NPP Krško Steam Generator Tube Rupture (SGTR) Accident Analysis using MELCOR Code

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ABSTRACT

Steam Generator Tube Rupture (SGTR) design basis event leads to contamination of the secondary side due to leakage of the radioactive coolant from the Reactor Coolant System (RCS) through the broken Steam Generator (SG) tube(s). Unlike other loss of coolant accidents, an early operator action is necessary to prevent radiological release to environment. The major concern for the SGTR event is the release of contaminated liquid through the secondary side relief or safety valves to the atmosphere that may result in an increase of radiological doses. The primary-to-secondary leakage results in the RCS depressurization, which leads to an automatic reactor trip and Safety Injection (SI) actuation. Since the RCS pressure tends to stabilize at the value where the incoming SI flow rate equals the break flow rate, the operator must terminate the SI flow to stop the primary-to-secondary leakage and subsequent broken SG overfill and radioactive releases to the atmosphere.

In the analysis presented in the paper, in addition to SGTR, the Station BlackOut (SBO) scenario following reactor trip was assumed, i.e. no active components such as pumps and fans were available. Unmitigated SBO sequence of events is a severe accident that will include core degradation and melting, RPV rupture and release of corium in the containment cavity, interaction between the corium and concrete (MCCI), release of non-condensable gases and containment pressurization. Passive autocatalytic recombiners are used to control hydrogen concentration in the containment. The Passive Containment Filter Vent (PCFV) system actuation, mentioned to restrict containment pressure below the containment damage limit, was not needed. The first operator action was assumed 24 hours after beginning of the transient and it includes containment spray actuation in order to reduce containment pressure.

SGTR accident with subsequent SBO was analysed using both MELCOR 1.8.6 and MELCOR 2.2.14959 codes. The results were compared with RELAP5/MOD 3.3 for the first 12000 seconds of the calculation. Double ended break of one U tube at the tube sheet was assumed. Both, the hot and cold leg side break locations were analysed. The comparisons of released reactor coolant system inventory as well as of released radioactive material mass to the environment have shown a good agreement between the two MELCOR code versions. The radiological consequences of the accident were not subject of the paper.

Keywords: *MELCOR, Station BlackOut (SBO), Steam Generator Tube Rupture (SGTR) accident*

INTRODUCTION

The Steam Generator Tube Rupture (SGTR) is design basis accident which provides the direct path for primary coolant release to the environment via the secondary side relief and safety valves, thereby bypassing the containment. The primary-to-secondary leakage causes the RCS depressurization which leads to automatic reactor trip due to either Overtemperature (OTDT) signal or due to low pressurizer pressure signal. The Safety Injection (SI) signal will be actuated, too, in order to make up for the loss of primary side inventory. An early operator action is necessary to stop the leakage on one side and to ensure RCS cooling using the intact SG on the other side. In order to propagate to severe accident, in this paper the SGTR analysis was performed together with the SBO scenario following reactor trip, i.e., only passive systems were assumed available. The operator actions were not credited apart from mitigation action consisting in a containment spray (one train) twenty-four hours after beginning of the transient. With SI system not available SGTR event leads to the loss of core inventory through the break. Due to unavailability of auxiliary feedwater, the secondary side inventory of both intact and ruptured SG would evaporate and the heat sink for the primary side would be lost. Further course of events involves development of core oxidation and degradation with subsequent Reactor Pressure Vessel (RPV) failure and melt ejection to the cavity. The discharged mass through the ruptured SG safety valve will be highly radioactive due to severely damaged reactor core. Along with the RPV failure, the primary pressure decreases and the SGTR break flow will be terminated. The accumulators will open following the primary pressure drop, but their inventory will be spilled over the melt in the cavity, ref [10].

The SGTR analysis with subsequent SBO was performed using severe accident code MELCOR and the results were compared against RELAP5/MOD 3.3 until a significant core heat-up took place (12000 seconds). The NPP Krško models for computer codes RELAP5/MOD 3.3 and MELCOR are being developed at FER, [1], [2], [3], [4], [5] and [6]. The NPP Krško model for RELAP5/MOD 3.3 has been used at FER in safety analyses as well as in the analyses of realistic plant events for more than three decades. The NPP Krško model for severe accident code MELCOR 1.8.6 as well as more advanced code versions, e.g., MELCOR 2.1 and MELCOR 2.2 have been verified by analysing design basis as well as severe accidents over a couple of years, e.g., the Station BlackOut (SBO) accident, ref. [7], small break Loss of Coolant Accident (LOCA) with all Engineering Safety Features (ESFs) available, ref. [8] and Large Break LOCA, ref [9].

The SGTR analysis presented in the paper was primarily aimed to determine the amount of the coolant mass as well as radioactive material mass discharged to environment through the ruptured SG safety valve. On the other hand, the accident outcome following the RPV failure and subsequent SGTR break flow termination has been investigated. These phenomena include the containment pressure behaviour following the melt ejection to the cavity, i.e., Molten Core Concrete Interaction (MCCI) and containment pressure rise due to evaporation of water in the cavity after accumulator opening. The containment behaviour and efficiency of the mitigation action (containment spray) one day after beginning of the transient was discussed as well.

CALCULATIONAL MODEL FOR NPP KRŠKO

RELAP5/MOD 3.3 model for NPP Krško consists of 533 control volumes and 572 junctions. The total number of heat structures is 403 with 2367 mesh points. There are 723 control variables and 197 variable and 221 logical trips to model the control systems as well as protection and Engineered Safety Features (ESF) behaviour, e.g., automatic rod control system, pressurizer pressure and level control system, steam generator level control, steam dump control, safety injection and auxiliary feedwater system. The model is being upgraded and improved along with changes accompanying plant modernization modifications, e.g. Steam Generators (SG) replacement and power uprate in 2000, Resistance Temperature Detector Bypass Elimination (RTDBE) in 2013 and Up-Flow Conversion in 2015. The model is used for calculation of plant transients and for the analysis of design bases accidents.

The MELCOR model of the primary and secondary system for NPP Krško consists of 131 control volumes, see Figure 1. The containment model, see Figure 3, consists of 17 control volumes and 13 control volumes are used to model the PCFV system (not shown here). There are 252 flow paths and 212 heat structures in the model. There are 396 control and 60 tabular functions aimed to model control and protection systems as well as ESF behaviour, e.g., SG level control system, auxiliary feedwater, safety injection, containment fan coolers and containment spray control.

SGTR accident is modeled as a double ended break of one tube in the steam generator in the loop with pressurizer (loop 1). Both the hot (HL) as well as cold leg (CL) side breaks were analyzed. The break is located at the top of the tube sheet (first end of the double ended break) and the second end of the break is located at the tube bottom at tube section inlet (HL side break) or at the tube bottom at tube section outlet (CL side break). The accident is initiated by the opening of two valves in flow paths (FL 197 and FL 198) to SG 1 riser bottom (volume 351), see Figure 2. The artificial valve that connects the end of affected tube to SG plenum FL127 is subsequently closed.

