure ES02-1 is developed (Figure 11). It shall be noted that the ***limiting cooldown rate is determined when apparent difference exists between active and inactive HL temperature decrease rate***. On the contrary, i.e., when resulting temperature decrease rates do not differ a lot, the cooldown rate is very low what was considered to be over restrictive. This can be supported by the fact that the flow stagnation/reversal (in the inactive loop) did not occur for the extended period applying the constant cooldown rate (Figure 6, Figure 8 and Figure 10. It can be seen (Table 4 and Figure 11) that the limiting cooldown rates are, more or less, linearly proportional to ΔT. That can be expected because the limiting cooldown rates decreases exponentially with time, analogous to decay heat, and ΔT follows the same trend. It can also be judged that above ΔT =16,4°C (corresponding to 20 MW decay heat) the cooldown rate can be limited to 14°C/hr because, before that point, the SG1 would not become completely dry (inactive). Anyhow, this relaxation was not drawn on the developed figure ES02-1 (Figure 11: Maximum allowable cooldown rate - Figure ES02-1 for EOP ES-0.2).

Table IV

Limiting Cooldown Rates vs. Active Loop ΔT (RELAP5 Calculation)

Time after shutdown (hours)	Q (MW)	DT (°C)	Cooldown rate (°C/hr)
3,6	17,6	15,6	10,8
6,2	15	14,1	8,8
24,7	10	11,0	4,9

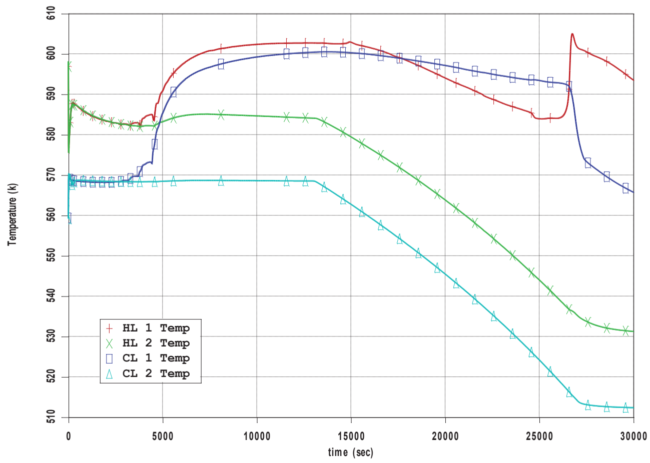

Fig. 5: Hot and cold temperatures - cooldown to 287 °C (560 K) ***from ΔT =15,6 °C***

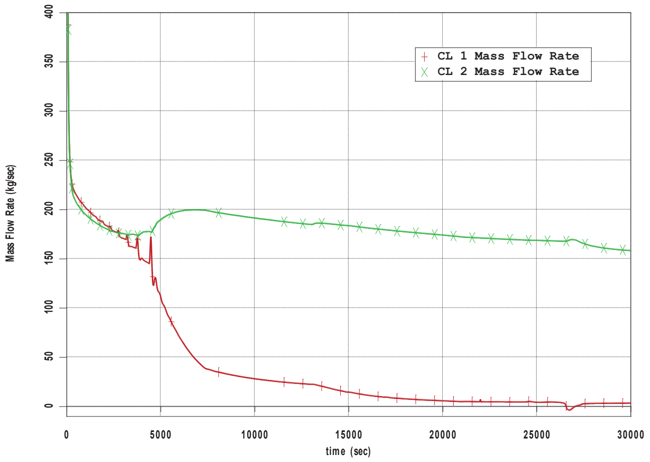

Fig. 6: Cold legs mass flow rates - cooldown to 287 °C (560 K) ***from ΔT=15,6 °C***

