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TRACE/RELAP5 Calculation of NPP Krško SGTR Accident Under Realistic and SRP Conditions

Prepared by:
Vesna Benčik, Davor Grgić, Siniša Šadek, Paulina Družijanić

University of Zagreb
Faculty of Electrical Engineering and Computing (FER)
Unska 3-10000, Zagreb, Croatia

A. Hsieh, NRC Program Manager

Division of System Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
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ABSTRACT

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). Unlike other loss of coolant accidents, an early operator action is necessary to prevent radiological release to environment. The SGTR for NPP Krško (NEK) was analyzed using TRACE 5.0p5 and RELAP5/MOD3.3 codes. Two groups of analyses, aimed to determine the Margin To ruptured SG Overfill (MTO) as well as Thermal Hydraulic conditions for radiological Dose (THD) calculation, have been performed. For each group two analyses were done; the analysis based on initial conditions resulting in most adverse outcome (so called SRP assumptions) and the analysis based on best-estimate initial conditions. Transient scenario and operator actions were taken from NPP Krško Emergency Operating Procedure (EOP) E-3, Steam Generator Tube Rupture, ref./7/. For THD analysis, cooldown and depressurization to Hot Shut Down (HSD) conditions (2.8 MPa, 450.15 K) has been performed. At that point Residual Heat Removal (RHR) system can be put in operation.

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EXECUTIVE SUMMARY

TRACE 5.0p5 input deck for NPP Krško is being developed at Faculty of Electrical Engineering (FER). The model is based on a detailed model for NPP Krško for RELAP5/MOD3.3 that is being developed at FER for more than three decades. The RELAP5 model encompasses detailed models of control and protection systems (e.g., Automatic Rod Control system, Safety Injection System, pressurizer pressure and level control system, steam generator level control system, steam dump control, etc). The model is being constantly upgraded in accordance to plant modifications. For on-transient qualification of a TRACE model, Steam Generator Tube Rupture (SGTR) accident was analyzed and the results were assessed against RELAP5 analysis.

The steady state has been obtained after 1000 seconds transient calculation with artificial steady state controllers for both RELAP5 and TRACE. A very good agreement of steady state results for best-estimate analysis with NEK referent data were obtained for both codes.

The authors have analyzed SGTR accident for NPP Krško (NEK) using TRACE 5.0p5 and RELAP5/MOD3.3 codes. Two groups of analyses, aimed to determine the Margin To ruptured SG Overfill (MTO) as well as Thermal Hydraulic conditions for radiological Dose calculation (THD), have been performed. For each group, the analysis based on initial conditions resulting in most adverse outcome (Standard Review Plan – SRP assumptions) and the analysis based on best-estimate (BE) initial conditions were performed. Transient scenario and operator actions were taken from NPP Krško Emergency Operating Procedure (EOP) E-3, Steam Generator Tube Rupture. For MTO and THD BE analysis the primary-to-secondary leakage was stopped around 31 minutes after transient begin whereas for THD SRP analysis the break flow was stopped 43 minutes after transient begin.

The maximum liquid volume was obtained for MTO SRP analysis using TRACE code (125.1 m^3) which is much smaller than the total SG volume (152.7 m^3). The maximum discharged mass for RELAP5 and TRACE were obtained for THD SRP analyses, i.e., 9637.3 kg and 8432.5 kg (1941.3 kg and 1443.1 kg for MTO case). In general, more conservative results regarding the maximum break flow vapor fraction as well as discharged mass through the ruptured SG relief valve were obtained for RELAP5 than for TRACE calculation.

For THD analysis, cooldown and depressurization to Hot Shut Down (HSD) conditions (2.8 MPa, 450.15 K) have been performed. At that point Residual Heat Removal (RHR) system can be put in operation. 30000 seconds after transient begin the hot shutdown conditions were established for both RELAP5 calculations. For TRACE BE calculation, the RCS average temperature value was reached at 37500 seconds and the value for RCS pressure was reached 30000 seconds after transient begin, respectively. For TRACE SRP calculation, the required value for RCS average temperature was reached earlier (35000 seconds after transient begin) and the target value for RCS pressure was reached 30000 seconds after transient begin. The RCS subcooling remained greater than 20 K during controlled cooldown and the ruptured SG liquid inventory was less than 91 m^3.

The scenarios were mainly related to the assessment of changes in NEK USAR Chapter 15 SGTR analyses and corresponding assumed operator action times, ref./8/. The radiological consequences calculation of SGTR event was not performed, but based on limited amount of discharged fluid, the doses to the environment are expected to be small.

ACKNOLEDGMENTS

The authors acknowledge the financial and other support from Krško Nuclear Power Plant within cooperation on CAMP program. The RELAP5/MOD3.3 base input model was originally developed for Krško nuclear power plant. Special thank goes to Engineering services division of Krško nuclear power plant and its director, for recognizing the need for such an analysis and for obtaining required plant data and permission to publish the results.

ABBREVIATIONS AND ACRONYMS

ACC	ACCumulator
AFW	Auxiliary FeedWater
ANS	American Nuclear Society
DVI	Direct Vessel Injection
ECCS	Emergency Core Cooling System
EOL	End Of Life
EOP	Emergency Operating Procedure
ESF	Engineering Safety Features
FER	Faculty of Electrical Engineering and Computing
HHSI	High Head Safety Injection
LHSI	Low Head Safety Injection
MFW	Main FeedWater
MTO	Margin To Ovefill
NEK	Nucleat Power Plant Krško
NPP	Nuclear Power Plant
OTDT	OverTemperature DT
RCS	Reactor Coolant System
RPV	Reactor Pressure Vessel
RT	Reactor Trip
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SI	Safety injection
SRP	Standard Review Plan
SV	Safety Valve
THD	Thermal Hydraulic Conditions for Radiological Dose (THD) Calculation
USAR	Update Safety Analysis Report
US NRC	United States Nuclear Regulatory Commission

1 INTRODUCTION

Calculation model for NPP Krško for computer code TRACE 5.0p5 is being developed and verified at FER Zagreb. The model is based on a detailed model for NPP Krško for RELAP5 that is being developed at FER for more than three decades now.

Currently, for TRACE code verification purposes, the on-transient qualification is performed by comparing the transient results with the results obtained using RELAP5 code. In this report the results of Steam Generator Tube Rupture (SGTR) accident for NPP Krško using RELAP5/MOD 3.3 and TRACE 5.0p5 are presented. The NEK TRACE nodalization without VESSEL component was used in the analysis. Steady state for both RELAP5 and TRACE was obtained after 1000 seconds transient calculation with artificial controllers active (pressurizer pressure and level and steam generator level). The results of steady state calculation for both RELAP5 and TRACE were compared with plant referent data.

The SGTR event causes the contamination of the secondary side due to leakage of the radioactive coolant from the RCS through the broken SG tube(s). The primary-to-secondary leakage causes the surge from the pressurizer and Reactor Coolant System (RCS) depressurization which leads to an automatic reactor trip (on low pressurizer pressure or OverTemperature DT (OTDT) trip) and Safety Injection (SI) actuation. Unlike other loss of coolant accidents, an early operator involvement is necessary to stop the leakage and prevent the radiological release to the environment. After SI actuation the RCS pressure will tend to stabilize at the value where SI flow equals the flow through the ruptured tube. The operator shall determine that the accident has occurred by observing: 1) the difference between steam and feedwater flow (if detected before reactor trip) and 2) the increase of the radiation level in the affected SG. The recovery procedure performed by the operator is primarily aimed to isolate the ruptured SG and to terminate the break flow before water level in the affected SG rises to the main steam pipe and liquid is discharged through the ruptured SG relief valve.

We have analyzed a double-ended break of one U-tube at the tube outlet in the loop with the pressurizer (SG 1). The operator actions begin after automatic reactor trip by isolating the ruptured SG followed by controlled cooldown and depressurization in order to terminate the SI and the primary-to-secondary leakage while maintaining the safe plant status, i.e., the adequate RCS subcooling margin, as well as pressurizer and intact SG inventory. Finally, the operator stops the safety injection and establishes normal charging and letdown. In the analysis it was assumed that the delay for the first operator action (isolation of ruptured SG) is equal to 16 minutes after reactor trip.

The major concern associated with SGTR event are the radiological consequences resulting from the release of radioactivity through the ruptured SG to the atmosphere. First, the Margin to Overflow (MTO) analysis was performed to demonstrate that the ruptured SG does not overfill since that may cause significant increase in the radiological consequences. In the MTO analysis, the minimum delay for auxiliary feedwater actuation as well as the maximum SG level setpoint in the ruptured SG were assumed. On the other hand, the radiological consequences depend on the amount of the airborne iodine that would increase along with flashing of break flow. Thermal Hydraulic conditions for radiological Dose (THD) calculation type of analysis was performed for initial and boundary conditions that would result in maximum break flow void fraction, i.e., the maximum delay for AFW flow and the minimum ruptured SG level setpoint. Both MTO and THD analyses were performed for best-estimate as well as Standard Review Plan (SRP) initial conditions. For the analyses based on SRP criteria the initial conditions based on the NEK operating window were used that would result in most adverse outcome. Operating window is range of average primary coolant temperatures (between low (turbine limit) and high value (fuel corrosion limit) allowed for operation, for given primary coolant mass flow rate and level of SG-tubes plugging. The most adverse outcome for MTO analysis was obtained for Low RCS average temperature and 5% U tube plugging. For THD analysis that was for High RCS average temperature and 0% tube plugging. The selected scenarios were mainly related to the assessment of changes in NEK USAR Chapter 15 SGTR analyses and corresponding assumed operator action times, ref./8/.

2 COMPUTATION MODEL OF NPP KRŠKO

2.1 Nodalization Description

The NPP Krško model for RELAP5/MOD3.3 has been developed at FER, Refs. 3 and 4. The model is being upgraded 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). RELAP5/MOD3.3 model for NPP Krško consists of 506 control volumes and 543 junctions, see Figure 2-1. The total number of heat structures is 383 with 2127 mesh points. There are 723 control variables and 197 variable and 221 logical trips to model the control systems as well as protection and ESF behavior (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 NPP Krško nodalization for TRACE code has been developed using RELAP5/MOD3.3 model. In this report, the base model with Reactor Pressure Vessel (RPV) model built of standard PIPE components and not using dedicated VESSEL component was used. In this model, the nodalization of the whole plant including also the reactor pressure vessel was built in the same manner as it was done in RELAP5 model, see Figure 2-1 and Figure 2-2. The RPV is modeled with PIPE components 101 through 175. Active core is represented with PIPE 111 consisting of 12 fluid cells; the Rod Control Cluster Assembly (RCCA) empty guide tubes inside core are presented with PIPE 113. The region between baffle and barrel is represented with PIPE 115. All the components that are parallel to the active core (113, 115 as well as part of the downcomer that is represented with PIPE 175) consist of 12 fluid cells. The flow paths that bypass the active core include the flow through the baffle-barrel region (PIPE 115), the empty guide tubes inside the core (PIPE 113) as well as upper downcomer (PIPE 165) – upper head (PIPE 151). In addition, the bypass flow path is modeled through the RCCA guide thimbles (PIPE 145) connecting core outlet (PIPE 121) and upper head (PIPE 153). Hot legs in each loop are modelled with five control volumes (PIPE 201 through 209 for the first loop and PIPE 301 through 309 for the second loop), intermediate legs with five control volumes (PIPE 251 through 259 for the first loop and PIPE 351 through 359 for the second loop) and cold legs with five volumes (PIPE 271 through 279 for the first loop and PIPE 371 through 379 for the second loop, respectively. Reactor coolant pumps (PUMP 265 and 365) are connected with PIPEs 259 and 271 (first loop) and PIPEs 359 and 371 for the second loop, respectively. Pressurizer surge line (PIPEs 51 through 55) is connected to hot leg 1 (PIPE 209). Pressurizer is represented with PIPEs 061, 063, 065, 067 consisting of 11 fluid cells and PIPE 069 representing the top of the pressurizer. During artificial steady state (0-1000 s) pressurizer pressure is controlled with BREAK component 901 that is connected to the top of the pressurizer with VALVE 911. Pressurizer inventory during artificial steady state is controlled with FILL 921 that is connected to PIPE 065. Pressurizer spray lines are represented with PIPEs 080, 081 and 084 and VALVEs 082 and 083, respectively. Pressurizer PORV and safety valves are modelled with PIPEs 011, 013, 021, 025 and 027 and VALVEs 014, 022 (safety valves) and 028 and 032 (pressurizer PORV valves). Steam generator primary side is modelled with PIPEs 215 through 245 (loop 1) and PIPEs 315 through 345 (loop 2).

A detailed model of both Emergency Core Cooling System (ECCS) loops with realistic models of High Head as well as Low Head (HHSI and LHSI) safety injection pumps has been included in TRACE model, see Figure 2-3. The model consists of 32 PIPEs, 24 VALVEs, 4 PUMPs and 5 BREAK components. ECCS has been modeled with volumes 701 (801) to 782 (882), that are connected to respective cold legs (volumes 273 and 373) as well as to RPV via Direct Vessel Injection (DVI) lines. The accumulators (volumes 701 and 801), are connected via high pressure injection lines to the respective cold legs (volumes 273 and 373).

On the secondary side, SG 1 downcomer is modelled with PIPEs 411 and 413, see Figure 2-4; heat exchanger section is modelled with PIPEs 415 and 417. The region from the top of U-tubes to the bottom of separator is modelled with PIPE 419. Separator is represented with TEE component 421 having three junctions; the inlet junction from PIPE 419, the main outlet junction representing the steam outlet (TEE 423) and the junction for liquid return (circulation flow) to SG drum volume around separators (PIPE 427). PIPE 425 represents upper plenum bypass volume, where the bypass flow path between steam dome (TEE 423) and PIPE 427 is established. The main outlet of TEE component 423 is connected with steam dome (PIPE 429). The respective components for the SG 2 are 511 through 529. A detailed model for main feedwater, see Figure 2-5, starts from feedwater header (BREAK 931 and TIME DEPENDENT JUNCTION (TDJ) 932. It is split after PIPE 500 into main feedwater lines for the SG 1 (PIPEs 471, 472, 473, 475 outside the SG and the PIPEs 407 and 409 inside the SG) and for the SG 2 (PIPEs 571 through 509). Realistic flow control valves 472 (SG 1) and 572 (SG 2) are governed by the output of the respective SG level control system. During artificial steady state control, SG level is controlled with FILLs 934 and 936. Auxiliary feedwater is modelled using FILLs 607 and 617. The main steam lines, see Figure 2-6, for SG 1 are represented with PIPEs 451 through 461 (551 through 561 for SG 2). The main steam isolation valves (VALVE 498 in steam line 1 and 598 in steam line 2) connect the PIPE 461 (PIPE 561 in steam line 2) outlet with steam header that is modelled with TEE 601. Turbine control valve 604 connects the PIPE 631 outlet and BREAK 605 that simulates the turbine pressure boundary condition. During steady state, the VALVE 604 opening is controlled so that the setpoint for the RCS average temperature (578.15 K) is achieved. VALVE 604 is closed upon receiving turbine trip signal. There are one relief valve (VALVE 482 in steam line 1 and 582 in steam line 2) and five safety valves in each steam line (VALVEs 484 through 494 in steam line 1 and VALVEs 584 through 594 in steam line 2). Currently, the steam dump system is modeled with TDJ 608 and BREAK 609.
The TRACE model consists of 284 hydraulic components, i.e., 178 PIPEs, 25 BREAK components, 6 TEEs, 10 FILLs, 2 TDJs, 6 PUMPs and 57 VALVEs, respectively.

There are 107 heat structures (HTSTR components) and 3 POWER components defining the reactor power (point-kinetics with table lookup of reactivity) as well as pressurizer proportional and backup heaters. The total number of Control blocks, Signal variables and Trip components is equal to 391, 314 and 87, respectively.