The Station BlackOut after reactor trip was assumed, i.e., only passive systems were available (pressurizer and steam generator safety valves, accumulators, Passive Autocatalytic Recombiners (PARs) and PCFV system). With no active systems available the transient will propagate into severe accident resulting in RPV lower head failure and melt ejection to cavity. Twenty-four hours after beginning of the transient mitigation action using containment spray (one train) was started. After the water from the Refuelling Water Storage Tank (RWST) had been depleted the containment spray suction lines were realigned, with five minutes delay, to the containment sump. The transient was simulated for 300000 seconds.

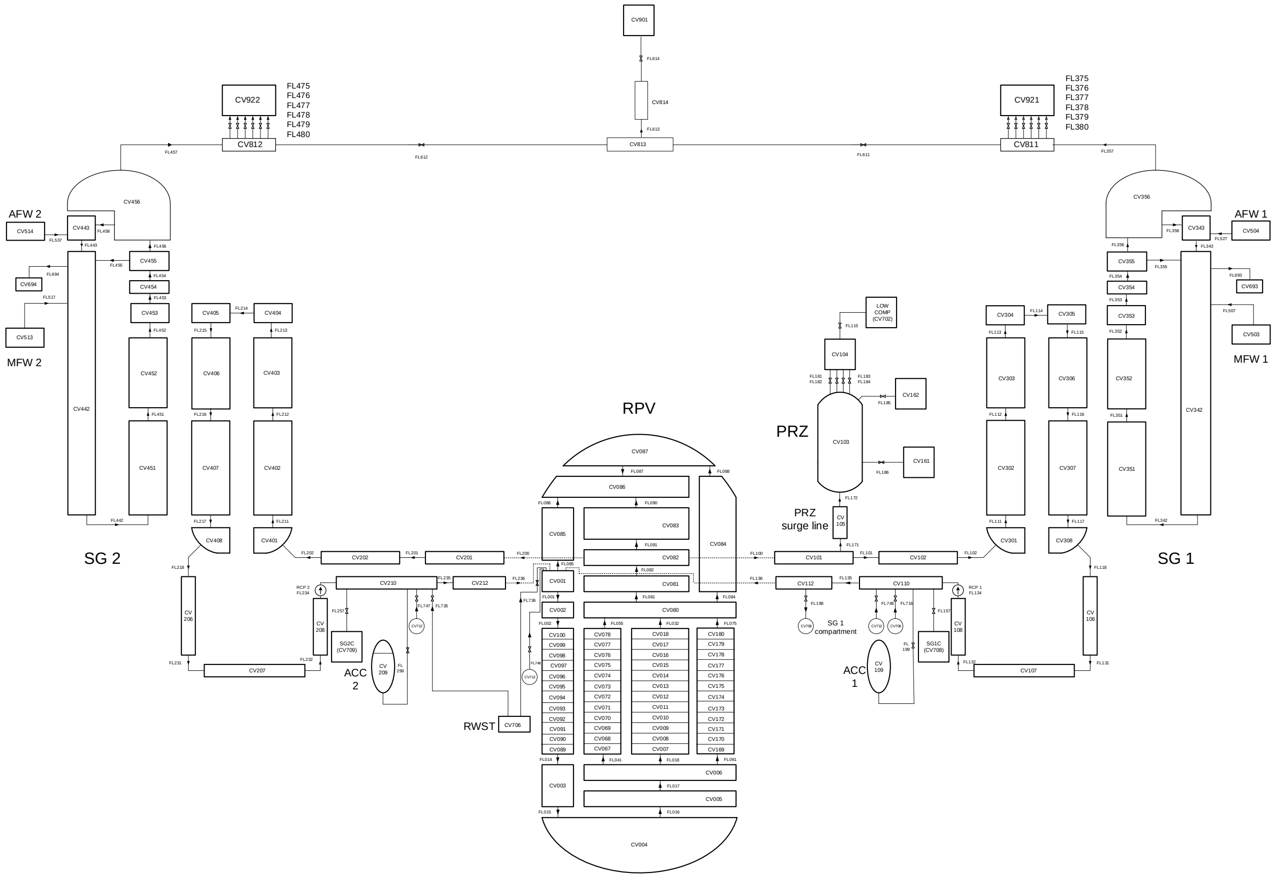

Figure 1: MELCOR nodalization scheme for NPP Krško

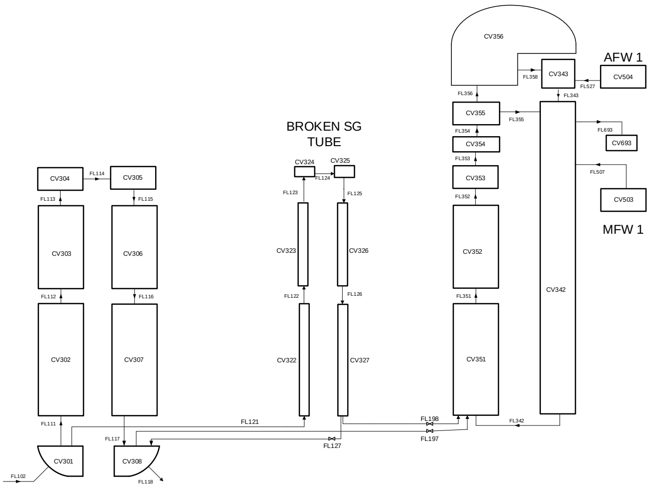

Figure 2: Cold leg (CL) side SGTR nodalization for MELCOR code

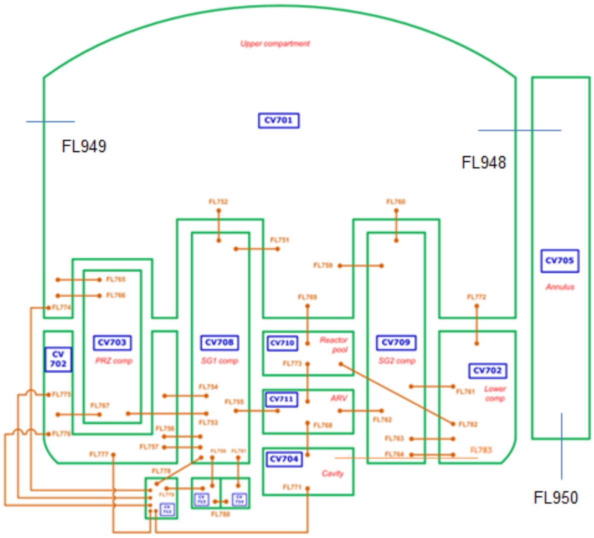

Figure 3: NPP Krško containment nodalization for MELCOR code

ANALYSIS OF STEAM GENERATOR TUBE RUPTURE ACCIDENT

Thermal-hydraulic analysis and severe accident outcome

The SGTR accident was initiated after 1000 seconds of steady state calculation. Following the beginning of the transient, the primary pressure decreased due to break, see Figure 4 and Figure 5. In the analysis it was assumed that the main feedwater control was active until reactor trip. Under realistic conditions, the reactor trip due to Overtemperature DT (OTDT) trips the reactor, but in the analysis, it was assumed that the OTDT trip was disabled and that the reactor trip was actuated on low pressurizer pressure signal. For hot leg side break, reactor trip signal was obtained 222.8 seconds after beginning of the transient in case of RELAP5 and 268.6 and 268.3 seconds after beginning of the transient for MELCOR 1.8.6 and MELCOR 2.2, respectively. For cold leg side break, the primary pressure decreased at a faster rate and the reactor trip occurred earlier (218.8 seconds after beginning of the transient for RELAP5 and 229.5 and 229.4 seconds after beginning of the transient for MELCOR 1.8.6 and MELCOR 2.2, respectively. For both break location RELAP5 predicted earlier trip occurrence and the difference in trip times between MELCOR versions is negligible.

