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NPP Krško Large Break Loss of Coolant Accident using MELCOR Code

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ABSTRACT

NPP Krško (NEK) input deck for severe accident code MELCOR is being developed at Faculty of Electrical Engineering and Computing (FER) Zagreb. MELCOR is fully integrated computer code that models the progression of severe accidents in light water nuclear power plants. Recently, the MELCOR 1.8.6 input deck was converted to MELCOR 2.1 as well as to a new code version MELCOR 2.2. In this paper the results of Large Break Loss of Coolant Accident (LB LOCA) using MELCOR 1.8.6 as well as MELCOR 2.1 and MELCOR 2.2 are presented. Both unmitigated scenario (Engineered Safety Features (ESF) not available) and design basis (DB) scenario (one train of ESF available) have been analyzed.

The postulated accident is initiated as a guillotine break in cold leg 1 (loop with pressurizer) discharging in Steam Generator (SG) 1 compartment. Simultaneously, an artificial valve connecting two previously connected volumes is closed. In the scenario with ESF available, one high head and one low head safety injection pump with maximum delay (30 seconds) were assumed available. The accumulator in the broken loop was assumed to spill into containment. Transient was simulated for 10000 seconds. Sensitivity analyses were performed for various values of break discharge coefficients (0.4, 0.6, 0.75 and 1.0) in order to find the most adverse scenario. The results for the analysis with ESF available were assessed against 10CFR50.46 criteria with relation to peak cladding temperature (1477 K) and hydrogen mass (1%). For all three MELCOR code versions the satisfactory behavior of ESF (1 ECCS train and 1 ESF train in containment), both in RCS and in the containment was demonstrated. For unmitigated scenario only short term results up to 10000 s including time of the Lower Head Failure (LHF) and mass of hydrogen in the core were determined.

1 INTRODUCTION

For the purpose of NEK transient/accident analyses the model for severe accident code MELCOR, [1], [2], has been developed at FER, ref. [3], [4], [5] and [6]. The models of reactor protection as well as engineered safety features have been provided in the model, e.g., 1) Reactor protection system, 2) Turbine trip logic, 3) Main steam line isolation, 4) Steam generator level control system in steady state, 5) Pressurizer level control system in steady state, 6) Safety injection system, 7) Auxiliary feedwater system, 8) Containment spray, 9) Containment fan coolers, 10) Passive Autocatalytic Recombiners (PARs) and 11) Passive Containment Filtered Vent System (PCFV).

MELCOR 1.8.6 input deck has been further converted into MELCOR 2.1 (version 2.1.6342) and MELCOR 2.2 (version 2.2.14959 and version 2.2.18019) input decks using

SNAP Version 2.6.1. Recently, MELCOR 1.8.6 was used to analyse Station Blackout (SBO) accident at NEK, ref. [7] and 3 inch cold leg LOCA with ESF available, [8].

In this paper the results of Large Break LOCA using three versions of MELCOR code (MELCOR 1.8.6, MELCOR 2.1 and MELCOR 2.2 (version 2.2.14959)) for NPP Krško are presented. First, the unmitigated scenario with subsequent station blackout was analysed. Due to loss of core liquid inventory, core degradation with subsequent Reactor Pressure Vessel (RPV) failure and melt ejection would occur. Only short term effects (0-10000 s) of unmitigated LB LOCA were analysed, i.e., the time of Lower Head Failure (LHF) and the amount of hydrogen produced in the MELCOR COR package. In MELCOR version 2.2.14959 the Eutectic model can be enabled. The model takes into account liquefaction of intact structures caused by eutectic reactions between materials within the structure and dissolution of intact structures by existing molten material. Thus, for Unmitigated scenario for MELCOR 2.2, the base case (model disabled) and the case with Eutectic model activated were analyzed. Further, Design Basis (DB) LOCA was analysed assuming the minimum (one train) of Engineered Safety Features (ESF), i.e., one High Head Safety Injection (HHSI) pump, one Low Head Safety Injection (LHSI) pump when injecting from Refuelling Water Storage Tank (RWST) and one LHSI pump for injection from containment sump as well as one train of containment fan coolers and of containment spray. In order to find the most conservative scenario both unmitigated and DB LOCA were analysed for four values of break discharge coefficients (0.4, 0.6, 0.75 and 1.0). The results for DB LOCA were assessed against the two of 10CFR50.46 criteria, i.e., peak cladding temperature is less than 1477 K and the amount of hydrogen generated from the chemical reaction of cladding with water or steam does not exceed 1%.

