Journal of Energy
VOLUME 68 Number 2-3 | 2019 | Special Issue
journal homepage: http://journalofenergy.com/

NPP Krško 3 inch Cold Leg Break LOCA Calculation using RELAP5/MOD 3.3 and MELCOR 1.8.6 Codes

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ABSTRACT

NPP Krško input deck developed at Faculty of Electrical Engineering and Computing (FER) Zagreb, for severe accident code MELCOR 1.8.6 is currently being tested. MELCOR is primarily used for the analyses of severe accidents including in-vessel and ex-vessel core melt progression as well as containment response under severe accident conditions. Accurate modelling of the plant thermal-hydraulic behaviour as well as engineering safety features, e.g., Emergency Core Cooling System, Auxiliary feedwater system and various containment systems (e.g., Passive Autocatalytic Recombiners, Fan Coolers and Containment spray) is necessary to correctly predict the plant response and operator actions. For MELCOR input data verification, the comparison of the results for small break (3 inch) cold leg Loss of Coolant Accident (LOCA) for NPP Krško using MELCOR 1.8.6 and RELAP5/MOD 3.3 was performed. A detailed RELAP5/MOD 3.3 model for NPP Krško has been developed at FER and it has been extensively used for accident and transient analyses. The RELAP5 model has been upgraded and improved along with the plant modernization in the year 2000. and after more recent plant modifications. The results of the steady state calculation (first 1000 seconds) for both MELCOR and RELAP5 were assessed against the referent plant data. In order to test all thermal-hydraulic aspects of developed MELCOR 1.8.6 model the accident was analysed, and comparison to the existing RELAP5 model was performed, with all engineering safety features available. After initial fast pressure drop and accumulator injection for both codes stable conditions were established with heat removal through the break and core inventory maintained by safety injection. Transient was simulated for 10000 seconds and overall good agreement between results obtained with both codes was found.

Keywords: *MELCOR, RELAP5, code comparison, input data verification, small break Loss of Coolant Accident*

1 INTRODUCTION

Calculation models for NPP Krško for computer codes RELAP5/MOD 3.3 and MELCOR are being developed at FER. Usually, these two codes are used for different purposes; RELAP5/MOD 3.3, ref. [1], is used as a best-estimate calculation tool for analysis of postulated accidents, whereas MELCOR, ref. [2] and [3] is used to model progression of severe accidents in light water reactors. After Fukushima accident in 2011. development of strategies for management of severe accidents as well as Beyond Design Basis Accidents (BDBAs) has gained awareness worldwide. The Slovenian Nuclear Safety Administration (SNSA) has issued a request for Safety Upgrade Program (SUP) for NPP Krško in relation to Plant Life Extension as well as new requirements regarding Design Extension Conditions (DEC – the conditions that are more challenging/severe than original conditions used in plant design) and BDBA. The program consists in a reassessment of Severe Accidents strategy and implementation of necessary safety improvements. As a part of this

Vesna Benčik, Davor Grgić, Siniša Šadek, Štefica Vlahović, NPP Krško 3 inch Cold Leg Break LOCA Calculation using RELAP5/MOD 3.3 and MELCOR 1.8.6 Codes, Journal of Energy, vol. 68 Number 2–3, Special Issue (2019), p.126–139
https://doi.org/10.37798/2019682-3197

program, in 2013. the electrical hydrogen recombiners were replaced by Passive Autocatalytic Recombiners (PARs) and the Passive Containment Filtered Vent (PCFV) system were installed at NEK. During the upcoming second phase of the program RCS and containment alternate long term cooling will be installed. In case of event (BDBA) Alternate Residual Heat Removal Pumps (ARHR) will be used to either supply the water for RCS safety injection or for containment spray. ARHR pumps can take the suction either from the Refueling Water Storage Tank (RWST) or from RCS hot/cold legs or from containment sump. Water taken from sump will be cooled in existing RHR or in Mobile Heat Exchangers (MHX).

At FER a detailed RELAP5/MOD 3.3 model for NPP Krško is being developed, ref. [4] and [5]. The model is being constantly updated to reflect changes after plant modernization and modifications, e.g., Steam Generators (SG) replacement and power uprate in 2000., Resistance Temperature Detector Bypass Elimination (RTDBE) in 2013. and Up-Flow Conversion (UFC) in 2015. RELAP5 model contains detailed nodalization of NPP Krško Safety Injection (SI) system, Main feedwater and Auxiliary feedwater (AFW) system as well as models of protection and control systems including the detailed models of automatic control rod, pressurizer pressure and level control, steam generator level control and steam dump control with realistic steam dump valves.

NEK data base that has been used for development of the RELAP5 model is being used for development of MELCOR model for NPP Krško, ref. [6] and [7], as well. Recently, MELCOR 1.8.6 was used to analyse Station Blackout (SBO) accident at NEK, ref. [8] and [9]. Transient scenario assumed that Engineering Safety Systems (ESF); e.g., safety injection, auxiliary feedwater system, containment fan coolers and containment spray system were not available. The calculation model includes the latest plant safety upgrade with addition of Passive Autocatalytic Recombiners (PAR) and the Passive Containment Filter Venting (PCFV) system. The results with MELCOR 1.8.6 were compared with the MAAP 4.0.7 calculation of the same transient scenario. The SBO sequence included core degradation, reactor vessel failure, release of corium to containment, Molten Core Concrete Interaction (MCCI), production of hydrogen and containment pressurization. The PCFV system provided controlled release of containment inventory to atmosphere thus maintaining the containment pressure at design limits whereas the PARs have reduced hydrogen concentration by controlling the chemical reaction between hydrogen and oxygen.

In this paper the part of our work at developing and verification of MELCOR input deck for NPP Krško is presented. In order to model the plant behaviour under non-severe accident conditions as well as planned mitigation actions, MELCOR input deck has been updated with realistic models of plant safety systems. For verification purposes, a Small Break LOCA (SB LOCA) consisting in a 3 inch break in cold leg 1 (loop with pressurizer) was analysed. In the analysis it was assumed that all the Engineering Safety Features are available and operating. The results of both steady state and transient calculation were assessed against RELAP5/MOD 3.3 analysis for the same transient scenario.

2 CALCULATIONAL MODEL FOR NPP KRŠKO

The schemes of NPP Krško nodalization for RELAP5/MOD 3.3 and MELCOR 1.8.6 are shown in Figure 1 and Figure 2, respectively. Both nodalizations have been updated according to the recent plant modifications; i.e., RTDBE (Resistance Temperature Detector Bypass Elimination) in 2013. and UFC (Up Flow Conversion) in 2015. The UFC modification was performed in order to minimize the baffle jetting across the baffle-barrel bypass and the core. The modification consisted in altering the reactor vessel internals in such way that the coolant downflow path in the baffle-barrel region was converted to an upflow path. The RELAP5 nodalization consists of 506 thermal-hydraulic volumes, 543 junctions, 383 heat structures with 2127 mesh points, 732 control variables and 197 variable and 221 logical trips.

MELCOR 1.8.6 nodalization consists of 123 thermal-hydraulic control volumes, 174 flow paths and 100 heat structures. There are 189 real valued and 91 logical valued control functions aimed to model the artificial steady state control as well as protection and ESF (Engineered Safety System) behaviour, e.g., Auxiliary Feedwater, Safety Injection, Containment fan coolers and Containment spray control. So far, MELCOR 1.8.6 model does not contain realistic models of plant control systems (pressurizer pressure and level control, SG level control, automatic rod control system and steam dump).