All codes predict larger flow coming from tube sheet side of the break, independent of break location (HL or CL), as expected. For RELAP5, calculated flows for both break sides are almost independent of the break location, see Figure 5. For MELCOR code, that is not true for break flow coming from tube sheet side, which is larger for CL break than for HL break. Due to that, predicted tube sheet break flow, in case of CL break, is larger in MELCOR than in RELAP5 calculation. For MELCOR calculation, the total break flow as well as discharged mass to the environment were larger for the CL than for HL break, but only until core uncovery when the total HL break flow had become larger than the CL side break flow. As a result, for MELCOR, similar amount of discharged cumulative mass to the environment for HL and CL side break was obtained, Figure 9. The differences between results obtained by both MELCOR versions are small.

Core heat-up and core uncovery occurred after approximately 10000 seconds, when both intact (SG 2) and ruptured SG (SG 1) were depleted, see Figure 6. Fuel cladding oxidation started approximately 13000 seconds after beginning of the transient and release of radioactivity to the environment started about 1000 seconds thereafter. Loss of heat sink along with the large amount of additional heat produced due to oxidation lead to core meltdown and relocation and finally to RPV rupture. After lower head failure, 5.2 hours from beginning of the transient, release of radioactivity through the ruptured SG safety valve was stopped due to rapid primary pressure drop. Generally speaking, both MELCOR versions calculate similar amounts of radioactive material mass, Table 1 and Table 2, and show similar time dependence, see Figure 10 and Figure 11. Slightly more aerosols mass and less total radioactive materials mass were released during HL compared to CL break case.

Following the RPV rupture, the melt from the core was ejected to the cavity, see Figure 8. The accumulators opened due to primary pressure decrease and the water from the accumulators has been emptied to the cavity, as well, see Figure 7. The MCCI reaction started immediately after melt ejection, see Figure 8. Containment pressure started to rise due to emission of gasses due to MCCI on one side and due to evaporation of water overlying the debris in the cavity on the other side. After water in the cavity had evaporated, containment pressure continued to rise but at a slower rate, see Figure 7. Twenty-four hours after beginning of the transient, mitigation was started using the containment spray (one train). The maximum containment pressure was in all cases well below PCFV rupture disk pressure setpoint (6 bar), and PCFV did not open throughout the simulation (300000 seconds). The peak values were 3.86 bar for MELCOR 1.8.6 HL break, 3.96 bar for MELCOR 2.2 HL break, 2.97 bar for MELCOR 1.8.6 CL break and 4.07 bar for MELCOR 2.2 CL break.

Containment pressure was reduced after start of containment spray due to condensation of steam on cold spray droplets. Approximately 100000 seconds after beginning of the transient the water level in the lower compartment (CV 702) reached the cavity vent elevation (FL 783) and the cavity was flooded for the second time. Despite of the fact that the cavity remained flooded till the end of simulation, approximately 125000 seconds after beginning of the transient containment pressure started to rise at a small but constant rate due to ongoing MCCI and emission of gases accompanying MCCI and concrete decomposition (CO and CO_2). Total mass of melt (CAV-MTOT) in the cavity (includes concrete melt) as well as cavity erosion (as described by CAV-MINALT and CAV-MAXRAD) continued to increase till the end of simulation, see Figure 8. In the analysis, conservative assumptions for CAVITY input were used, i.e., low default value for thermal conductivity in a solid crust sublayer in contact with water as well as conservative values for debris-to-surface heat transfer coefficient to the top of the crust. Additional sensitivity analyses with more realistic CAVITY input parameters will be performed in order to investigate the MCCI behavior as well as melt cooling capabilities when cavity is flooded.

Table 1: Time sequence of main events: SGTR hot leg side break

Event	RELAP5/MOD 3.3	MELCOR 1.8.6	MELCOR 2.2
Reactor trip (on low-1 PRZ pressure signal)	222.8 s	268.6 s	268.3 s
Loss of offsite power	222.8 s	268.6 s	268.3 s
The core has uncovered	9720 s	11350 s	11170 s
Steam generators are depleted	9750 s (SG 1)/7470 s (SG 2)	7720 s (SG 1)/5850 s (SG 2)	8030 s (SG 1)/6190 s (SG 2)
Lower head failure	-	18459 s	18664 s
Accumulators empty	-	18480 s	18783 s
Begin of mitigation (containment spray)	-	86400 s	86400 s
Maximum containment pressure	-	3.86 bar	3.96 bar
Total discharged mass to environment (SG 1 SV 1)	124.82 t (12000 s)	161.27 t	161.49 t
Total radioactive mass discharged to environment	NA	133.17 kg	123.9 kg
Total radioactive aerosol mass discharged to environment	NA	9.01 kg	9.85 kg
Total radioactive mass in atmosphere and pool regions	NA	447.1 kg (300000 s)	450.3 (300000 s)
Total radioactive mass deposited on heat structures	NA	24.1 kg (300000 s)	32.4 (300000 s)

Table 2: Time sequence of main events: SGTR cold leg side break

Event	RELAP5/MOD 3.3	MELCOR 1.8.6	MELCOR 2.2
Reactor trip (on low-1 PRZ pressure signal)	218.8 s	229.5 s	229.4 s
Loss of offsite power	218.8 s	229.5 s	229.4 s
The core has uncovered	11090 s	9500 s	8975 s
Steam generators are depleted	9940 s (SG 1)/7500 s (SG 2)	10575 s (SG 1)/6030 s (SG 2)	10680 s (SG 1)/5950 s (SG 2)
Lower head failure	-	18525 s	18524 s
Accumulators empty	-	18546 s	18656 s
Begin of mitigation (containment spray)	-	86400 s	86400 s
Maximum containment pressure	-	2.97 bar	4.07 bar
Total discharged mass to environment (SG 1 SV 1)	126.25 t (12000 s)	160.83 t	161.94 t
Total radioactive mass discharged to environment	NA	145.3 kg	138.0 kg
Total radioactive aerosol mass discharged to environment	NA	5.87 kg	7.42 kg
Total radioactive mass in atmosphere and pool regions	NA	442.6 kg (300000 s)	444.2 kg (300000 s)
Total radioactive mass deposited on heat structures	NA	33.54 kg (300000 s)	43.7 kg (300000 s)