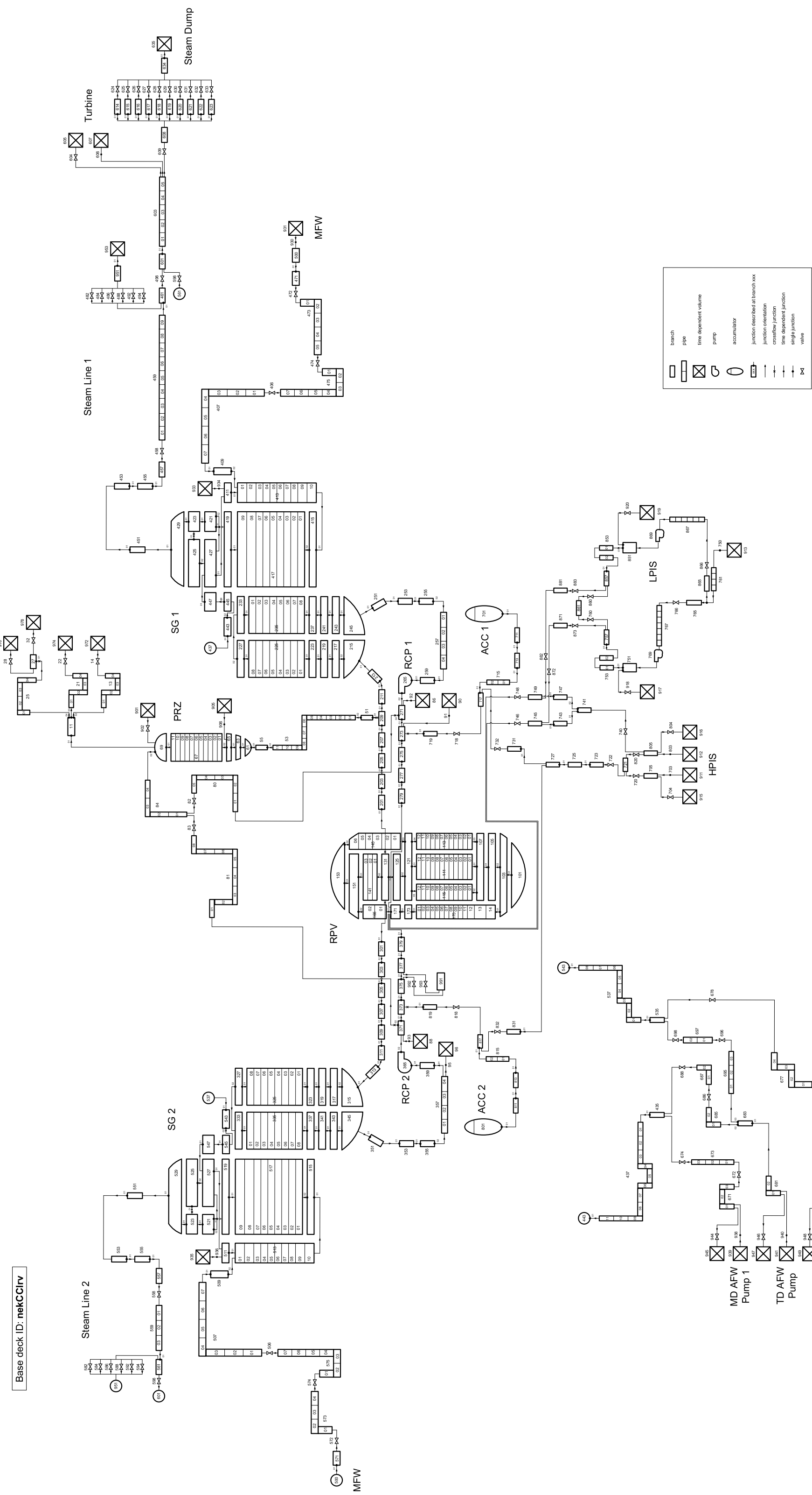

Figure 2-1 RELAP5/MOD3.3 Nodalization Scheme for NPP Krško

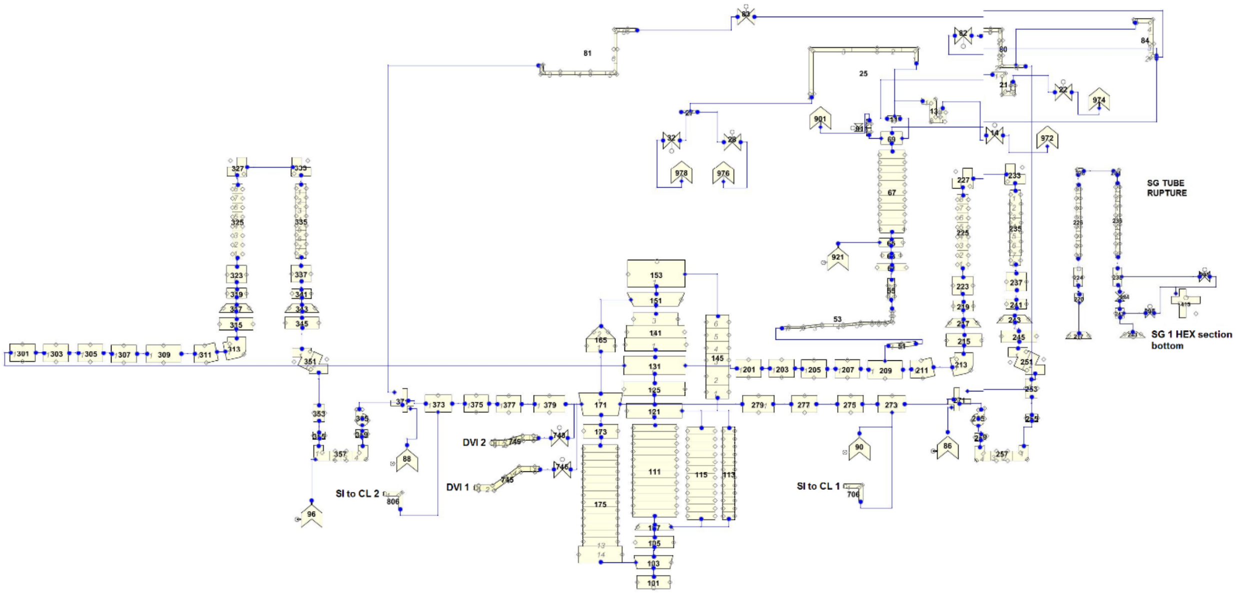

Figure 2-2 TRACE Nodalization Scheme for NPP Krško (Primary Circuit, with Broken SG Tube)

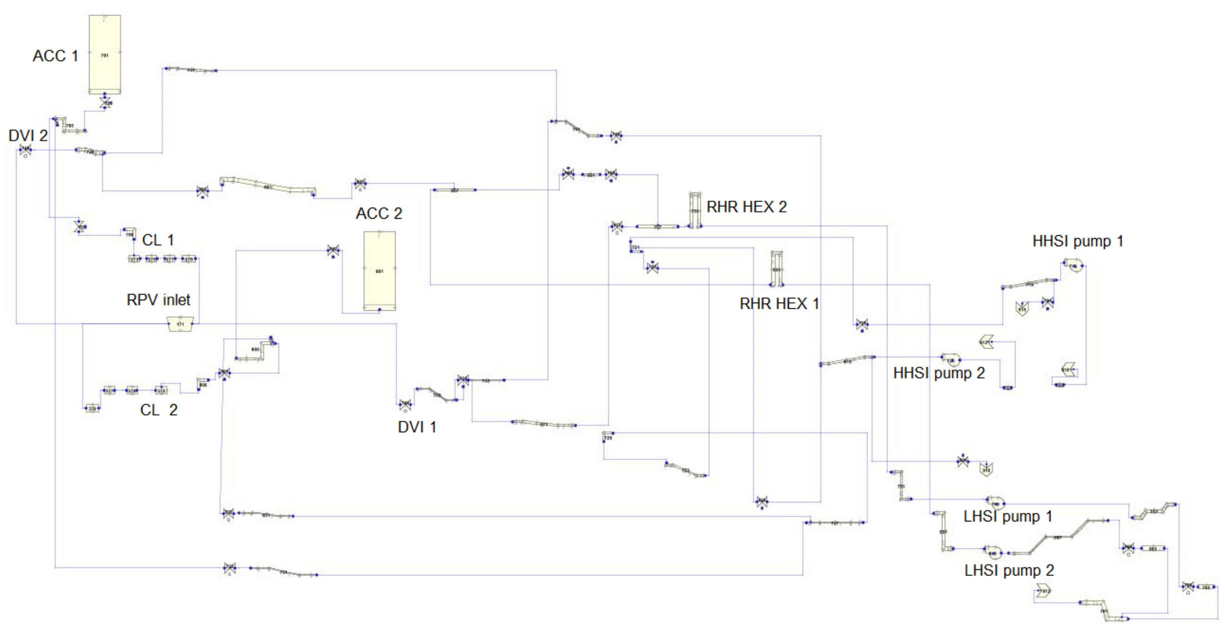

Figure 2-3 TRACE Model for NPP Krško (ECCS – Emergency Core Cooling System)