Reactor pressure vessel (RPV) is modelled with 40 control volumes. The lower plenum is represented with 3 CVs, the downcomer with 5 CVs, the upper plenum with 4 CVs and the upper head with 2 CVs. Reactor core is represented with 12 control volumes (CV 007-018), as well as the baffle-barrel region (CV 067-078). The guide tubes bypass is represented with CV 079.

Reactor core and lower plenum for MELCOR COR package are represented with 7 radial rings, 12 axial levels in reactor core, 2 axial levels in lower plenum and 10 axial segments in non-cylindrical part of lower head, respectively. Five radial rings are used to represent the active core, one ring for the region between the baffle and the barrel, and one additional ring in the lower plenum as requested by the code. The lower head is represented with 10 radial rings for better prediction of the RPV wall temperature which is used to calculate the RPV rupture.

The NEK containment model for MELCOR code is based on the NPP Krško containment nodalization notebook, ref. [10] which contains detailed calculations of containment volumes and heat structures' dimensions. Containment nodalization is shown in Figure 3. The containment building is represented with 12 control volumes. There are four additional volumes:

1. CV 706 – refuelling water storage tank
2. CV 707 – connection between the upper compartment and the environment, added to control opening/closing of the PCFV valve.
3. CV 716 – RHR heat exchanger volume
4. CV 900 (environment) – a large volume (10^8 m^3) at constant temperature (307 K) and pressure (10^5 Pa)

Containment control volumes are connected by 30 flow paths. Heat sinks representing outside containment wall, internal walls, floors, polar crane, fan coolers, platforms and other miscellaneous stainless and carbon steel structures are modelled with 20 heat structures.

During steady state, both in RELAP5 and MELCOR, control systems for artificial steady state maintain the pressurizer pressure as well as pressurizer and SG level at their setpoint values. On the secondary side, turbine valve opening is controlled in order to maintain the RCS average temperature at its setpoint value (578.15 K). Steady state was simulated for 1000 seconds for both RELAP5 and MELCOR 1.8.6. The results for relevant physical parameters are summarized in Table 1. A very good agreement for both RELAP5 and MELCOR 1.8.6 calculation with NEK referent data were obtained.