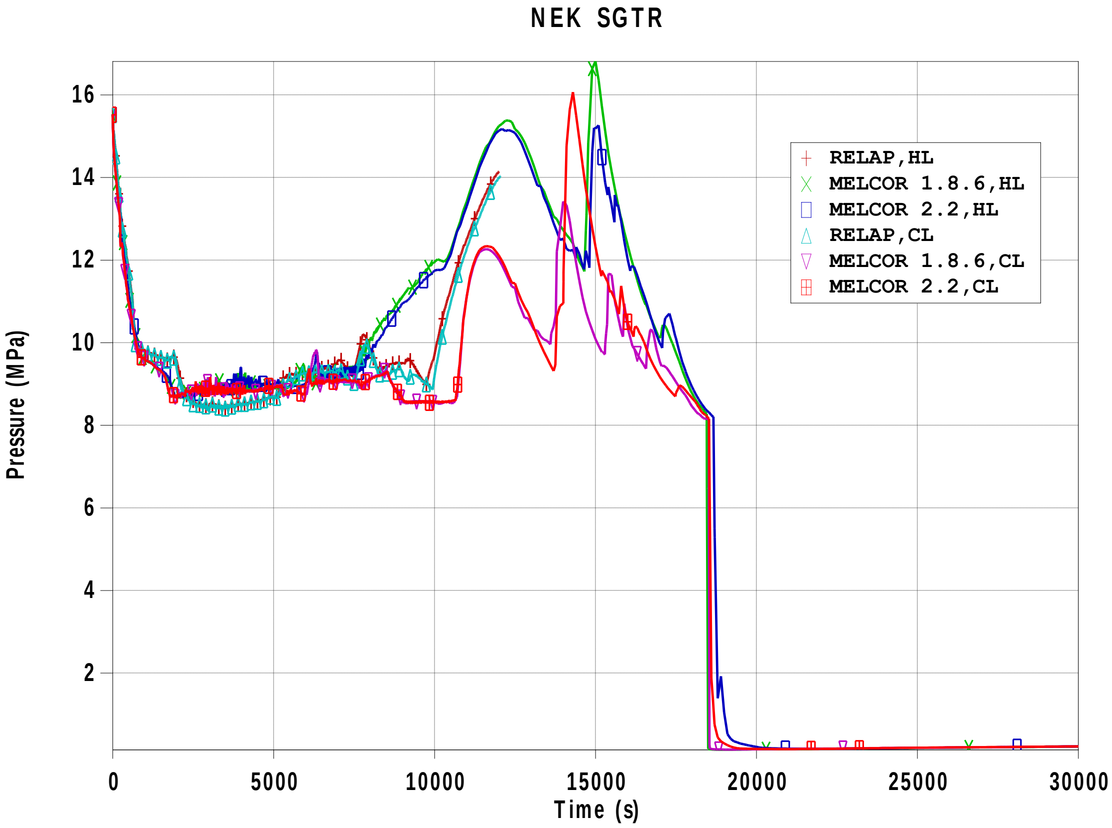

Figure 4: Pressurizer pressure

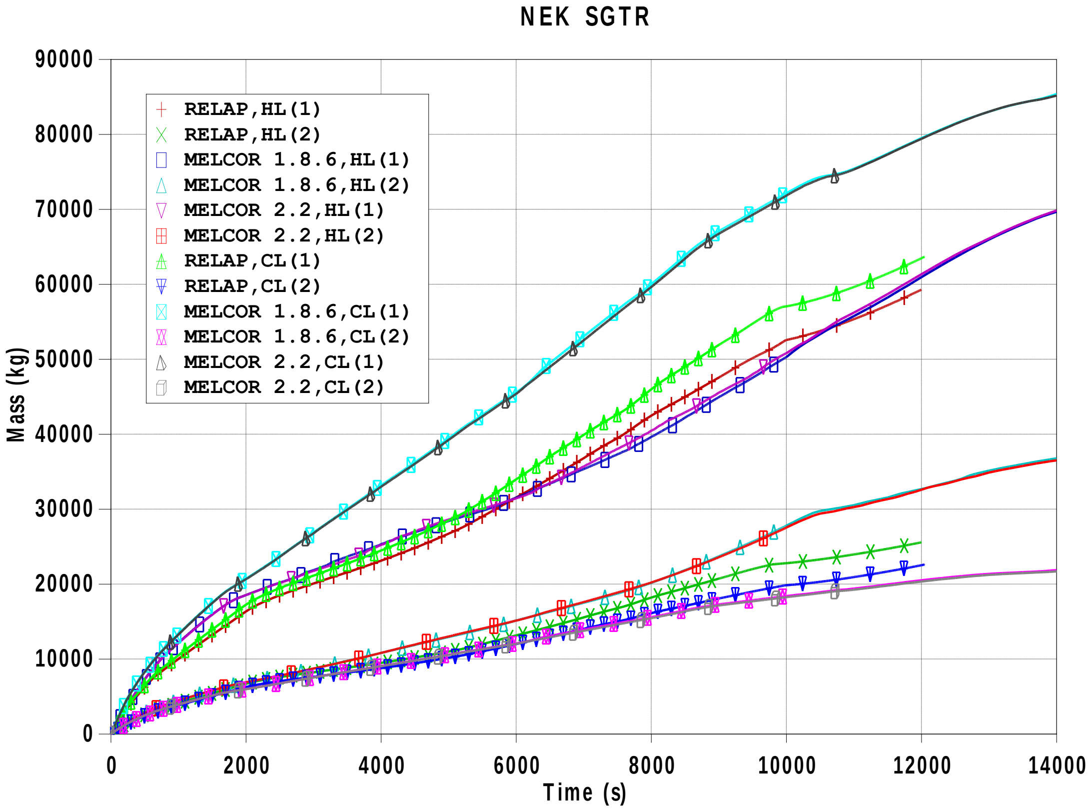

Figure 5: Integral of break flow; (1- flow from tube sheet, 2-flow from U-tube)

