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

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EMUG Meeting, Ljubljana, April 12-14, 2023

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Contents

- Transient description
- Description of nodalization changes for SGTR transient. Double-ended break of one U-tube was assumed: 1) the break at the tube sheet on the hot leg side and 2) the break at the tube sheet on the cold leg side.
- Initial and boundary conditions.
- Analysis of SGTR accident using MELCOR code and comparison with RELAP5/MOD 3.3 (0-12000 s) results.

Steam Generator Tube Rupture (SGTR) Transient description

- Steam Generator Tube Rupture (SGTR) 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). The release of radioctivity occurs through the ruptured SG relief and/or safety valves thereby bypassing the containment.

- Unlike other loss of coolant accidents, an early operator action aimed to stop the primary-to-secondary leakage is necessary to prevent radiological release to environment. <u>In this analysis no provisions for operator actions were credited.</u> Severe accident scenario was assumed with Station Black Out (SBO) after reactor trip.

- Conservative assumptions of break size and location were used in the analysis. The analyses have shown that SGTR of one tube at the tube sheet on the cold leg side (SG outlet) leads to maximum break flow before and SGTR at the hot leg side leads to maximum break flow after core uncovery. Both cold leg side and hot leg side SGTR at the tube sheet were analyzed.

Steam Generator Tube Rupture (SGTR) - Transient scenario

- SGTR is assumed (100% nuclear power) in the loop with pressurizer (loop 1) at time=0.0.

- Normal feedwater flow was assumed until reactor trip in order to maximize filling of the ruptered SG.

- Reactor trip on low-1 pressurizer pressure.

- Station Black Out (SBO) after reactor trip (trip of both RC pumps, loss of main feedwater, Auxiliary feedwater not available).

- Both intact and ruptured SG inventory is released through SG safety valves since the steam dump is assumed unavailable.

- Core heat-up followed by Reactor Pressure Vessel (RPV) failure is expected due to loss of RCS inventory and loss of heat sink.

- 24 hours after transient begin containment spray (one train) is put in operation. After RWST had been depleted the suction of containment spray pumps is realigned from RWST to containment sump.

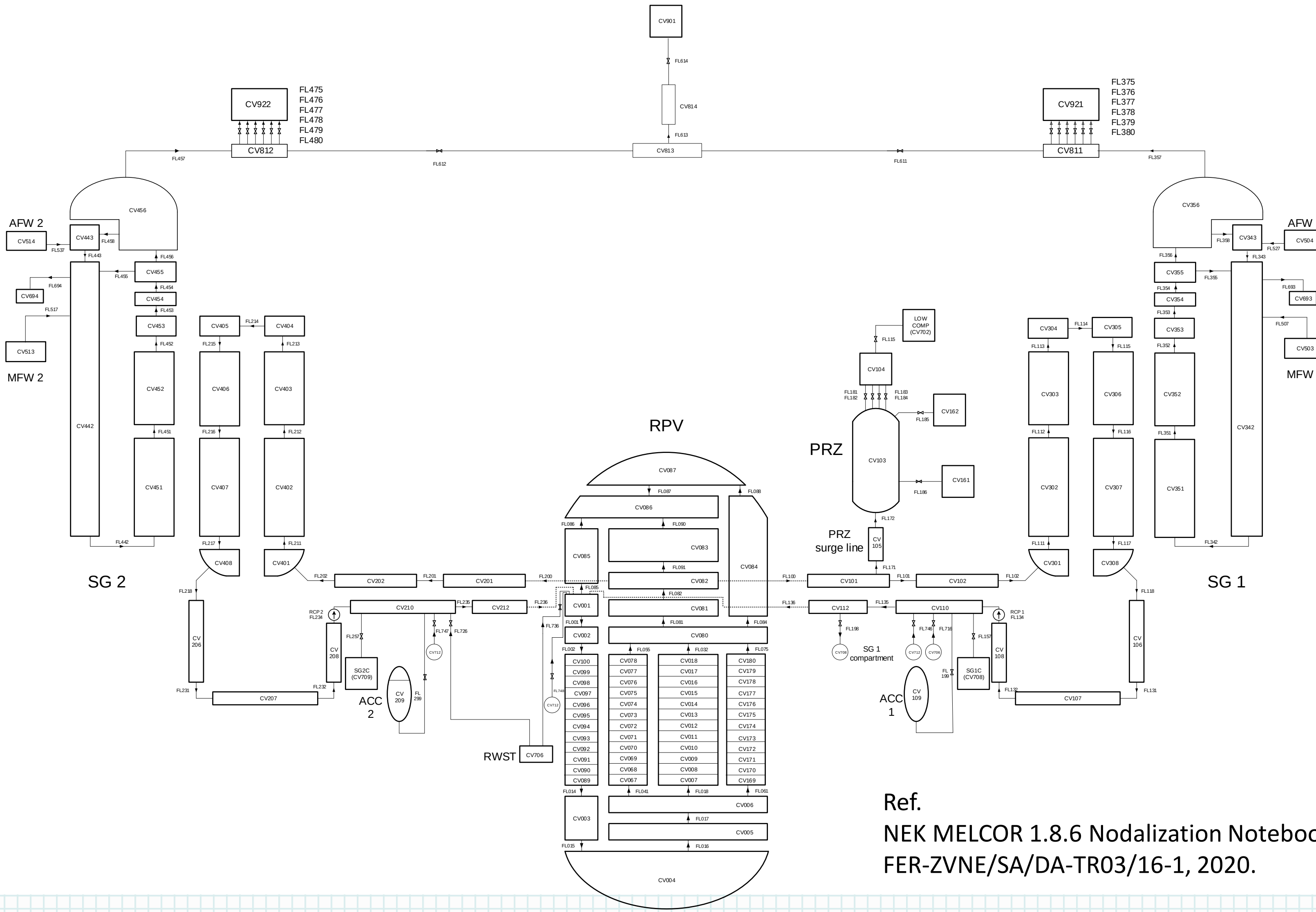
Steam Generator Tube Rupture (SGTR) - Aims of the analysis

- Investigate the influence of different nodalization; the "true " double-ended tube rupture, single tube model on one side with leakage from the lumped volume on other side (leakage) or just the simple leakage from one lumped volume to the secondary side. The comparison with RELAP5 calculation was made using NEK RELAP5 nodalization adapted for the detailed double-ended SGTR accident on both the cold and hot leg side.

- Analyze both the cold leg and hot leg side SGTR and calculate the released mass of Reactor Coolant System (RCS) inventory and released radioactive mass to the environment. However, the analyses are not yet aimed to provide the source term for assessment of radiological consequences.

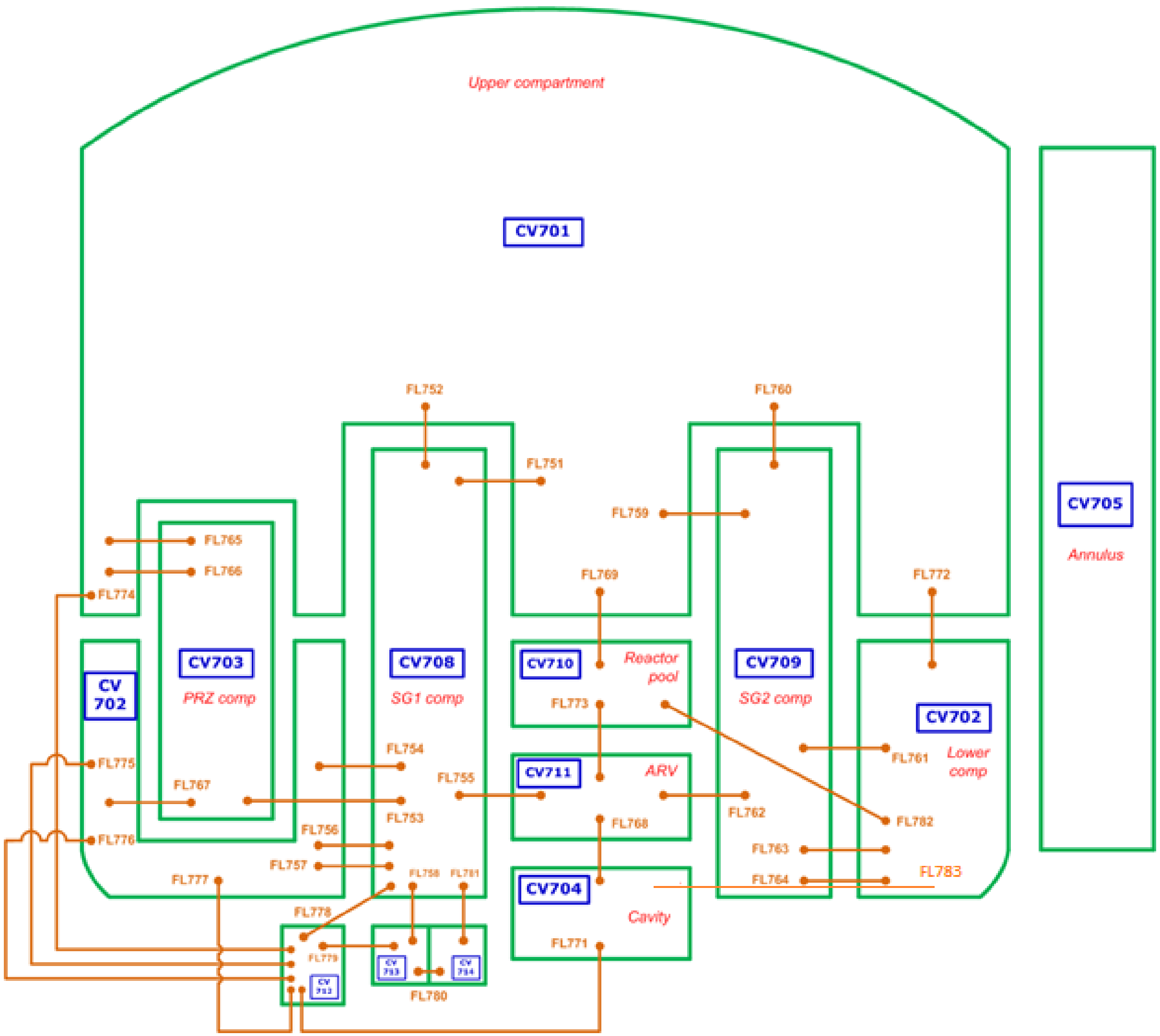
- The presented analyses are primarily aimed to investigate the influence of different MELCOR nodalization on main transient outcome (leakage from primary to secondary side and discharge through the damaged SG, including radioactivity release, core heat-up and reactor pressure vessel failure and containment pressure behavior).

NEK nodalization of primary and secondary system for MELCOR code, (July 2020)

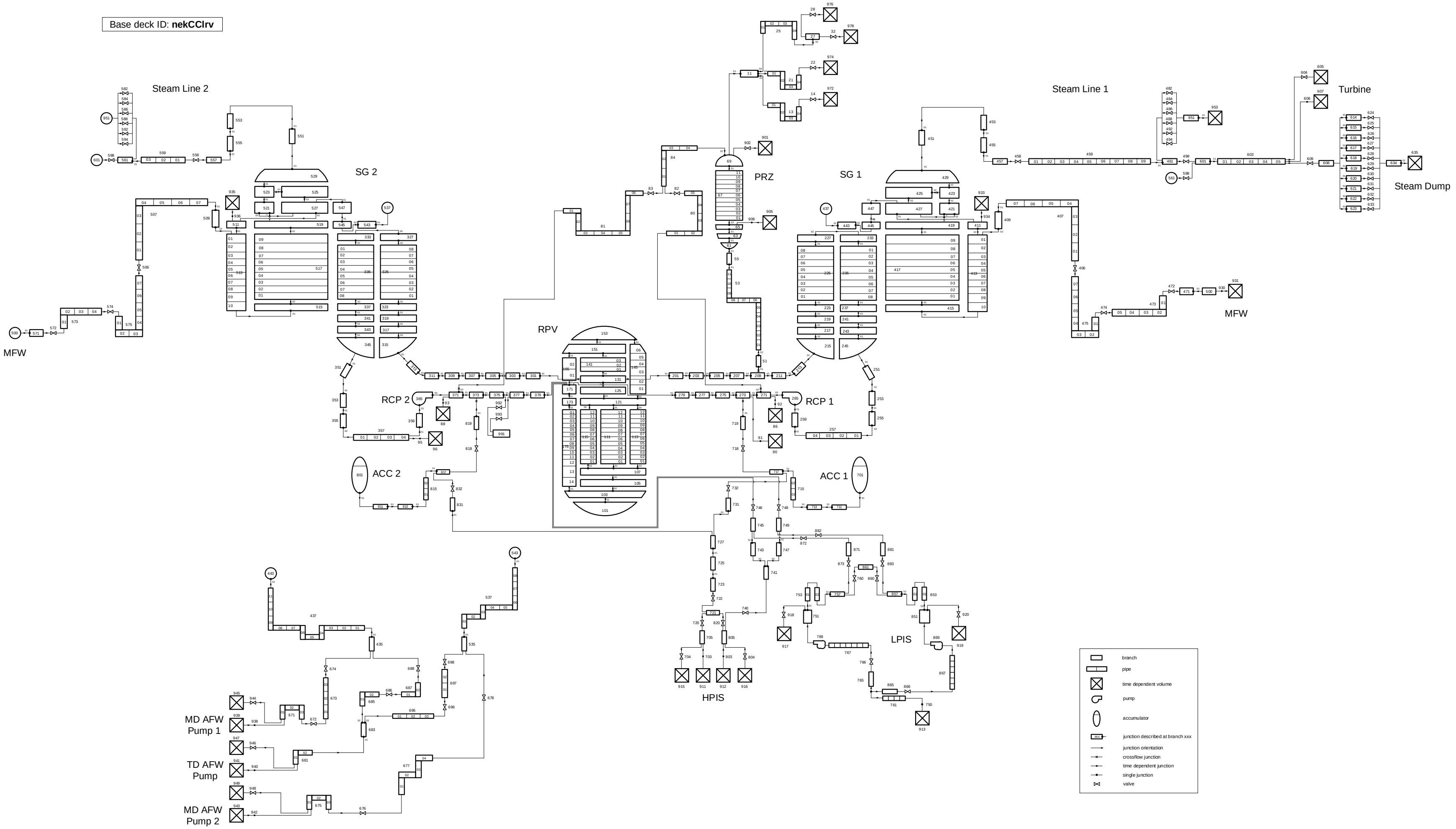


Ref.
NEK MELCOR 1.8.6 Nodalization Notebook, FER-ZVNE/SA/DA-TR03/16-1, 2020.

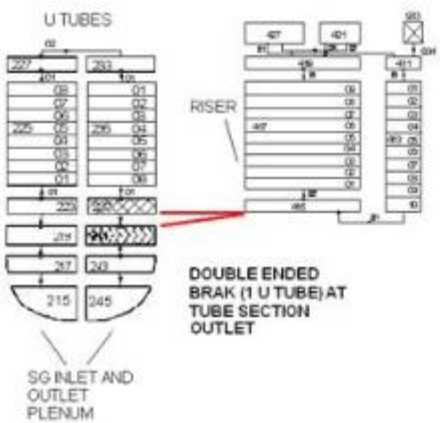
NEK nodalization of containment MELCOR code, rev. 1 (July 2020)

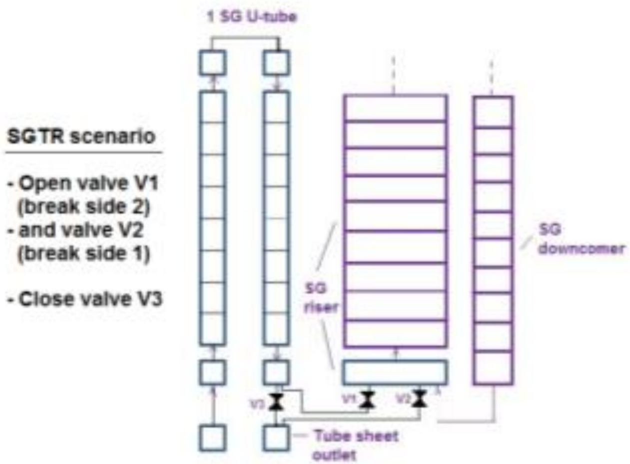


NEK nodalization for RELAP5/MOD 3.3 Code, December 2022.