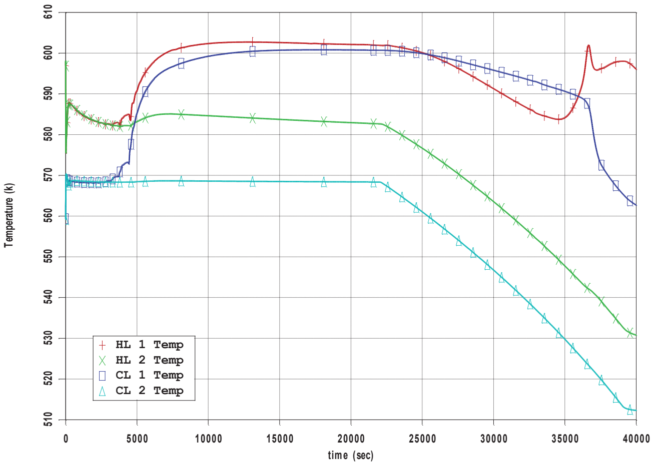

Fig. 7: Hot and cold leg temperatures - cooldown to 287 °C (560 K) ***from ΔT=14,1 °C***

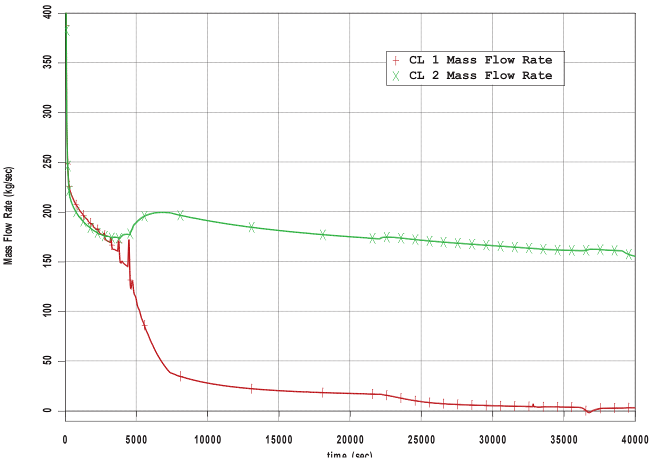

Fig. 8: Cold legs mass flow rates - cooldown to 287 °C (560 K) ***from ΔT=14,1 °C***

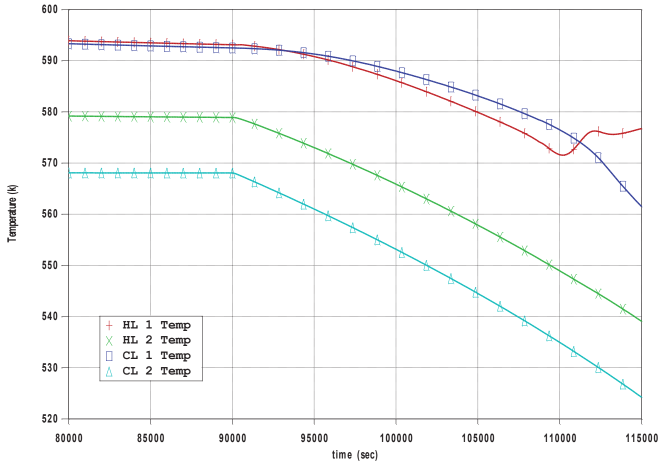

Fig. 9: Hot and cold leg temperatures - cooldown to 287 °C (560 K) ***fromΔT=11,0 °C***

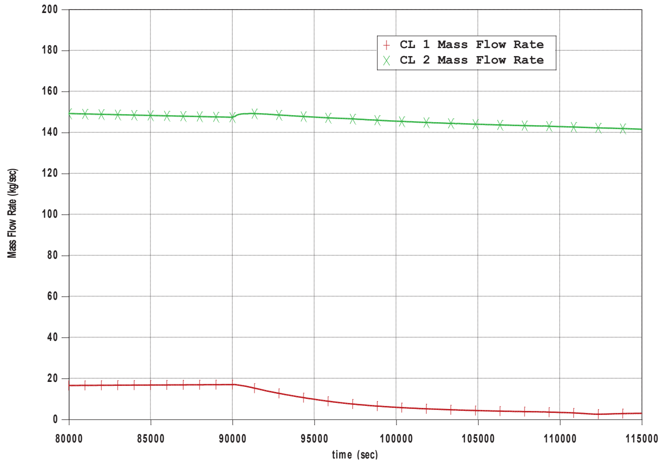

Fig. 10: Cold legs mass flow rates - cooldown to 287 °C (560 K) ***from ΔT=11,0 °C***