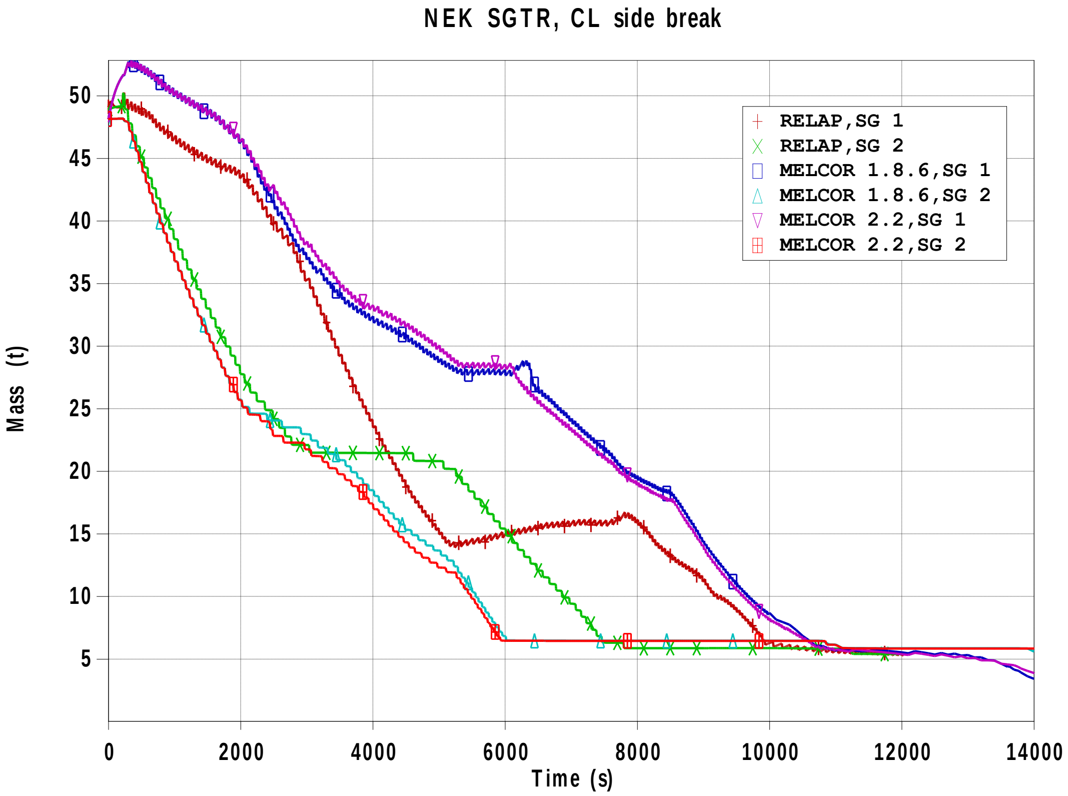

Figure 6: SG mass, CL side break

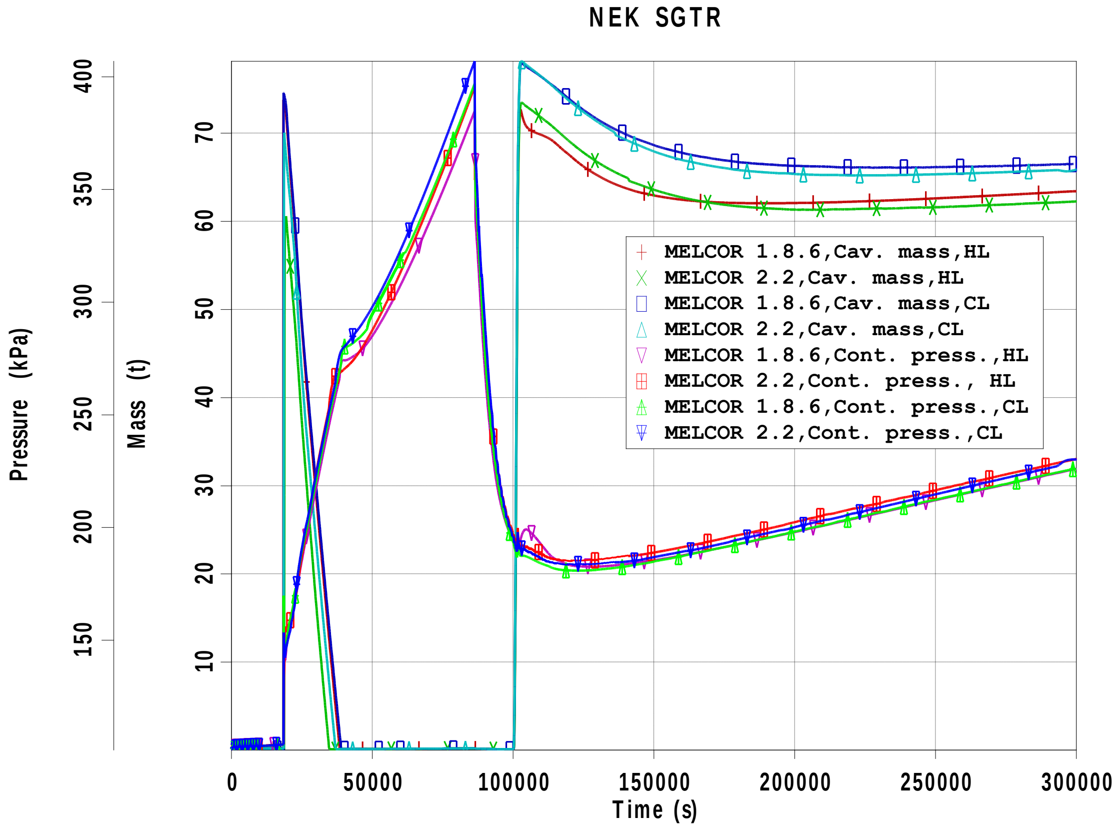

Figure 7: Mass of water in the cavity and containment pressure

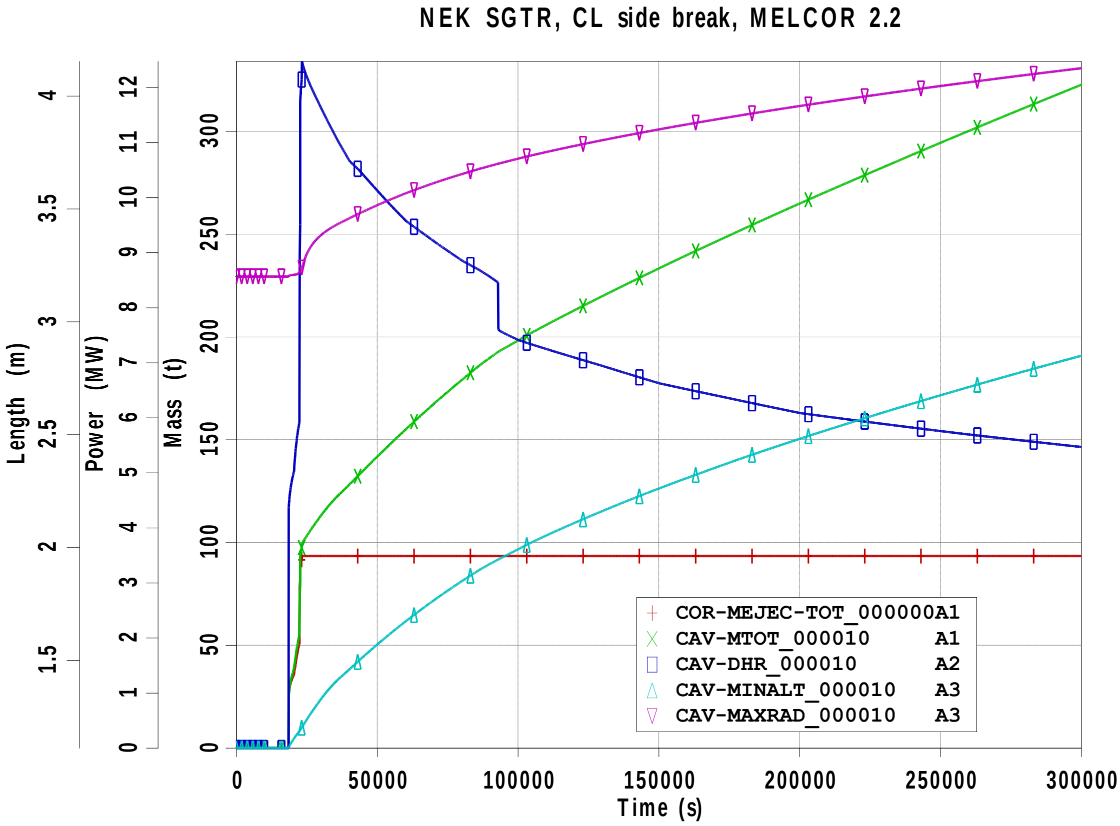

Figure 8: COR-MEJEC-discharged debris mass to the cavity, CAV-MTOT-mass of melt in the cavity, CAV-DHR-cavity decay heat rate, CAV-MINALT-min. cavity altitude, CAV-MAXRAD-max. cavity radius, MELCOR 2.2, CL side break

Analysis of radioactive mass discharged to the environment

The results for radioactive material mass discharged to the environment and the total radioactive material mass in containment are presented in Figure 9 through Figure 13. As already discussed, similar results for the total discharged mass through the safety valve of ruptured SG were obtained for both locations of the break (HL and CL) as well as for different codes, see Figure 9, Table 1 and Table 2. Total radioactive material mass discharged to environment, see Figure 11, was larger for CL break than for HL type break with maximum of 145.3 kg for MELCOR 1.8.6, CL side break. The discharged radioactive aerosol mass was larger for HL type break, see Figure 10, with maximum mass obtained for MELCOR 2.2 (9.85 kg). The total radioactive material mass in the system was approximately 