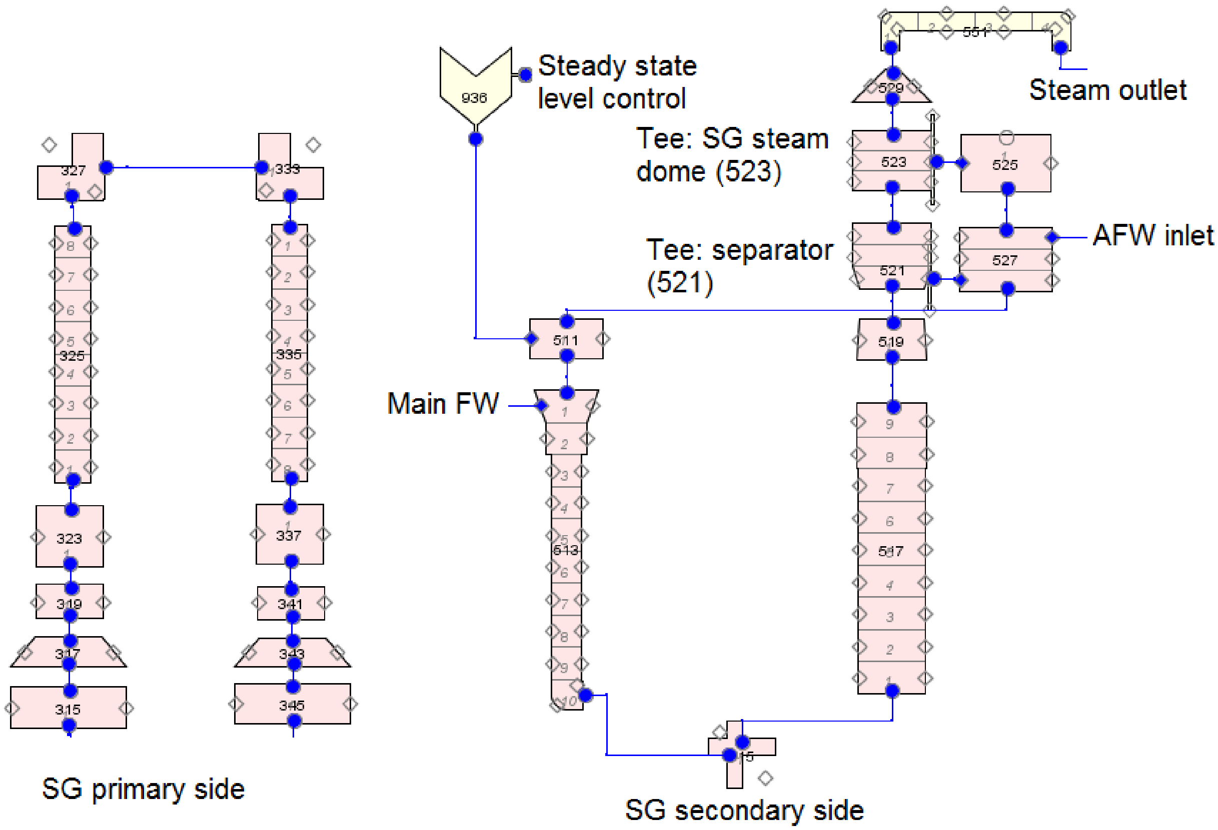

Figure 2-4 Steam Generator (SG 2) Model - TRACE

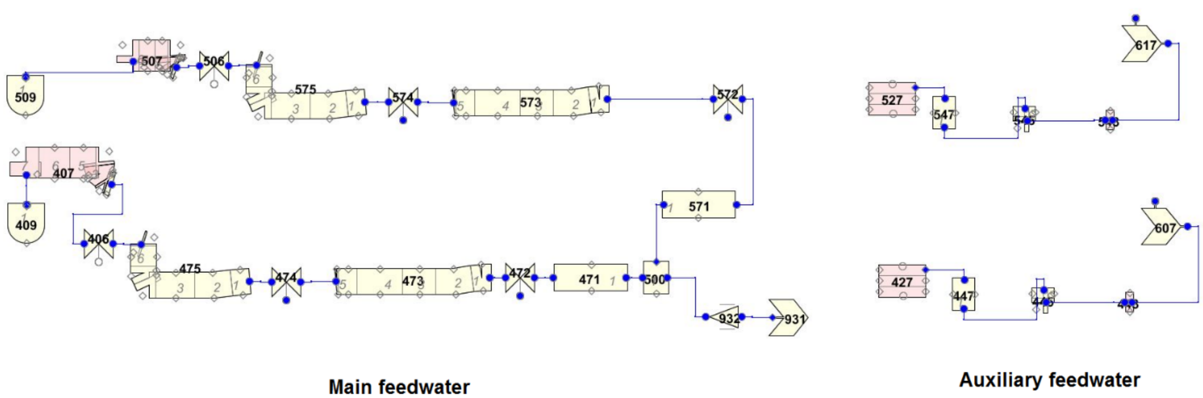

Figure 2-5 TRACE Nodalization: Main Feedwater and Auxiliary Feedwater System

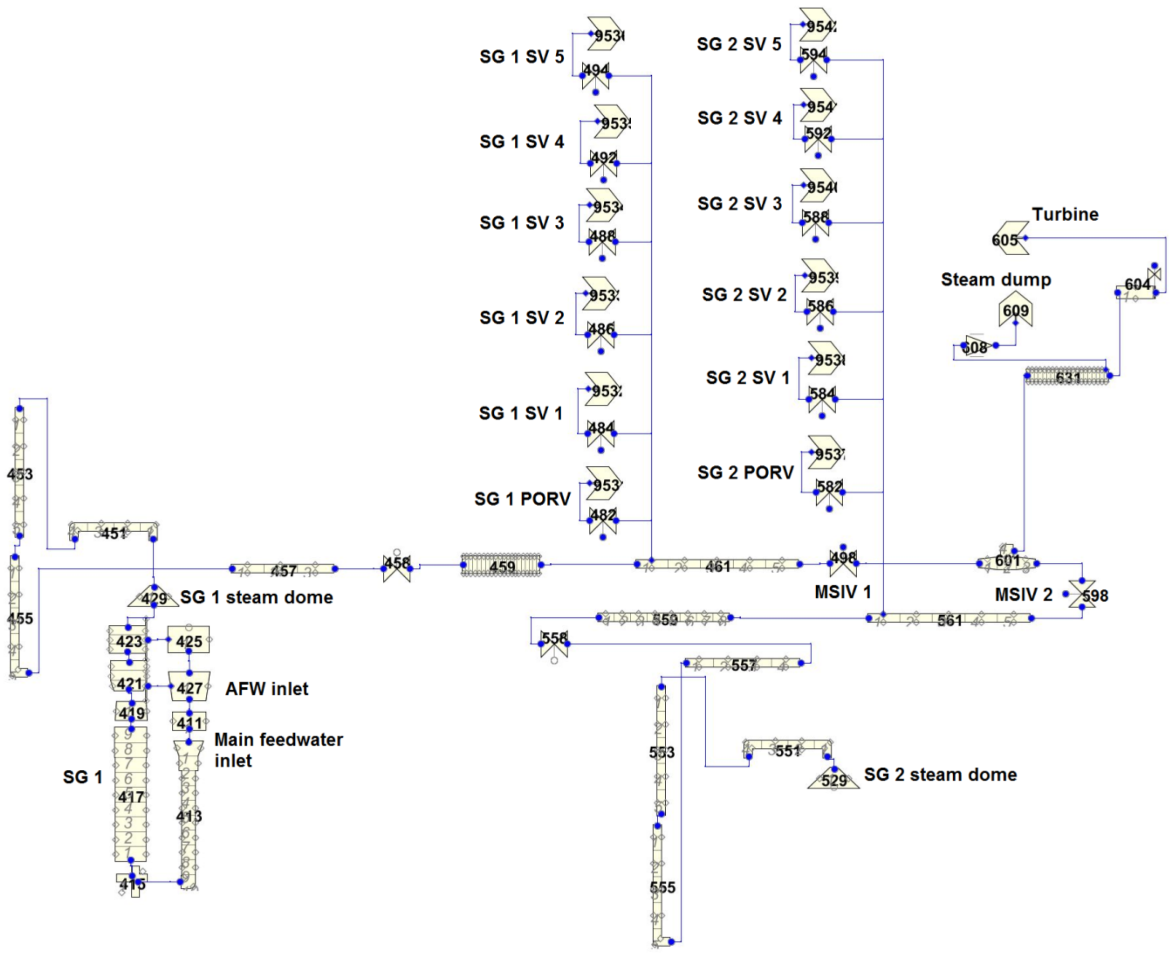

Figure 2-6 TRACE Nodalization: SG 1 Secondary Side and Main Steam System

2.2 Evaluation of Steady State

Steady state calculation has been performed for 1000 seconds. During that period pressurizer pressure as well as pressurizer and steam generator level are maintained at setpoint values using an artificial control. The average RCS temperature is maintained at its setpoint value by controlling the secondary side pressure, i.e., the pressure drop on turbine valve (VALVE 604). Reactor power was calculated using point kinetics model with reactivity feedback included. The results of steady state calculation (at 1000 s) for both RELAP5 and TRACE for MTO and THD analyses are summarized in Table 1 and Table 2, respectively. For each type of analysis the best-estimate as well as data that would result in most adverse outcome are provided (Standard Review Plan - SRP analyses). For Margin to Overflow (MTO) analysis the most adverse results were obtained for Low RCS average temperature and 5% tube plugging. For calculation of thermal-hydraulic conditions required for radiological dose calculation (THD) the most adverse results were obtained for High RCS average temperature and 0% plugging. For both MTO and THD SRP analyses the conservative values from operating window were used, i.e., high initial nuclear power (102%), low RCS pressure (15.168 MPa) and thermal design flow instead of best-estimate primary mass flow rate. A very good agreement for both RELAP5 and TRACE best-estimate calculation with NEK referent data were obtained. The largest discrepancy between calculated TRACE steady state values and NEK referent data were obtained for secondary side pressure (0.94%).

Table 1 Comparison Between NEK Reference Data and Calculated Steady State Data, MTO Analysis

Parameter	NEK referent data, cycle 29	RELAP5, best-estimate	TRACE, best-estimate	RELAP5, SRP analysis	TRACE, SRP analysis
1. Pressure (MPa)					
Pressurizer	15.513	15.513	15.51	15.166	15.164
Steam generator	6.281	6.275/6.286	6.32/6.34	5.78/5.78	5.83/5.84
Accumulator	4.93	4.93	4.93	4.93	4.93
2. Fluid Temperature (K)					
Cold leg	558.75	559.5/559.3	559.4/559.3	554.8/554.5	554.8/554.5
Hot leg	597.55	596.8/596.8	596.9/596.9	594.8/594.82	594.8/594.8
Feedwater	492.6	492.7	492.6	492.7	492.6
3. Mass Flow (kg/s)					
Core	8899.7	8925.2	8893.9	8601.9	8603.0
Cold leg	4697.4	4711.7/4710.7	4694.2/4693.0	4539.6/4541.2	4555.3/4524.7
Main feedwater	544.5	540.9/544.7	539.1/542.1	549.8/554.0	549.5/550.8
Main steam line	544.5	540.9/544.7	539.1/542.1	549.8/554.0	549.6/550.9
Core bypass flow (total)	5.27%	5.28%	5.26%	5.28%	5.26%
4. Liquid level (%)					
Pressurizer	55.7	55.8	55.8	52.1	52.1
Steam generator narrow range	69.3	69.3/69.3	69.3/69.3	69.3/69.3	69.3/69.3
5. Fluid Mass (t)					
Primary system	-	131.3	130.9	129.9	129.6
Steam generator (secondary)	47.0	49.1/48.9	50.3/49.4	47.7/47.6	49.2/49.9
6. Power (MW)					
Core	1994.0	1994.0	1991.3	2033.88	2033.19
Steam generator	1000.0	995.9/1003.0	991.9/997.7	1015.4/1023.4	1009.9/1012.8

Table 2 Comparison Between NEK Reference Data and Calculated Steady State Data, THD Analysis

Parameter	NEK referent data, cycle 29	RELAP5, best-estimate	TRACE, best-estimate	RELAP5, SRP analysis	TRACE, SRP analysis
1. Pressure (MPa)					
Pressurizer	15.513	15.513	15.51	15.166	15.164
Steam generator	6.281	6.275/6.286	6.32/6.34	6.43/6.42	6.52/6.52
Accumulator	4.93	4.93	4.93	4.93	4.93
2. Fluid Temperature (K)					
Cold leg	558.75	559.5/559.3	559.4/559.3	561.0/560.8	561.0/560.7
Hot leg	597.55	596.8/596.8	596.9/596.9	600.1/600.1	600.1/600.1
Feedwater	492.6	492.7	492.6	492.7	492.6
3. Mass Flow (kg/s)					
Core	8899.7	8925.2	8893.9	8538.6	8522.6
Cold leg	4697.4	4711.7/4710.7	4694.2/4693.0	4505.4/4507.9	4511.9/4483.7
Main feedwater	544.5	540.9/544.7	539.1/542.1	552.4/556.1	551.6/552.9
Main steam line	544.5	540.9/544.7	539.1/542.1	552.4/556.1	552.6/553.9
Core bypass flow (total)	5.27%	5.28%	5.26%	5.29%	5.26%
4. Liquid level (%)					
Pressurizer	55.7	55.8	55.8	67.1	67.1
Steam generator narrow range	69.3	69.3/69.3	69.3/69.3	69.3/69.3	69.6/69.3
5. Fluid Mass (t)					
Primary system	-	131.3	130.9	131.7	130.9
Steam generator (secondary)	47.0	49.1/48.9	50.3/49.4	49.1/48.9	49.4/49.4
6. Power (MW)					
Core	1994.0	1994.0	1991.3	2033.88	2033.72
Steam generator	1000.0	995.9/1003.0	991.9/997.7	1015.6/1022.6	1018.3/1020.7

3 ANALYSIS OF STEAM GENERATOR TUBE RUPTURE (SGTR) ACCIDENT FOR NPP KRŠKO

3.1 Analysis of SGTR Accident – Margin to Overfill (MTO) Calculation

The analysis has been performed with most conservative assumptions regarding Margin to Overflow (MTO) concern, i.e., the AFW flow was actuated immediately after reactor trip and it was terminated first after SG level in the ruptured SG increased above 75%. Both the best-estimate (BE) and conservative (SRP) cases (102% power, low RCS average temperature and 5% plugging) were analyzed. Following the double-ended tube rupture, the primary pressure decreases due to loss of inventory through the break, see Figure 3-1, Figure 3-2, Figure 3-3 and Figure 3-4. The RCS subcooling decreases due to pressure decrease and OTDT signal trips the reactor, see Figure 3-5, Figure 3-10 and Figure 3-11. For BE analysis reactor trip signal was generated 113.9 s after transient begin for RELAP5 and 112.1 s after transient begin for TRACE. For SRP analysis reactor trip times are 64.6 s for RELAP5 and 43.5 s for TRACE. Along with reactor trip the RCS pumps were stopped and the main feedwater was isolated too. The CVCS charging and letdown flow were isolated on reactor trip signal as well. Before reactor trip, the reactor power was reduced due to negative moderator reactivity feedback caused by coolant density decrease. In the analysis it was conservatively assumed that the auxiliary feedwater (AFW) flow (80 m^3/hr for each SG) was initiated immediately after reactor trip and it was isolated in the ruptured SG first after SG level exceeded 75%. For intact SG it was assumed that AFW flow was controlled to maintain SG 2 NR level in the range (20, 70%), see Figure 3-18, Figure 3-19, Figure 3-20 and Figure 3-21. After reactor trip, RCS pressure continued to decrease until safety injection was actuated on low-2 pressurizer pressure, see Figure 3-14 and Figure 3-15. In the analysis it was assumed that the operator isolated the ruptured SG by closing the main steam isolation valve (VALVE 498) 16 minutes after reactor trip. Two minutes later, i.e., for SRP analysis 1124 seconds after transient begin for TRACE and 1145 seconds after transient begin for RELAP5, the operator started the cooldown according to Emergency Operating Procedure (EOP) E3, ref./7/., at a maximum rate. For BE analyses the times are 1192 seconds for TRACE and 1194 seconds after transient begin for RELAP5. At the same time (1081 seconds after transient begin) the operator started the maximal charging flow (36 m^3/hr) in order to maintain the RCS inventory due to break. The cooldown is finished when the core exit temperature (CET) decreases below value that depends on ruptured SG pressure at the start of cooldown. For BE analysis that CET temperature was equal to 536.8 K for RELAP5 and 539.3 K for TRACE. For SRP analysis the respective CET values for RELAP5 and TRACE were 538.2 K and 537.9 K. In the MTO analysis it was assumed that operator maintained the CET at these values till the end of simulation (3000 seconds). In the analysis it was assumed that steam dump system was not available. Thus, for RCS cooldown, the operator used the intact SG relief valve, see Figure 3-25. The cooldown lasted between 8.6 minutes (RELAP5 SRP analysis) and 9.2 minutes (TRACE SRP analysis), see Table 3. The SG 2 secondary side inventory was significantly reduced during cooldown because the AFW was closed until SG level fell below 20%, see Figure 3-18 through Figure 3-21. The subsequent ON/OFF behavior of SG 2 PORV can be observed by temporary SG 2 NR level increase due to rise of water droplets during PORV operation, see Figure 3-25. Two minutes after the cooldown has ended the operator initiated RCS depressurization using pressurizer PORV. The depressurization lasted for 100 seconds in both TRACE BE and SRP calculation when the primary pressure fell below the ruptured SG pressure. In RELAP5 the depressurization was terminated before the primary pressure fell below ruptured SG pressure because the pressurizer NR level exceeded 66%, see Figure 3-16 and Figure 3-17. Finally, the SI was terminated with 30 seconds delay after end of depressurization. One can observe the sharp increase of SI flow, see Figure 3-14 and Figure 3-15, due to RCS depressurization. Six minutes after end of depressurization the maximum charging flow was stopped and the operator established normal charging and letdown. The leakage flow was stopped after SI termination for both RELAP5 and TRACE, i.e., for BE analysis 1914 seconds after transient begin for RELAP5 and 1941 seconds after transient begin for TRACE. For SRP analysis leakage flow was ended at 1859 s for RELAP5 and at 1882 seconds for TRACE. The stable conditions for both codes were attained approximately 2500 seconds after transient begin when the increase of liquid volume in ruptured SG and the discharge through the ruptured SG were terminated, see Figure 3-22 and Figure 3-23. The maximum liquid volume in ruptured SG for both RELAP5 (for BE analysis 124.4 m^3 and 124.5 m^3 for SRP analysis) and TRACE (122.4 m^3 for BE analysis and 125.1 m^3 for the SRP analysis, respectively) were well below total SG volume (152.7 m^3). Also, the small amount of steam, see Figure 3-23 and Figure 3-24 was discharged through the ruptured SG PORV (1941.3 kg and 446.5 kg in RELAP5 BE and SRP analysis and 1443.1 kg and 127.4 kg in TRACE BE and SRP analysis, respectively). The maximum break flow vapor fraction, see Figure 3-12 and Figure 3-13, was obtained in the RELAP5 SRP calculation (39.9%) for the hot leg side flow. Both TRACE BE and SRP calculations predicted much lower void fractions (around 3.7% for BE calculation). The major concern related to break flow flashing is related to the transport of gaseous fission products from primary side to the ruptured SG where they can be discharged directly through the ruptured SG relief valve to the atmosphere. In general, small differences between RELAP5 and TRACE were encountered and the main trends were well predicted by both codes. The major part of obtained differences between TRACE and RELAP5 is related to somewhat larger break flow and break flow void fractions in RELAP5. This results in a larger maximum ruptured SG liquid volume and larger amount of discharged mass through the ruptured SG PORV in RELAP5 than in TRACE.

The timing of operator actions (ruptured SG steamline isolation 16 minutes after RT, cooldown initiation and charging actuation 2 minutes after steamline isolation, depressurization initiation 2 minutes after cooldown termination, SI termination 30s after end of depressurization, charging termination 6 minutes after end of depressurization) was assumed in the analyses based on NEK operator training and full scope simulator exercises.

Table 3 Time Sequence of the Main Events: SGTR, MTO Analysis

Event	RELAP5, BE analysis	RELAP5, SRP analysis	TRACE, BE analysis	TRACE, SRP analysis
Tube rupture (s)	0	0	0	0
Reactor trip (s)	113.9 (OTDT)	64.6 (OTDT)	112.1 (OTDT)	43.5 (OTDT)
AFW initiation (s)	on reactor trip	on reactor trip	on reactor trip	on reactor trip
SI actuation (s)	402.4 (low-2 PRZ p)	357.7 (low-2 PRZ p)	374.3 (low-2 PRZ p)	342.4 (low-2 PRZ p)
SG 1 AFW isolation (s)	799.4 (level > 75%)	727.4 (level > 75%)	762.0 (level > 75%)	678.5 (level > 75%)
Ruptured SG steamline isolation (s)	1073.9 (960 s after RT)	1024.6 (960 s after RT)	1072.1 (960 s after RT)	1003.5 (960 s after RT)
Initiation of cooldown with intact SG (s)	1193.9 (1080 s after RT)	1144.6 (1080 s after RT)	1192.1 (1080 s after RT)	1123.5 (1080 s after RT)
Charging actuation (36 m^3/h) (s)	1194.9 (1081 s after RT)	1145.6 (1081 s after RT)	1193.1 (1081 s after RT)	1124.5 (1081 s after RT)
Break flow flashing stops (s)	1179 s (max void 38.8%)	1180 s (max void 39.9%)	780 s (max void 3.7%)	698 s (max void 3.5%)
Cooldown termination (s)	1718.5	1661.5	1730.4	1675.2
Depressurization initiation (120 s after cooldown)	1838.5 s	1781.5 s	1850.4 s	1795.2 s
Depressurization termination (s)	1963.7 (PRZ level > 66%)	1922.0 (PRZ level > 66%)	1952.6 (PRZ p < SG 1 p)	1891.0 (PRZ p < SG 1 p)
Stop SI flow (s)	1993.7 (30 s delay)	1952.0 (30 s delay)	1982.6 (30 s delay)	1921.0 (30 s delay)
Balance charging and letdown flow (charging termination)	2323.7 s (6 min after end of depressurization)	2282.0 s (6 min after end of depressurization)	2312.6 s (6 min after end of depressurization)	2251.0 s (6 min after end of depressurization)
Break flow reversal	1914.0 s	1859.0 s	1941.0 s	1882.0 s
Integral of SG 1 PORV mass flow (0-3000 s)	1941.3 kg	446.5 kg	1443.1 kg	127.4 kg
Minimum SG 1 PORV flow void fraction	0.9881	0.9807	0.9958	0.9975
Maximum ruptured SG water volume reached	124.4 m^3	124.5 m^3	122.4 m^3	125.1 m^3