2 CALCULATIONAL MODEL FOR NPP KRŠKO

The scheme of NPP Krško nodalization for MELCOR code is shown in Figure 1. The primary and secondary systems, including control systems and necessary boundary conditions, consist of 145 thermal-hydraulic volumes, 197 flow paths and 140 heat structures. The Reactor Pressure Vessel (RPV) lower plenum is represented with 3 control volumes (CVs), the downcomer with 15 CVs, the upper plenum with 4 CVs and the upper head with 2 CVs. The flow inside the reactor core is represented with 12 control volumes (CV 007-018), as well as the baffle-barrel flow (CV 067-078) and RCCA guide tubes (CV 169-180). The COR model aimed for evaluation of fuel and other core and lower plenum structures consists of 126 calculation cells. Active part of the core is subdivided into 5 radial rings and 12 axial levels having the same height as corresponding thermal-hydraulic volumes. Baffle-barrel region up to the top of baffle plates is presented as bypass control volume at radial boundary of the active core (5^{th} ring). There are 7 radial rings and 3 axial levels in lower head and 2 axial levels in cylindrical part of lower plenum. There is one additional axial level in COR model describing the region above the top of active fuel up to the top of baffle plates that contains the non-active parts of fuel assemblies. The total number of thermal-hydraulic volumes used as boundary volumes in COR package equals to 29.

Hot legs in each loop are modelled with two control volumes (CV 101 and 102 for the first loop and CV 201 and 202 for the second loop), intermediate legs with three and cold legs with two volumes. Reactor coolant pumps (CV 108 and CV 208) are connected with cold leg volumes (CV 110 and CV 210) via flow paths with QUICK-CF model. The pressurizer is modelled with CV 103 and pressurizer surge line is modelled by CV 105, while the volume CV104 represents the pressurizer relief tank. CV 109 and CV 209 represent accumulators. Safety injection (SI) is modelled by time dependent flow paths 716, 726 and 736 representing injection from RWST to respective cold leg (CV 110 and CV 210) and downcomer (CV 001) volumes. The steam generator (SG) inlet part is modelled with one volume, the outlet part also with one CV, and U-tubes with six control volumes. On the secondary side, SG 1 downcomer is modelled with CV 342 (CV 442 for SG 2); heat exchanger section is modelled by three CVs (351, 352 and 353) and riser section (the region from the top of U-tubes to the bottom of separator is modelled with CV 354. Separator (CV 355) has three junctions; the inlet junction to CV 355 from the riser (CV 354) and two outlet junctions; the steam outlet flow path to upper plenum and steam dome represented by CV 356 and the junction for liquid return (circulation flow) to downcomer (CV 342). CV 343 represents upper plenum bypass volume, where the bypass flow path between steam dome (CV 356) and downcomer (CV 342) is established. Main and auxiliary feedwater flow are modelled using control volumes (CV 503 and CV 504 for SG 1 and CV 513 and CV 514 for SG 2, respectively) together with respective time dependent flow paths. The steam header and the steam line to the turbine are represented with the control volumes CV 813 and CV 814, respectively. CV 814 is connected to CV 901 (pressure boundary condition that simulates the turbine) by the valve that closes after turbine trip. Containment model consists of 17 control volumes, 44 flow paths and 20 heat structures, respectively.

Steady state was simulated for 1000 s. The results for relevant physical parameters at the end of steady state calculation are assessed against NEK referent data (see Table 1). In general, a very good agreement between MELCOR steady state results and NEK referent data were obtained. The largest difference between MELCOR steady state calculation and referent data is for secondary pressure (1.9%) and feedwater/steam mass flow rate (1.02%), whereas the differences between different MELCOR versions can be neglected.