3.3 times larger than the discharged mass through the ruptured SG SV 1. The maximum amount of radioactive material mass (450.3 kg) was obtained for MELCOR 2.2, HL side break, see Table 1 and Table 2. In general, larger total radioactive mass was obtained for HL than for CL side break. On the contrary, the larger amount of discharged mass through the ruptured SG safety valve was obtained for CL than for HL side break. Radioactive material mass released due to containment leakage (flow paths 948, 949 and 950, Figure 3) accounted for less than 0.05% of total mass released to environment. About 100000 seconds after beginning of the transient, a steep release of radioactive aerosols from the debris in cavity took place, see Figure 12 and Figure 13. The release of radioactive material mass is also demonstrated with the steep drop in cavity decay heat 100000 seconds after beginning of the transient, see Figure 8, accounting for the loss of radioactive debris mass. Total radioactive material mass was increased by about 140 kg. Thereafter, the total radioactive material mass in the containment continued to increase at a slow rate.

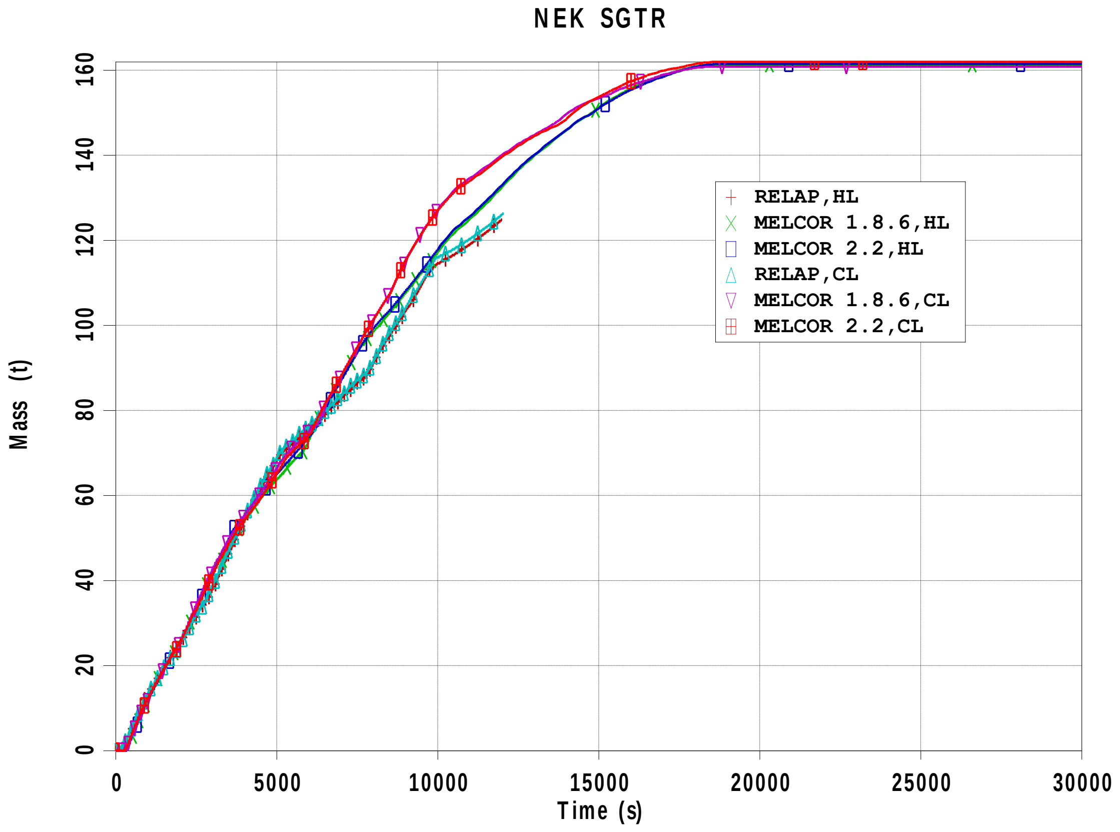

Figure 9: Total discharged mass (radioactive and non-radioactive) to the environment through SG 1 SV 1