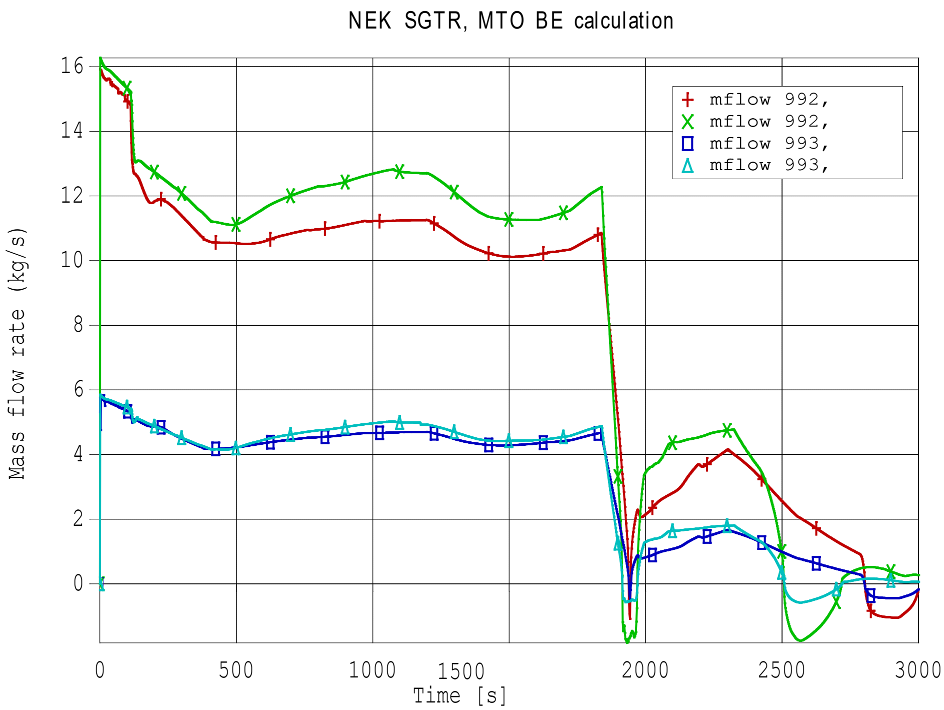

Figure 3-1 NEK SGTR, MTO BE Calculation, Break Mass Flow Rate

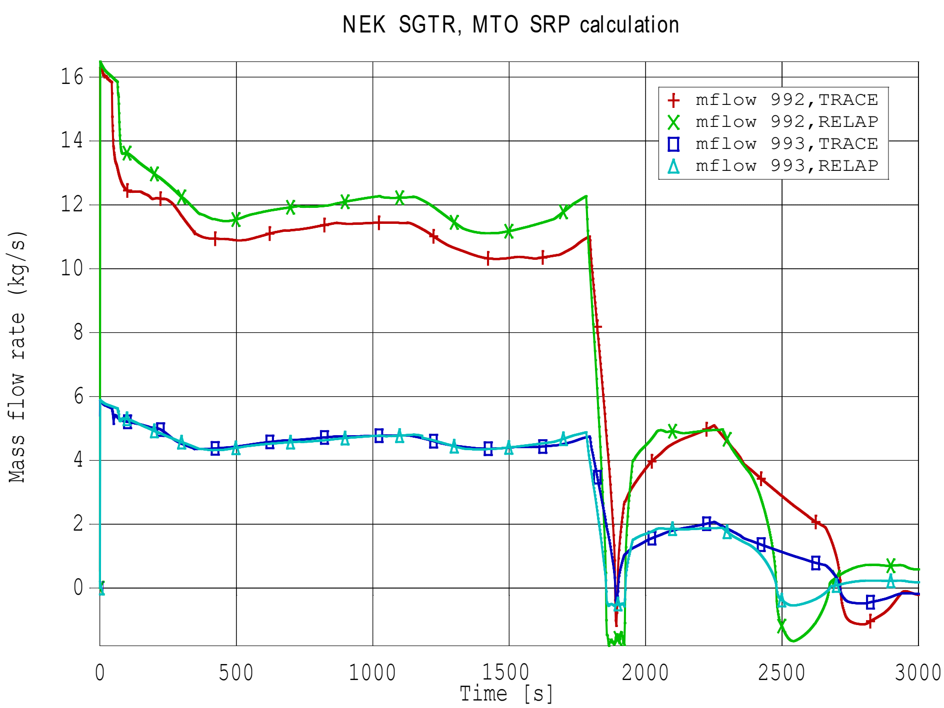

Figure 3-2 NEK SGTR, MTO SRP Calculation, Break Mass Flow Rate

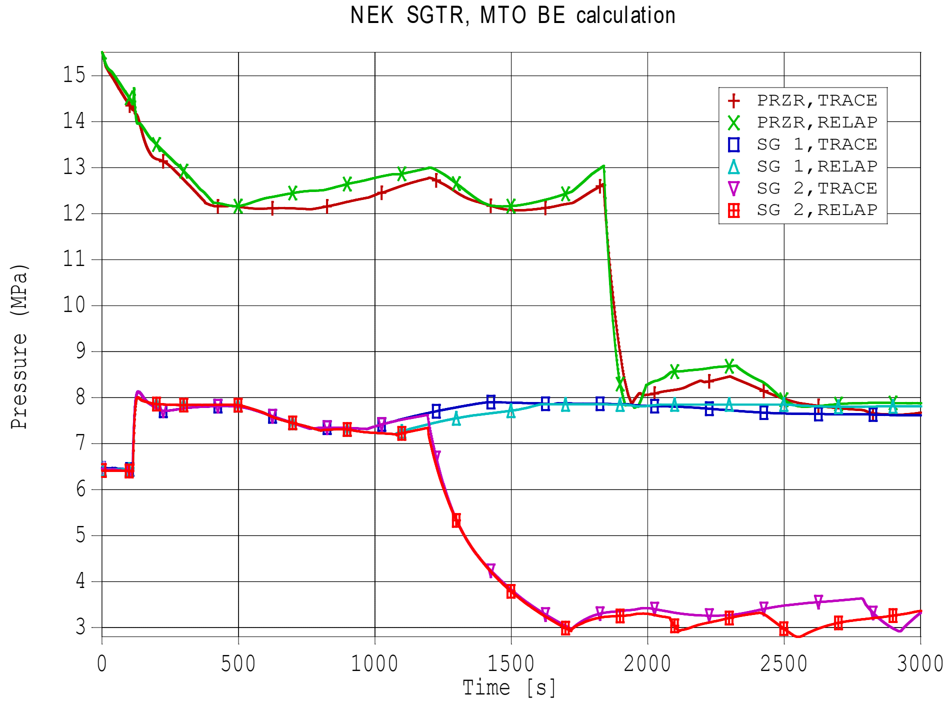

Figure 3-3 NEK SGTR, MTO BE Calculation, Pressurizer and SG Pressure

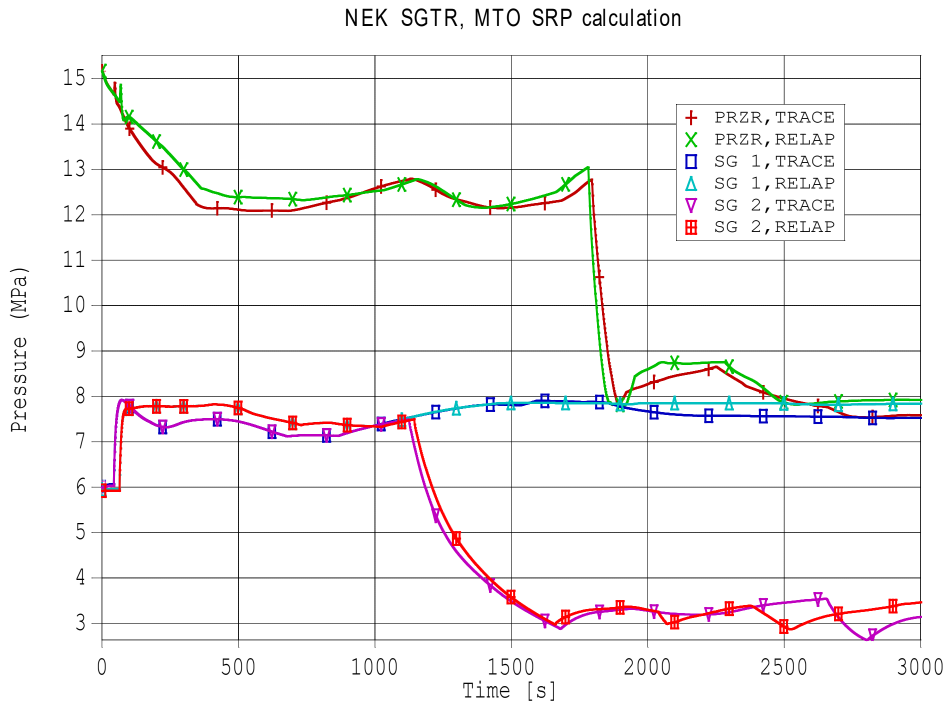

Figure 3-4 NEK SGTR, MTO SRP Calculation, Pressurizer and SG Pressure

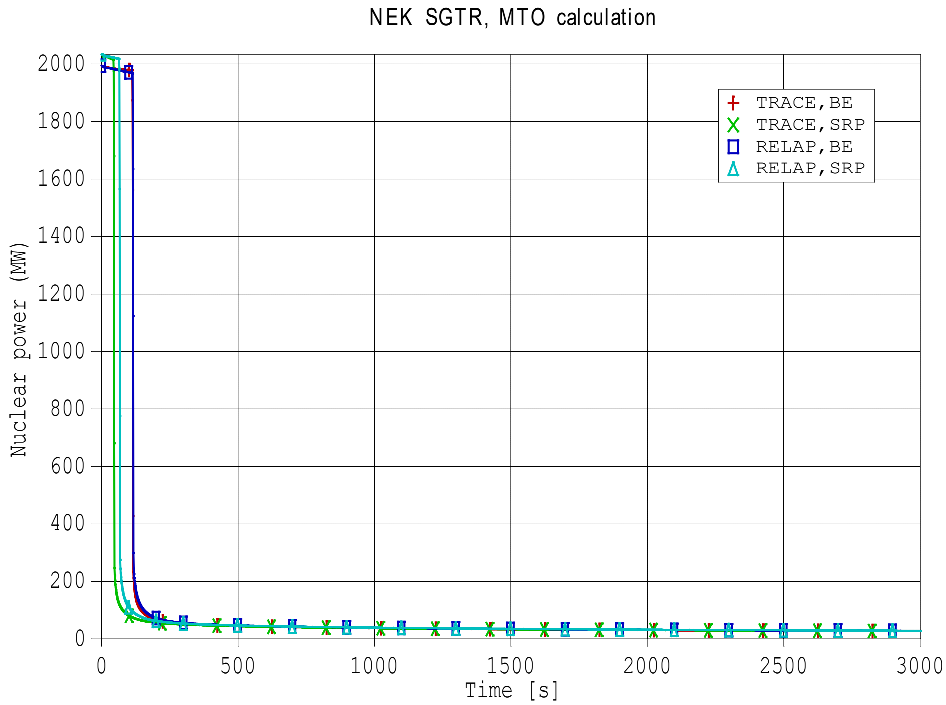

Figure 3-5 NEK SGTR, MTO Calculation, Nuclear Power

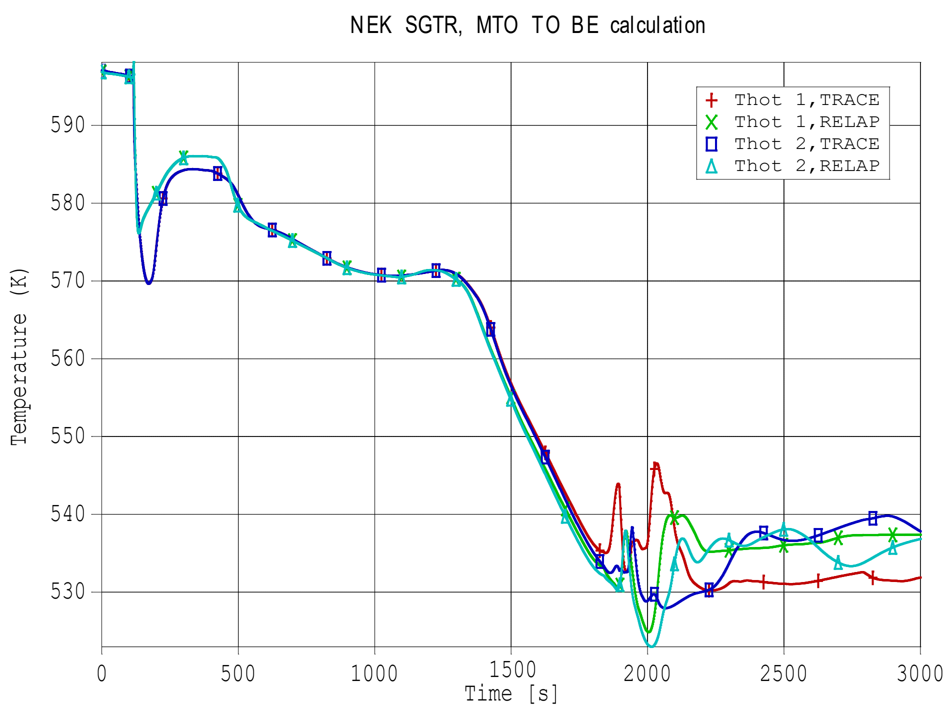

Figure 3-6 NEK SGTR, MTO BE Calculation, Hot Leg Temperature

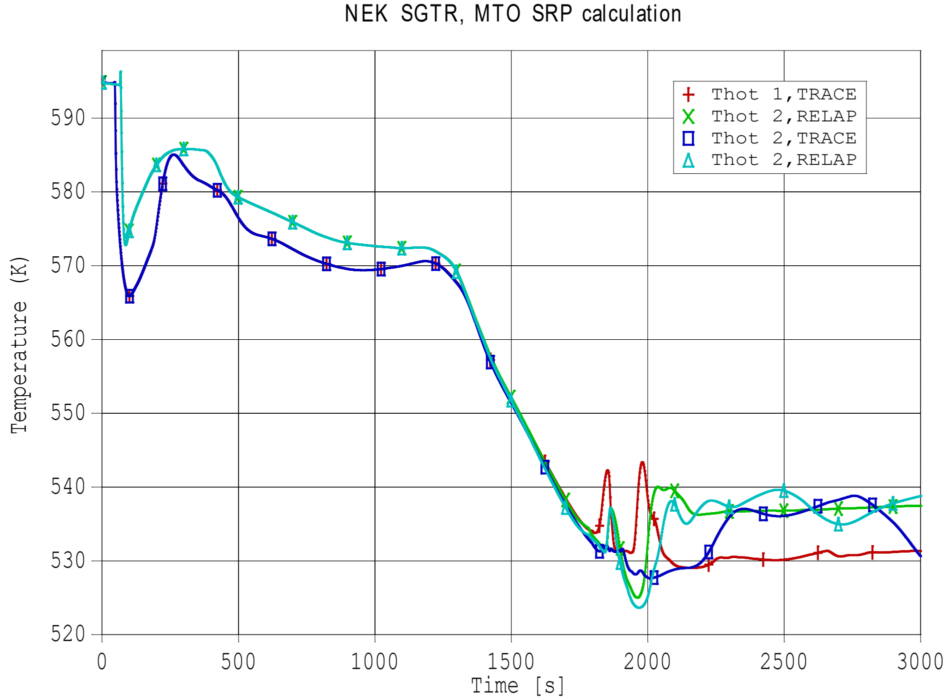

Figure 3-7 NEK SGTR, MTO SRP Calculation, Hot Leg Temperature

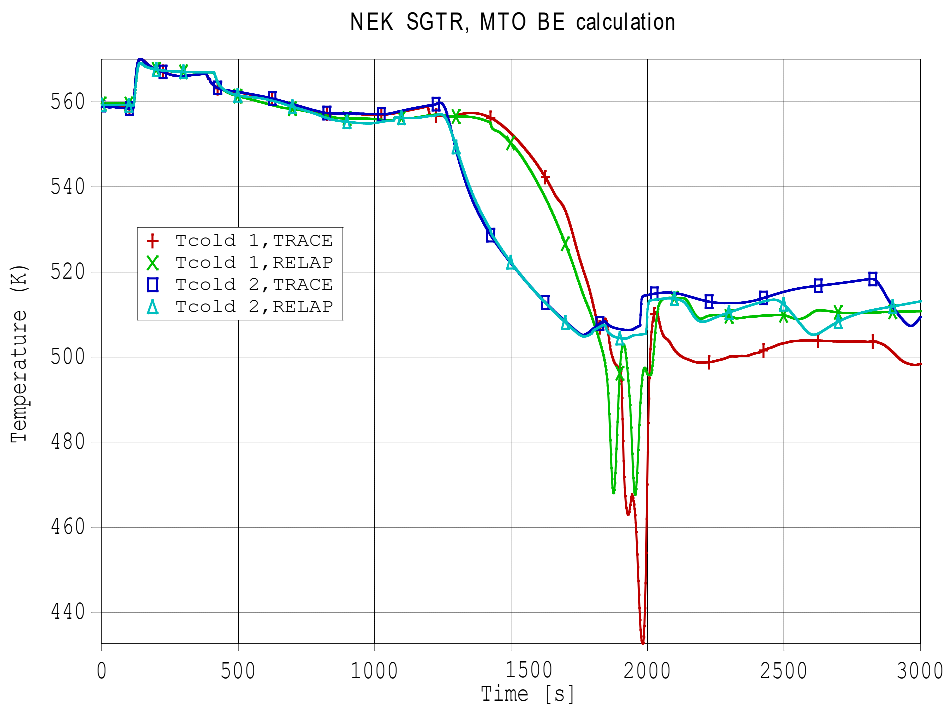

Figure 3-8 NEK SGTR, MTO BE Calculation, Cold Leg Temperature

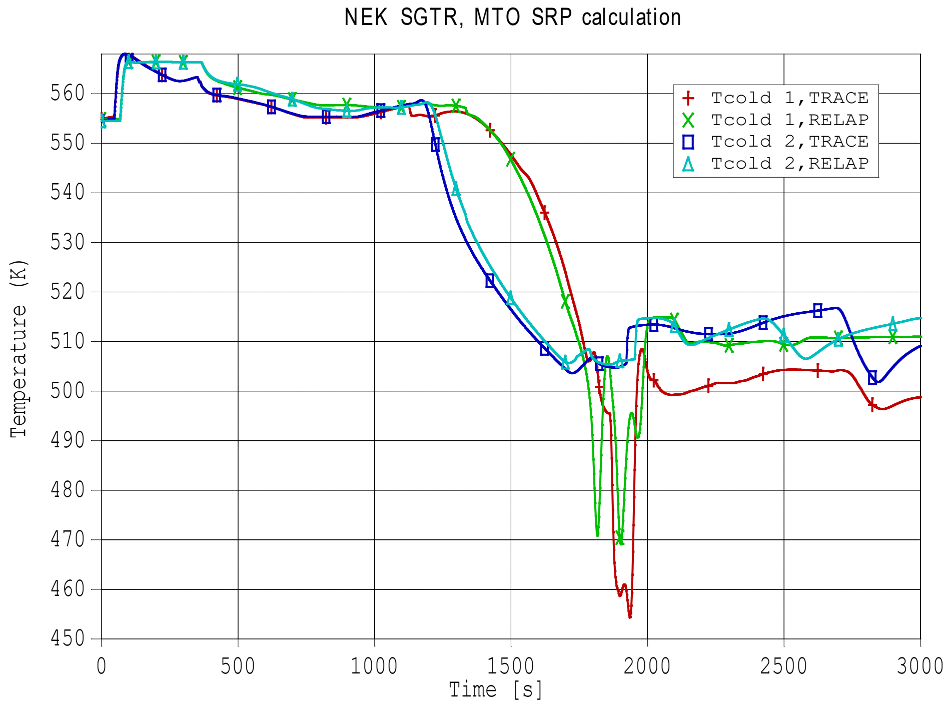

Figure 3-9 NEK SGTR, MTO SRP Calculation, Cold Leg Temperature

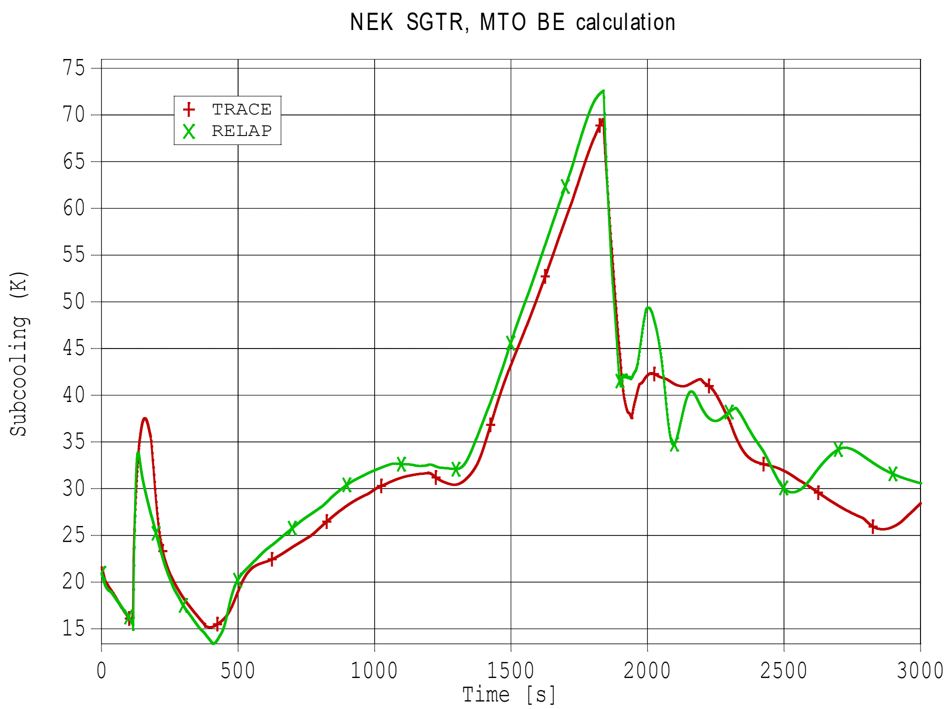

Figure 3-10 NEK SGTR, MTO BE Calculation, RCS Subcooling

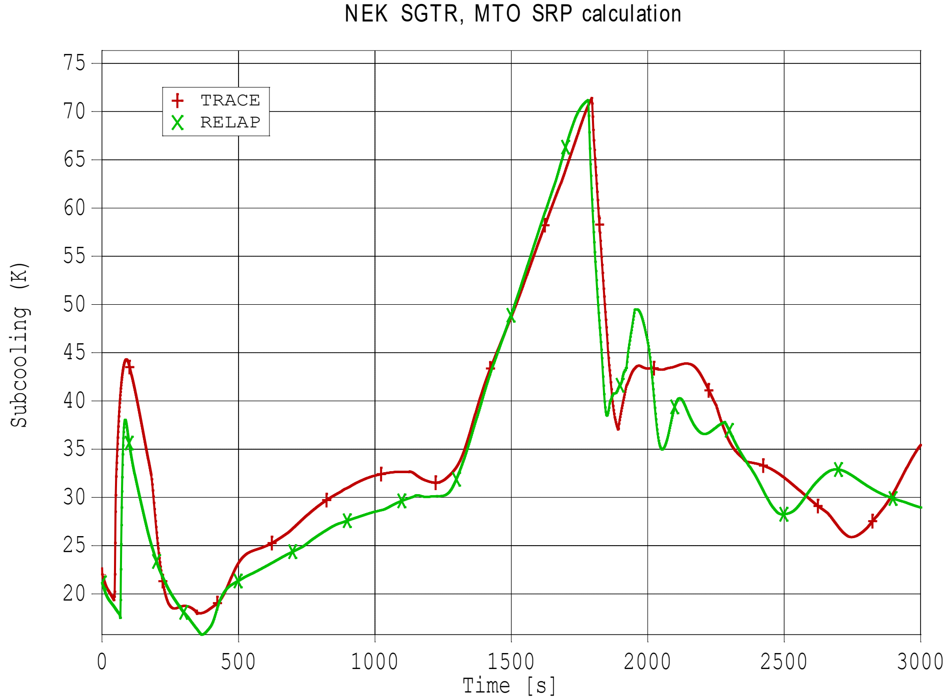

Figure 3-11 NEK SGTR, MTO SRP Calculation, RCS Subcooling

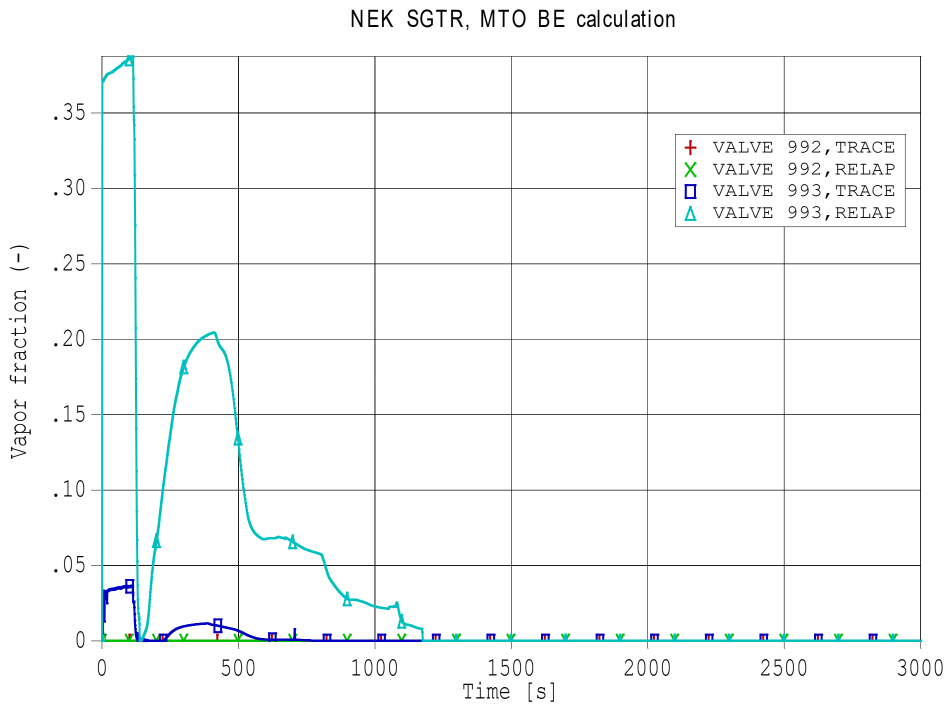

Figure 3-12 NEK SGTR, MTO BE Calculation, Break Flow Vapor Fraction

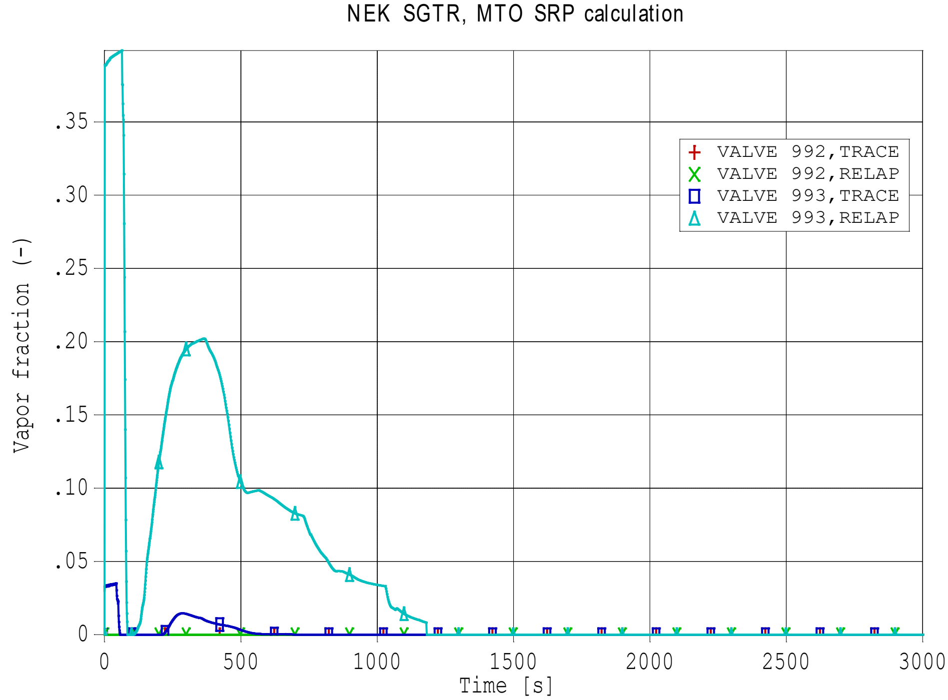

Figure 3-13 NEK SGTR, MTO SRP Calculation, Break Flow Vapor Fraction

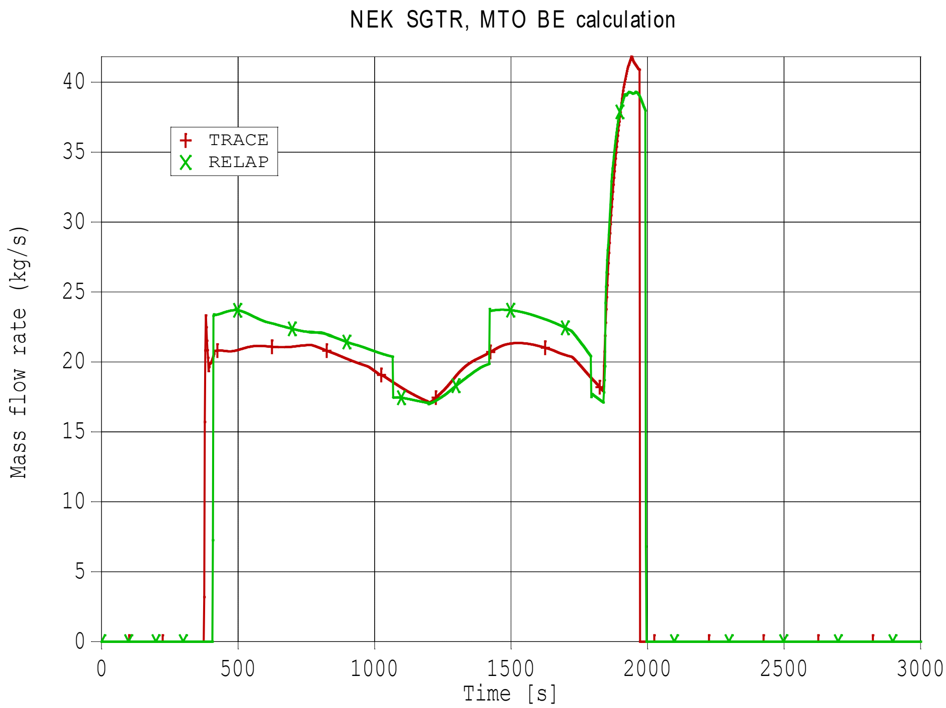

Figure 3-14 NEK SGTR, MTO BE Calculation, ECCS Flow

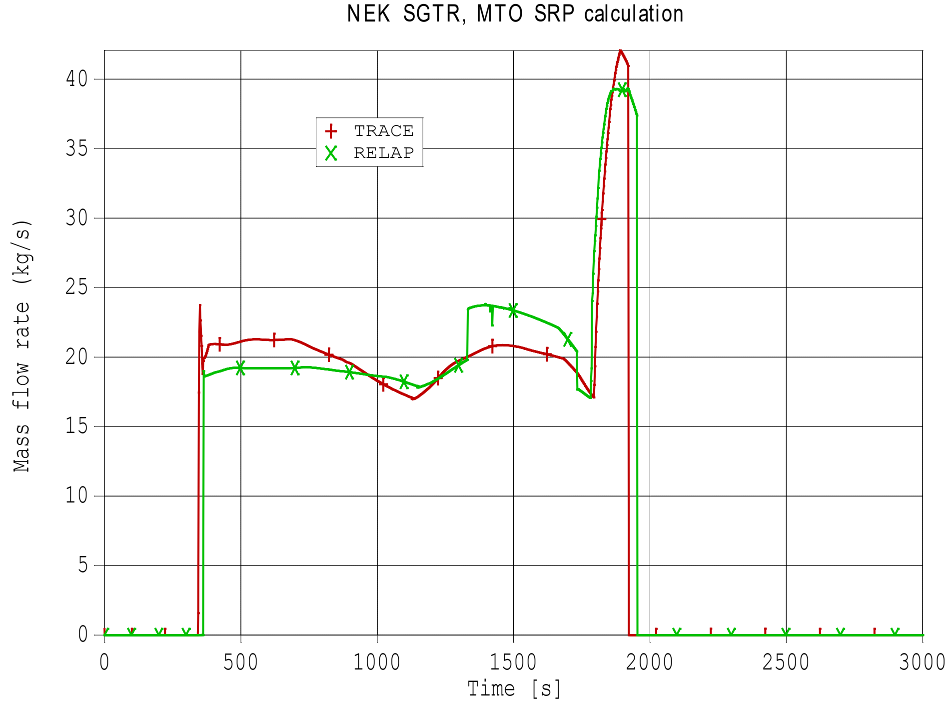

Figure 3-15 NEK SGTR, MTO SRP Calculation, ECCS Flow

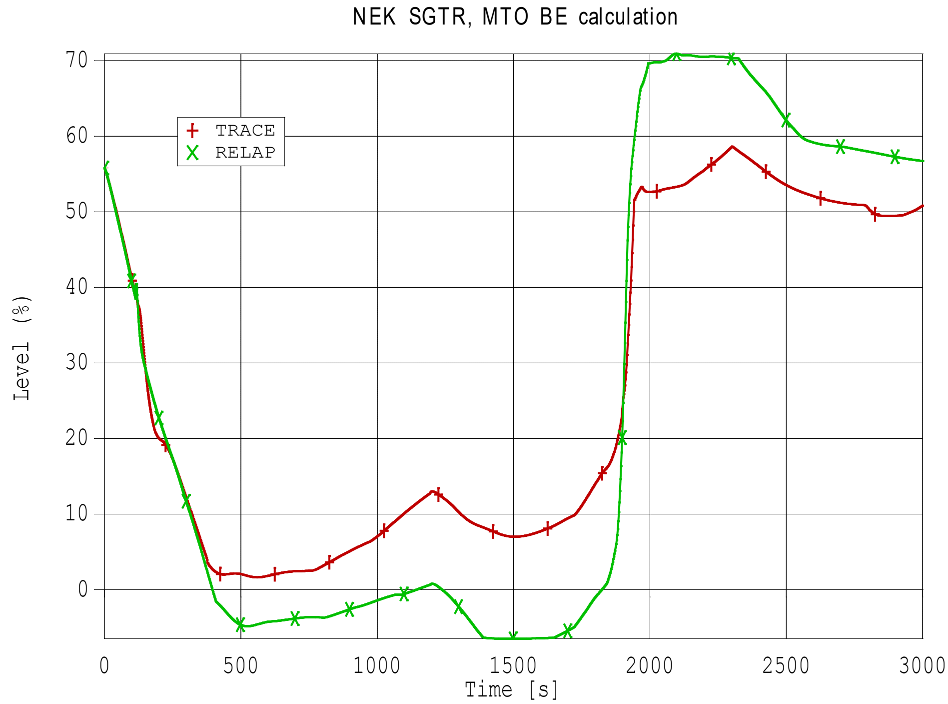

Figure 3-16 NEK SGTR, MTO BE Calculation, Pressurizer Level

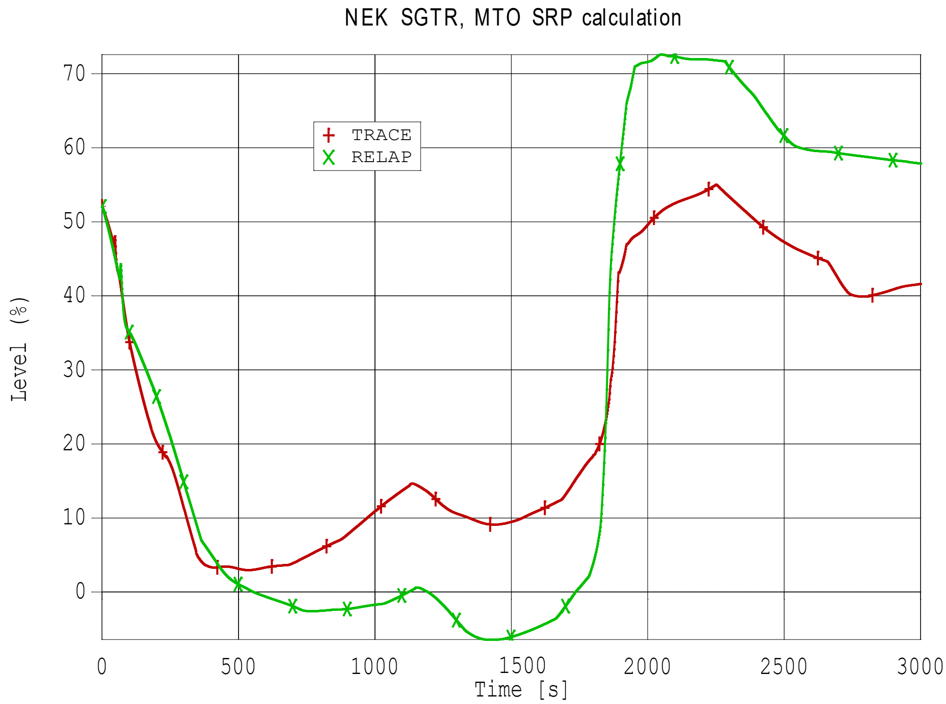

Figure 3-17 NEK SGTR, MTO SRP Calculation, Pressurizer Level

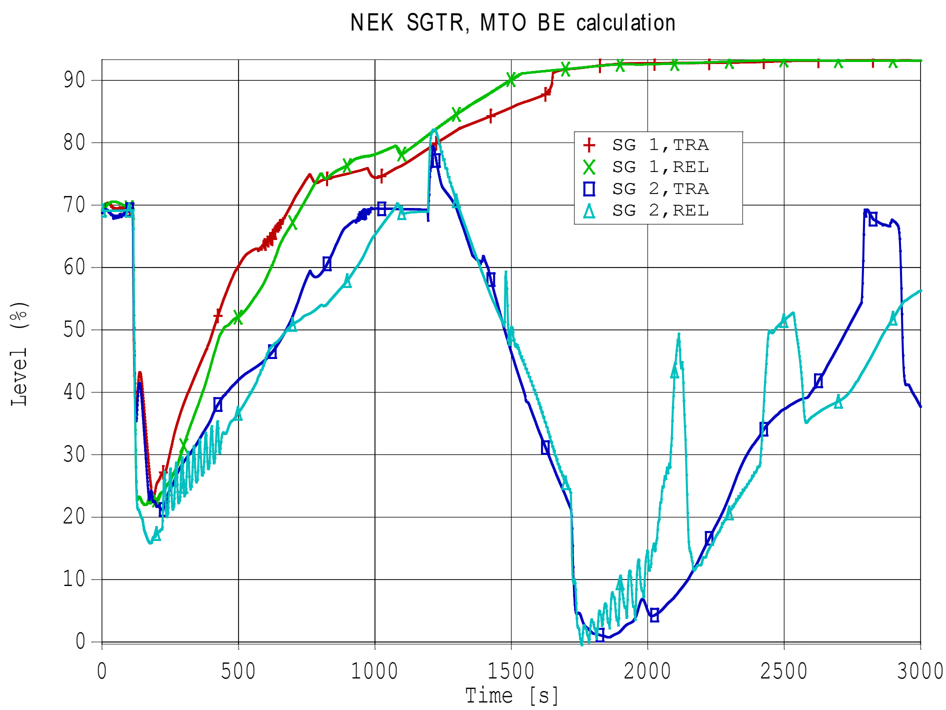

Figure 3-18 NEK SGTR, MTO BE Calculation, SG NR Level

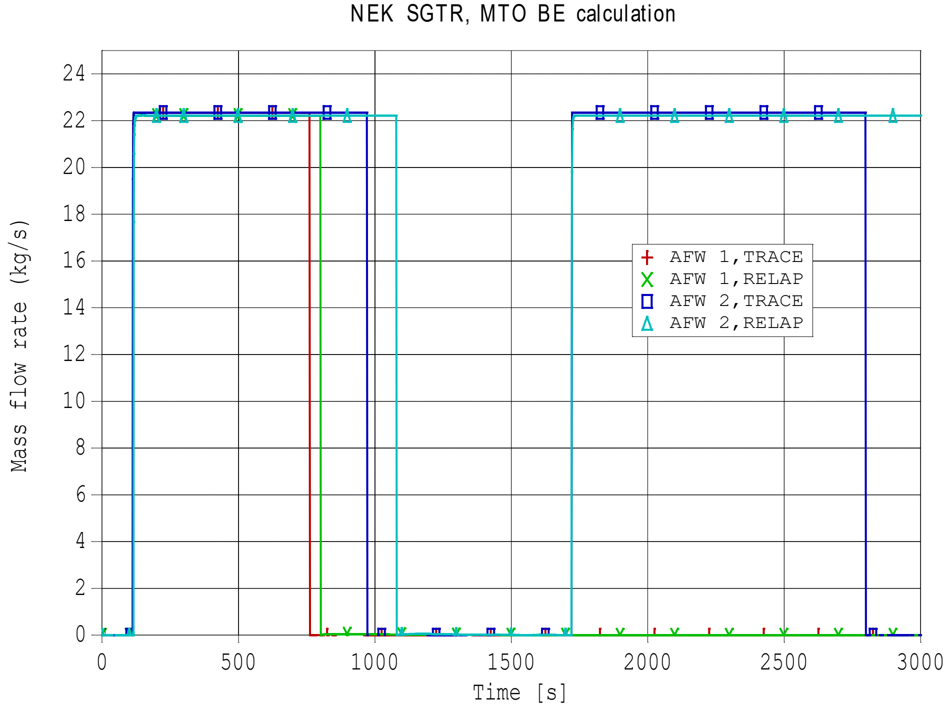

Figure 3-19 NEK SGTR, MTO BE Calculation, AFW Flow

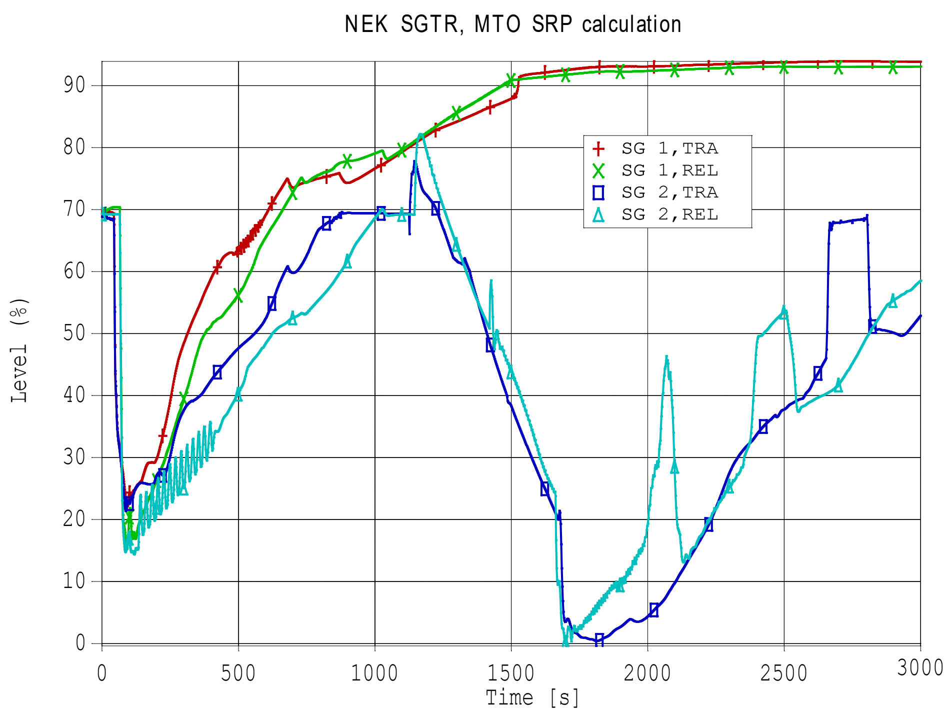

Figure 3-20 NEK SGTR, MTO SRP Calculation, SG NR Level

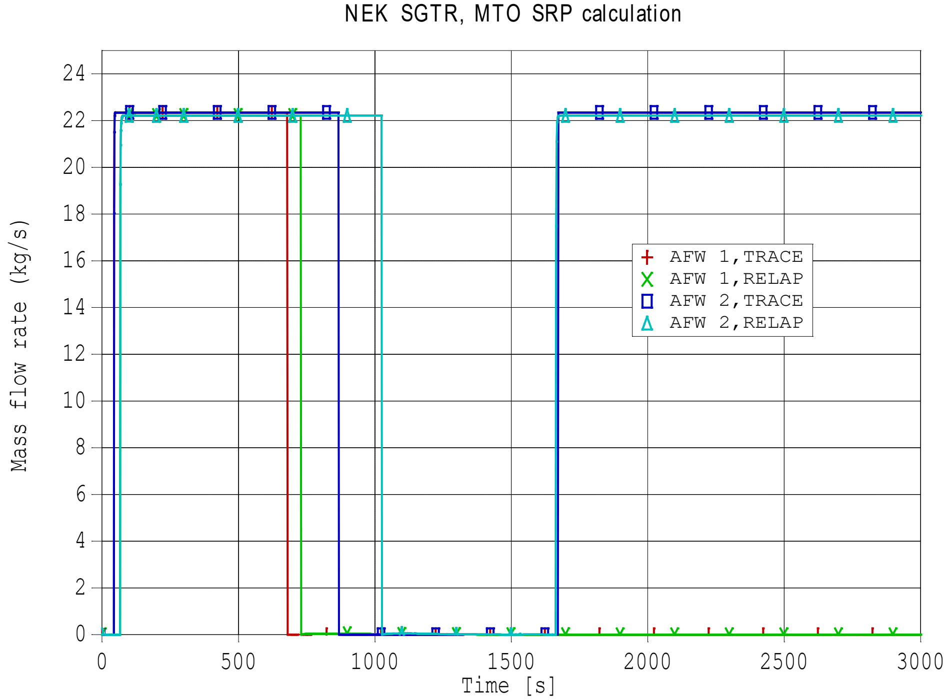

Figure 3-21 NEK SGTR, MTO SRP Calculation, AFW Flow

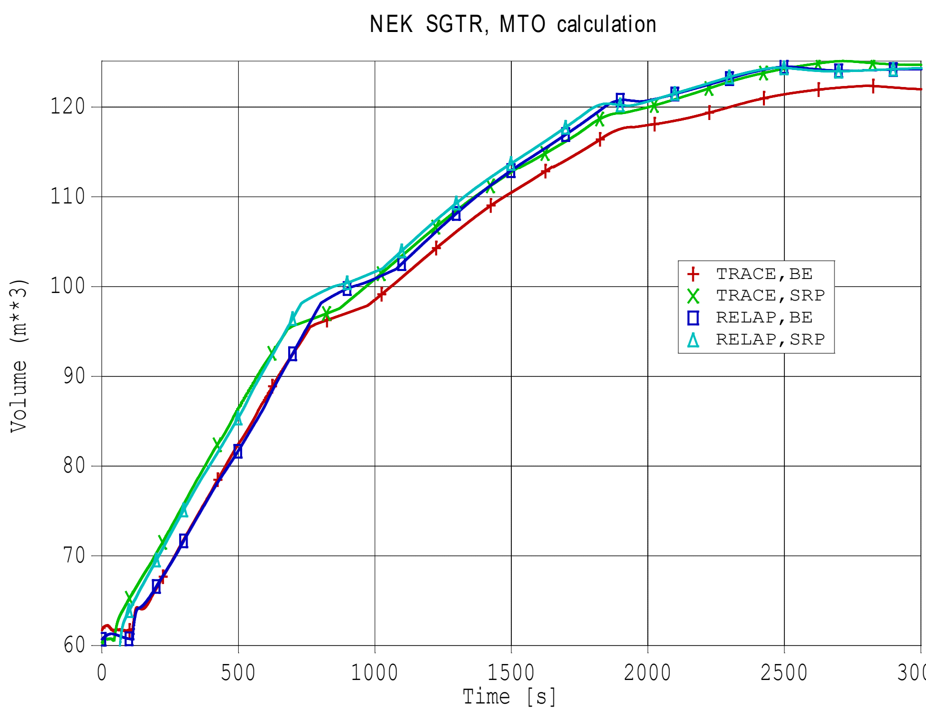

Figure 3-22 NEK SGTR, MTO Calculation, SG 1 Liquid Volume

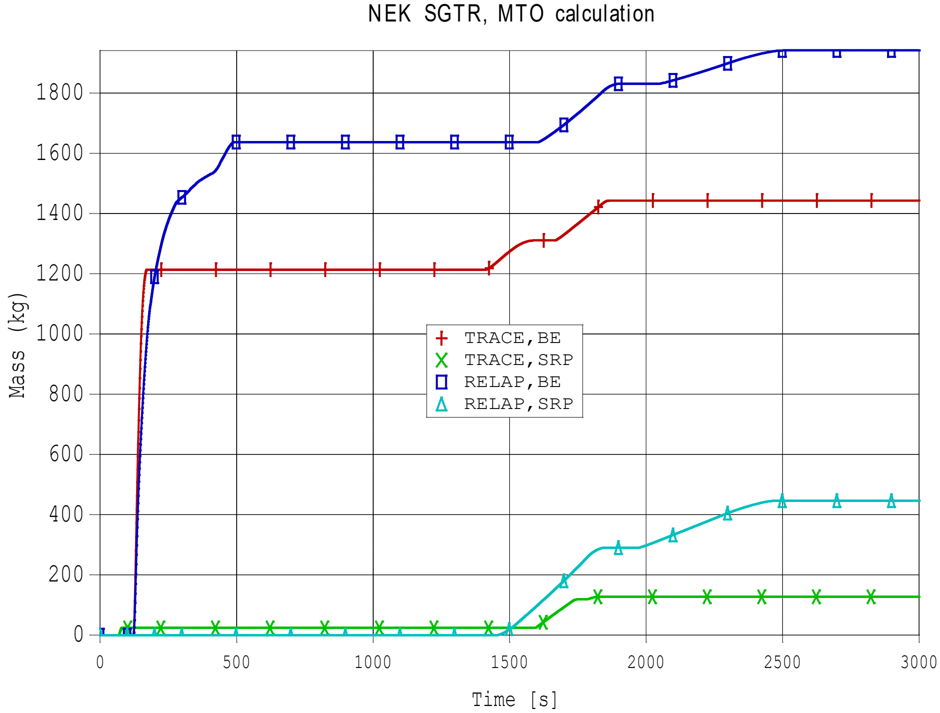

Figure 3-23 NEK SGTR, MTO Calculation, Integrated SG 1 PORV Flow

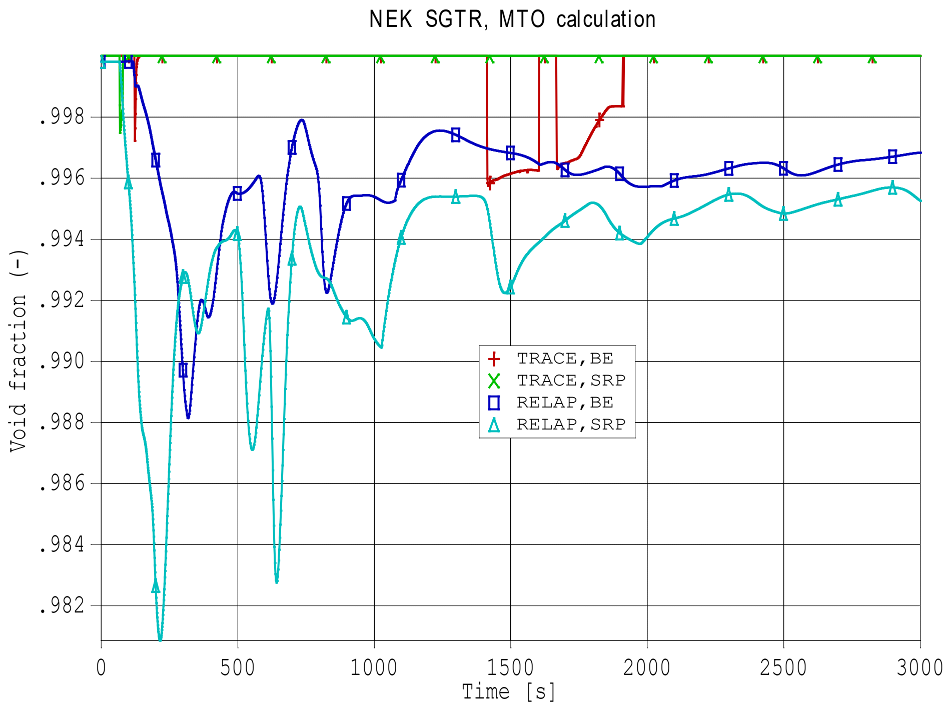

Figure 3-24 NEK SGTR, MTO Calculation, SG 1 PORV Flow Void Fraction

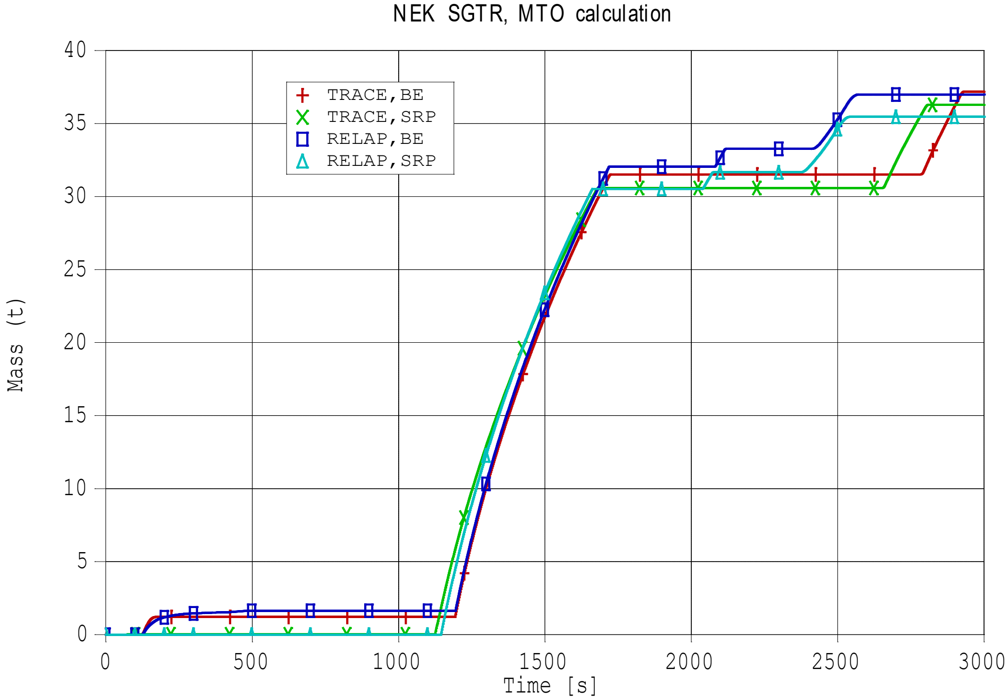

Figure 3-25 NEK SGTR, MTO Calculation, Integrated SG 2 PORV Flow

3.2 Analysis of SGTR Accident – Thermal Hydraulic Conditions for Dose Calculation (THD)

Transient results for THD scenario are presented in Table 4 and Figure 3-26 through Figure 3-58. Thermal hydraulic conditions for dose calculation (THD) analysis has been aimed to determine maximum flashing of break flow and maximum of steam release through the ruptured SG relief valve. THD analysis was performed for best-estimate as well as for SRP case obtained from the operating window that was found to result in most adverse results regarding the amount of break flow flashing and discharged steam mass through the ruptured SG relief valve. In the THD SRP analysis, the high Tavg case, 102% initial power and zero U-tube plugging was found to result in most conservative results. The analysis has been subdivided