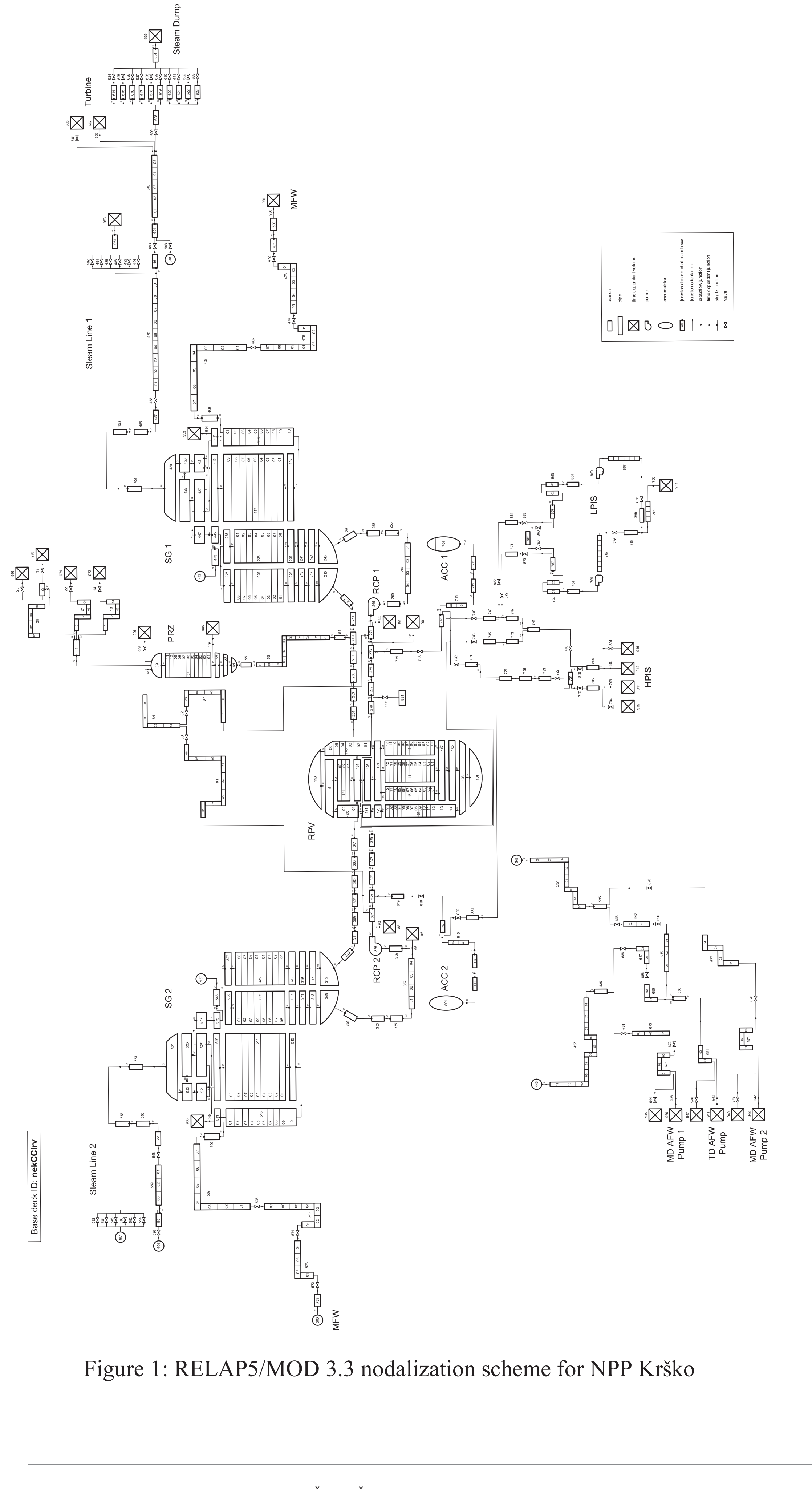

Figure 1: RELAP5/MOD 3.3 nodalization scheme for NPP Krško

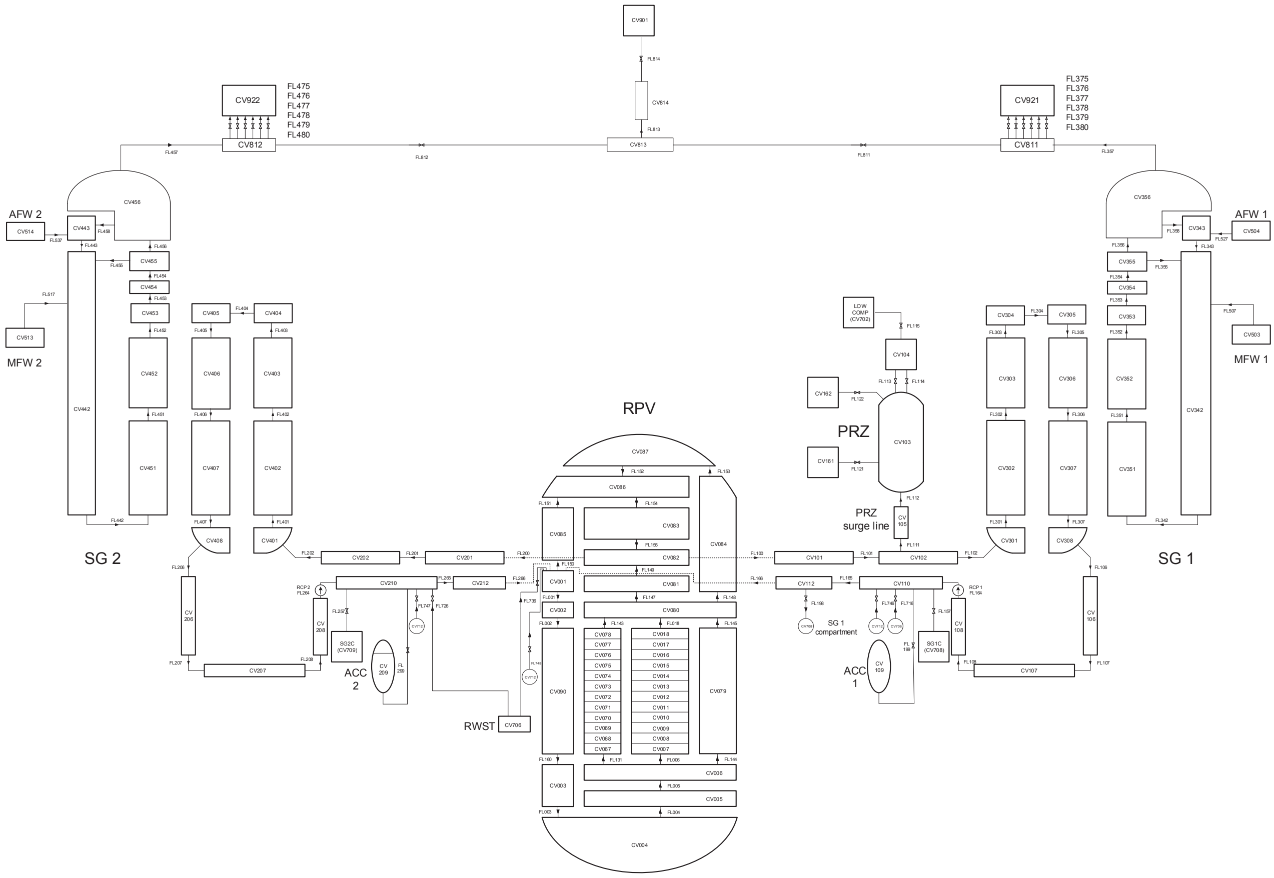

Figure 2: MELCOR 1.8.6 nodalization scheme for NPP Krško

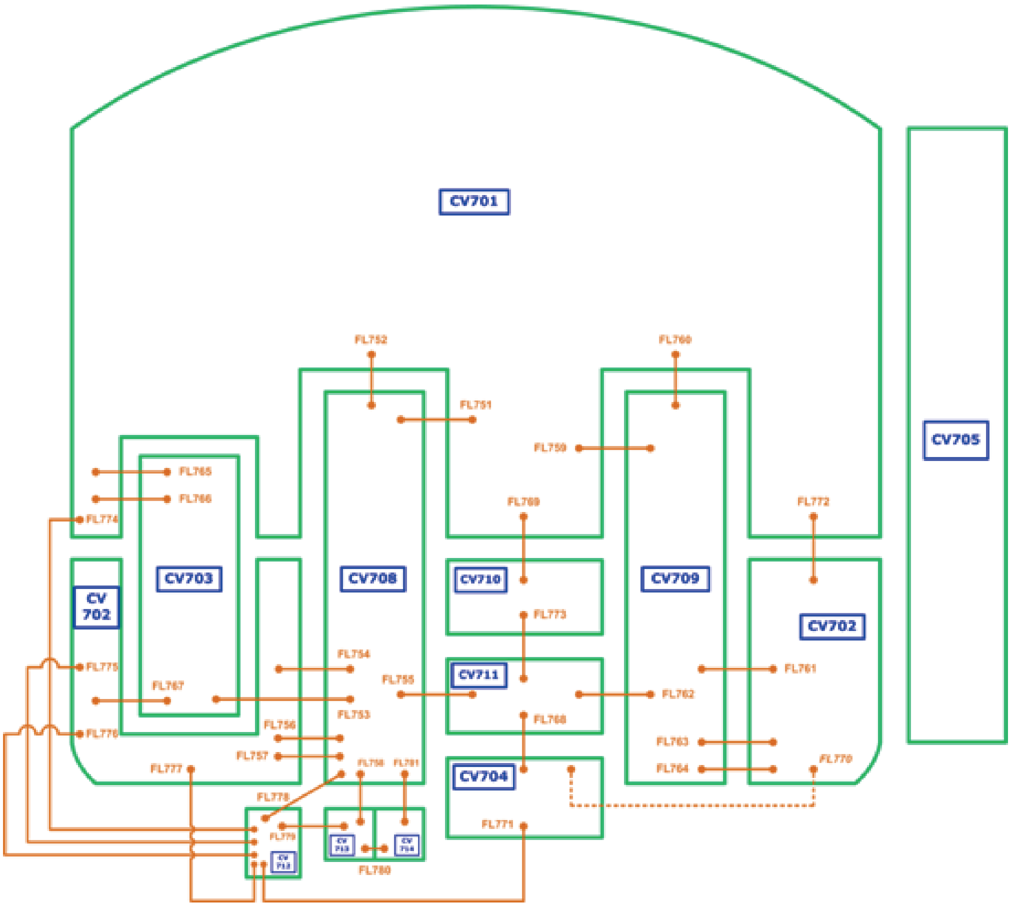

Figure 3: MELCOR 1.8.6 nodalization scheme for NPP Krško containment

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

Parameter	**NEK referent data, cycle 28**	**RELAP5/MOD 3.3**	**MELCOR 1.8.6**
1. Pressure (MPa)			
Pressurizer	15.513	15.513	15.517
Steam generator	6.281	6.275/6.286	6.19/6.16
Accumulator	4.93	4.93	4.93
2. Fluid Temperature (K)			
Cold leg	558.75	559.49/559.25	559.36/559.15
Hot leg	597.55	596.82/596.82	596.94/596.94
Feedwater	492.6	492.7	492.6
3. Mass Flow (kg/s)			
Core	8899.7	8925.3	8876.4
Cold leg	4697.4	4711.7/4710.7	4683.7 /4686.2
Main feedwater	544.5	540.9/544.7	538.9/541.8
Main steam line	544.5	540.9/544.7	538.9/541.8
DC-UP bypass	0.0%	0.0%	0.0%
DC-UH bypass	0.346%	0.371%	0.346%
Baffle-barrel flow	1.0939%	1.094%%	1.094%
RCCA guide tubes	3.32%	3.81% (includes core cavity flow)	3.83% (includes core cavity flow)
Core cavity (0.5067%)	0.5067%	-	-
4. Liquid level (%)			
Pressurizer	55.7	55.8	55.8
Steam generator narrow range	69.3	69.3/69.3	69.2/69.2
5. Fluid Mass (t)			
Primary system	-	131.3	131.8
Steam generator (secondary)	47.0	49.1/48.9	48.08/48.07
6. Power (MW)			
Core	1994.0	1994.0	1994.0
Steam generator	1000.0	995.9/1003.0	997.1/1002.6