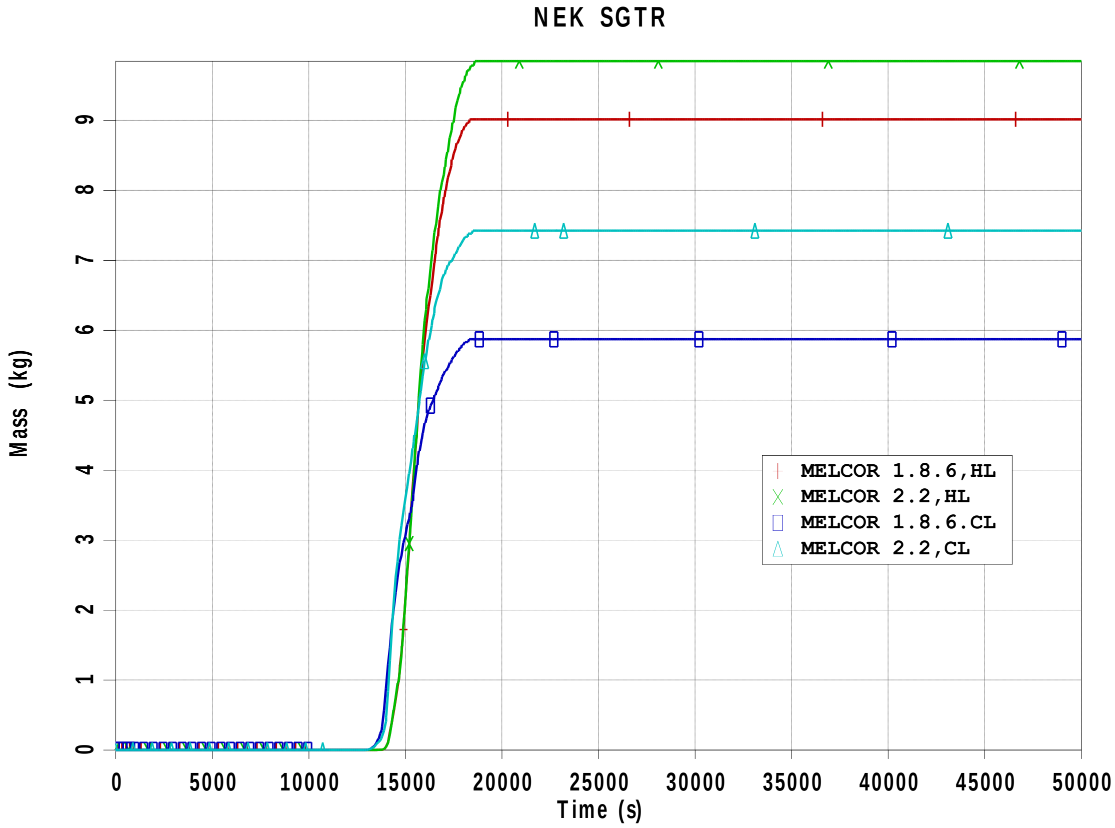

Figure 10: Discharged radioactive aerosol mass through SG 1 SV 1 to environment

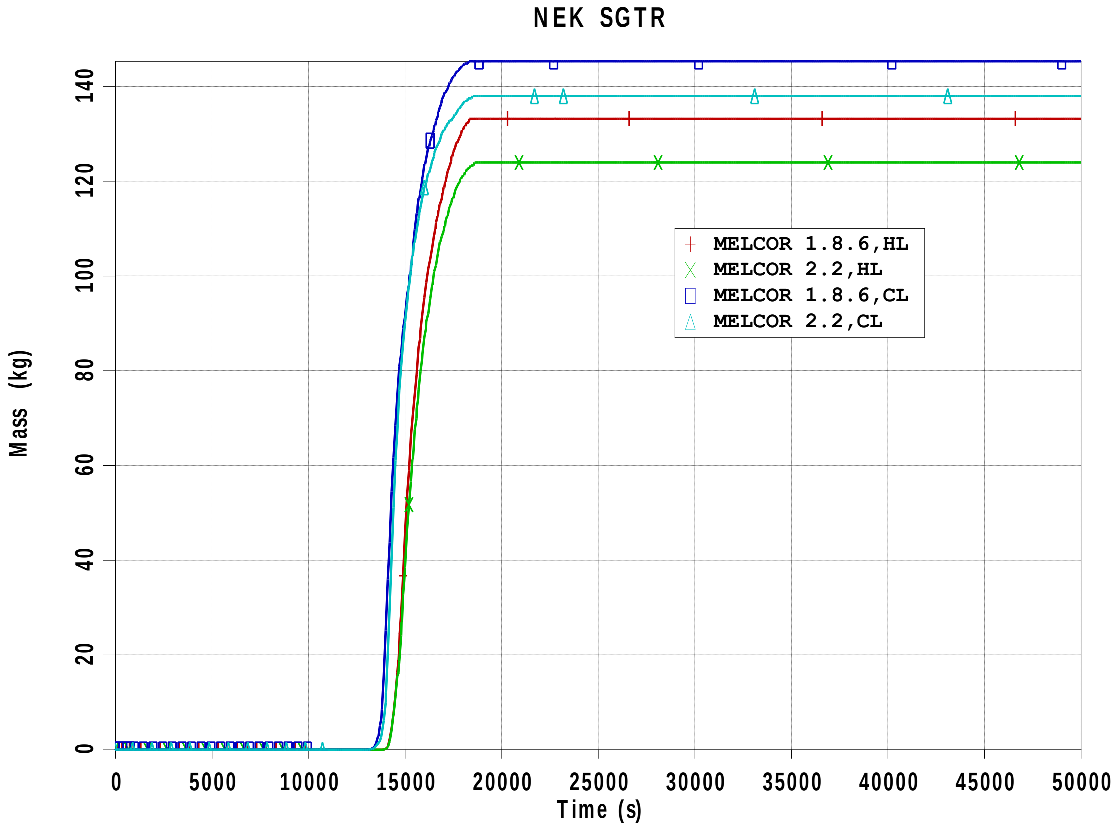

Figure 11: Total radioactive material mass discharged through SG 1 SV 1 to environment