into three parts. In the first hour after transient begin the operator is expected to stop the primary to secondary leakage. The delay for operator actions do not differ from the MTO case, see Table 3 and Table 4. The only difference when compared with MTO case lays in the fact that the AFW was actuated with 60 seconds delay after reactor trip (immediately after reactor trip for MTO case) and the AFW to the ruptured SG was isolated for level greater than 50%(75% for MTO analysis). The minimization of AFW flow to the ruptured SG in THD analysis will maximize the flashing of the break flow and the steam release through the ruptured SG relief valve. The characteristic variables for THD BE case (break flow, primary and secondary pressures, NR water level in both steam generators, and mass discharged through SG-1 PORV) for the first hour of the accident are shown in Figure 3-26 through Figure 3-29. As already said, main difference compared to corresponding MTO case, are delayed AFW actuation and more fluid discharge through SG-1 PORV.

During the time of one to two hours after transient begin the operator is expected to maintain the stable plant conditions, (i.e., the primary pressure close to ruptured SG pressure (7.8 MPa) and the average RCS hot leg temperature equal to 537.0 K).

Two hours after transient begin the operator starts the cooldown and depressurization of primary side to hot shutdown condition (primary pressure less than 2.8 MPa and RCS average temperature less than 450.15 K) when RHR system can be put in operation. The setpoint for average RCS hot leg temperature and the primary pressure were modulated linearly in 19300 seconds (5.36 hours) from 537.0 K to 450.15 K and 7.8 MPa to 2.8 MPa, respectively. Similarly to the MTO analysis, loss of offsite power was assumed after reactor trip. Thus, the primary pumps were stopped and the steam dump was not available. The operator used the intact SG (SG 2) relief valve and pressurizer PORV to reduce the RCS temperature and primary pressure. In the analysis it was assumed that pressurizer PORV operation was allowed for pressurizer level not larger than 66% in order to prevent the pressurizer liquid solid condition. After pressurizer level exceeded 66% and pressurizer PORV was closed the next opening is enabled first after pressurizer level dropped below 45% in order to prevent the pressurizer PORV oscillating behavior. The setpoint values for the intact SG AFW start and stop were set to 20% and 70% of NR level throughout the calculation. The ruptured SG level setpoint for AFW operation was set to (50%, 60%). One hour after transient begin the operator has turned on the normal CVCS charging and letdown. In the analysis it was assumed that the setpoint for pressurizer level was set to 50% till the end of simulation (50000 seconds). Additionally, it was assumed that for pressurizer level less than 20% the operator turned off the letdown flow. Two hours after transient begin when the controlled cooldown has begun, the operator imposed the minimum charging flow regardless of normal charging flow demand resulting from pressurizer level control in order to prevent the pressurizer level off the span condition. For RELAP5 calculation the minimum charging flow was equal to 40% for both BE and SRP calculation, whereas for TRACE calculation the minimum charging flow demand for BE and SRP