3 ANALYSIS OF 3 INCH COLD BREAK LOCA

The analysed accident is the 3 inch Loss of Coolant Accident (LOCA) in the cold leg 1 (loop with pressurizer. Transient is actuated after 1000 seconds steady state calculation. Small break LOCA is initiated in cold leg volume 275 by opening the valve 992 (RELAP5) to containment (volume 991). In MELCOR, valve simulating the break is opened in FL 198 connecting cold leg volume 112 and SG 1 compartment volume 708. Main events for both RELAP5 and MELCOR calculations are summarized in Table 2. Reactor trip is initiated on low pressurizer pressure signal. Thereupon, turbine trip and main steam isolation valve (MSIV) closure are actuated. Until trip, turbine valve opening in both RELAP5 and MELCOR is maintained at the value that would result in steady state turbine flow. In the analysis it was assumed that pressurizer pressure and level as well as SG level control are not active after transient begin. Under realistic conditions main feedwater is usually isolated on reactor scram & low-1 RCS average temperature. Here, trip of main FW as well as trip of both reactor coolant pumps are actuated on reactor trip. In the analysis all ESF systems are assumed available with minimum delay. Thus, Safety injection pumps are available with 5 seconds and auxiliary feedwater with 60 seconds delay. In MELCOR safety injection pumps initially take suction from Refueling Water Storage Tank (RWST). In the analysis it was assumed that upon the signal: RWST empty (RWST level equal to 38.6%) operator stops the injection from RWST and switches to recirculation mode with LPIS pumps only, taking suction from containment sump (CV 712). Before it is injected in reactor vessel, pumped water is cooled in the Residual Heat Removal (RHR) heat exchangers. Assumed delay for operator action (stopping the suction from RWST and realigning to containment sump) is 5 minutes. Water level in containment sump has to be monitored in order to assure the required Net Pump Suction Head (NPSH) of LPIS pumps. In RELAP5 calculation an uninterrupted supply from RWST to HPIS and LPIS pumps is assumed.

Following the break opening, Figure 4 RCS rapidly depressurizes, Figure 6 and its inventory decreases. Reactor trip is actuated on low pressurizer pressure (12.995 MPa) at 12.8 s for RELAP5 and at 14.5 s for MELCOR code, respectively. Following actions are performed following reactor trip: turbine trip, MSIV isolation, trip of both RC pumps and main feedwater trip. Auxiliary feedwater will be enabled 60 seconds after trip of main feedwater pumps. Heat produced in the core is primarily removed through the break although in the first phase of the transient heat is also removed in steam generators thus coupling primary and secondary pressure during the first 600 seconds, Figure 6. However, along with the RCS inventory depletion heat transfer in steam generators ceases and the primary pressure decouples from the secondary pressure and begins to decrease more rapidly. At the very beginning of the transient, SG safety valves (SG relief valves are assumed unavailable) open for a short time after turbine trip since the steam dump was assumed unavailable. As a consequence, steam generator mass slightly decreases since the main feedwater is isolated along with reactor trip, Figure 11. Auxiliary feedwater is actuated 60 seconds after main feedwater isolation (72.8 s in RELAP5 and 74.5 s in MELCOR). It is aimed to maintain SG narrow range level in the range (60, 70 %). After decoupling the primary and secondary pressure secondary pressure is affected by auxiliary feedwater injection only in a way that its decrease is stopped first after terminating the auxiliary feedwater flow.

Accumulators open about 11 minutes after transient begin (at 655 s in RELAP5 and at 649 s in MELCOR) and their inventory is injected into RCS approx. for the next 20 minutes. Safety injection signal is initiated on low-2 pressurizer pressure (12.27 MPa) signal in both RELAP5 (17.4 s) and in MELCOR (18.8 s). Safety injection with its full capacity (two High head – HPIS and two Low head – LPIS Safety Injection pumps) is enabled with minimum delay (5 s), Figure 8. In MELCOR, water source for safety injection is Refueling Water Storage Tank (RWST) until RWST empty signal (RWST level less than 38.6%) is generated (at 5391 seconds). Thereafter, the operator starts (with 5 minutes delay) the recirculation phase by switching the suction of LPIS pumps from the RWST to containment sump. After 2200 s the average break flow in MELCOR becomes larger than in RELAP5. Consequently, the primary pressure continues to decrease in MELCOR, whereas in RELAP5 primary pressure slightly increases. This results in a larger amount of injected SI flow in MELCOR and in lower cold leg temperature than in RELAP5, Figure 6, Figure 8 and Figure 10. Accumulator flow in MELCOR is also considerably larger than in RELAP5, Figure 8 and the accumulators have emptied earlier than in RELAP5, as well. After terminating the injection from RWST and by starting the recirculation from containment sump using LPIS pumps only, cold leg temperature in MELCOR increases to a new higher average value. Water from the sump is cooled in RHR heat exchangers before it is injected into RCS, but its temperature is still higher than the RWST temperature. In RELAP5 an oscillatory behaviour of safety injection flow was obtained after approx. 7000 seconds. This is due to the fact that in RELAP5 HPIS pumps are in operation throughout the simulation while the sufficient cooling can be achieved with LPIS pumps only. Oscillations of safety injection flow have caused the oscillations of other parameters, e.g., break flow, RCS temperature and pressure as well as fuel cladding temperature.

In a long term, stable conditions with break flow equal to safety injection flow as well as stable average hot and cold leg temperature for both RELAP5 and MELCOR have been established, Figure 4, Figure 8, Figure 9 and Figure 10. Core dry-out (max. cladding temperature=823 K) occurred in MELCOR during a short period, Figure 12, but fuel cladding oxidation did not occur. Containment pressure increases following the break opening, Figure 7. In MELCOR, containment pressure is being reduced due to heat removal by fan coolers (1 train available, 35 sec delay). In RELAP5 the simple one-volume containment model is used. Despite of the lack of ESF systems in containment (fan coolers and containment spray) containment pressure in RELAP5 is reduced in the long term due to condensation on containment inner surfaces and convective heat transfer loss from containment outer surface to atmosphere.

Table 2: Time sequence of the main events (3 inch cold leg 1 LOCA)

Event	RELAP5/MOD 3.3	MELCOR 1.8.6
Transient begin	0 s	0 s
Reactor trip	12.8 s (on low PRZ pressure)	14.5 s (on low PRZ pressure)
Turbine trip, MSIV isolation, Main feedwater isolation, RCP trip	12.8 s (on reactor trip signal)	14.5 s (on reactor trip signal)
Safety injection signal	17.4 s (on low-2 PRZ pressure)	18.8 s (on low-2 PRZ pressure)
Safety injection enabled	22.4 s (5 s delay)	23.8 s (5 s delay)
AFW enabled	72.8 s (60 s delay)	74.5 s (60 s delay)
Start of containment fan coolers	-	75.0 s (35 s delay)
Start of accumulator injection	655.0 s	649.0 s
Accumulators empty	1990.0 s	1670.0 s
RWST empty	-	5391.0 s
Start of recirculation from sump	-	5991.0 s (5 minutes delay)
Maximum fuel cladding temperature	610 K (steady state value)	823 K (430 s)
End of transient	10000 s	10000 s