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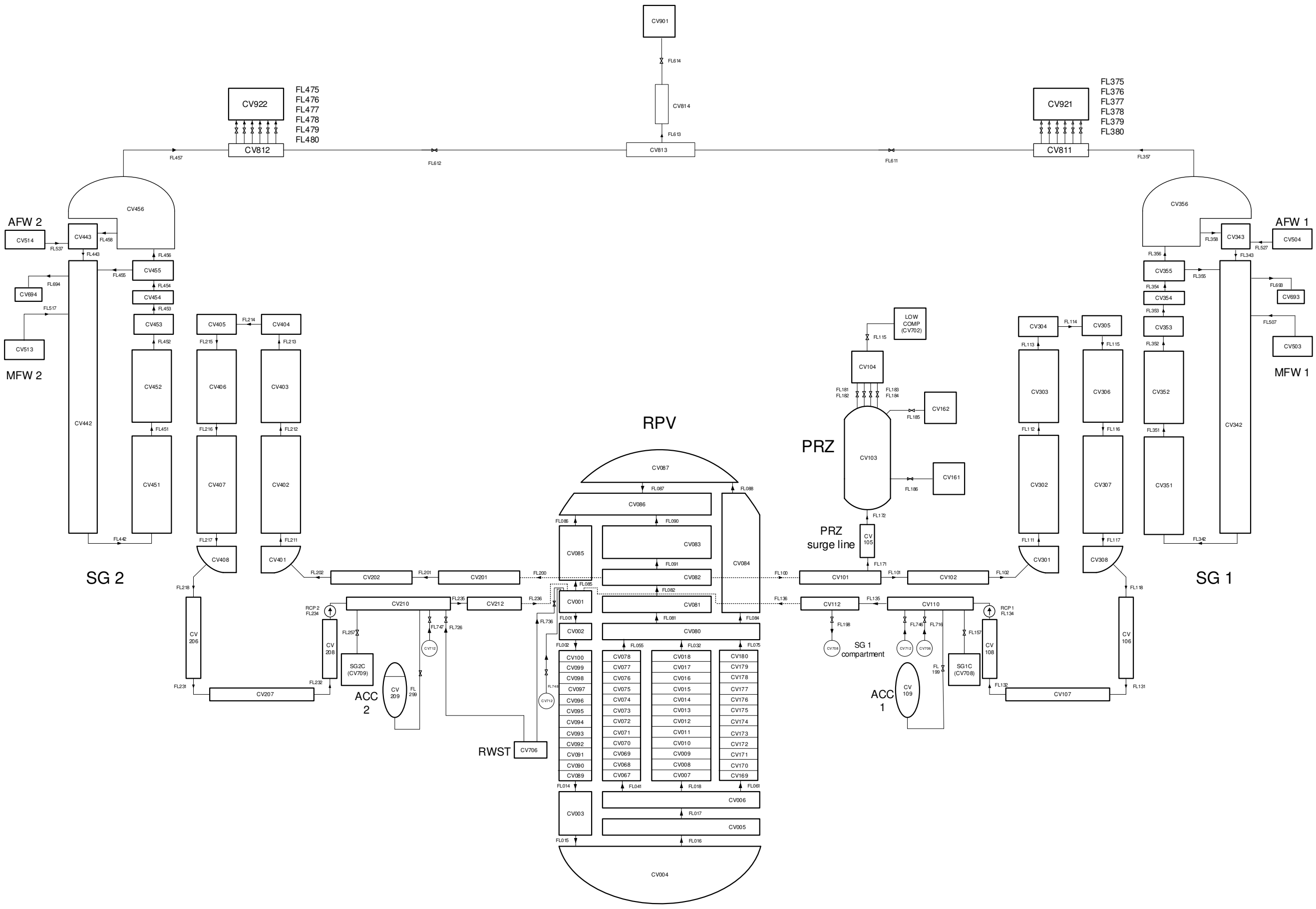

Figure 1: NEK nodalization of primary and secondary system for MELCOR code

Table 1: Results of steady state calculation (1000 s)