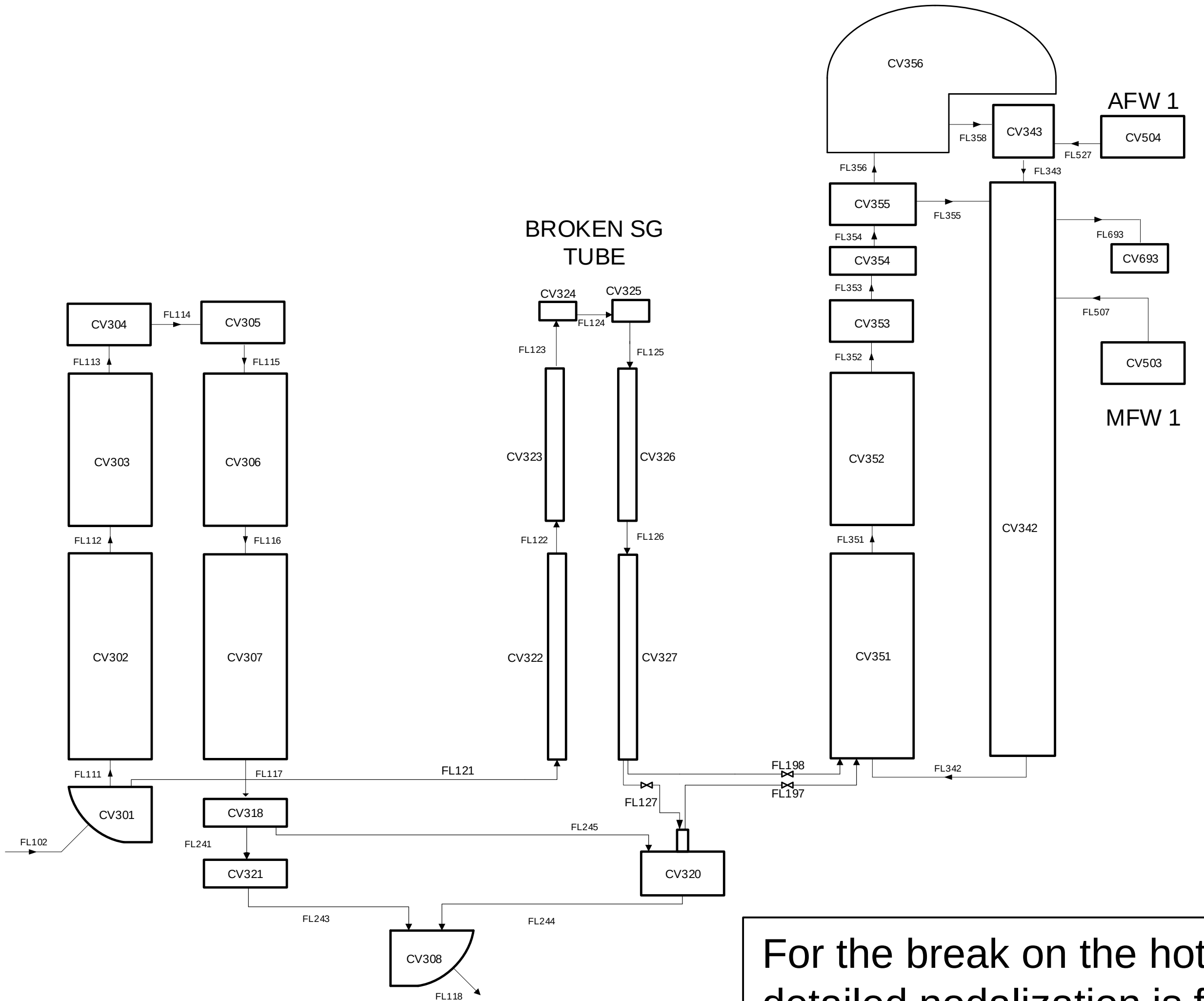


Nodalization changes: double ended break of one tube (cold leg side) in the loop with pressurizer - RELAP5





MELCOR nodalization for "true" double ended break of one tube (cold leg side)

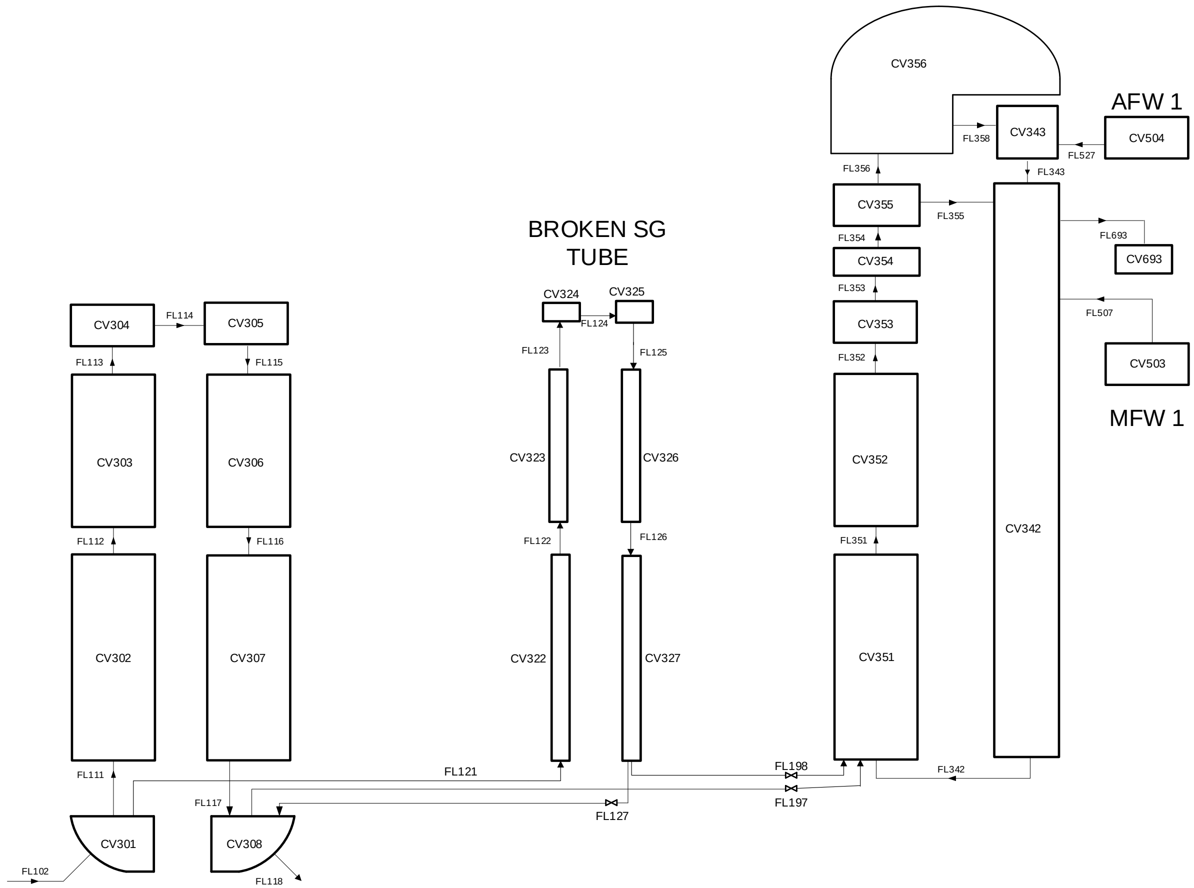


SGTR scenario:

- Valve in FL127 closes
- Valves in FL197 and FL198 open.

For the break on the hot leg side the more detailed nodalization is for SG inlet plenum.

MELCOR nodalization for double ended break - leakage on the side of the tube sheet

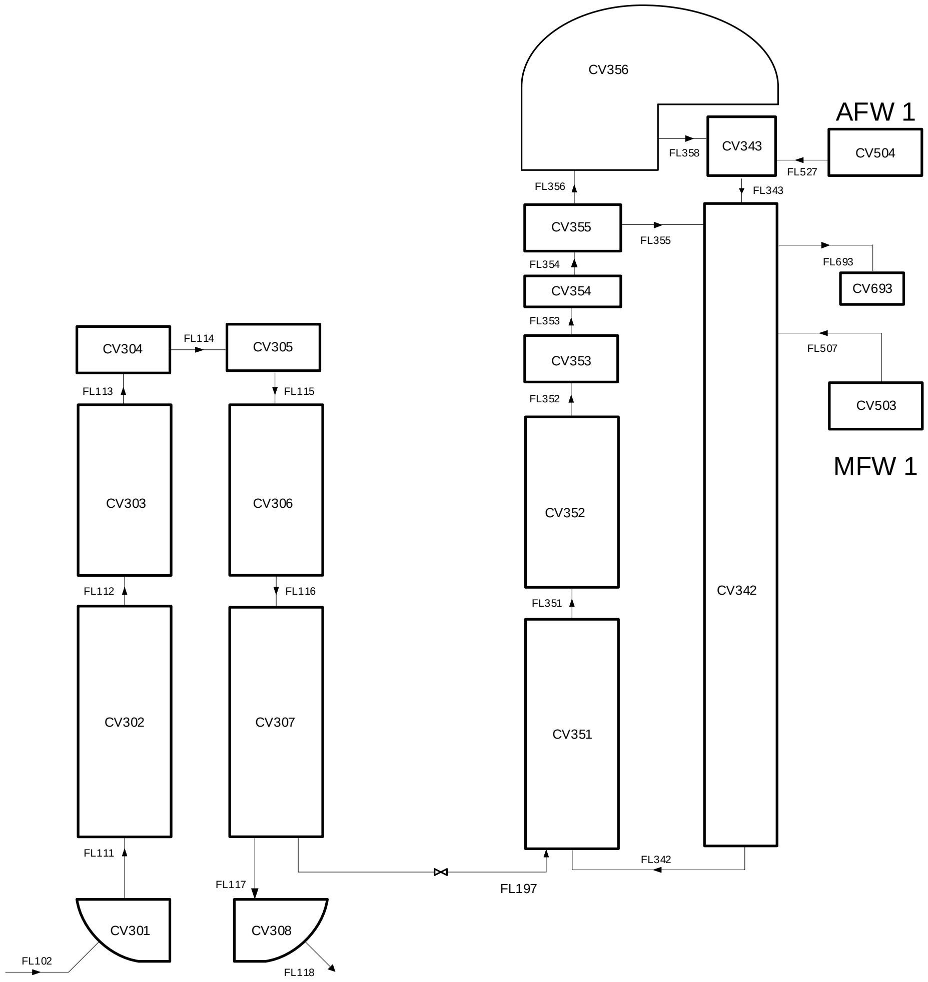


SGTR scenario:

- Valve in FL127 closes
- Valves in FL197 and FL198 open.

For the break on the hot leg side the more detailed nodalization is for SG inlet plenum.

MELCOR nodalization using simple leakage from the tube outlet



SGTR scenario:

- Valve in FL197 opens

Analysis of SGTR accident for NPP Krško using MELCOR code – transient description

Initial and boundary conditions:

- Double ended break of one tube at the top of the tube sheet. Accident started with the opening of two valves at the ends of affected tube to SG 1 riser bottom (volume 351) and by closing an artificial valve that connects volume 327 (322 for hot leg side break) and volume 320.
- reactor trip from 100% power (on low pressurizer pressure), turbine trip on reactor trip
- Station black-out after reactor trip (w/o RCP seal leakage): RCPs trip (on reactor trip), feedwater closure on reactor trip (trip of MFW), AFW pumps N/A)
- steam dump turned off, charging and letdown flows turned off,
- Mitigation action including containment spray (one train) one day after transient begin.
- Available systems after reactor trip and prior to mitigation: accumulators, pressurizer safety valves, SG safety valves, PCFV system, Passive autocatalytic recombiners (PARs).

Analysis of SGTR – Main events

- Following the SGTR initiation the primary pressure decreases and low-1 pressurizer pressure signal trips the reactor.
- Turbine trip is actuated on reactor trip and the pressure on the secondary side rises. Safety valves on the secondary side open and the heat is removed by SGs safety valves as long as there is enough inventory on the secondary side. Since auxiliary feedwater is not available the heat sink (SGs) will eventually be lost.
- Inventory from the primary side is constantly being lost through the break. This, together with the fact that the heat sink on the secondary side is lost, leads finally to core heat-up, core cladding oxidation, melting of the fuel and of structures in the RPV.
- Accumulators open after RPV lower head failure.
- Pressure rises in the containment due to evaporation of the water in the cavity after accumulator injection on one side and on the other side due to MCCI reaction.
- One day after transient begin containment spray (one train) is enabled. This leads to steep containment pressure decrease. After RWST had been depleted the containment spray pumps take suction from containment sump.
- In this analysis the PCFV did not open.

Analysis of SGTR – cold leg side SGTR

Table 1: Time sequence of main events cold leg side break

Event	RELAP5 (0-12000 s)	MELCOR 1.8.6 (double-ended)	MELCOR 1.8.6 (leakage)	MELCOR 1.8.6 (simple leakage)	MELCOR 2.2.14959 (double-ended)	MELCOR 2.2.14959 (simple leakage)
Reactor trip (on low-1 PRZ pressure signal)	218.8 s	227.23 s	229.87 s	212.1 s	229.7 s	212.0
Loss of offsite power	218.8 s	227.23 s	229.87 s	212.1 s	229.7 s	212.0
The core has uncovered	9929 s	9500 s	9800 s	8900 s	8900 s	9370 s
SGs depleted	9940 s (SG 1)/7500 s (SG 2)	11160 s (SG 1)/6130 s (SG 2)	10000 s/SG 1)/5800 s (SG 2)	10980 s (SG 1)/6080 s (SG 2)	10520 s (SG 1)/6100 s (SG 2)	10740 s (SG 1)/6080 s (SG 2)
Lower head failure (LHF)	-	18564.5 s	18464.0 s	17870 s	17421 s	19510 s
Accumulators (1/2) empty	-	18586 s	18480 s	18110 s	17457 s	19546 s
Begin of mitigation (containment spray)	-	86400 s	86400 s	86400 s	86400 s	86400 s
PCFV rupture disc broken	-	-	-	-	-	-

Analysis of SGTR – hot leg side SGTR

Table 2: Time sequence of main events hot leg side break

Event	RELAP5 (0-12000 s)	MELCOR 1.8.6 (double-ended)	MELCOR 1.8.6 (simple leakage)	MELCOR 2.2.14959 (double-ended)	MELCOR 2.2.14959 (simple leakage)
Reactor trip (on low-1 PRZ pressure signal)	222.8 s	269.1 s	256.6 s	268.8 s	256.4
Loss of offsite power	222.8 s	269.1 s	256.6 s	268.8 s	256.4
The core has uncovered	9720 s	10000 s	9910 s	8900 s	9630 s
SGs depleted	9750 s (SG 1)/7470 s (SG 2)	7754 s (SG 1)/6137 s (SG 2)	10770 s (SG 1)/6185 s (SG 2)	10520 s (SG 1)/6100 s (SG 2)	10270 s (SG 1)/6160 s (SG 2)
Lower head failure (LHF)	-	18835 s	18630 s	17721 s	18597 s
Accumulators (1/2) empty	-	19000 s	18800 s	17972 s	18629 s
Begin of mitigation (containment spray)	-	86400 s	86400 s	86400 s	86400 s
PCFV rupture disc broken	-	-	-	-	-