calculation were equal to 20% and 30%, respectively. The minimum charging flow demand was imposed till 26500 seconds (29000 seconds for SRP calculation) after transient begin when the setpoint values for primary pressure and temperature have reached their final values. For pressurizer level less than 30% the operator increased the charging flow to the maximum value until the pressurizer level exceeded 50%. After 26500 seconds the operator had to maintain the primary pressure and RCS average temperature at the values acceptable to switch to RHR operation, i.e., at the values not greater than 2.8 MPa and 450.15 K, respectively. Below, the results of analyses are discussed in a more detail.

Phase 1: 0 – 3600 seconds after transient begin
The THD BE case does not differ from the MTO BE analysis until reactor trip when for the MTO BE case the AFW flow was actuated immediately after reactor trip whereas for the THD case the AFW flow was initiated with 60 seconds delay. The OTDT reactor trip for the BE case was actuated at the same time as for MTO BE case, (i.e., 112.1 seconds after transient begin in TRACE and 113.9 seconds after transient begin for RELAP5). For the SRP case the OTDT trip was actuated considerably earlier (49.5 seconds after transient begin for TRACE and 73.9 seconds after transient begin for RELAP5). In general, the smaller AFW injection in the THD case has resulted in larger ruptured SG pressure and the larger amount of discharged mass through the SG 1 PORV than in MTO case. The vapor fraction of break flow was identified as the second critical parameter in THD analysis in addition to discharged mass through the ruptured SG. The maximum vapor break fraction in RELAP5 was again much larger (40.9%), see Figure 3-43 and Figure 3-44, than in TRACE (4%). In RELAP5 analysis both critical parameters (discharged mass through SG 1 PORV and the break flow vapor fraction) were more conservative (larger) than in TRACE analysis. Thereby, the RELAP5 vs TRACE difference for the discharged mass through the ruptured SG (9637 kg vs. 8433 kg) is much smaller than for the maximum break vapor void fraction (40.9% vs. 4%). In general, the obtained differences between RELAP5 and TRACE can be partly assigned to the larger break flow in the former case. The maximum ruptured SG liquid volume in THD case was smaller than in the MTO

analysis due to larger AFW flow in the latter case. Thereby, the maximum liquid volume in RELAP5 (107 m^3) is larger than the maximum liquid volume in TRACE (98.3 m^3) due to larger break flow in RELAP5 than in TRACE, Figure 3-52. There is a significantly larger amount of discharged inventory through the ruptured SG PORV in SRP (9637.3 kg for RELAP5 and 8432.5 kg for TRACE) than in BE analysis (4145.6 kg for RELAP and 3535.4 kg in TRACE), Figure 3-55. The difference in initial reactor power (100% in BE and 102% in the SRP case) as well as the difference in initial secondary side pressure values for BE and SRP case has led to the larger amount of discharged mass in the SRP than in BE case. Only steam was discharged through the SG 1 PORV, see Figure 3-56. In general, the similar values for the time to stop the break flow was obtained for both TRACE BE and RELAP BE case (around 1900 seconds after transient begin). For both codes the break flow in the THD SRP case was stopped later in the transient (2590 seconds after transient begin) due to the fact that the RCS depressurization using pressurizer PORV had to be stopped before the primary pressure fell below ruptured SG pressure because pressurizer level rose above 66%, see Table 4. In general, after stop of primary-to-secondary leakage, the operator is expected to maintain the core exit temperature at 539.3 K and the primary pressure at the value close to ruptured SG pressure (7.8 MPa).