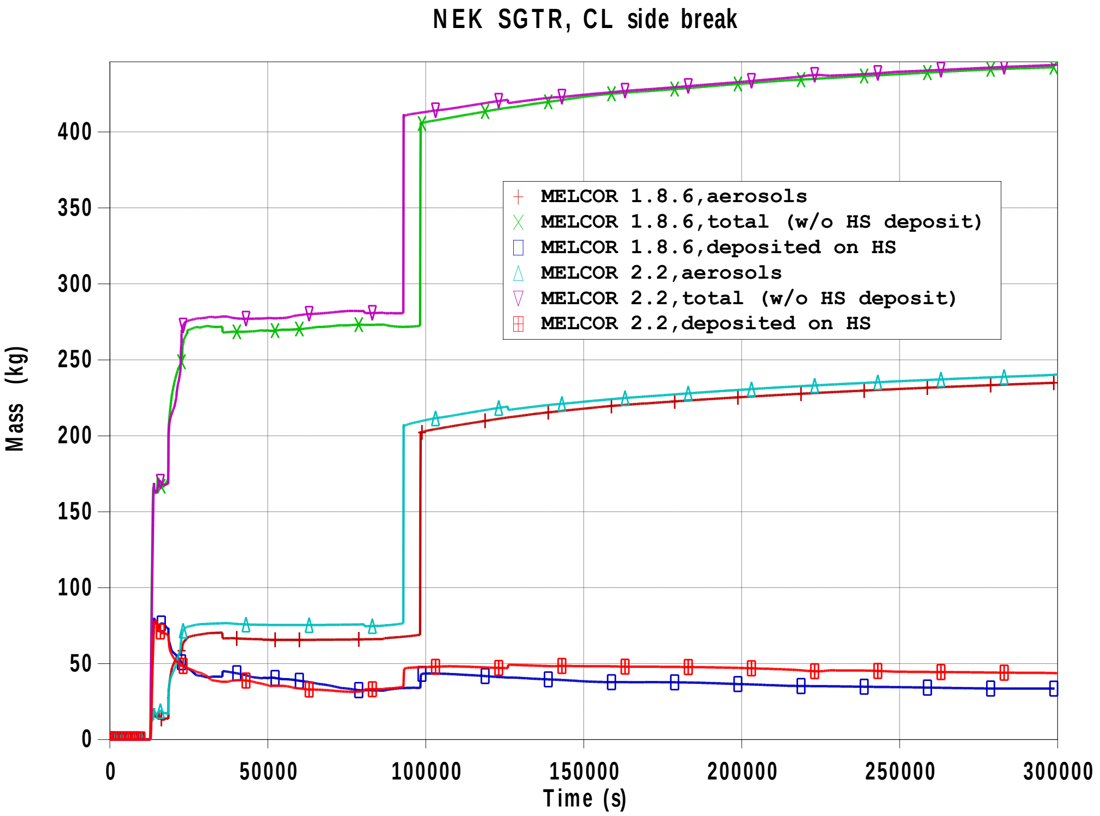

Figure 12: Total radioactive material mass in the containment atmosphere and pool regions and total radioactive material mass deposited on all heat structures, CL side break

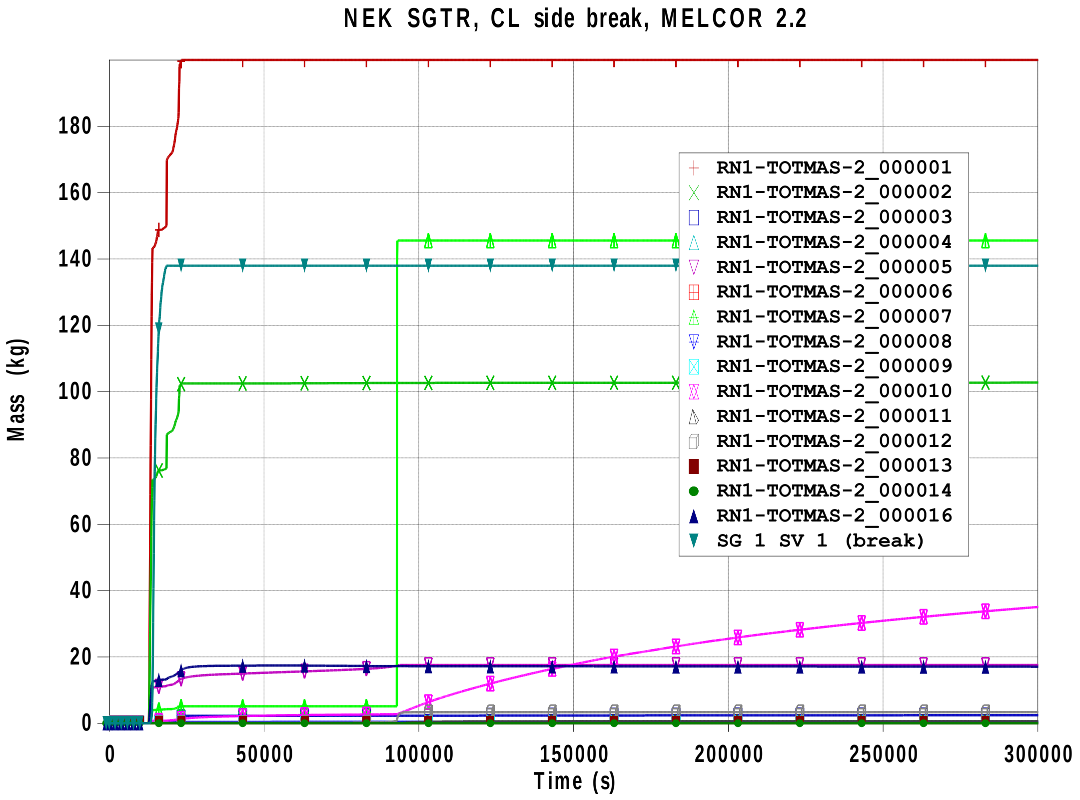

Figure 13: Total radioactive material mass for RN classes, MELCOR 2.2, CL side break

CONCLUSION

Following conclusions can be drawn from the presented analyses.

The comparison of transient results for MELCOR code with RELAP5 has shown that for the CL side break a larger amount of discharged mass through the break side 1 (tube sheet) than through the tube side (2) was obtained for MELCOR than for the RELAP5. For HL side break similar amount of discharged mass through the both sides of double ended break were obtained for both MELCOR and RELAP5. In general, a good agreement between MELCOR and RELAP5 for the SG behavior and the time of core uncovery were obtained. For RELAP5, a very small difference for the total amount of discharged inventory to environment between HL and CL side break was obtained (124.82 t against 126.25 t). For MELCOR, a larger amount of discharged mass to environment was obtained for CL side break, but only until the significant core heat-up had begun when the discharged total mass for HL has become larger than the discharged mass for CL side break. As a result, similar amount of cumulative discharged mass to the environment for HL and CL side break for both MELCOR code versions were obtained. Total radioactive material mass discharged to environment was larger for the CL side than for the HL side break but the total amount of discharged aerosol mass was larger for the HL than for the CL side break. A very good agreement between MELCOR 1.8.6 and MELCOR 2.2 for the total and radioactive material mass discharged to atmosphere was obtained. The radiological consequences calculation was not subject of the paper.

After lower head failure the primary pressure was rapidly reduced and the leakage from the primary to secondary side as well as discharge from the ruptured SG safety valve to environment were stopped. Containment pressure started to rise due to emission of gases accompanying the MCCI reaction on one side and evaporation of water in the cavity after accumulator injection. MELCOR 2.2 code calculated larger containment peak pressures; for both CL side break (4.07 bar) and for HL side break (3.96 bar). Corresponding MELCOR 1.8.6 values of the containment peak pressure were 3.86 bar for HL and 2.97 bar for CL side break.

Containment pressure was reduced after start of containment spray, but it has begun to rise again at approximately 125000 seconds, at a small but constant rate. In the analyses it was shown that despite of the fact that the cavity was flooded at approximately 100000 seconds, the MCCI and the emission of the gases related to MCCI and concrete decomposition as well as cavity erosion were not stopped. Such behavior is not completely realistic and it is consequence of conservative default input parameters related to thermal conductivity of the crust as well as conservative values for debris-to-surface heat transfer coefficient to the top of the crust. Additional sensitivity analyses with more realistic CAVITY input parameters will be performed in order to investigate the MCCI behavior as well as melt cooling capabilities when cavity is flooded.

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