Analysis of SGTR – Comparison of MELCOR 1.8.6 with RELAP5 – cold leg side SGTR

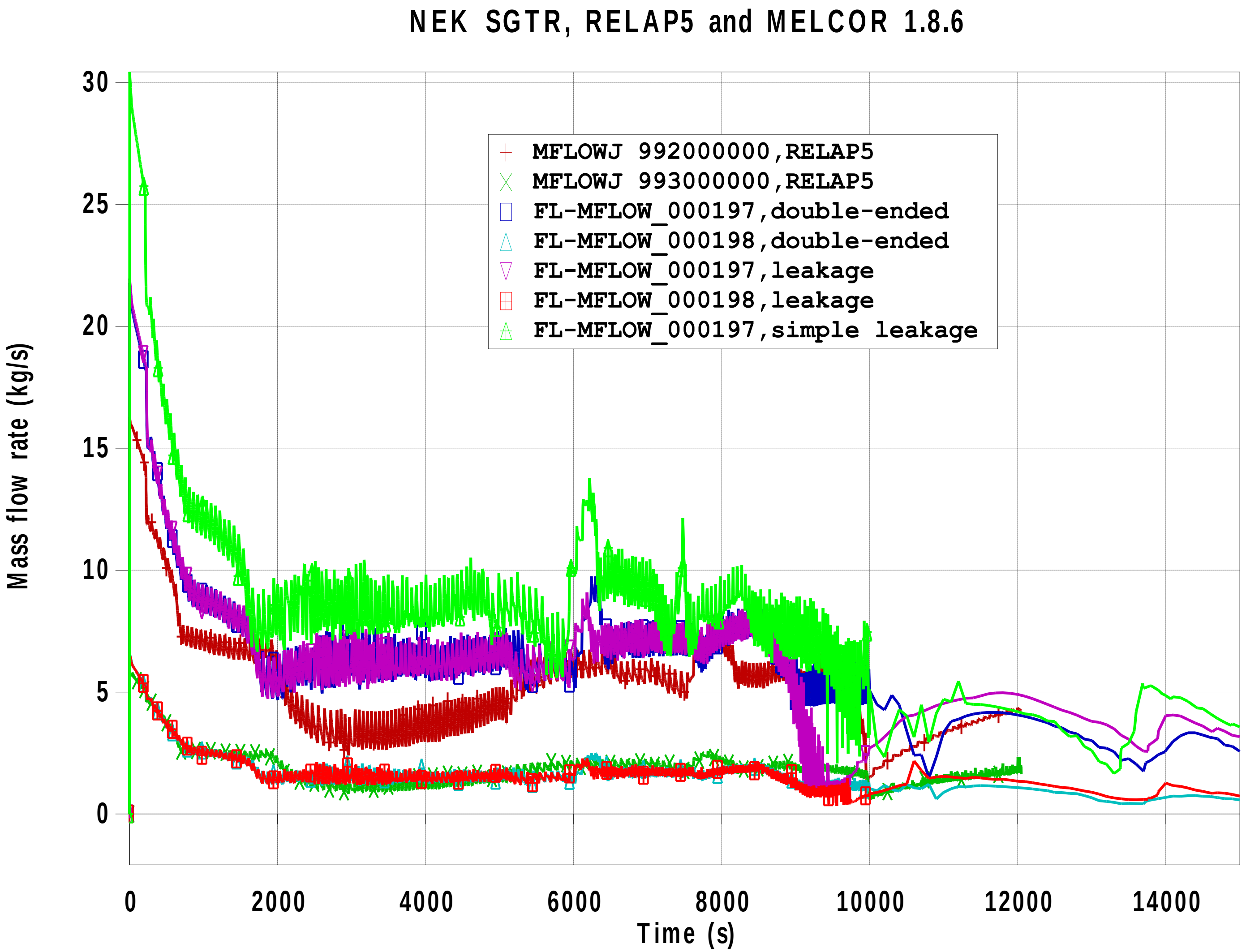


Figure 1: Break mass flow rate; 197, 992 – RC pump side, 198, 993 – hot leg side

Analysis of SGTR – Comparison of MELCOR 1.8.6 with RELAP5 – cold leg side SGTR

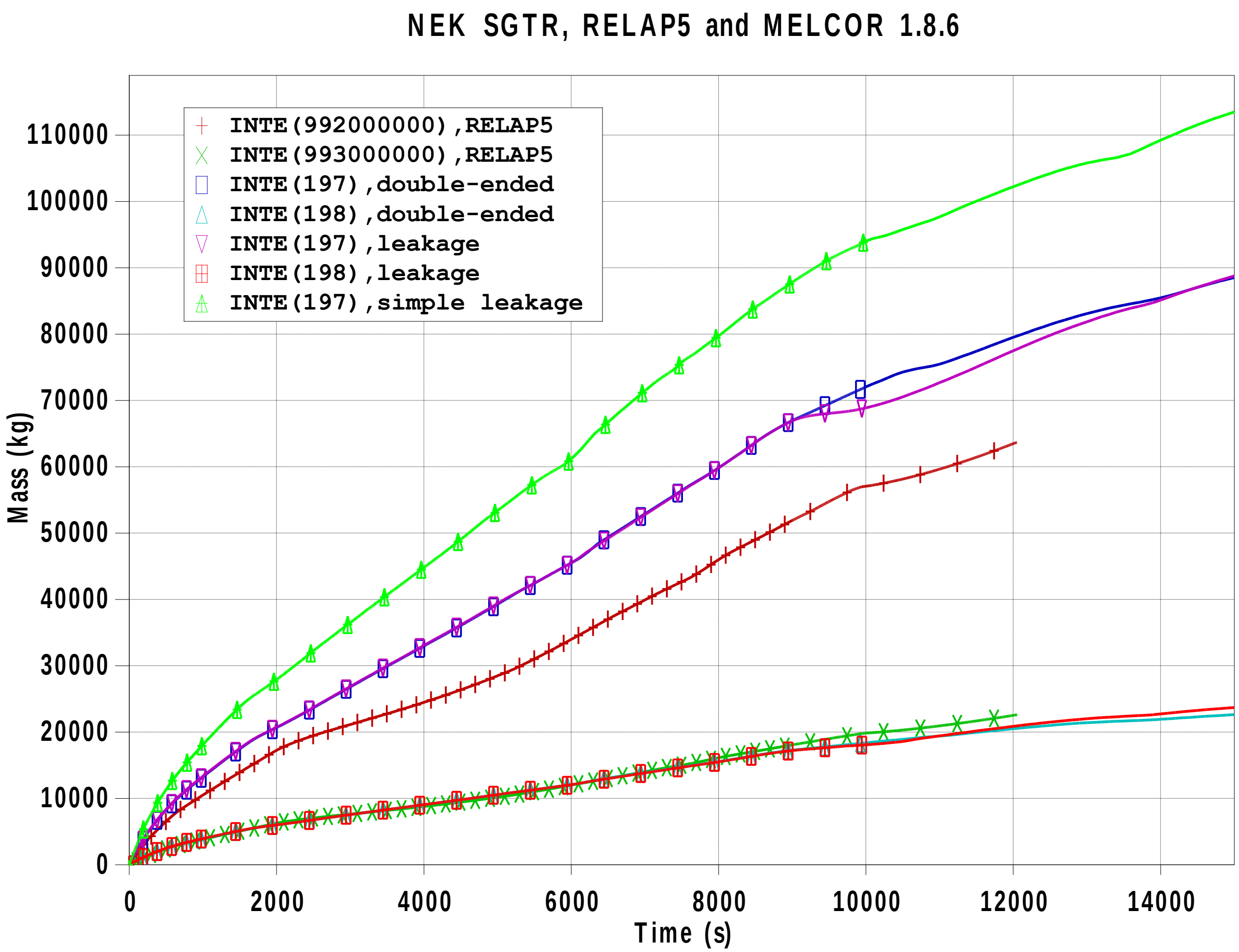


Figure 2: Integral of break flow; 197, 992 – RC pump side, 198, 993 – hot leg side

Analysis of SGTR – Comparison of MELCOR 2.2.14959 with RELAP5 – cold leg side SGTR

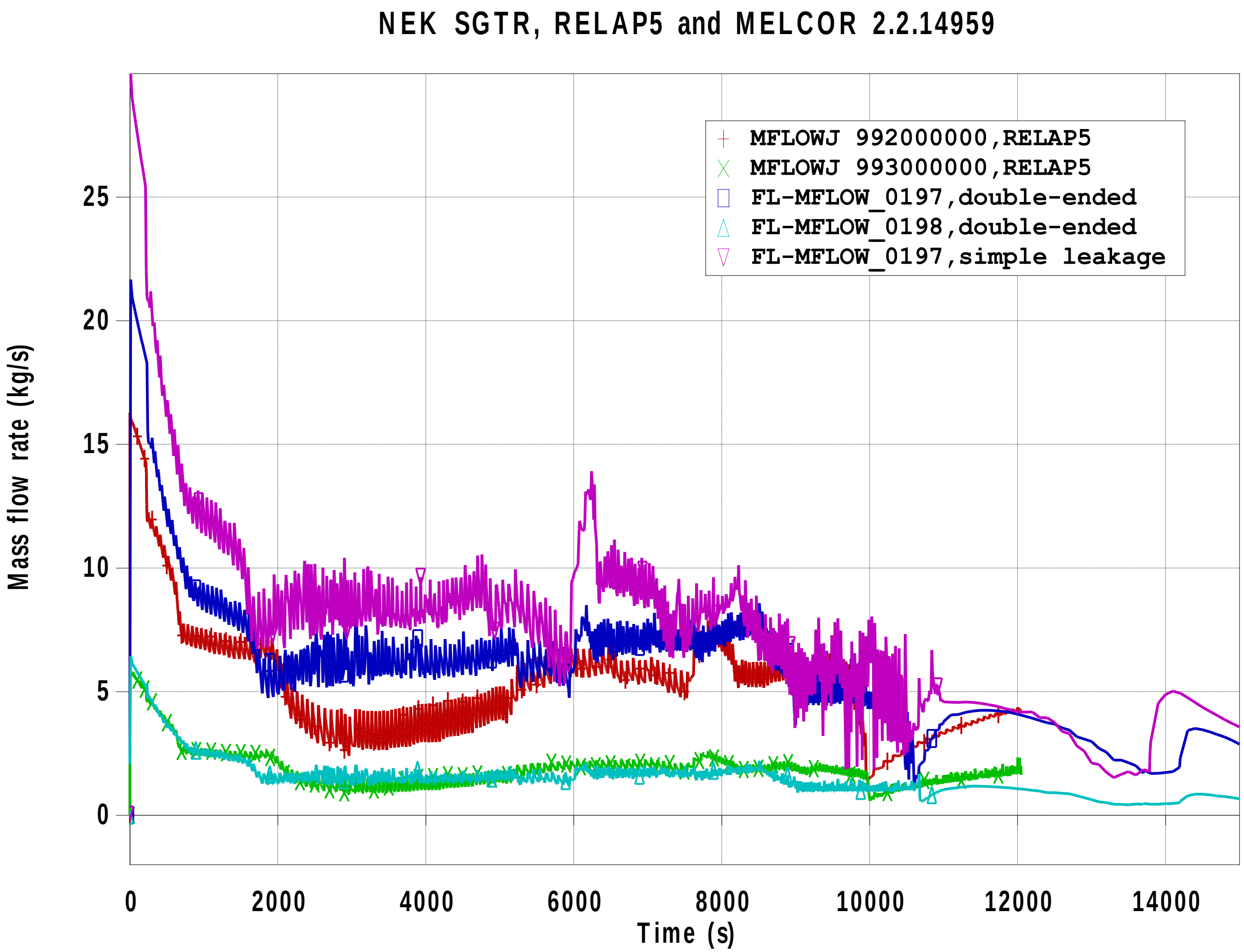


Figure 3: Break mass flow rate; 197, 992 – RC pump side, 198, 993 – hot leg side

Analysis of SGTR – Comparison of MELCOR 2.2.14959 with RELAP5 – cold leg side SGTR

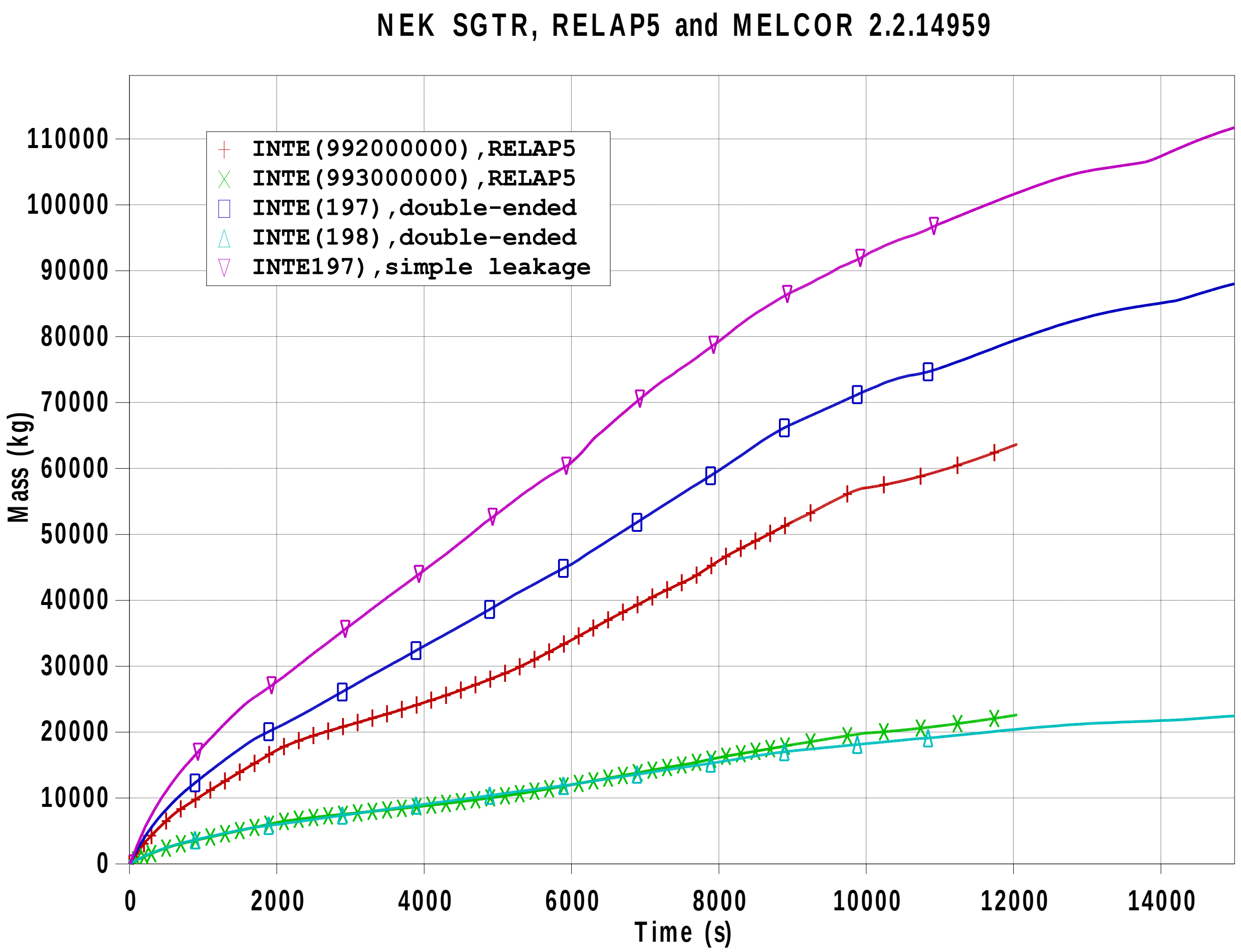


Figure 4: Integral of break flow; 197, 992 – RC pump side, 198, 993 – hot leg side