Parameter	NEK referent data, cycle 28	MELCOR 1.8.6 1000 s	MELCOR 2.1 1000 s	MELCOR 2.2 1000 s
PRZR pressure (MPa)	15.513	15.517	15.517	15.517
SG 1/2 pressure (MPa)	6.281	6.19/6.16	6.18/6.16	6.18/6.16
Cold leg (1/2) temp.(K)	558.75	559.25/559.04	559.25/559.04	559.25/559.04
Hot leg (1/2) temp. (K)	597.55	597.06/597.06	597.06/597.06	597.06/597.06
Feedwater temp. (K)	492.6	492.6	492.6	492.6
Core mass flow (kg/s)	8899.7	8824.1	8824.0	8822.8
Loop (1/2) mass flow (kg/s)	4697.4	4655.5 /4658.1	4655.5 /4658.1	4655.2 /4658.2
Main FW (1/2) mass flow (kg/s)	544.5	538.9/541.8	538.9/541.8	538.9/541.8
Main steam line (1/2) mass flow (kg/s)	544.5	538.9/541.8	538.9/541.8	538.9/541.8
DC-UH bypass flow	0.346%	0.35%	0.35%	0.35%
Baffle-barrel flow	1.094%	1.094%	1.094%	1.094%
RCCA guide tubes bypass flow	3.32%	3.81% (incl. core cavity flow)	3.81% (incl. core cavity flow)	3.81% (incl. core cavity flow)
Core cavity bypass flow	0.507%	-	-	-
Pressurizer level (%)	55.7	55.8	55.8	55.8
SG NR level (%)	69.3	69.2/69.2	69.2/69.2	69.2/69.2
SG 1/2 sec. mass (t)	47.0	48.2/48.2	48.2/48.2	48.2/48.2
Core power (MW)	1994.0	1994.0	1994.0	1994.0
SG 1/2 power (MW)	1000.0	997.1/1002.6	997.1/1002.6	997.1/1002.6

3 ANALYSIS OF LARGE BREAK LOCA

3.1 Analysis of Large Break LOCA (Unmitigated scenario)

Double ended guillotine break was assumed in cold leg 1 (loop with pressurizer). The accident started with the opening of two valves at the ends of volumes 110 and 112 to SG 1 compartment volume and by closing an artificial valve that connects volumes 110 and 112. Transient is simulated for 10000 seconds. The main events are summarized in Table 2. For each MELCOR version used, the results for discharge coefficient (CD) resulting in the earliest Lower Head Failure (LHF) were given. In Table 3 the results for LHF and the mass of hydrogen produced in MELCOR COR package for all CDs are presented. Following the break opening, cold leg volumes 110 and 112 are disconnected and their both ends are opened to containment. HI-1 containment pressure signal (0.65 s) generates SI signal, that on the other hand actuates reactor trip and turbine trip signal. In the analysis it was assumed that RC pump trip and main feedwater isolation are actuated on reactor trip. Accumulators open early (when pressure drops below 4.93 MPa) in the transient due to fast pressure drop. In the analysis it was conservatively assumed that accumulator in loop 1 spills directly to containment. At the beginning of the transient, core cladding temperature rapidly increases due to loss of inventory in the core. Following the reactor trip and accumulator injection as well as decrease of break flow due to pressure decrease, cladding temperature temporarily decrease (see Figure 2), but start to rise again after accumulators were emptied. RCS coolant is subcooled before the break opening, but when spilling into containment, a part of the coolant flashes to steam at the lower pressure of the containment. Consequently, containment pressure increases rapidly until end of blowdown when primary and containment pressure become equal and release of coolant to containment has stopped (see Figure 3). Since no safety injection was assumed and only a small amount of steam is produced in the core after emptying of accumulators, containment pressure first decreased due to condensation on containment structures and then stabilized at approximately