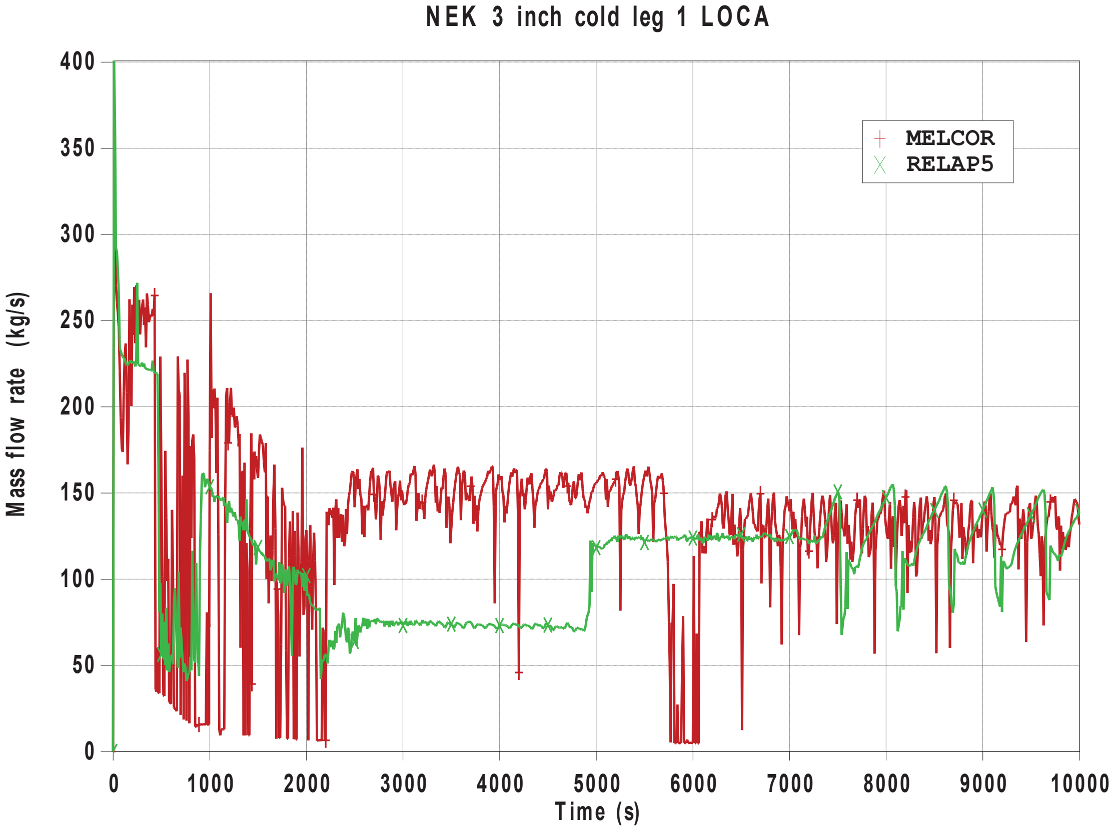

Figure 4: 3 inch cold leg 1 LOCA: Break mass flow rate

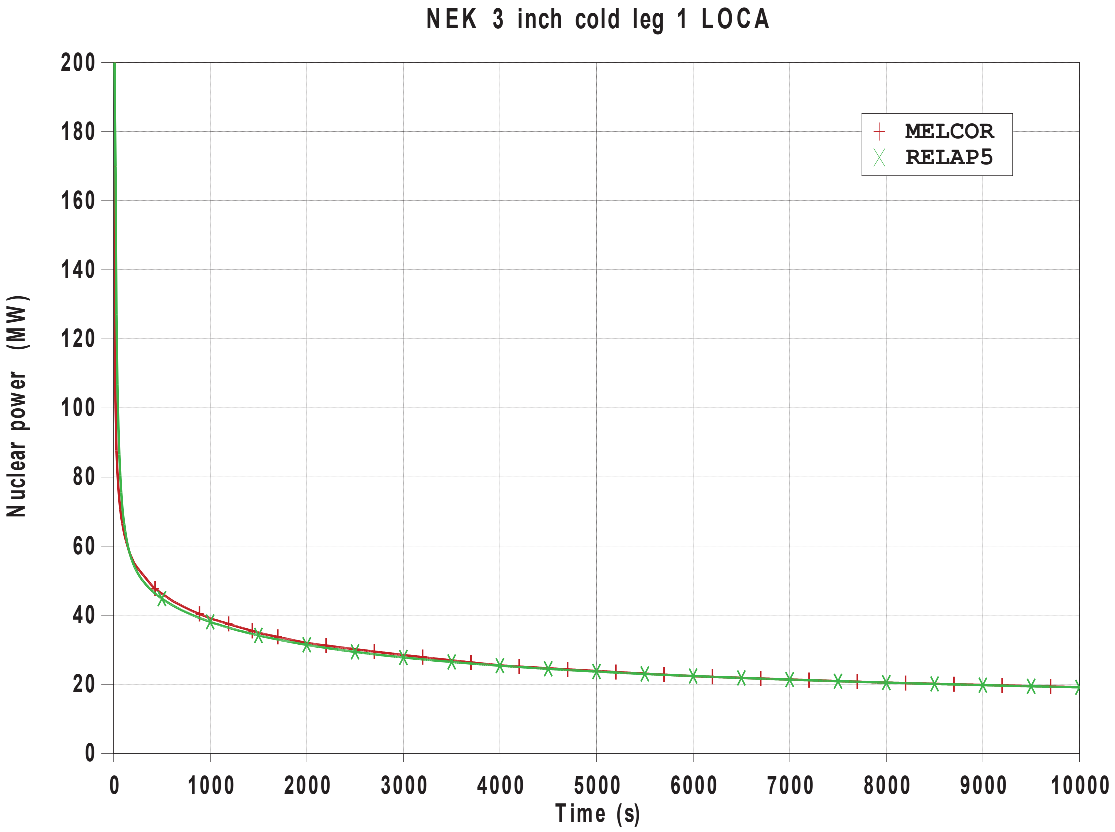

Figure 5: 3 inch cold leg 1 LOCA: Nuclear power (0-200 MW)