Analysis of SGTR – Comparison of MELCOR 1.8.6 with RELAP5 – hot leg side SGTR

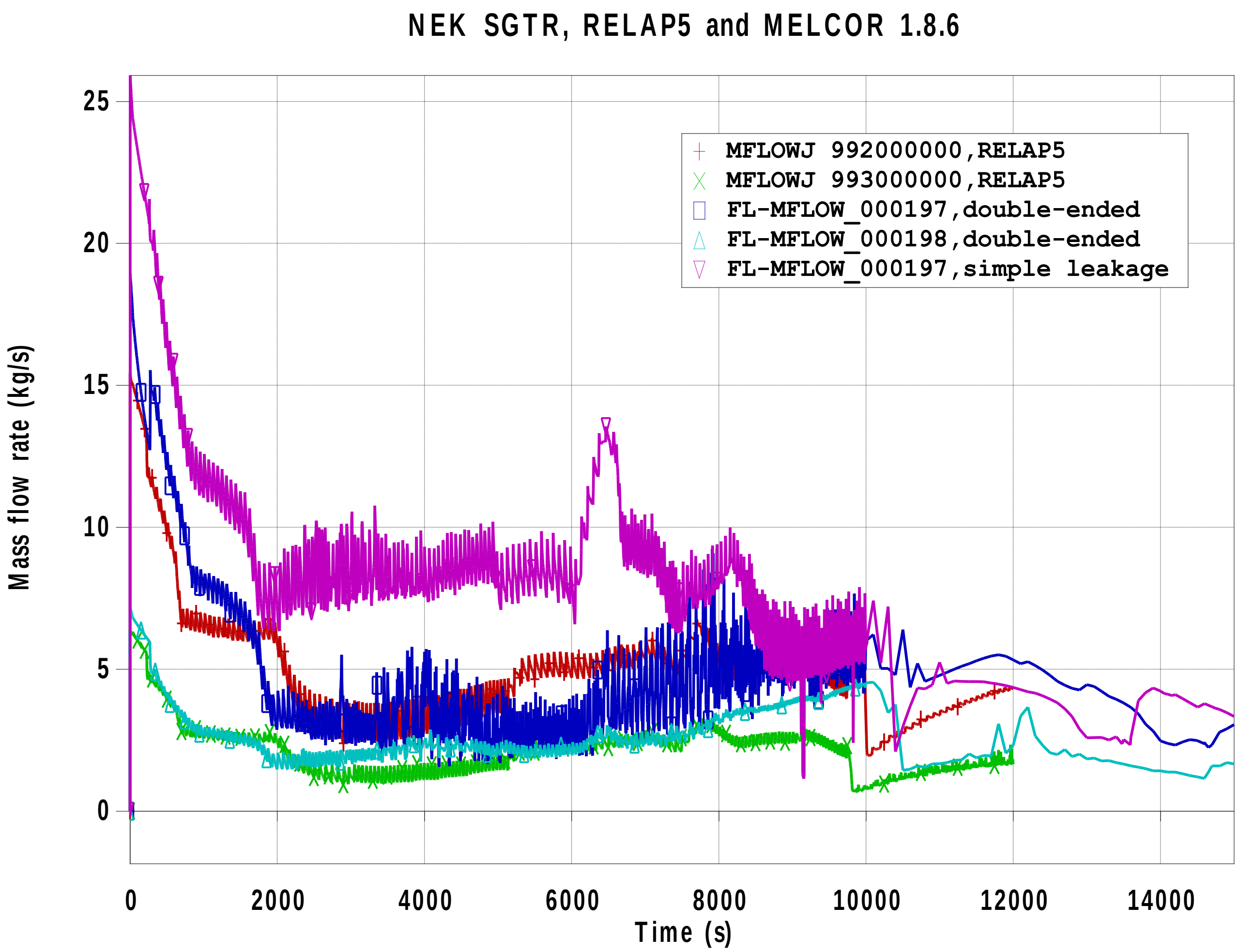


Figure 5: Break mass flow rate; 197, 992 – RPV side, 198, 993 – SG side

Analysis of SGTR – Comparison of MELCOR 1.8.6 with RELAP5 – hot leg side SGTR

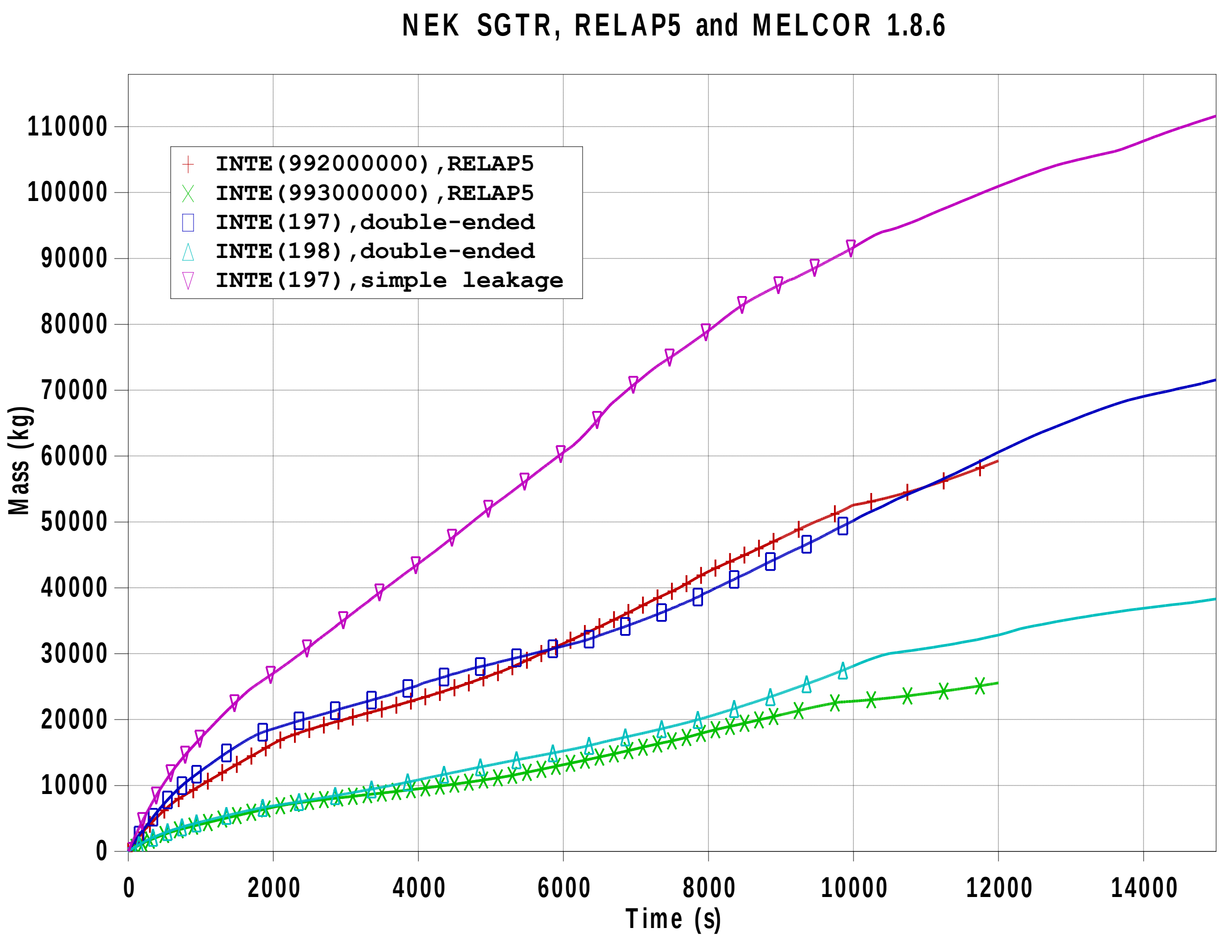


Figure 6: Integral of break flow; 197, 992 – RPV side, 198, 993 – SG side

Analysis of SGTR – Comparison of MELCOR 2.2.14959 with RELAP5 – hot leg side SGTR

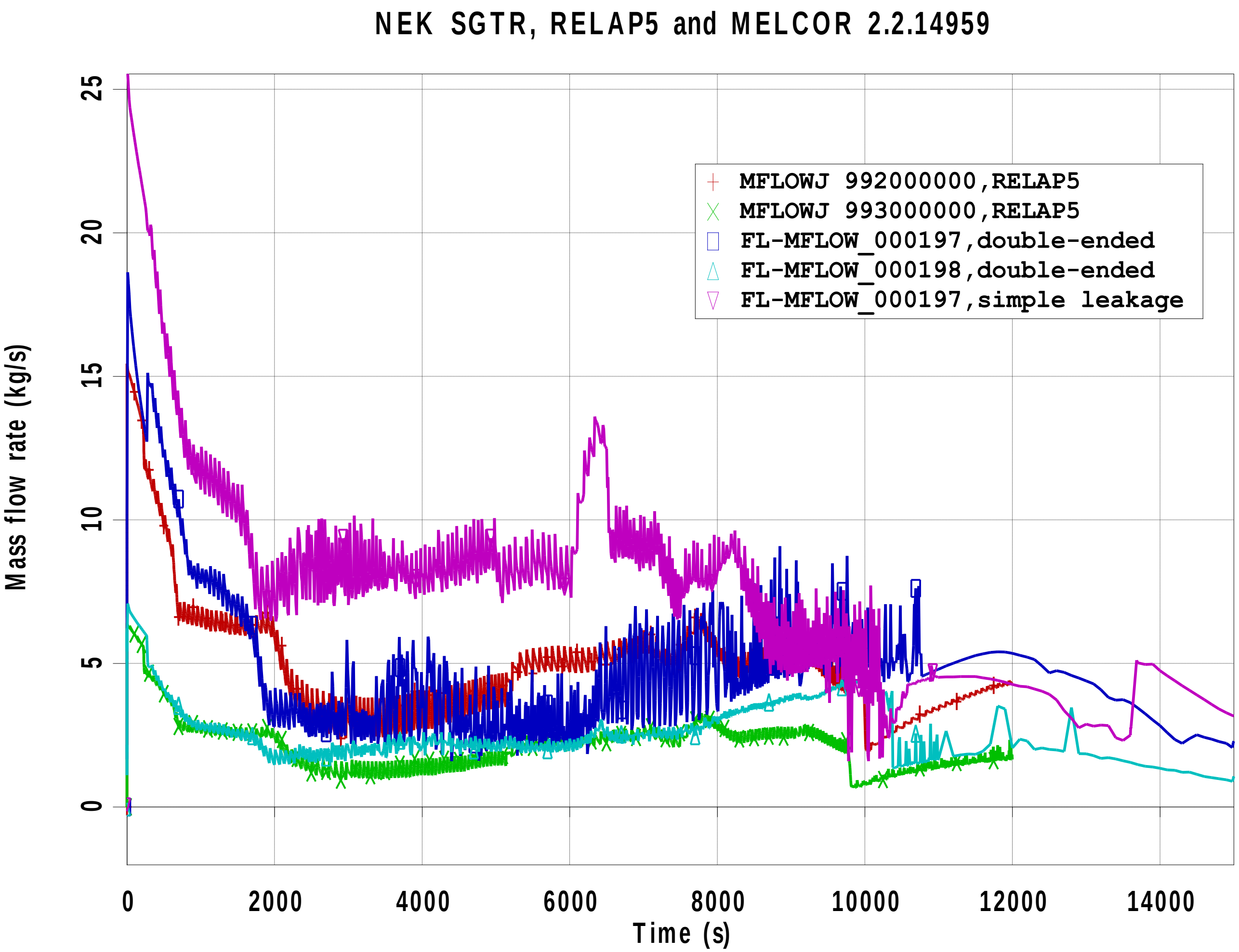


Figure 7: Break mass flow rate; 197, 992 – RPV side, 198, 993 – SG side

Analysis of SGTR – Comparison of MELCOR 2.2.14959 with RELAP5 – hot leg side SGTR

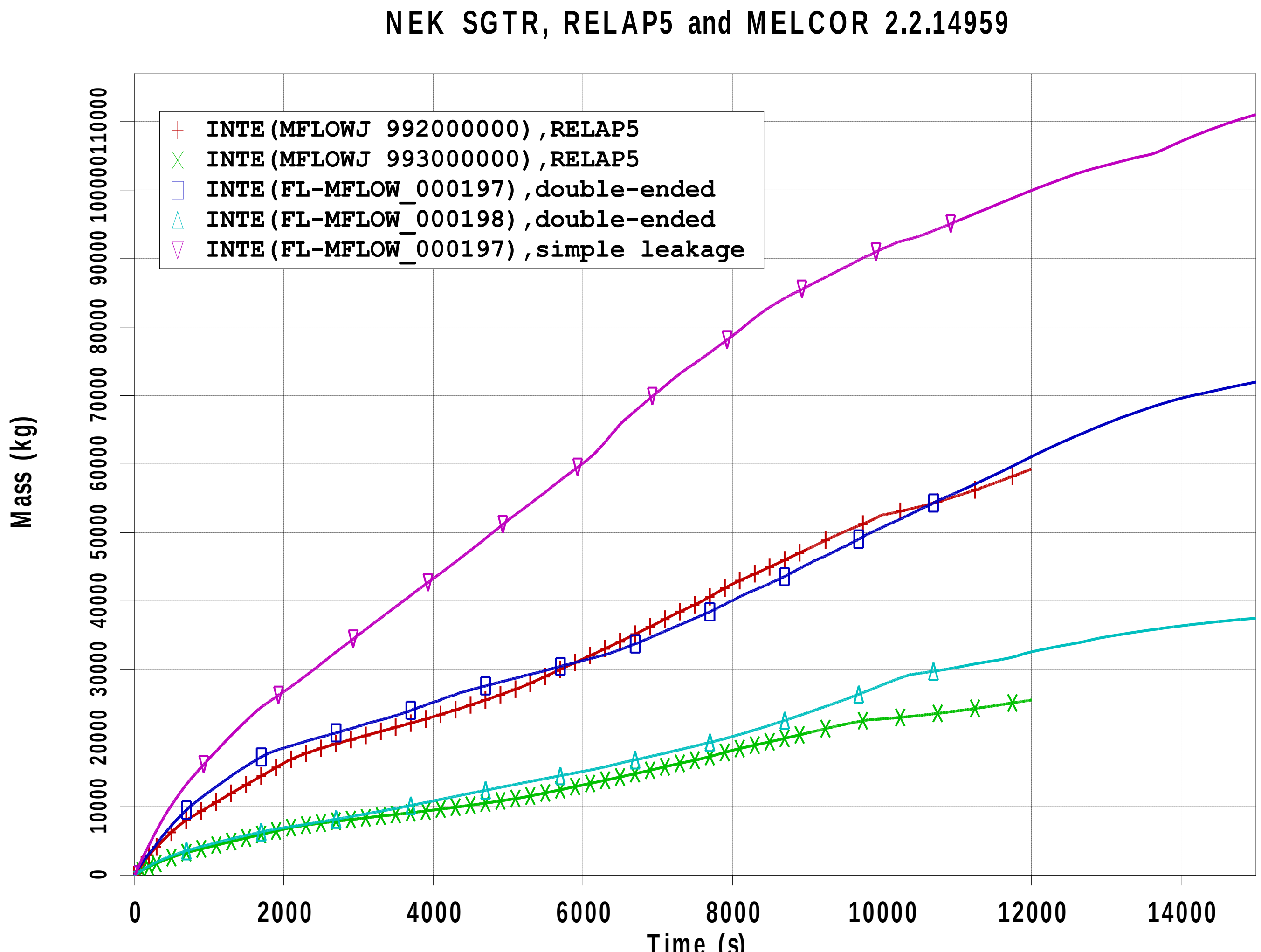


Figure 8: Integral of break flow; 197, 992 – RPV side, 198, 993 – SG side

Analysis of SGTR – Comparison of MELCOR with RELAP5 – cold leg side SGTR

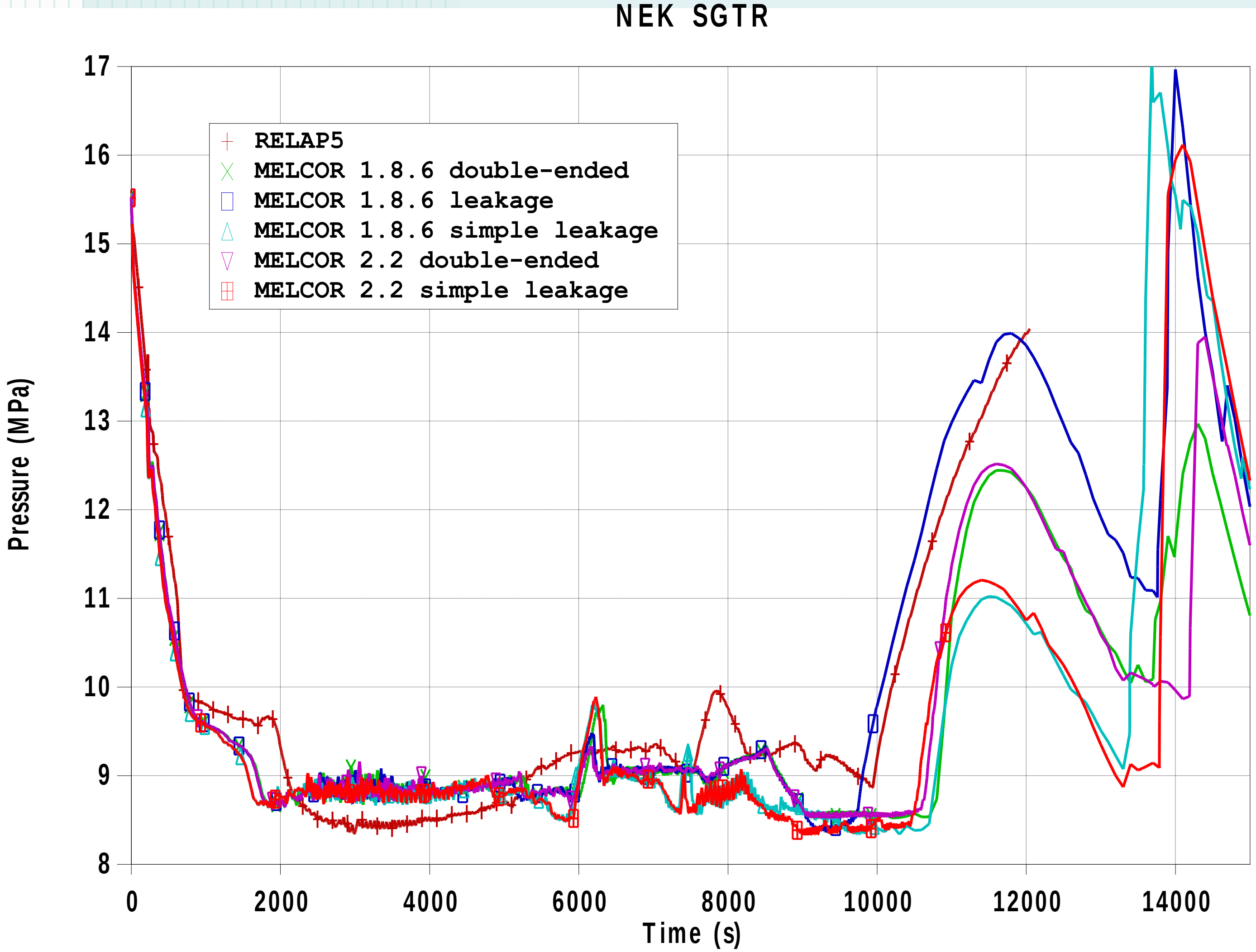


Figure 9: Pressurizer pressure

Analysis of SGTR – Comparison of MELCOR 1.8.6 double-ended break with RELAP5 – cold leg side SGTR

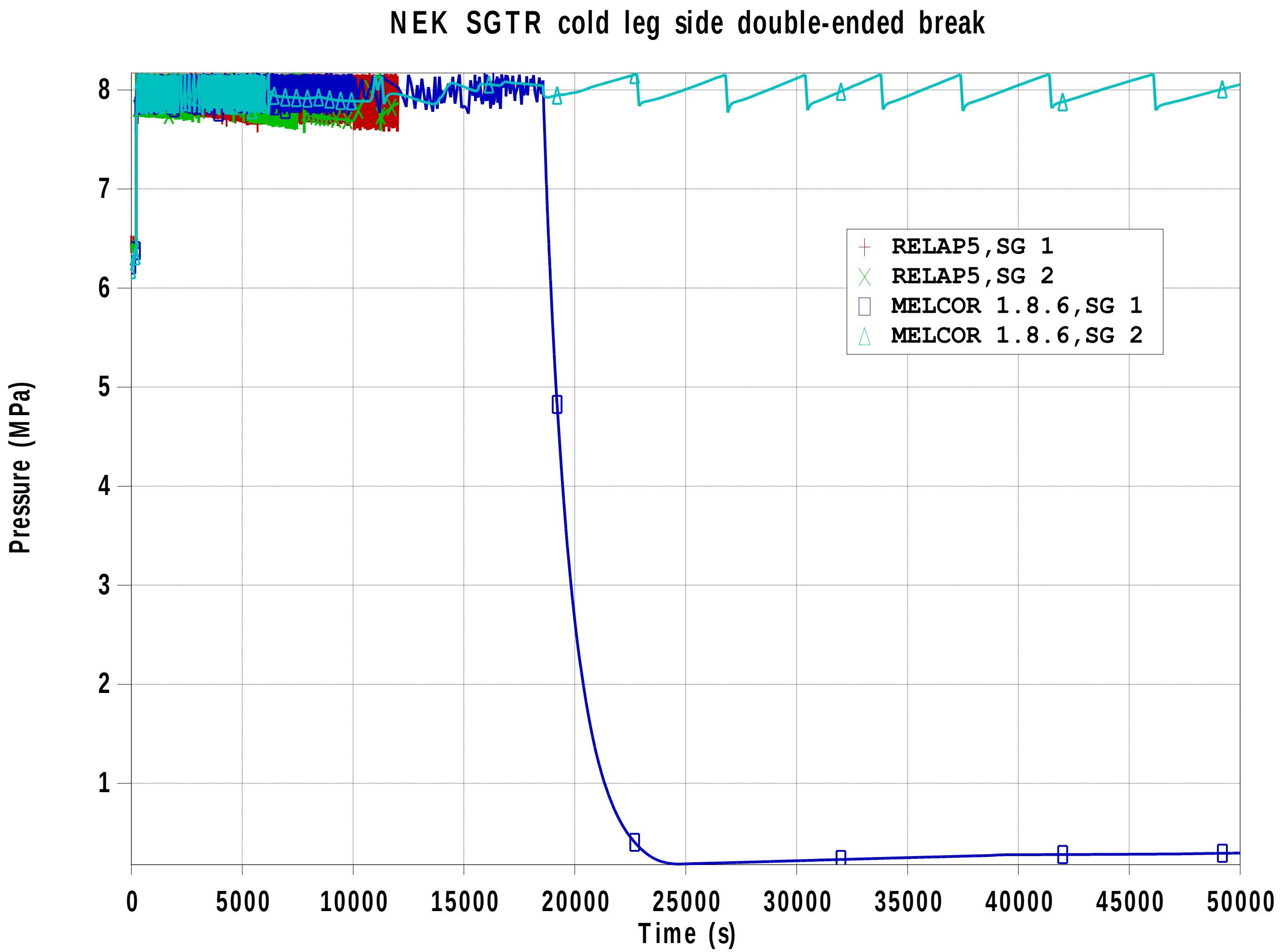


Figure 10: Steam generator pressure

Analysis of SGTR – Comparison of MELCOR 1.8.6 double-ended break with RELAP5 – cold leg side SGTR