Phase 2: 3600 – 30000 seconds after transient begin

3600 seconds after transient begin the operator has decreased the average RCS hot leg temperature from 539.3 K to 537 K in three minutes. The normal CVCS charging and letdown were enabled as well. Until two hours after transient begin the operator is expected to maintain the pressurizer pressure and level at 7.8 MPa and 50%, respectively. The main difference between RELAP5 and TRACE for both BE and SRP case lay in the fact that one hour after transient begin, in TRACE an immediate back flow from the secondary side of the ruptured SG to primary side was established, see Figure 3-52, whereas in RELAP5 after initial back flow the ruptured SG liquid volume increased again and reached the value close to the maximum liquid volume value during the first hour of simulation. Two hours after transient begin the programmed linear cooldown to the new average RCS hot leg temperature setpoint (450.15 K) and RCS depressurization to 2.8 MPa was initiated. RCS temperature and pressure setpoint were linearly changed during 19300 seconds (until 26500 seconds after transient begin). RCS cooldown and depressurization were performed using intact SG relief valve, see Figure 3-57 and Figure 3-58. Pressurizer proportional heaters were enabled as well. Due to RCS depressurization the back flow from the ruptured SG to the RCS was established. As already mentioned, the main difference between TRACE and RELAP5 was established already during the first hour after transient begin before normal CVCS flow was established when much larger amount of primary inventory was lost through the break in the RELAP5 calculation, see Figure 3-48, Figure 3-49 and Figure 3-52. Along with establishing normal letdown and charging flow much more cold water from CVCS was injected in RELAP5 than in TRACE where the intensive back flow from the ruptured SG has led to the significant difference between the hot and cold leg temperature before the begin of cooldown (7200 seconds after transient begin), see Figure 3-35 through Figure 3-38. In general, the cooldown and depressurization caused the back flow from the ruptured SG to the primary side on one side and decrease of pressurizer level on the other side. 30000 seconds after transient begin the hot shutdown conditions (pressurizer pressure less than 2.8 MPa and RCS average temperature less than 450.15 K were fulfilled for both RELAP5 calculations. For TRACE BE calculation, the RCS average temperature, see Figure 3-39, the RCS average temperature setpoint was reached 37500 seconds after transient begin whereas the setpoint for RCS pressure was reached 30000 seconds after transient begin, see Figure 3-32. For TRACE SRP calculation, the setpoint for RCS average temperature was reached earlier (35000 seconds after transient begin, see Figure 3-40 but with oscillations). The setpoint for RCS pressure was reached 30000 seconds after transient begin, see Figure 3-33.