2.3 bar. After emptying of accumulators, loss of cooling in the core causes further the steep cladding temperature rise. After cladding temperature had exceeded 1100 K, the cladding oxidation accompanied with additional heat and hydrogen production took place. Oxidation of steel components including baffle plates was also taken into account. Fuel melting started approx. 1000 s after start of the transient. Melted material is transported to RPV lower plenum and then to lower head what is accompanied with subsequent failures of lower core support structures. Finally, the LHF occurs and melt is ejected to reactor cavity. Similar values (see Table 3) for the time of LHF for different MELCOR versions and different CDs were obtained (varying between 4083 s for MELCOR 2.1, CD=0.4 and 5130 s for MELCOR 2.2, CD=1.0). Here it is important to note that smaller CD implies slower loss of coolant following the break but also the later opening of accumulators than larger CD. Thus, the conclusion for the most adverse scenario based on CD only is not straightforward. The liquid in the cavity heats up and starts to evaporate following the core melt ejection. Consequently, the containment pressure starts to rise (see Figure 3). Since an unmitigated scenario is assumed (fan coolers and containment spray not available) containment pressure will continue to rise due to evaporation of water in reactor cavity and Molten Corium Concrete Interaction (MCCI). After water in the cavity had evaporated containment pressure increase is somewhat slower but this is not shown here. Finally, much later, if none of the mitigation actions is taken, the Passive Containment Filtered Vent System would open (at 6 bar) to atmosphere in order to limit containment pressure.

Table 2: Time sequence of main events (LB LOCA at t=0 s) – Unmitigated scenario

Event	**MELCOR 1.8.6, CD=0.6**	**MELCOR 2.1, CD=0.4**	**MELCOR 2.2, CD=0.6**	**MELCOR 2.2 (eutectic) CD=1.0**
Reactor trip (on SI signal)	0.65 s	0.65 s	0.65 s	0.65 s
Accumulators (1/2) open	5.6/6.4 s	8.3/8.9 s	5.6/6.4 s	3.0/4.5 s
Accumulators (1/2) empty	22.1/25.2 s	24.9/28.8 s	22.1/24.7 s	19.2/22.1 s
Begin of Zr-H2O reaction	185 s	163 s	120 s	105 s
Begin of UO2 melting	1352 s	1102 s	928 s	716 s
1st failure of lower support structures	971 s	1054 s	678 s	1109 s
Lower head failure (LHF)	4337.3 s	4083.3 s	4532.7 s	4132.7 s
Total hydrogen produced in the core (kg)	260.1	230.7	278.5	253.9

Table 3: LB LOCA: Time of LHF and total mass of hydrogen in COR package

Event	**CD=0.4**	**CD=0.6**	**CD=0.75**	**CD=1.0**
MELCOR 1.8.6				
LHF (s)	4435.4	4337.3	4563.0	4682.7
M_H (kg)	308.8	260.1	262.5	299.2
MELCOR 2.1				
LHF (s)	4083.3	4465.5	4463.1	4427.7
M_H (kg)	230.7	223.9	226.7	231.9
MELCOR 2.2				
LHF (s)	4823.8	4532.7	4942.3	5129.9
M_H (kg)	272.6	278.5	286.9	274.1
MELCOR 2.2 (eutectic)				
LHF (s)	4146.2	4530.1	4297.9	4132.7
M_H (kg)	314.8	322.3	272.9	253.9

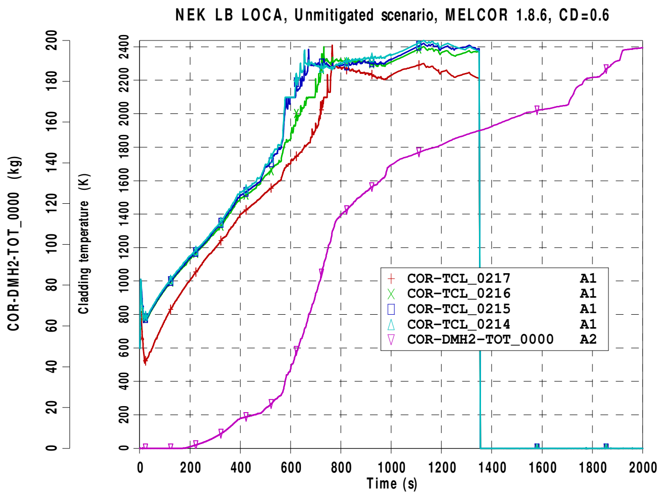

Figure 2: LB LOCA, Unmitigated scenario, MELCOR 1.8.6, CD=0.6, Cladding temperature and mass of hydrogen (core)