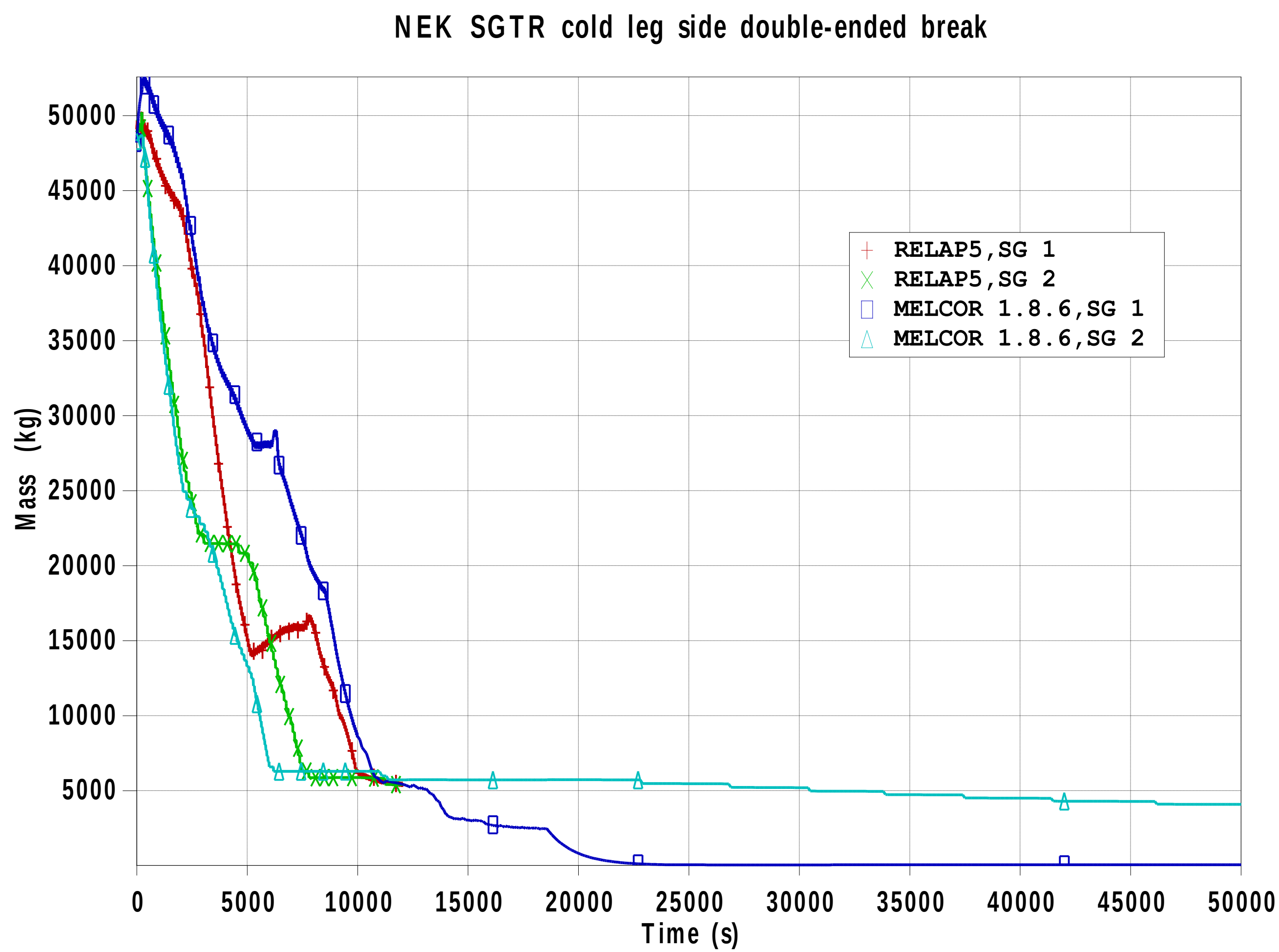


Figure 11: Steam generator mass

Analysis of SGTR – Comparison of MELCOR with RELAP5 – hot leg side SGTR

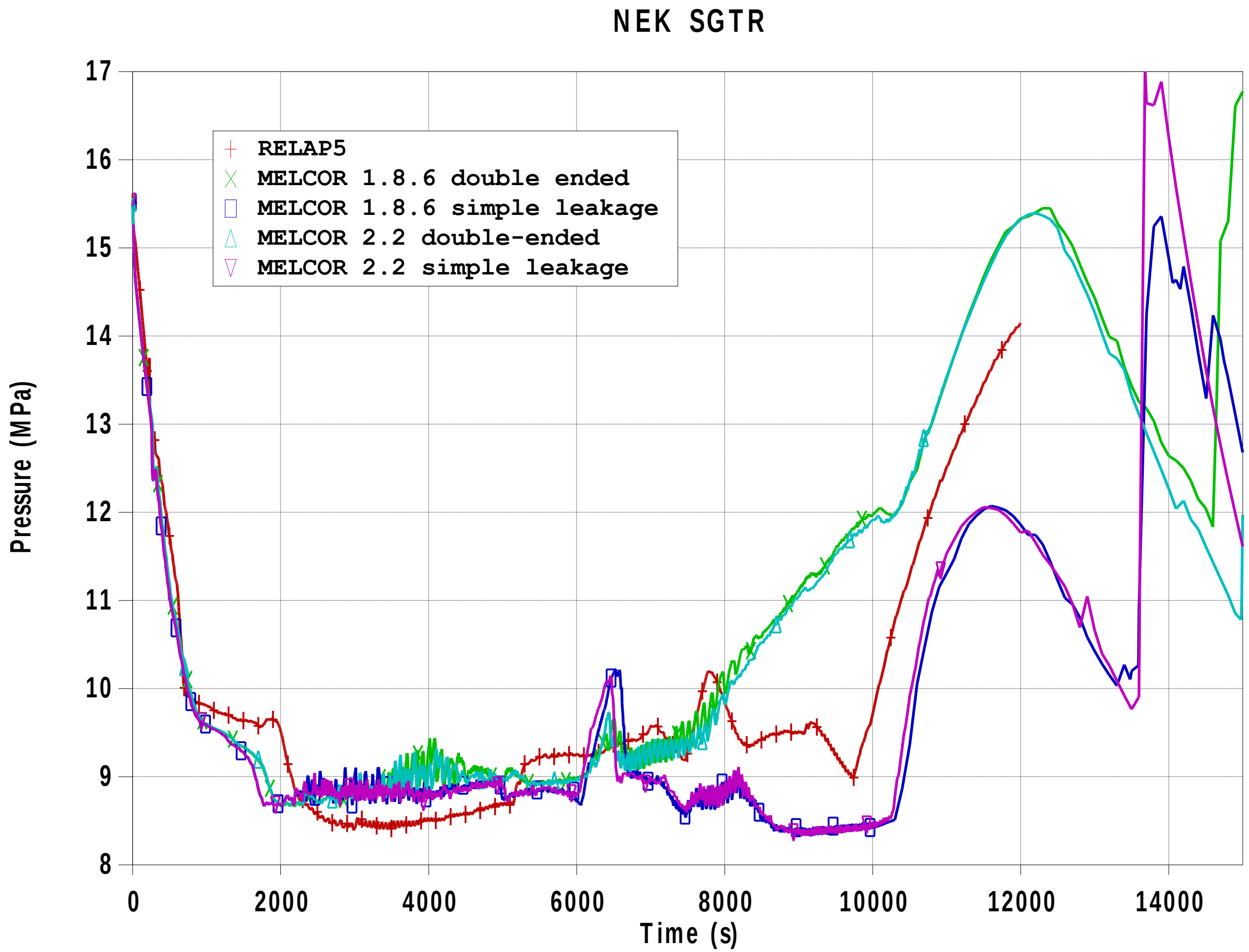


Figure 12: Pressurizer pressure

Analysis of SGTR – Break flow void fraction, double-ended break

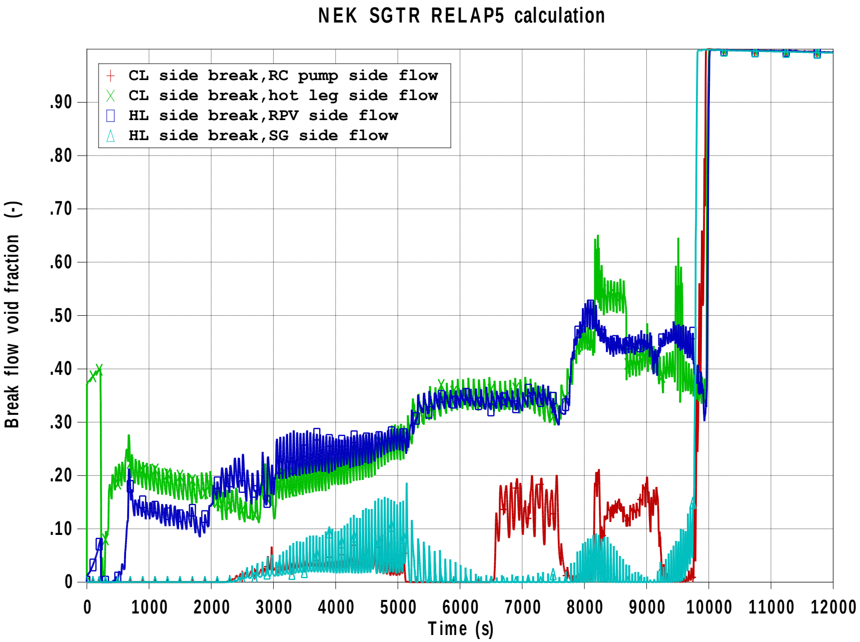


Figure 13: Break flow void fraction, RELAP5

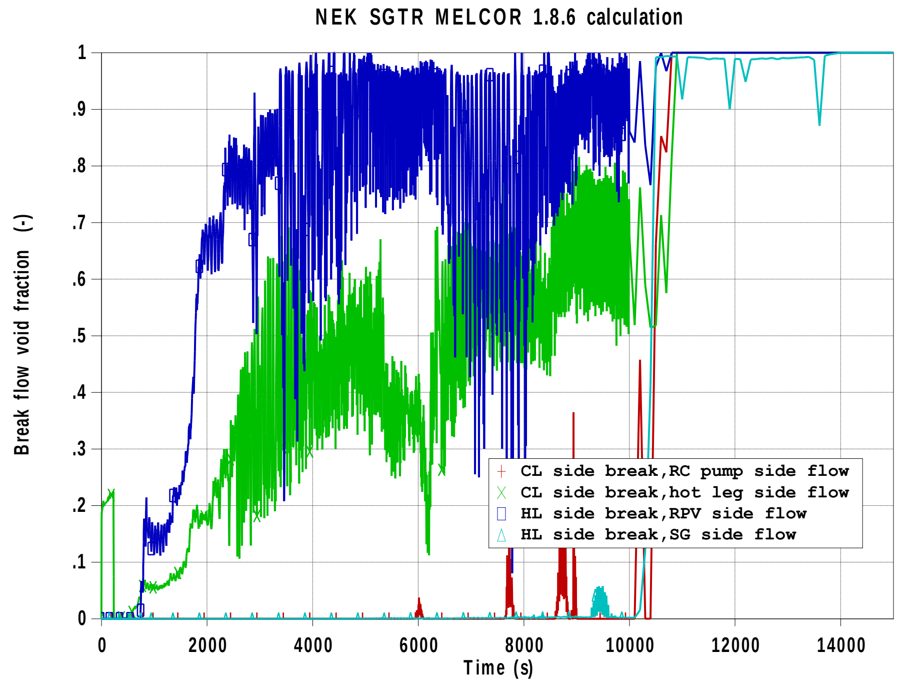


Figure 14: Break flow void fraction, MELCOR 1.8.6

Analysis of SGTR – Released radioactive aerosol mass through SG 1 safety valve - cold leg side SGTR, MELCOR 1.8.6, double-ended

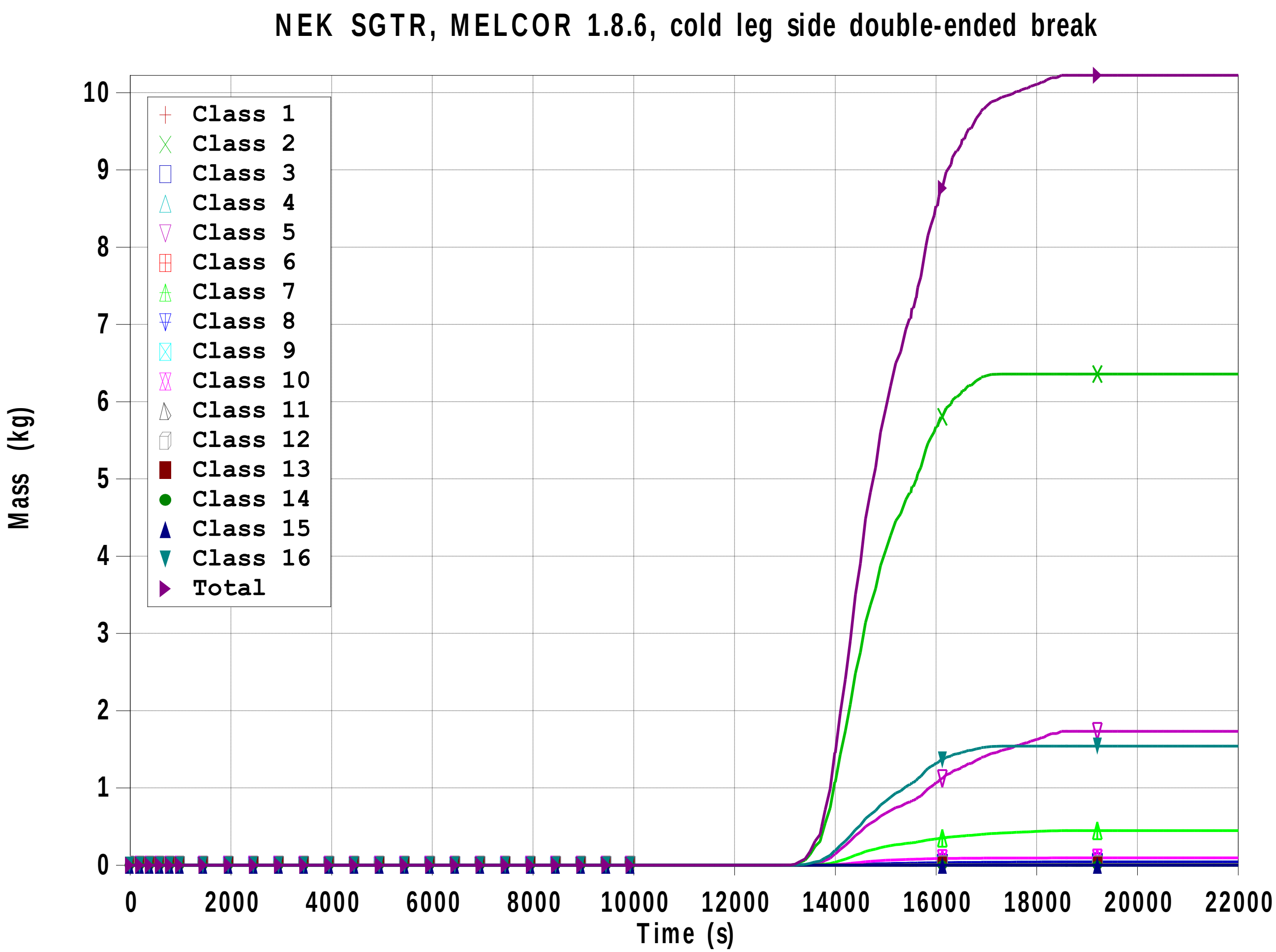


Figure 15: Released radioactive aerosol mass

Analysis of SGTR – Total released radioactive mass through SG 1 safety valve - cold leg side SGTR, MELCOR 1.8.6, double-ended