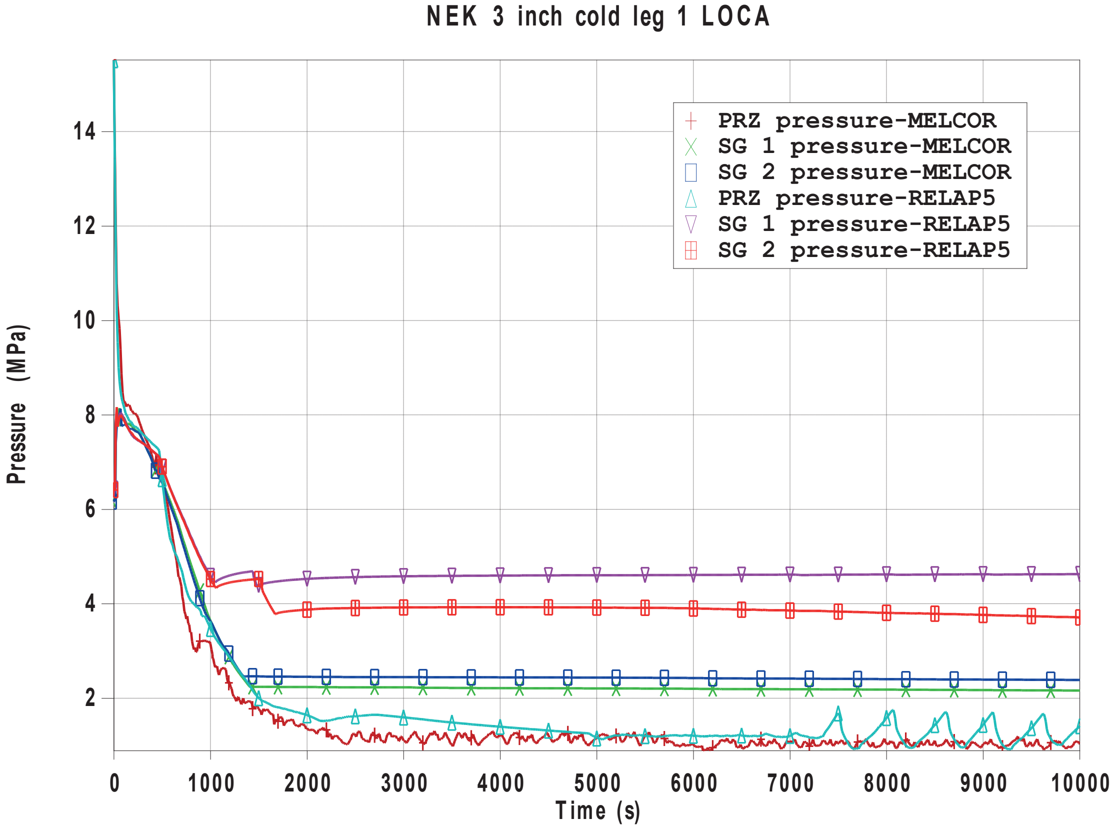

Figure 6: 3 inch cold leg 1 LOCA: Pressurizer and SG pressure

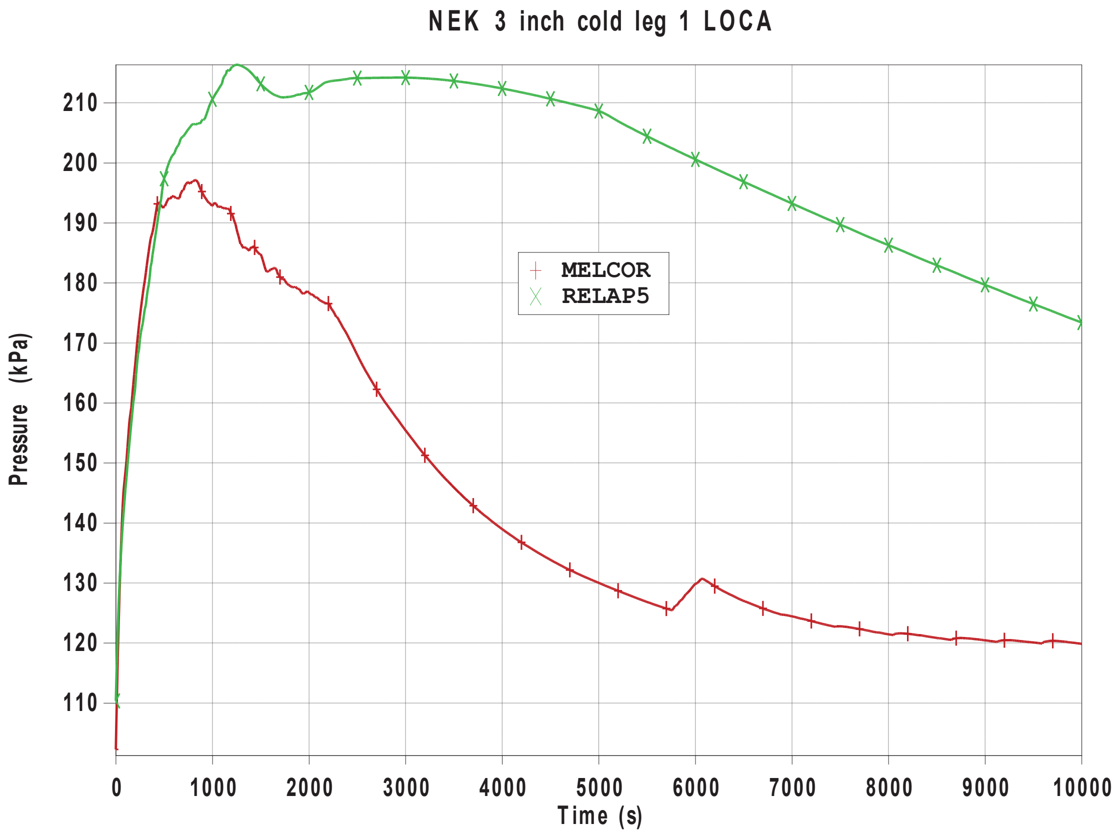

Figure 7: 3 inch cold leg 1 LOCA: Containment pressure

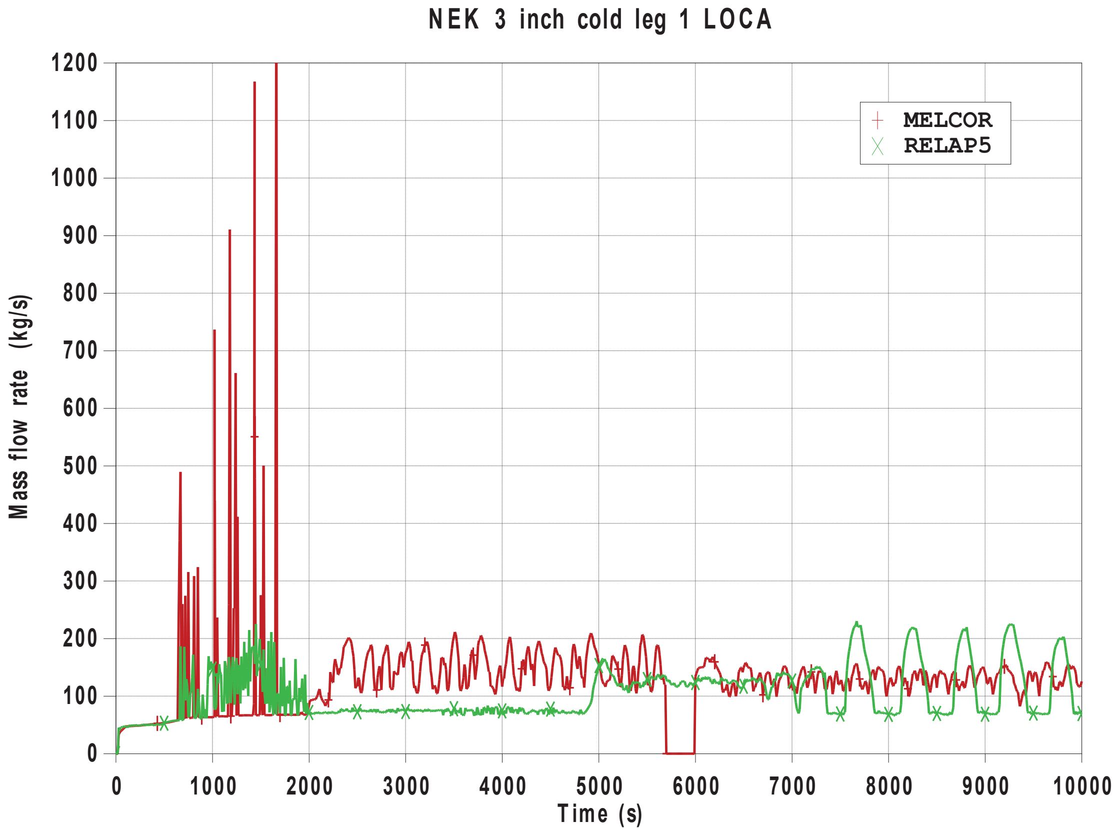

Figure 8: 3 inch cold leg 1 LOCA: ECCS flow

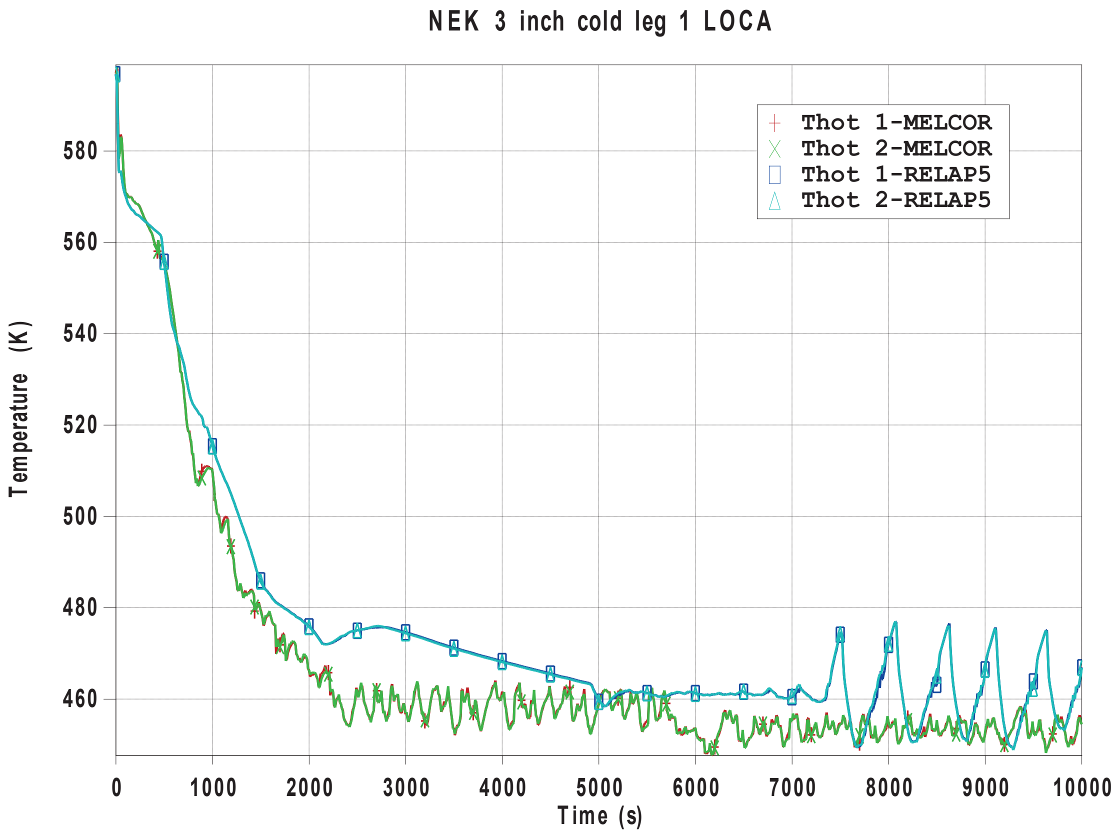

Figure 9: 3 inch cold leg 1 LOCA: RCS hot leg temperature

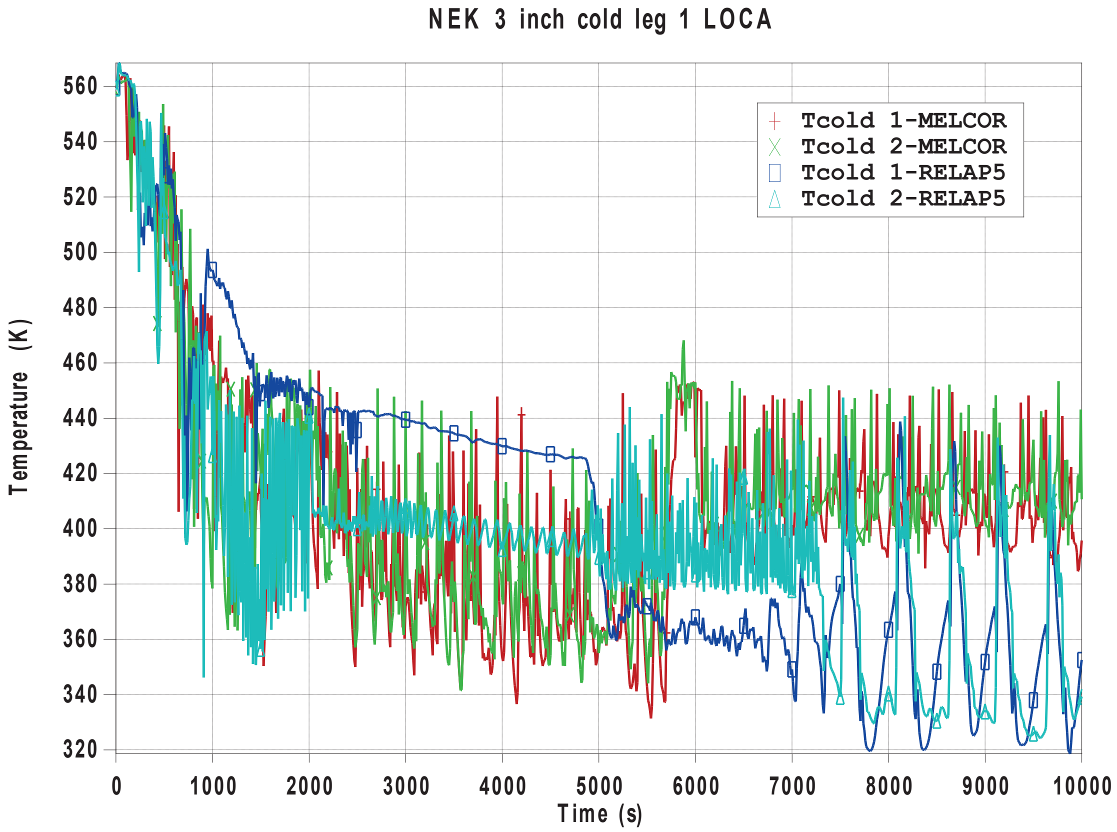

Figure 10: 3 inch cold leg 1 LOCA: RCS cold leg temperature

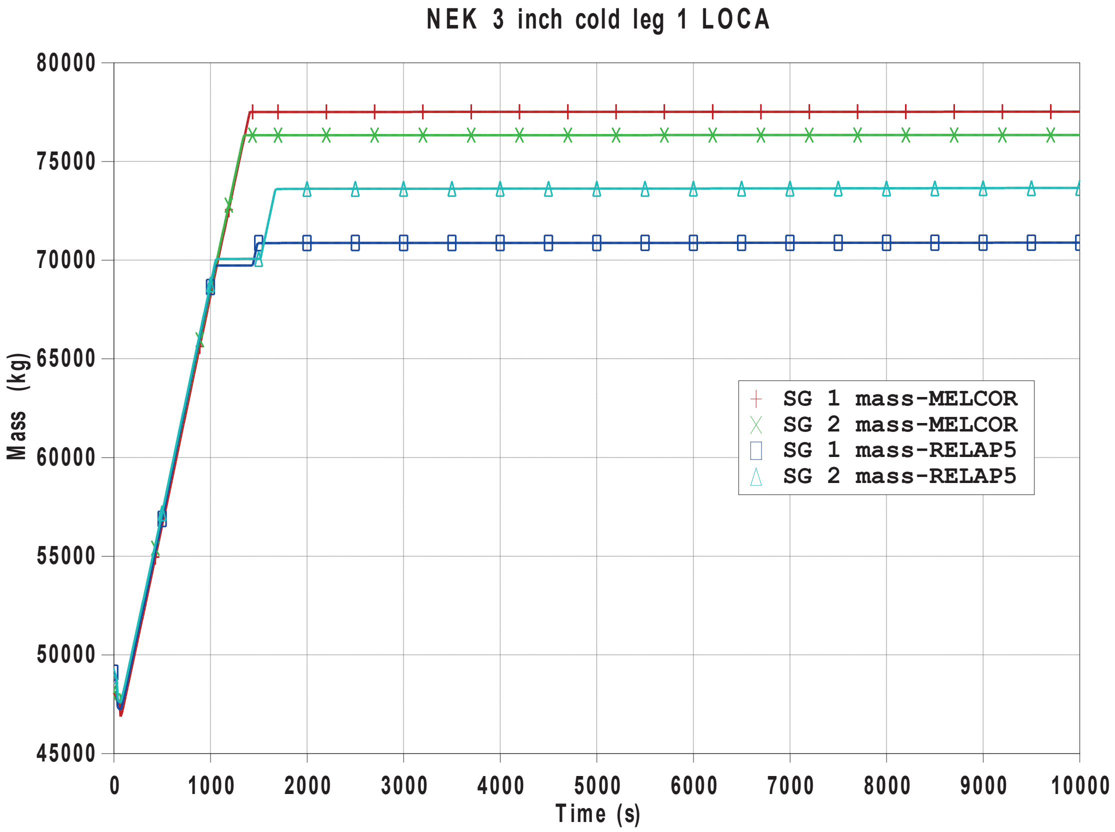

Figure 11: 3 inch cold leg 1 LOCA: SG mass

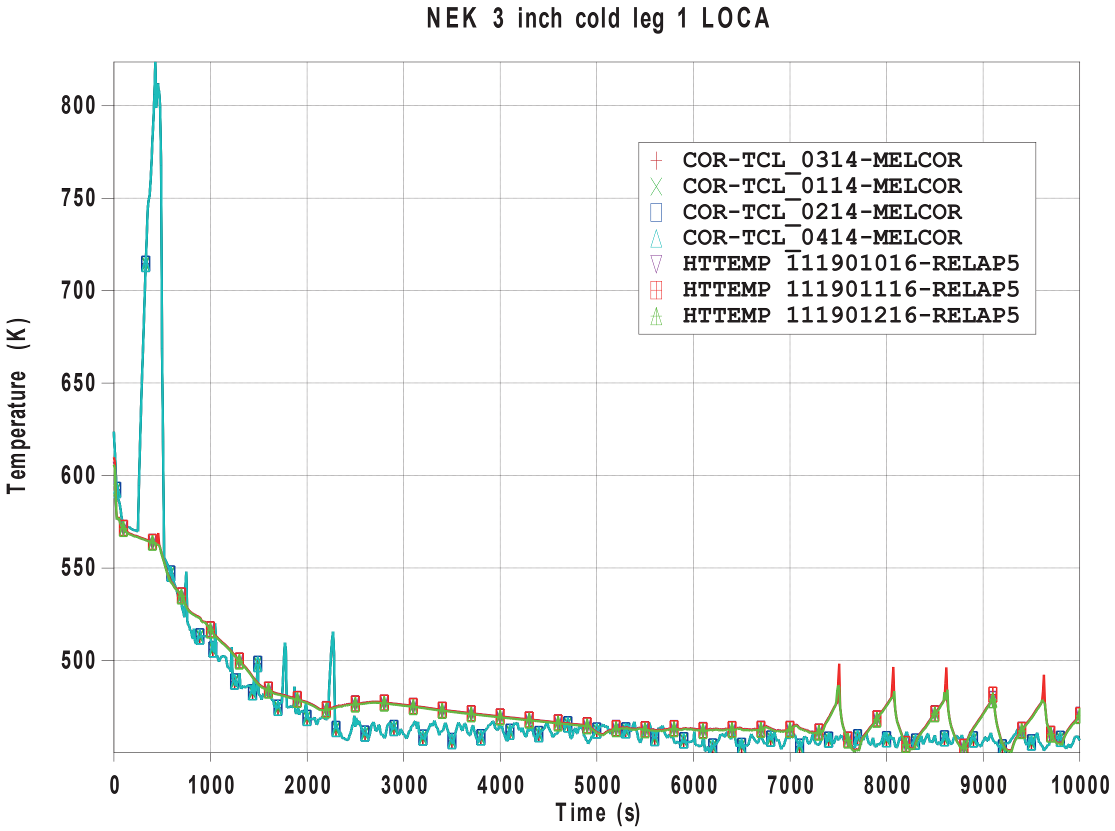

Figure 12: 3 inch cold leg 1 LOCA: Fuel cladding temperature

4 CONCLUSION

As a part of verification of developed MELCOR 1.8.6 model for NPP Krško, SB LOCA (3 inch cold leg LOCA) with all the engineering safety features available was analysed. The results were assessed against the RELAP5/MOD 3.3 analysis for the same transient scenario. Following conclusions can be drawn from the presented RELAP5/MOD 3.3 and MELCOR 1.8.6 analyses:

- Steady state calculation has been performed for 1000 seconds. Very small differences between the results for both RELAP5/MOD 3.3 and MELCOR 1.8.6 and the referent data were obtained.
- In MELCOR calculation, a larger break flow than in RELAP5 was obtained. This difference is mainly caused by different choked flow models in the two codes. Containment back pressure is lower in MELCOR than in RELAP5 due to fan coolers operation, but this had a small influence on break flow in MELCOR.
- Larger break flow in MELCOR has led to larger safety injection flow than in RELAP5. As a consequence, lower RCS temperatures were obtained in MELCOR than in RELAP5. After RWST depletion in MELCOR operator switched the suction of LPIS pumps to containment sump. Since the HPIS pumps did not operate further in MELCOR and the temperature of injected water is higher than the RWST temperature, cold leg temperature stabilized at a new higher value. In RELAP5 a continuous operation of HPIS pumps led to ON/OFF operation of LPIS pumps what on the other hand has caused the oscillatory behaviour of break flow as well as primary pressure and temperature.
- Core dry-out occurred for a short time period in MELCOR before the beginning of accumulator injection (max. temperature=823 K), but fuel cladding oxidation did not occur. In a long term, stable conditions were established for both codes with heat removal through the break and core inventory maintained by safety injection. The presented analyses have demonstrated the capability of available safety systems to ensure adequate core cooling as well as containment integrity.
- Similar trends of main physical parameters for both codes were obtained and the differences were identified and mainly well understood. One part of the obtained differences can be assigned to the differences in codes' physical models and numeric procedure as well as user effect. The rest of the differences can be assigned to phenomena that are transient specific; e.g., here, the break flow sustained by safety injection flow that has influence on other variables, e.g., RCS pressure and temperature.

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