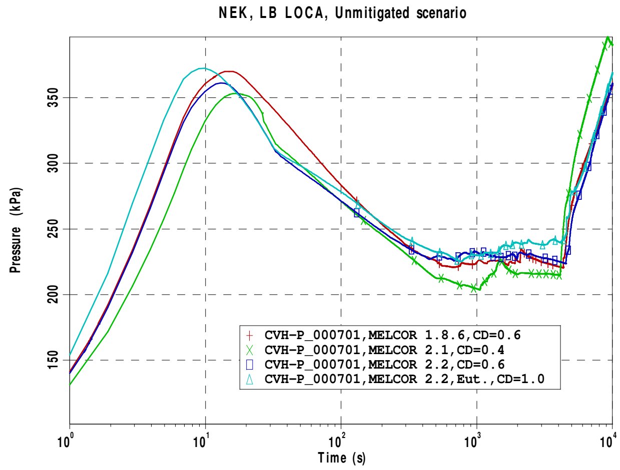

Figure 3: LB LOCA, Unmitigated scenario, Containment pressure

3.2 Analysis of Design Basis Large Break LOCA (DB LOCA)

The same scenario for double ended guillotine break in cold leg 1 as in Unmitigated scenario was assumed. For DB LOCA one train of SI (one HHSI and one LHSI pump were assumed available for injection into RCS with max. delay (30 s) after SI signal. After RWST level had dropped below 38.6% it was assumed that operator switches the suction of LHSI pump (HHSI pump is not used in recirculation) from RWST to containment sump. During recirculation the flow is directed to artificial volume representing the Residual Heat Exchanger (RHR) first, and then to RPV downcomer inlet via two Direct Vessel Injection (DVI) lines. One train of containment fan coolers and containment spray were assumed available. In the analysis it was assumed that according to Severe Accident Management Guidelines (SAMG) the fan coolers and spray are stopped for severe accident conditions (core exit temperature greater than 923 K) and containment pressure less than 2.48 bar.

In MELCOR 2.2 calculation the unrealistically high values for cladding temperature during reflood were obtained for new default values for pool bridging model. In the presented analysis, in MELCOR 2.2 input deck, the sensitivity coefficients for pool bridging parameters were set to default values used in MELCOR 1.8.6 and MELCOR 2.1.

In Table 4 the time sequence of events for CD resulting in either maximum cladding temperature (MELCOR 1.8.6 and MELCOR 2.1) or maximum amount of hydrogen produced

(MELCOR 2.2, CD=0.4) is provided. In Table 5 the maximum cladding temperature and mass of produced hydrogen is presented. Contrary to Unmitigated scenario fuel cladding temperature rise following emptying of accumulators is limited due to continuous SI injection and RPV liquid recovery (see Figure 4). Finally, the refilling of core continued and cladding temperature began to decrease (core reflood). RWST empty signal (RWST level less than 38.6%) was generated about 52 minutes after beginning of the transient for all the cases. Thereafter, the operator starts (with 5 minutes delay) the recirculation phase by switching the suction of LHSI pumps from the RWST to containment sump. While for MELCOR 1.8.6 and MELCOR 2.1 similar results for the maximum cladding temperature as well as temperature behaviour during quench/reflood were obtained, for MELCOR 2.2 a significantly higher maximum cladding temperature and much slower quenching of the core can be observed (see Figure 5). The cladding temperature for MELCOR 2.2 exceeded 1100 K and a small amount of hydrogen was produced (max. 1.973 kg for CD=0.4). Containment pressure behaviour (see Figure 6) did not differ from Unmitigated scenario (see Figure 3) until start of SI (31 s). For DB LOCA it was assumed that relatively early in the transient both containment spray and fan coolers were turned off following the SAMG procedure. Containment pressure, however, did not rise significantly due to effective condensation on containment heat structures. At the end of simulation containment pressure for all three code versions stabilized at about 280 kPa. For all three code versions the results were below 10CFR50.46 criteria, i.e., the maximum cladding temperature was below 1477 K and the amount of generated hydrogen was below 1%.