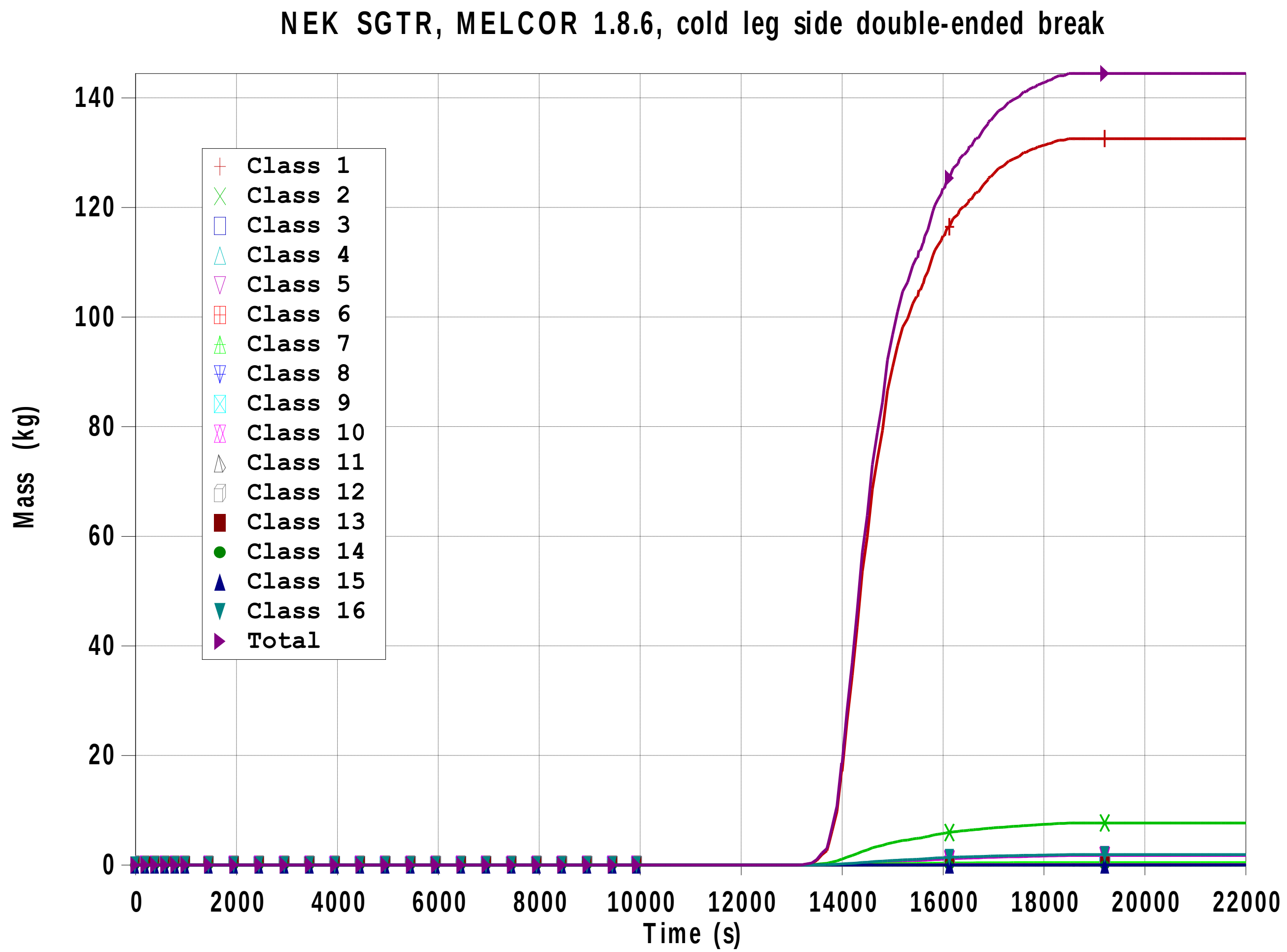


Figure 16: Total released radioactive mass

Analysis of SGTR – Released radioactive aerosol mass through SG 1 safety valve - cold leg side SGTR, MELCOR 2.2, double-ended

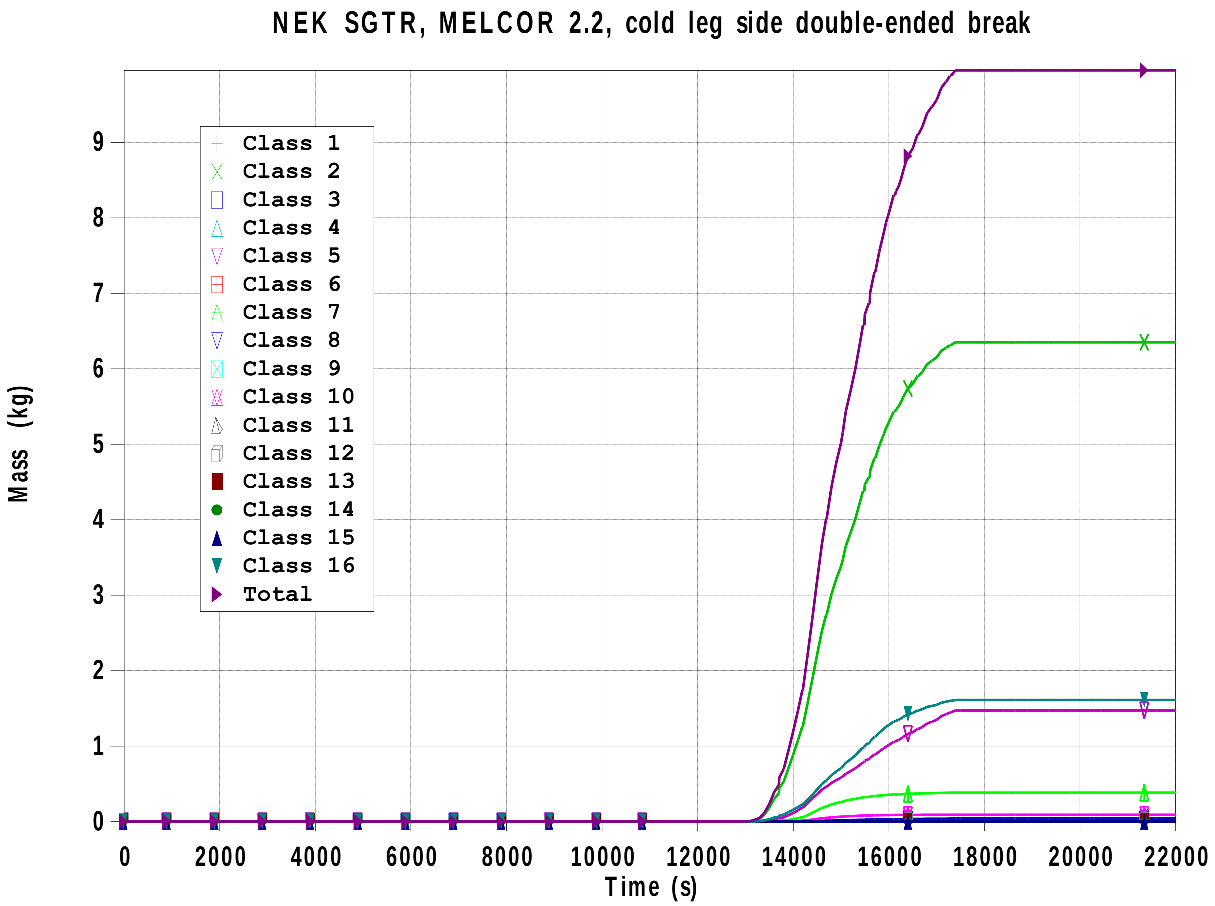


Figure 17: Released radioactive aerosol mass

Analysis of SGTR – Total released radioactive mass through SG 1 safety valve - cold leg side SGTR, MELCOR 2.2, double-ended

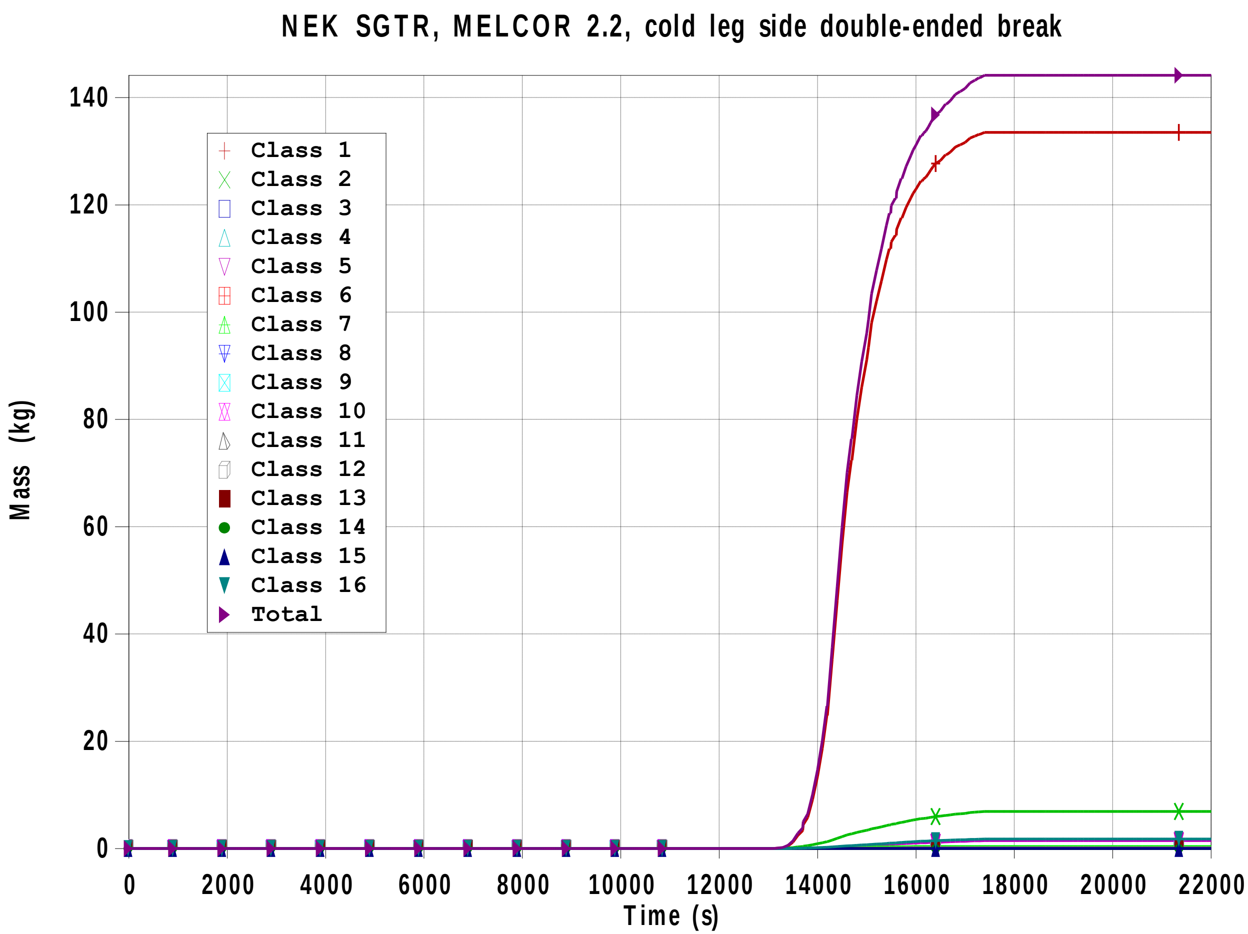


Figure 18: Total released radioactive mass

Analysis of SGTR – Released radioactive aerosol mass through SG 1 safety valve - hot leg side SGTR, MELCOR 1.8.6, double-ended

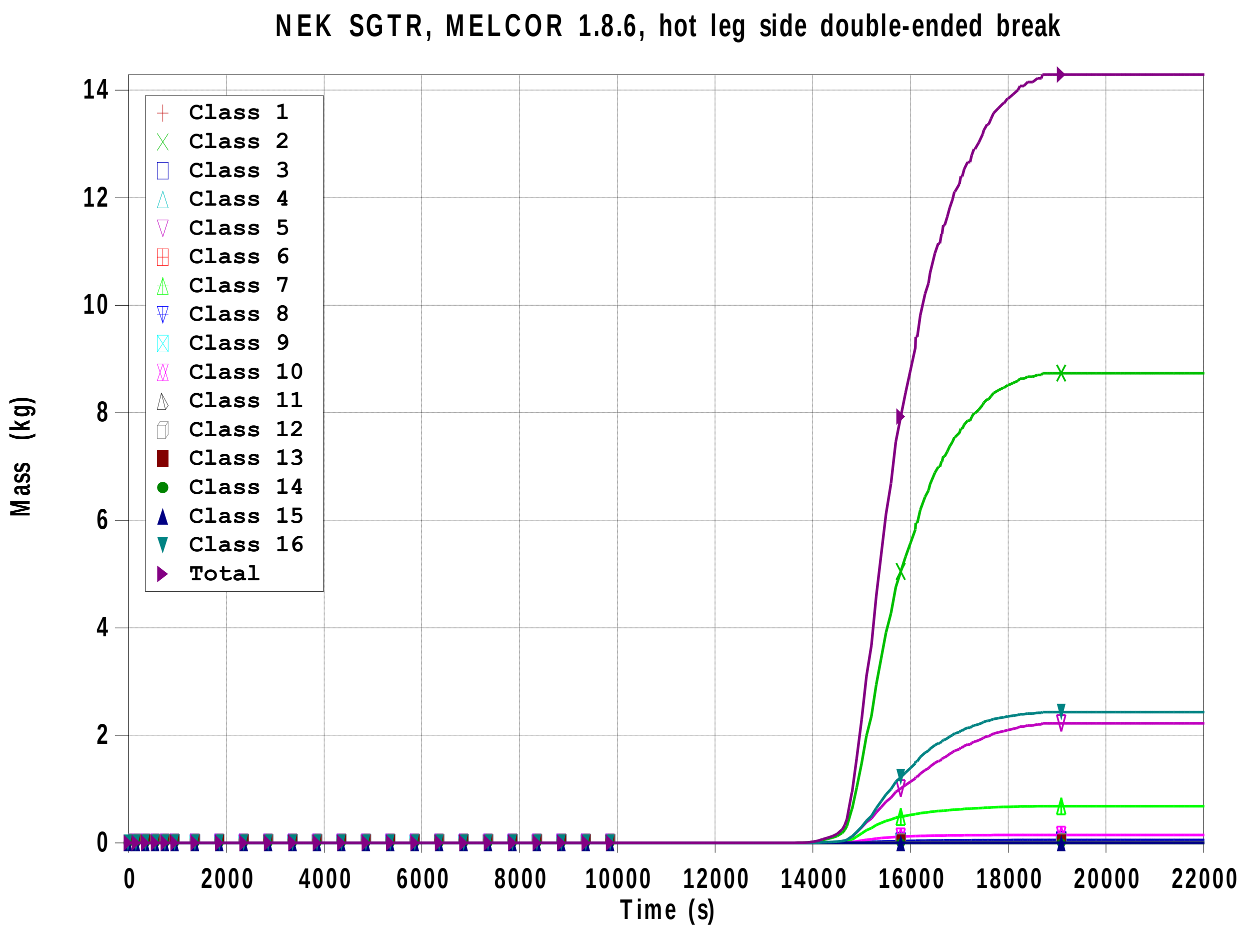


Figure 19: Released radioactive aerosol mass

Analysis of SGTR – Total released radioactive mass through SG 1 safety valve - hot leg side SGTR, MELCOR 1.8.6, double-ended

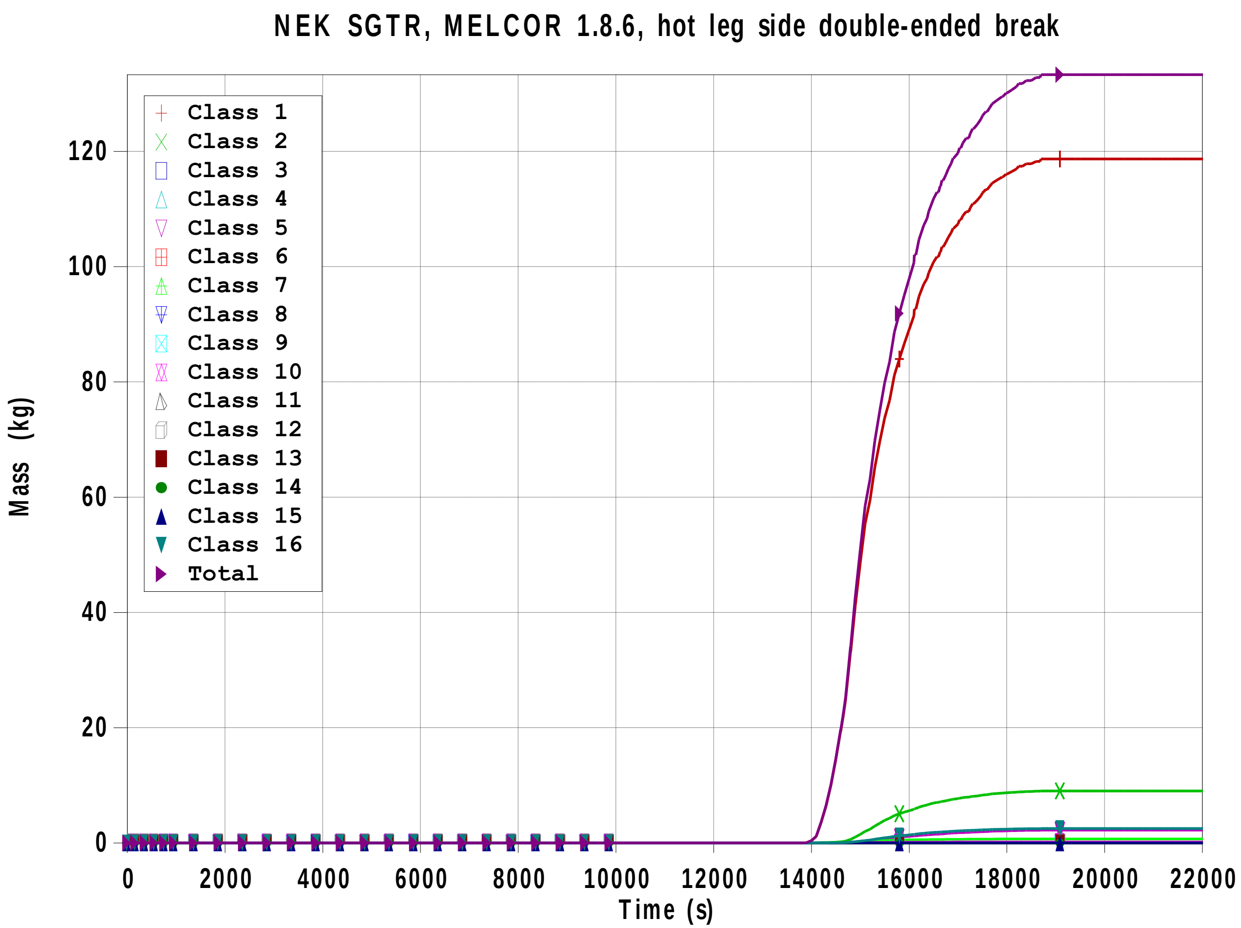


Figure 20: Total released radioactive mass

Analysis of SGTR – Released radioactive aerosol mass through SG 1 safety valve - hot leg side SGTR, MELCOR 2.2, double-ended