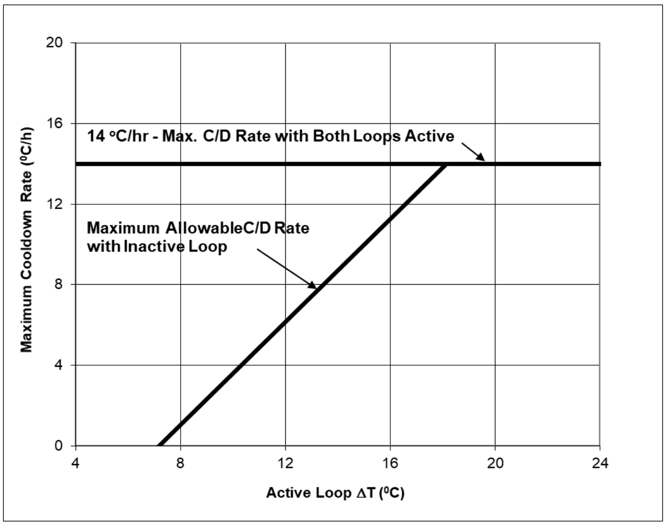

Fig. 11: Maximum allowable cooldown rate - Fig. ES02-1 for EOP ES-0.2 [3]

Conclusion

Determination of the maximum allowable cooldown rate with one inactive loop for NEK could not be done in straightforward way based on the instructions given in Westinghouse documents ([1] and [2]). The reason is rather different steam generators compared to standard Westinghouse SG types. NEK SG is rather high and, in addition, ΔT vs. decay heat is different than in presented Westinghouse plants. Taking this into account, the specific analysis was needed for NEK in order to determine maximum allowable cooldown rate. The analysis was performed using RELAP5/mod3.3 computer program. Since this problem is asymmetric the existing NEK RELAP model was changed, i.e., models of the reactor vessel and core were axially divided in two parts. After that the several transients of cooldown, with one inactive loop, were performed according to the guidelines from [1]. It shall be noted that the extreme conservative assumptions was applied for the analyses, i.e. the complete loss of FW and AFW (including loss of TD AF pump) and the cooldown has started after the SG is completely dry (inactive). The results show that the cooldown rate shall be significantly reduced (Figure 11), what was expected according to the analysis assumptions and, also, to a certain extent, due to the physical characteristics of NEK steam generators.

Based on this analysis and conclusion the procedure ES-0.2 "Natural Circulation Cooldown" [3] was changed as required by DW-04-001 [2].

References

[1] WCAP-16632 "Inactive Loop Flow Stagnation During Natural Circulation Cooldown, PA-ASC-0145", Rev. 0, 2009

[2] Direct Work Request - DW-04-001

[3] ES-0.2 "Natural Circulation Cooldown" Rev. 13, 2009

[4] RELAP5/mod3.3 Code Manual Volume II: User's Guide and Input Requirements, NUREG/CR 5535/Rev 1-Vol II, ISL, Inc., Rockville, Maryland, December 2001.

[5] NEK RELAP5/MOD3.3 Nodalization Notebook, NEK ESD-TR-01/09, Rev.0.

[6] NEK RELAP5/MOD3.3 Steady State Qualification Report, NEK ESD-TR-02/09, Rev.0.

[7] SSR-NEK-AADB "Krško Accident Analysis Database", Rev. 1, June 2001.

[8] Background Information for Westinghouse Owners Group Emergency Response Guidelines, Generic Issues, Generic Instrumentation, HP/LP-Rev.2, April 30, 2005.