The observed differences between MELCOR 1.8.6 and MELCOR 2.1 on one side and MELCOR 2.2 for cladding temperature behaviour during quench/reflood need further investigation.

Table 4: Time sequence of main events (DB LOCA at time=0.0)

Event	MELCOR 1.8.6, CD=1.0	MELCOR 2.1, CD=0.75	MELCOR 2.2, CD=0.4
Reactor trip (on SI signal)	0.65 s	0.65 s	0.65 s
Accumulators (1/2) open	3.0/4.6 s	4.3/5.5 s	8.3/8.8 s
Accumulators (1/2) empty	19.3/22.4 s	20.9/23.7 s	24.8/28.3 s
SI start	31 s	31 s	31 s
Start of fan coolers (35 s delay)	35.7 s	35.8 s	36.0 s
Start of containment spray (55 s delay)	57.7 s	58.1 s	60.0 s
Stop of containment spray	236.7 s	166.8 s	119.9 s
Stop of fan coolers (SAMG procedure)	524.7	580.5 s	232.1 s
Start of recirculation from sump	3416.7 s	3438.8 s	3456.7 s
Max. fuel cladding temperature (K)	1083 K (300 s)	1094 K (272 s)	1168 K (465 s)

Table 5: Maximum cladding temperature and mass of hydrogen in the core (DB LOCA)

Event	CD=0.4	CD=0.6	CD=0.75	CD=1.0
MELCOR 1.8.6				
Max. Tcl, M_H	1067 K, 0.0 kg	1082 K, 0.0 kg	1082 K, 0.0 kg	1083 K, 0.0 kg
MELCOR 2.1				
Max. Tcl, M_H	1071 K, 0.0 kg	1080 K, 0.0 kg	1094 K, 0.0 kg	1077 K, 0.0 kg
MELCOR 2.2				
Max. Tcl, M_H	1168 K, 1.973 kg	1164 K, 1.391 kg	1158 K, 1.178 kg	1171 K, 1.945 kg