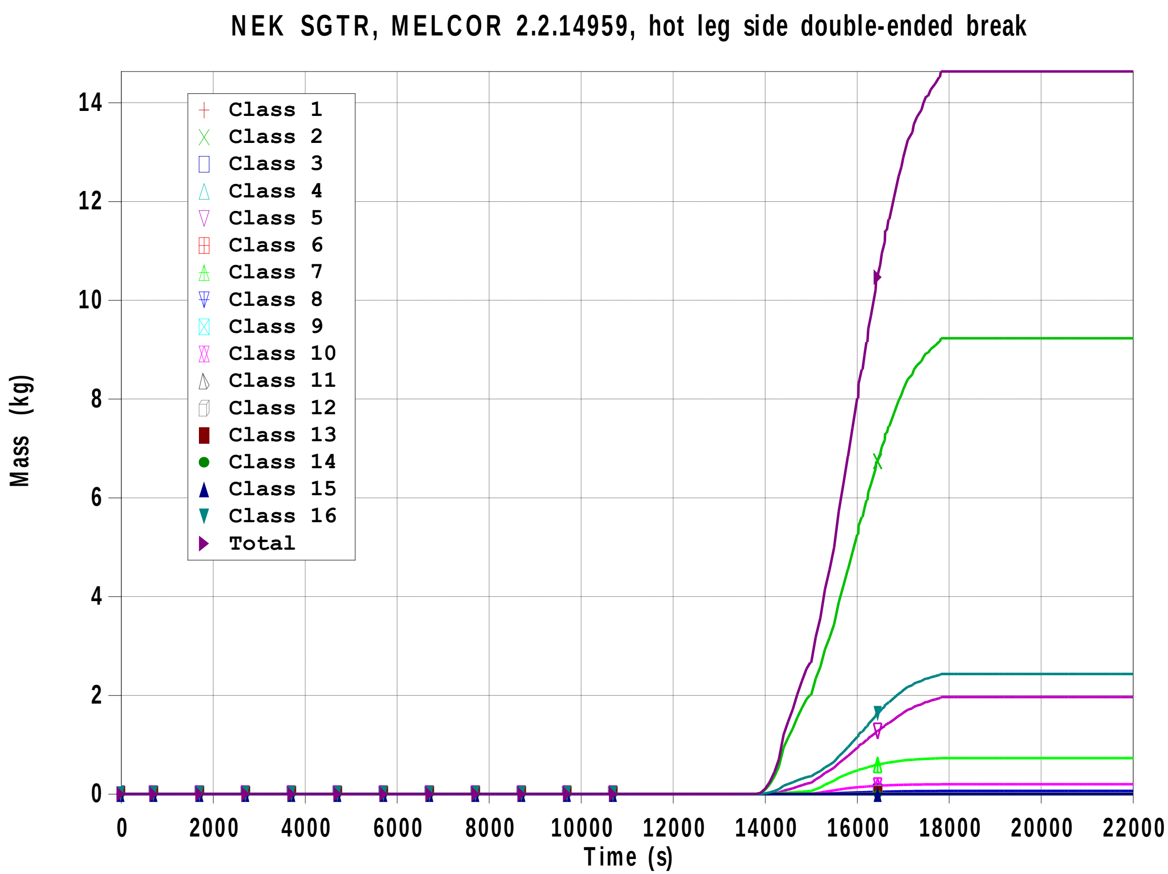


Figure 21: Released radioactive aerosol mass

Analysis of SGTR – Total released radioactive mass through SG 1 safety valve - hot leg side SGTR, MELCOR 2.2, double-ended

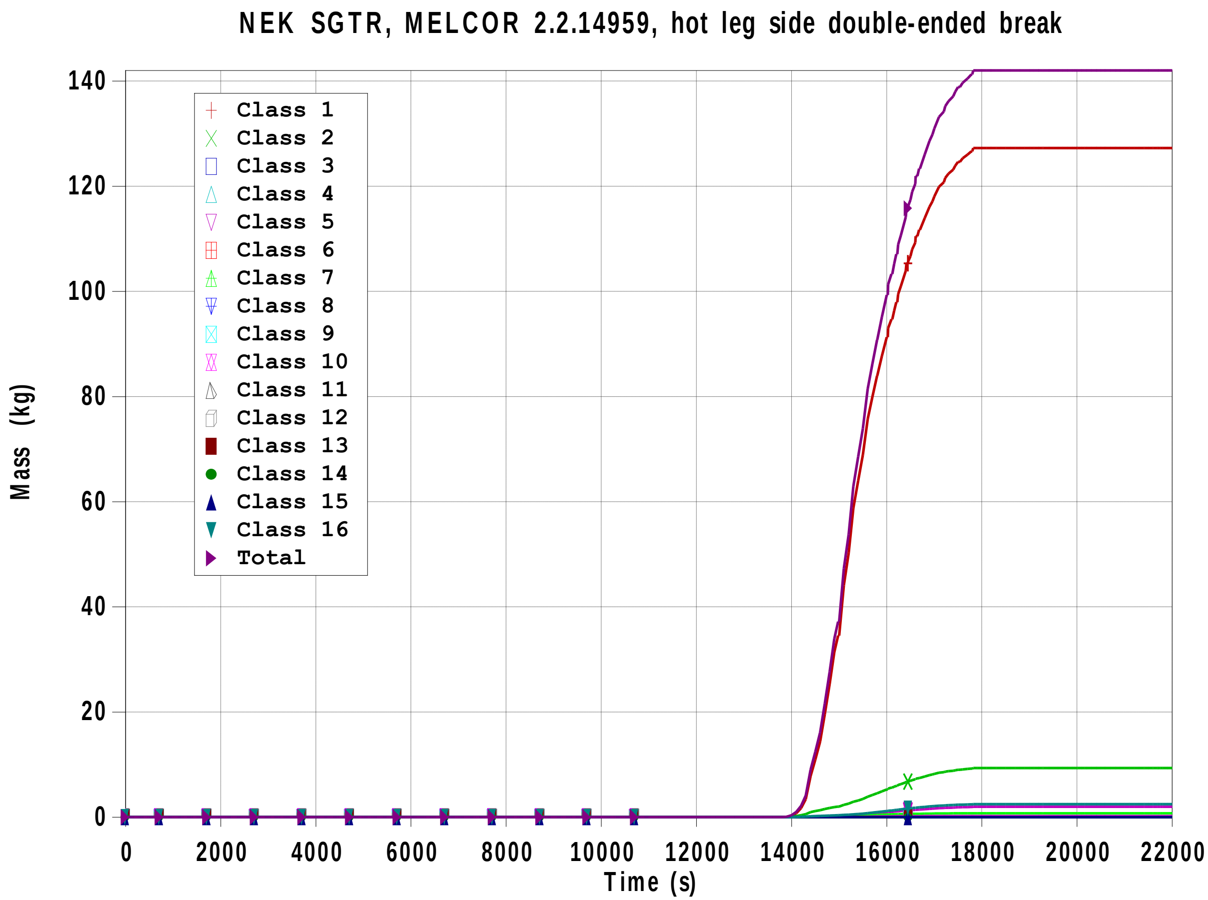


Figure 22: Total released radioactive mass

Analysis of SGTR – Discharged mass through SG 1 safety valve

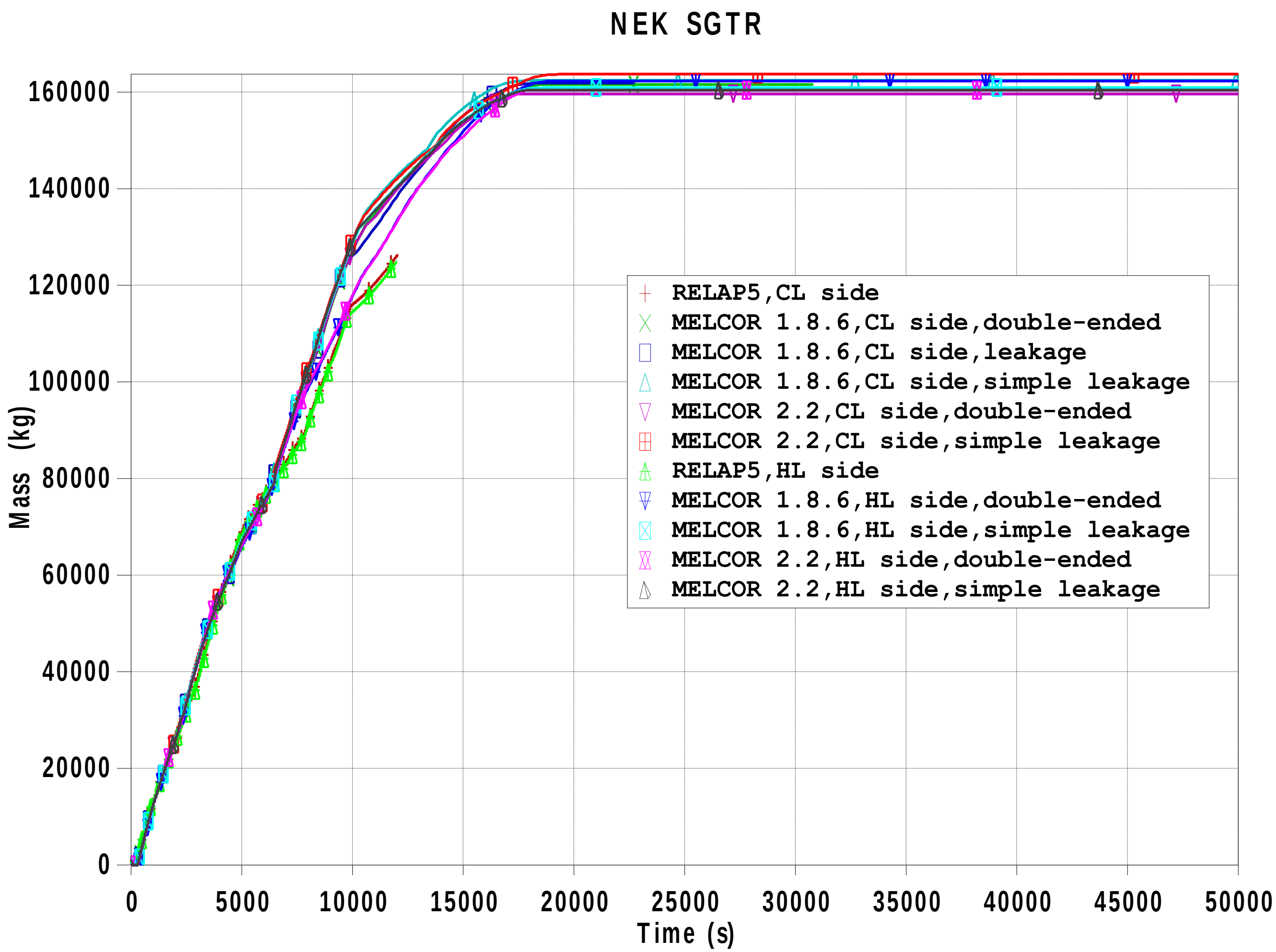


Figure 23: Discharged mass through SG 1 safety valve

Analysis of SGTR – Released radioactive aerosol mass through SG 1 safety valve - cold leg side SGTR

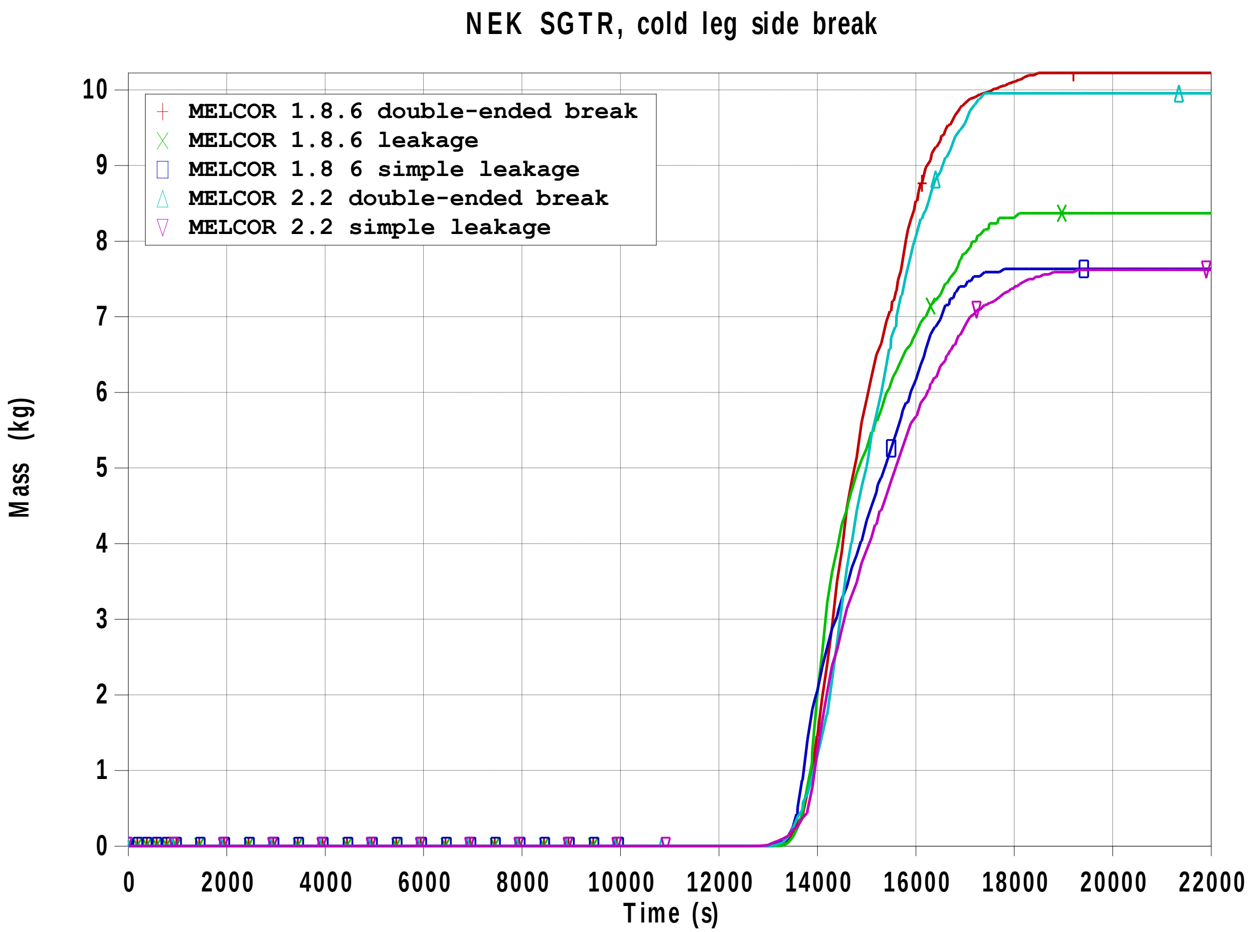


Figure 24: Released radiaoctive aerosol mass through SG 1 safety valve

Analysis of SGTR – Released radioactive mass through SG 1 safety valve - cold leg side SGTR