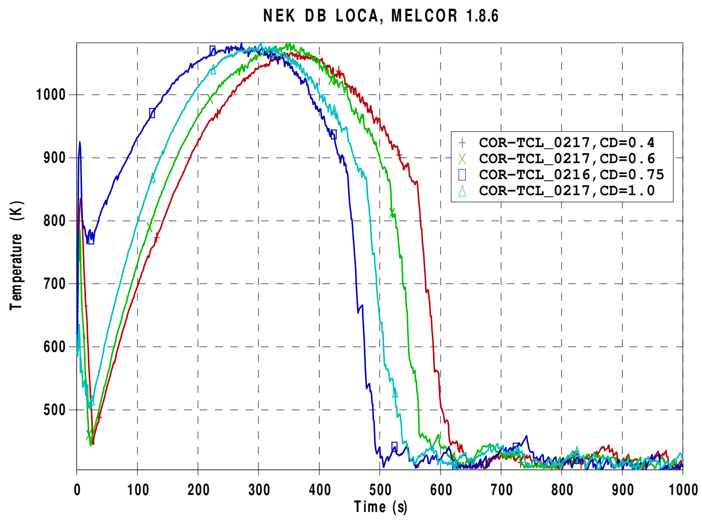

Figure 4: DB LOCA, MELCOR 1.8.6, Cladding temperature

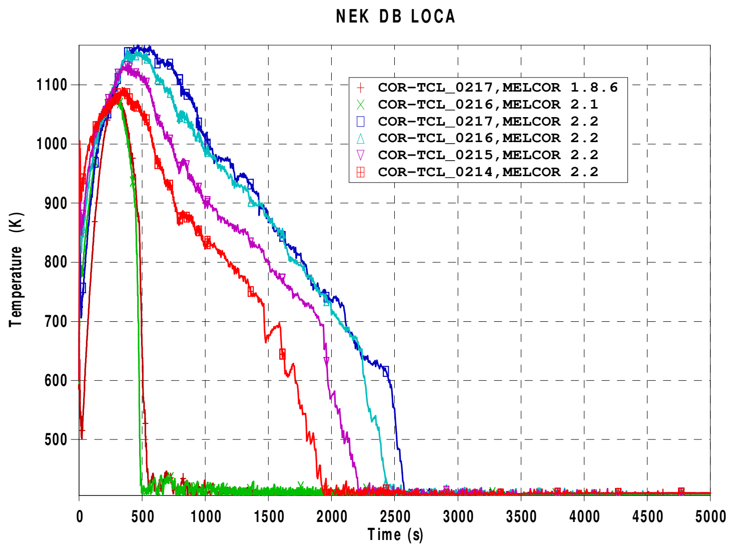

Figure 5: DB LOCA, Cladding temperature (MELCOR 1.8.6-CD=1.0, MELCOR 2.1-CD=0.75, MELCOR 2.2-CD=0.4)

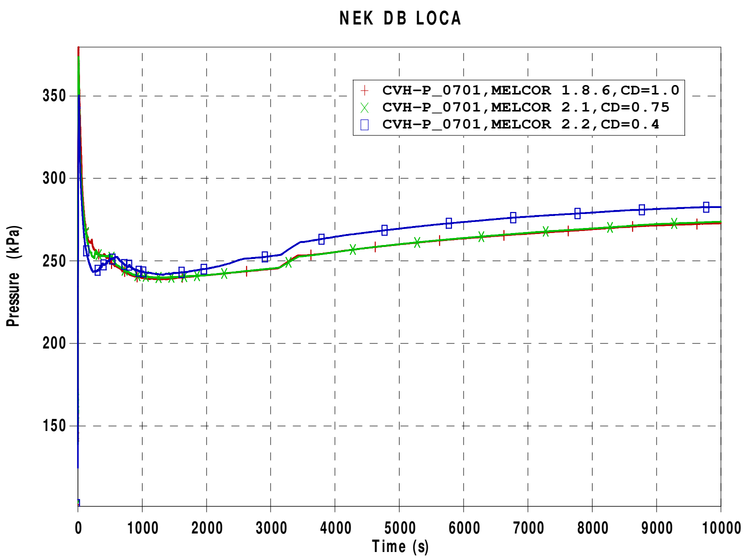

Figure 6: DB LOCA, Containment pressure

4 CONCLUSION

In the paper a part of work related to developing and verification of MELCOR input deck (MELCOR 1.8.6 as well as advanced MELCOR code versions; MELCOR 2.1 and MELCOR 2.2) for NPP Krško is presented. Following conclusions can be drawn from presented analyses. The steady state differences between MELCOR code versions for relevant physical parameters can be neglected. The largest differences between MELCOR results for steady state and referent NEK data at 100% power were obtained for secondary pressure (1.9%) and feedwater/steam mass flow rate (1.02%). The results for LB LOCA Unmitigated scenario were aimed to investigate only short term effects (time of lower head failure (LHF) and amount of hydrogen generated in COR package). Similar results for the time of LHF were obtained for different MELCOR versions (varying between 4083 s and 5130 s). In general, MELCOR 2.2 with Eutectic model activated resulted in a smaller time of LHF than MELCOR 2.2 without model activated. The largest difference is for CD=1.0 (4133 s for Eutectic model and 5130 s for the base model). The comparison of the results for different break discharge coefficients (CDs) has shown that due to opposite effects of CD on the break flow and the start of accumulator injection the conclusion on most adverse case with regard to time of LHF cannot be drawn. The analysis of DB LOCA with one train of ESF available has shown that for all three code versions the results were below 10CFR50.46 criteria, i.e., the maximum cladding temperature was below 1477 K and the amount of generated hydrogen was below 1%. Whereas the maximum cladding temperature for MELCOR 1.8.6 and MELCOR 2.1 were below the threshold for start of cladding-water/steam interaction (1100 K) and hydrogen was not generated, for MELCOR 2.2 the maximum cladding temperature was higher (maximum difference 94 K) and a small amount of hydrogen was generated (maximum 1.973 kg). When compared with MELCOR 1.8.6 and MELCOR 2.1, for MELCOR 2.2 in addition to higher maximum values also much slower cladding temperature decrease during quench/reflood was obtained which needs further investigation.

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