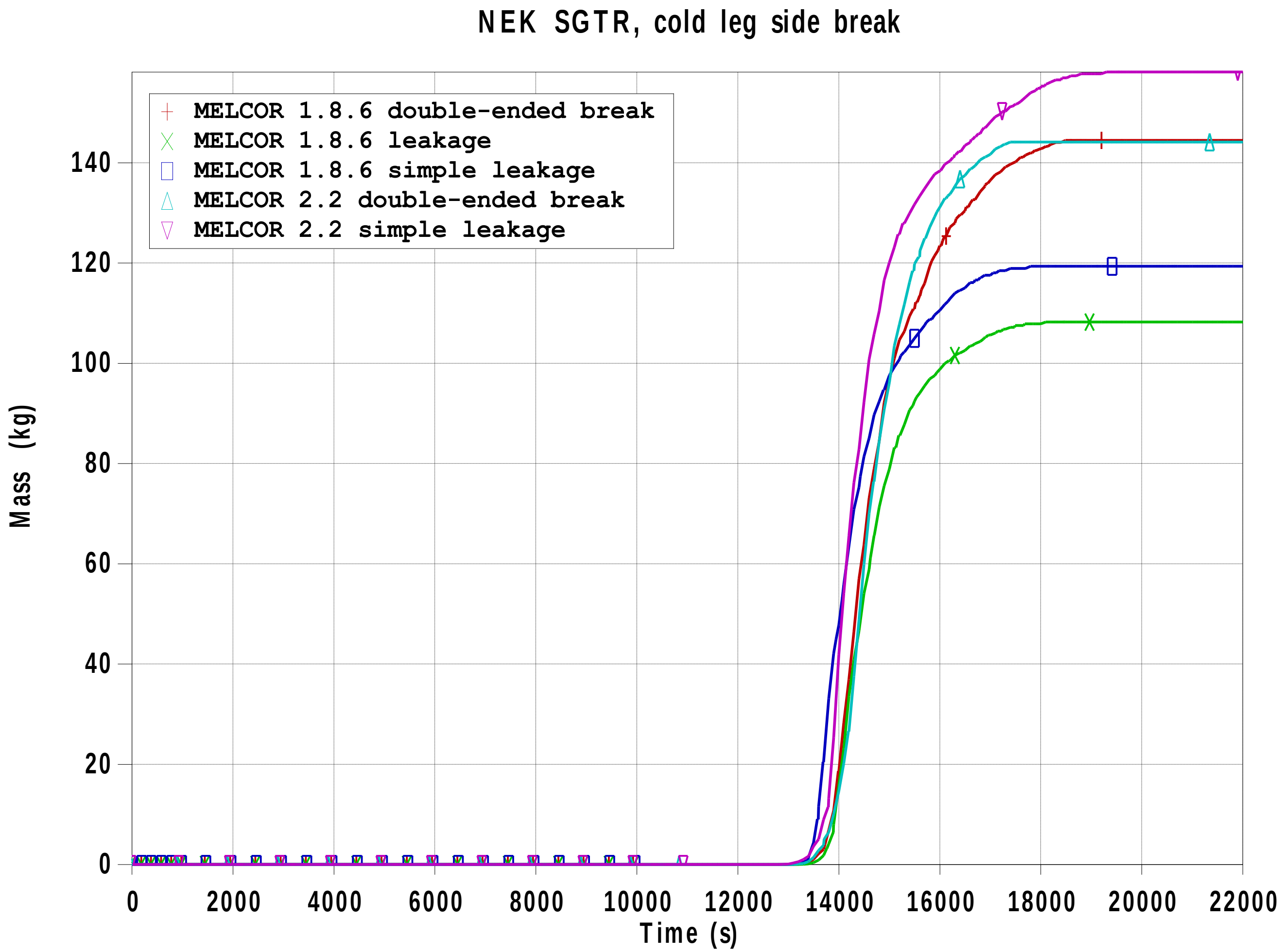


Figure 25: Released radioactive mass through SG 1 safety valve

Analysis of SGTR – Released radioactive aerosol mass through SG 1 safety valve - hot leg side SGTR

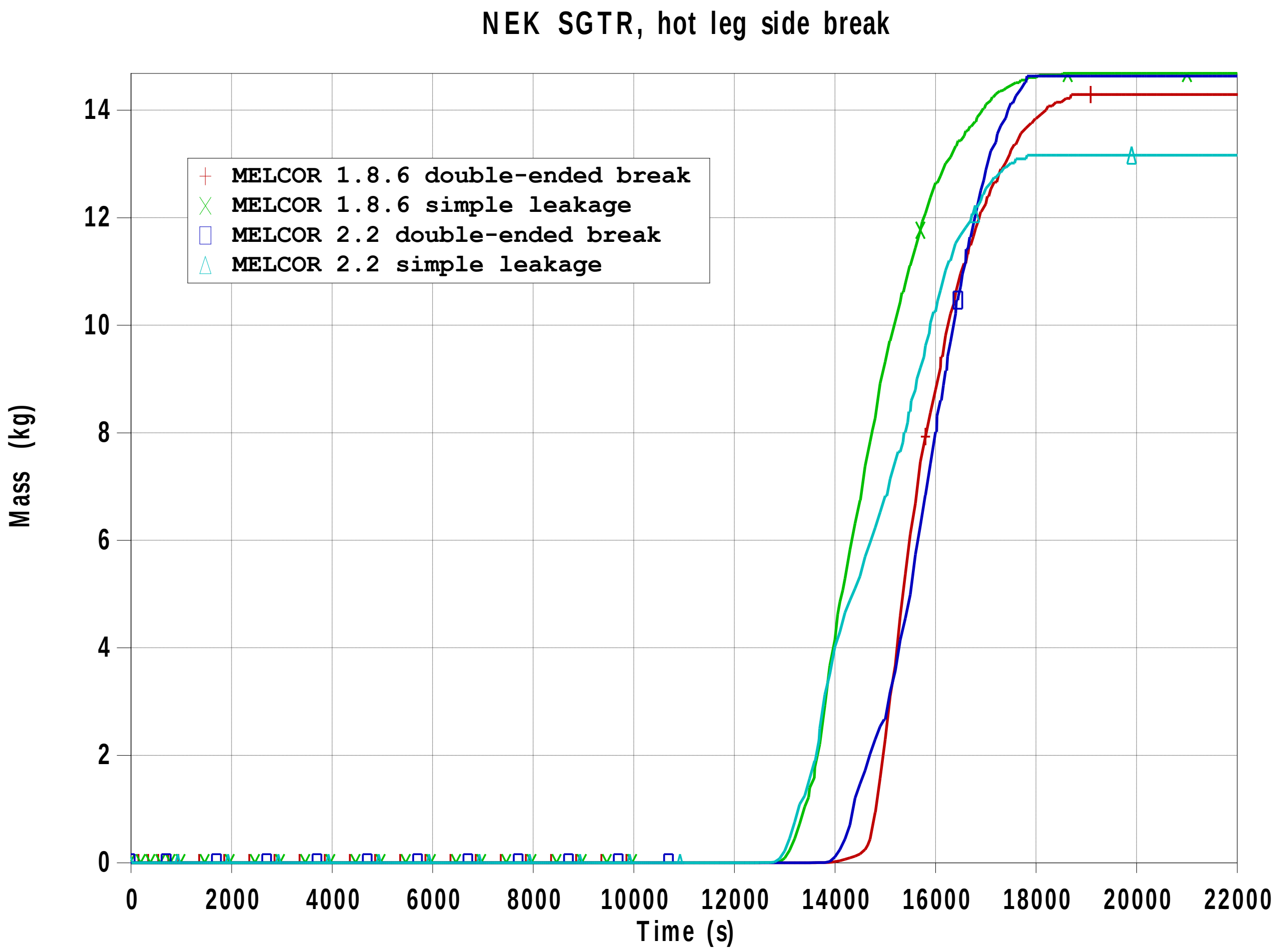


Figure 26: Released radioactive aerosol mass through SG 1 safety valve

Analysis of SGTR – Released radioactive mass through SG 1 safety valve - hot leg side SGTR

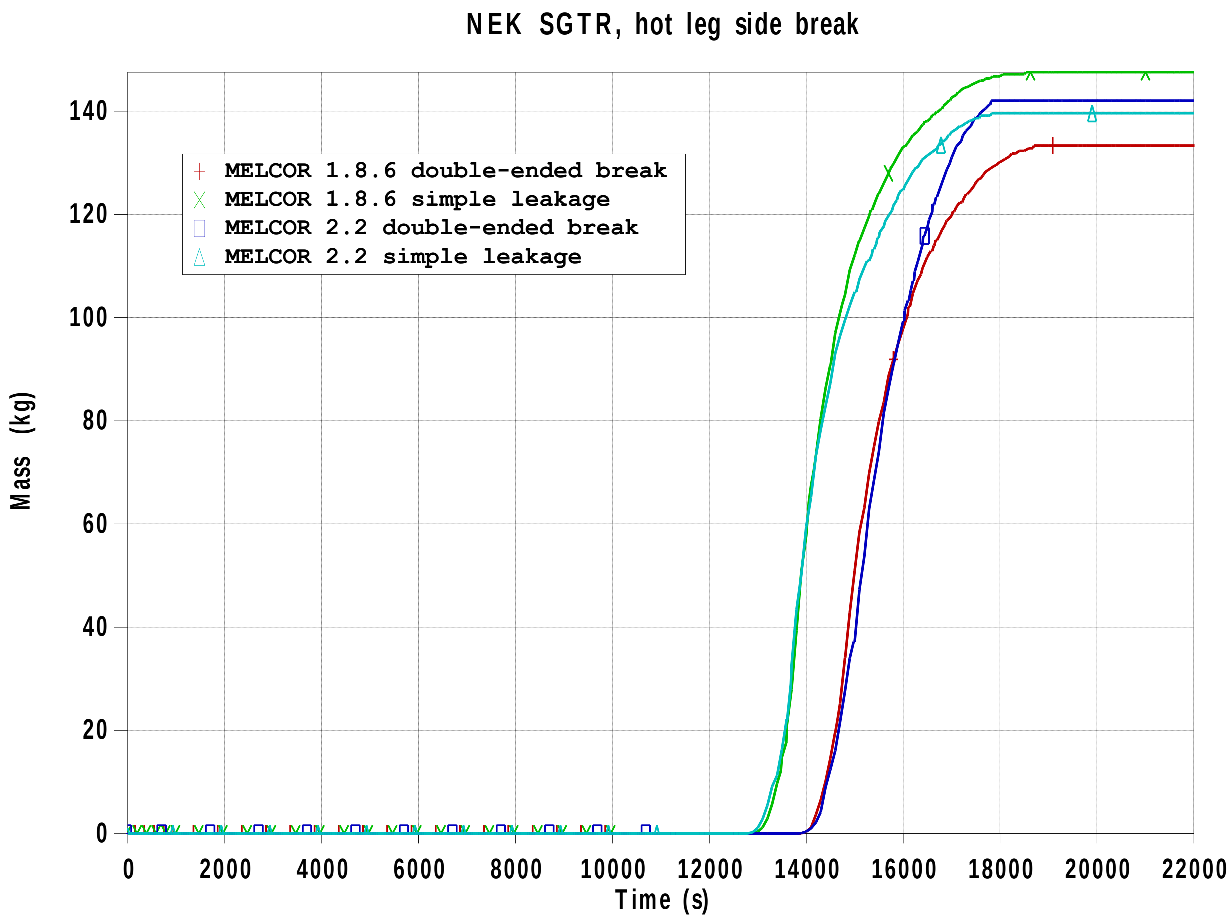


Figure 27: Released radioactive mass through SG 1 safety valve

Analysis of SGTR – MELCOR 1.8.6 double-ended break

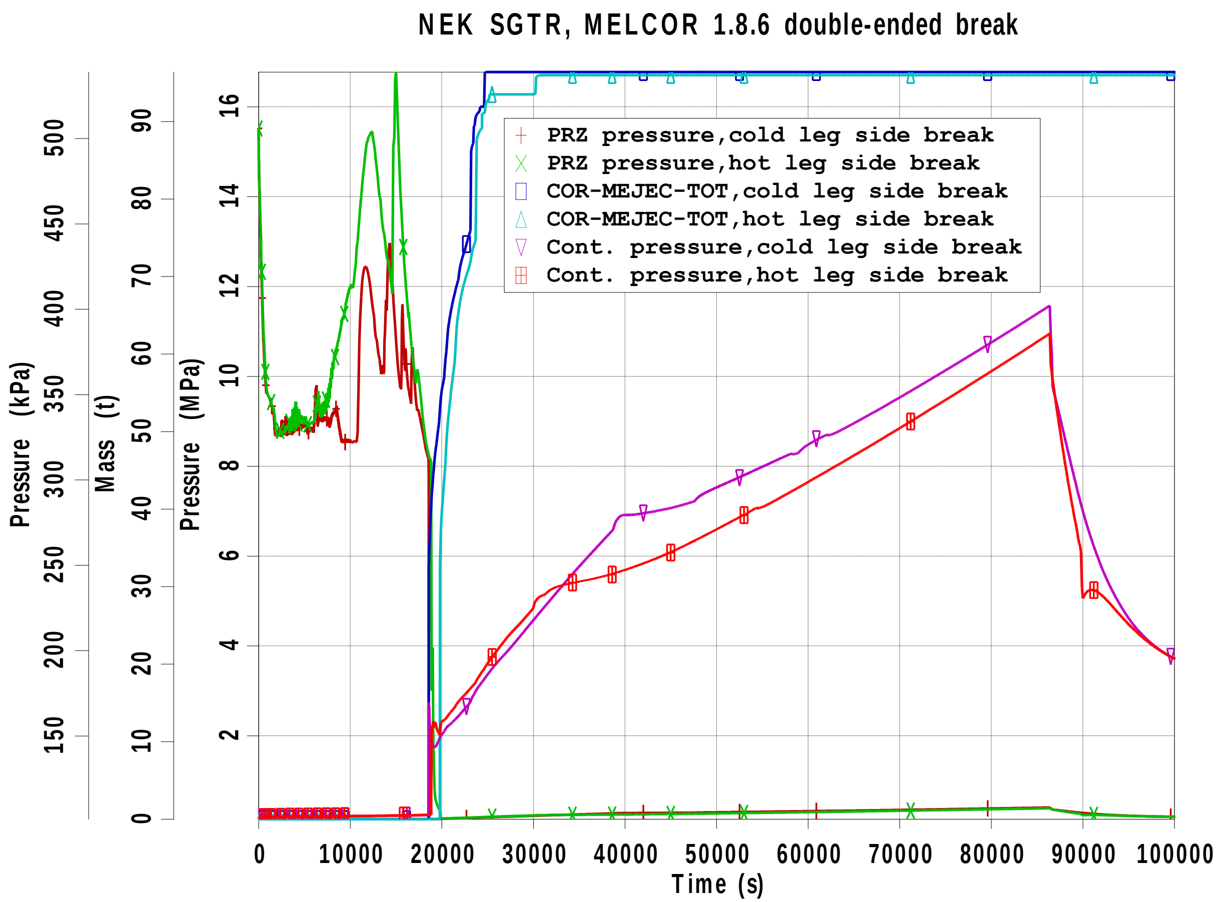


Figure 28: Pressurizer pressure, ejected mass to cavity and containment pressure

Analysis of SGTR: Conclusion remarks

- Different nodalization for SGTR break modelling for MELCOR have been analyzed; i.e. double-ended, leakage and simple leakage. The results were compared with RELAP5 analysis (double-ended break). For simple leakage calculation the break area was adjusted to obtain similar break flow, i.e. the time of reactor trip due to low pressurizer pressure when compared with double-ended break.

- The comparison of parameters between the codes (time of reactor trip due to low-1 PRZ pressure, integral of break flow and discharged mass through SG 1 safety valve) shows a good qualitative agreement for both hot and cold leg side break.

- In addition to the break flow, different SG level control (detailed control in RELAP5 and simplified model in MELCOR) has an influence on transferred heat from primary to secondary side and consequently on time of reactor trip. After reactor trip (about 230 s after transient begin) main feedwater is closed.

Analysis of SGTR: Conclusion remarks, cont.

- The comparison of integrated break mass flow rate (long-term) for double-ended break on hot leg side has shown a very good agreement for MELCOR and RELAP5. For cold leg side break both in MELCOR 1.8.6 and MELCOR 2.2 larger amount of integrated break flow on cold leg side than for RELAP5 was obtained.

- In general, similar results for integrated break flow were obtained for double-ended break for MELCOR 1.8.6 and MELCOR 2.2 while for simple leakage nodalization the differences between the two codes are larger.

- The use of double-ended break nodalization for MELCOR 1.8.6 results in a longer CPU time (52%) when compared with simple leakage break. Since the analyses for double-ended and leakage type nodalization for cold leg side break with MELCOR 1.8.6 have shown no difference in CPU time, only double-ended and simple leakage nodalization were used for MELCOR 2.2 and hot leg side break.

- The CPU time for MELCOR 2.2.14959 calculation (100000 s of transient) is significantly larger (188% for double-ended break and 176% for simple leakage) than the same calculation using MELCOR 1.8.6 code.

Analysis of SGTR: Conclusion remarks, cont.

- The transient scenario with loss of main feedwater and auxiliary feedwater not available has led to the depletion of both steam generators and to the similar values for the total amount of discharged inventory (160-162 tons, Figure 23) as well as for released radioactive mass for both cold and hot leg side break. The results have shown that there is only one distinctive difference between cold and hot leg side break regarding the radioactive release: released radioactive aerosol mass is greater for the hot leg than for the cold leg side side break for both MELCOR versions and different types of nodalization.
- The results for the rest of the parameters (time of core uncovery, SG depletion, time of lower head failure) have shown small differences between different location of the break (cold or hot leg side), types of break (double-ended, leakage or simple leakage) and different MELCOR versions, see Table 1 and Table 2.
- In general, better agreement for the released radioactive mass was obtained for double-ended break for two MELCOR versions than for the different nodalization types for the same MELCOR version, but the differences are still very small.
- The maximum containment pressure before the mitigative action (containment spray (one train) one day after transient begin) was not greater than 420 kPa, so that PCFV system was not actuated (600 kPa).

Analysis of SGTR: Future work

- Improve SG level control in MELCOR in order to obtain more realistic behavior before closing the main feedwater.
- For hot leg side break model the hot leg and steam generator with special natural circulation flow paths (SOARCA, Figure 3-40).
- Analyze the long term behavior of the containment for severe accident scenario in a more detail.
- Propagate analysis to radiological consequences calculation (MACCS2).