Phase 3: 30000 – 50000 seconds after transient begin
After 30000 seconds till the end of simulation the operator had to maintain the stable primary side pressure and temperature as well as pressurizer level and stable ruptured SG level inventory. One has to note that the back flow from the ruptured SG to the primary side leads to decrease of ruptured SG level. The injection of cold AFW water into ruptured SG leads to a significant pressure drop in ruptured SG and subsequently it may lead to an increased break flow from primary to secondary side. In order to prevent the ruptured SG from refilling, the operator has to decrease the primary pressure which on the other side may lead to the decrease of RCS subcooling, see Figure 3-42. Thus, after 30000 seconds the operator has to balance between the maintenance of stable plant conditions with required RCS subcooling and stable ruptured SG liquid inventory. In TRACE analysis the minimum charging flow demand was not used after 30000 seconds while in RELAP5 the minimum charging flow equal to 30% was used till the end of simulation. The RCS subcooling remained greater than 20 K after the begin of controlled cooldown and the ruptured SG inventory did not rise above 86 m^3, see Figure 3-42 and Figure 3-52.

Following conclusions can be drawn from the presented analyses. During the first hour after transient begin the operator has brought the plant to stable conditions with primary-to-secondary side leakage flow terminated. Similar results for the time of operator actions (e.g., cooldown termination, SI flow stop, termination of primary-to-secondary leakage were obtained when compared to MTO analyses.). THD calculation was conservative regarding the flashing of break flow and the amount of discharged mass through the ruptured SG relief valve. The differences for the maximum vapor fraction of break flow between MTO and THD case are very small (e.g., for THD case the maximum break flow vapor fraction is equal to 40.9% for RELAP5 and 4% for TRACE while for MTO case the corresponding values for RELAP5 and TRACE were equal to 39.9% and 3.7%, respectively). The difference for the discharged mass through the ruptured SG relief valve between MTO and THD case was larger, (i.e., for THD case the maximum discharged mass for RELAP5 and TRACE were equal to 9637.3 kg and 8432.5 kg (1941.3 kg and 1443.1 kg for MTO case). On the other side, the maximum liquid volume was smaller in THD than in MTO case due to less amount of injected AFW flow in the former case. In general, more conservative results regarding the maximum break flow vapor fraction as well as discharged mass through the ruptured SG relief valve were obtained for RELAP5 than for TRACE. At least a part of the obtained differences between RELAP5 and TRACE can be assigned to the difference in break flow that is somewhat larger in RELAP5 than in TRACE throughout the calculation. Similarly to the MTO case, the maximum ruptured SG liquid volume was larger in RELAP5 than in TRACE.

One hour after transient begin the normal CVCS charging and letdown flow was established. The operator had to maintain the RCS average hot leg temperature at its setpoint value (537.0 K) until two hours after transient when the controlled cooldown and depressurization to HSD conditions was started. One hour after transient begin pressurizer level in RELAP5 was much smaller than in TRACE due to larger break flow. As a consequence, in RELAP5 the CVCS charging flow was increased in order to recover the pressurizer level whereas in TRACE an immediate back flow from the ruptured SG was established and the charging flow was equal to zero until the constant charging flow (30% charging flow demand) was imposed in TRACE after begin of controlled cooldown two hours after transient begin. In RELAP5 the back flow from ruptured SG was established first two hours after transient begin following the start of RCS cooldown and depressurization. During cooldown and depressurization to HSD conditions CVCS charging flow was tuned on with different values of minimum charging flow demand for different code (20% and 30% for TRACE and 40% for RELAP5). In the period: 30000-37500 seconds the final RCS average temperature and RCS pressure were attained for both RELAP5 and TRACE.

Table 4 Time Sequence of the Main Events: SGTR, THD Analysis

Event	RELAP5, BE analysis	RELAP5, SRP analysis	TRACE, BE analysis	TRACE, SRP analysis
Time: 0-3600s				
Tube rupture (s)	0	0	0	0
Reactor trip (s)	113.9 (OTDT)	73.9 (OTDT)	112.1 (OTDT)	49.5 (OTDT)
AFW initiation (s) (60 s after RT)	173.9	133.9	172.1	109.5
SI actuation (s) (low-2 PRZ p)	400.8	321.0	377.0	370.2
SG 1 AFW isolation (s)	525.3 (level > 50%)	546.2 (level > 50%)	459 (level > 50%)	423 (level > 50%)
Ruptured SG steamline isolation (s)	1073.9 (960 s after RT)	1033.9 (960 s after RT)	1072.1 (960 s after RT)	1009.5 (960 s after RT)
Initiation of cooldown with intact SG (s)	1193.9 (1080 s after RT)	1153.9 (1080 s after RT)	1192.1 (1080 s after RT)	1129.5 (1080 s after RT)
Charging actuation (36 m^3/hr) (s)	1194.9 (1081 s after RT)	1154.9 (1081 s after RT)	1193.1 (1081 s after RT)	1130.5 (1081 s after RT)
Break flow flashing stops (s)	1347.0 (max. void 38.8%)	1356.0 (max. void 40.9%)	542 (max. void 3.7%)	901 (max. void 4%)
Cooldown termination (s)	1676.8	1726.8	1711.4	1714.3
Depressurization initiation (s) (120 s after cooldown)	1796.8	1846.8	1831.4	1834.3
Depressurization termination (s)	1913.9 (PRZ level > 66%)	1936.0 (PRZ level > 66%)	1910.0 (PRZ p < SG 1 p)	1935.5 (PRZ level > 66%)
Stop SI flow (s)	1943.9 (30 s delay)	1966.1 (30 s delay)	1940.0 (30 s delay)	1965.5 (30 s delay)
Balance charging and letdown flow (charging termination)	2273.9s (6 min after end of depressurization)	2296.0s (6 min after end of depressurization)	2270.0s (6 min after end of depressurization)	2295.5s (6 min after end of depressurization)
Break flow reversal (s)	1880.0	2590.0	1920.0	2590.0
Minimum SG 1 PORV flow void fraction	0.9919	0.9957	0.9974	0.9982
Maximum ruptured SG water volume reached (0-15000 s)	106.0 m^3	107.0 m^3	101.5 m^3	98.3 m^3
Time: 3600–50000s: Cooldown and depressurization to HSD conditions				

Event	RELAP5, BE analysis	RELAP5, SRP analysis	TRACE, BE analysis	TRACE, SRP analysis
End of cooldown and depressurization	30000s	30000s	37500s	35000s (oscillating Tavg 1)
Total discharged mass through SG 1 PORV	4145.6 kg	9637.3 kg	3535.5 kg	8432.5 kg
Total discharged mass through SG 2 PORV	358055.0 kg	434139.0 kg	356631 kg	420752 kg
Total discharged mass through pressurizer PORV	5144.5 kg	4839.7 kg	3205.2 kg	3353.1 kg
Max. SG 1 liquid volume (15000-50000 s)	90.6 m^3	85.5 m^3	85.4 m^3	83.3 m^3

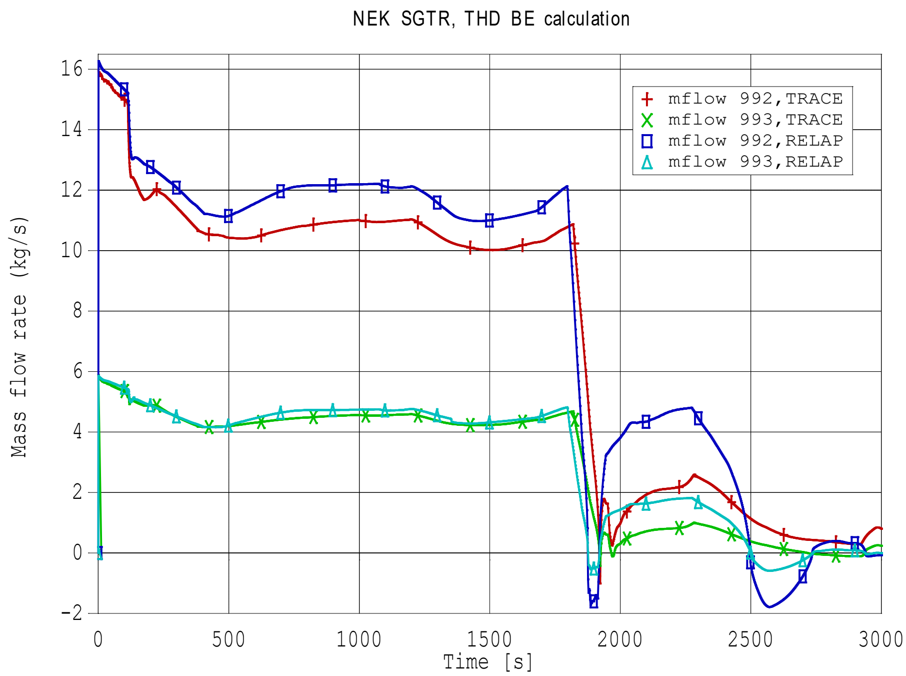

Figure 3-26 NEK SGTR, THD BE Analysis, Break Mass Flow Rate, RELAP5 and TRACE (0-3000s)

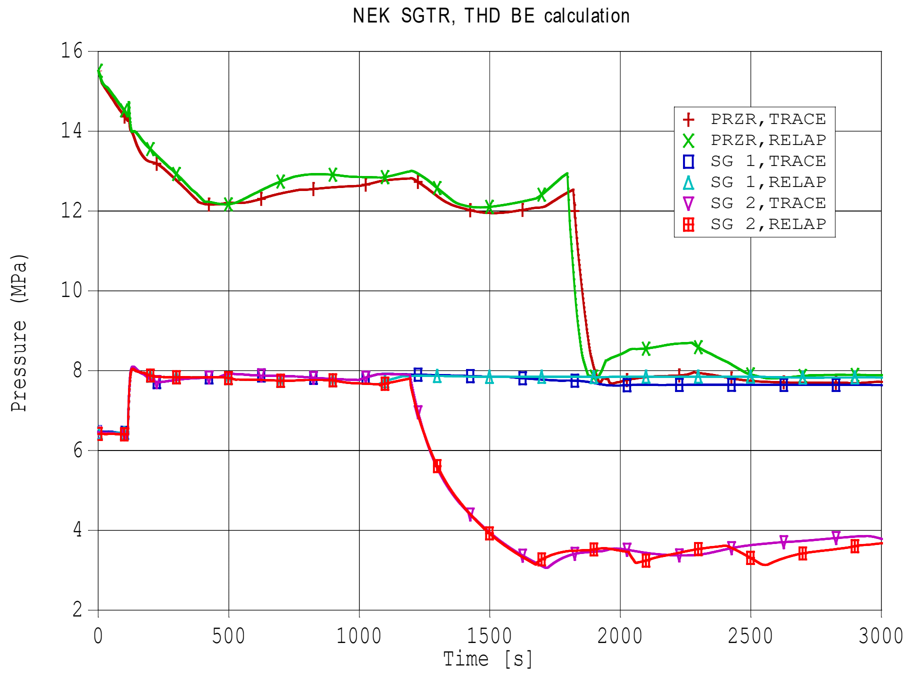

Figure 3-27 NEK SGTR, THD BE Analysis, Pressurizer and SG Pressure, RELAP5 and TRACE (0-3000s)

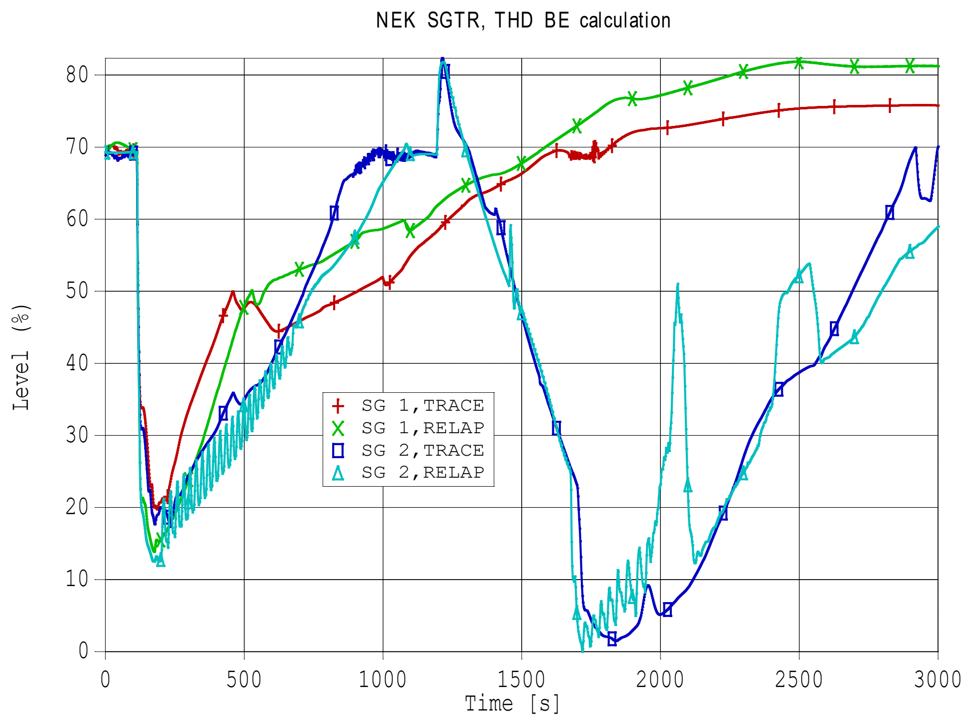

Figure 3-28 NEK SGTR, THD BE Analysis, SG NR Level, ACE (0-3000s)

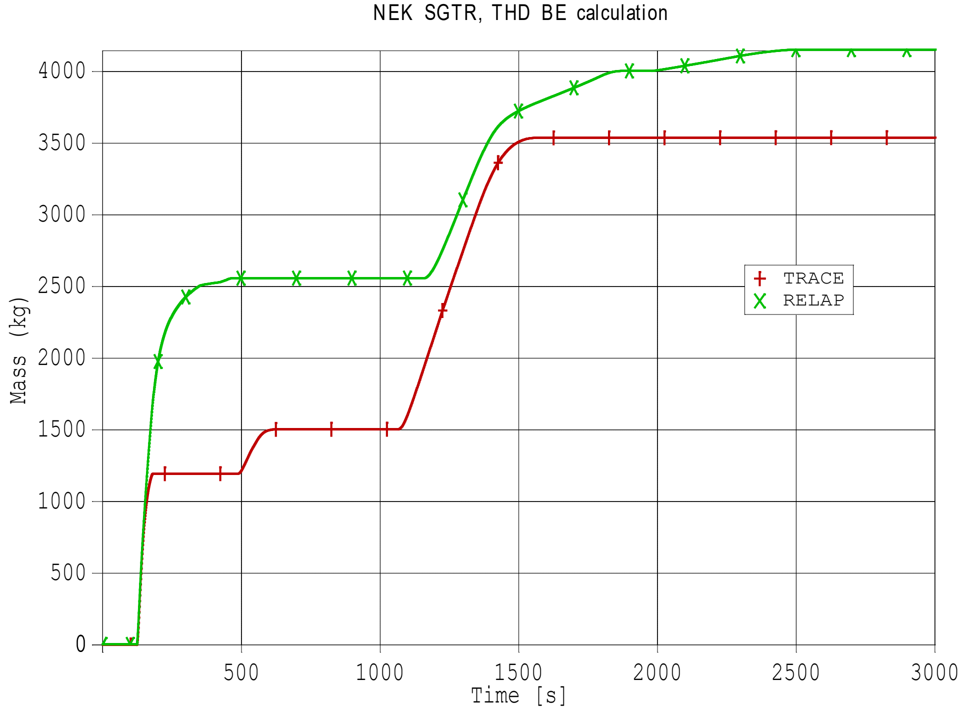

Figure 3-29 NEK SGTR, THD BE Analysis, Discharged SG 1 PORV Mass, RELAP5 and TRACE (0-3000s)

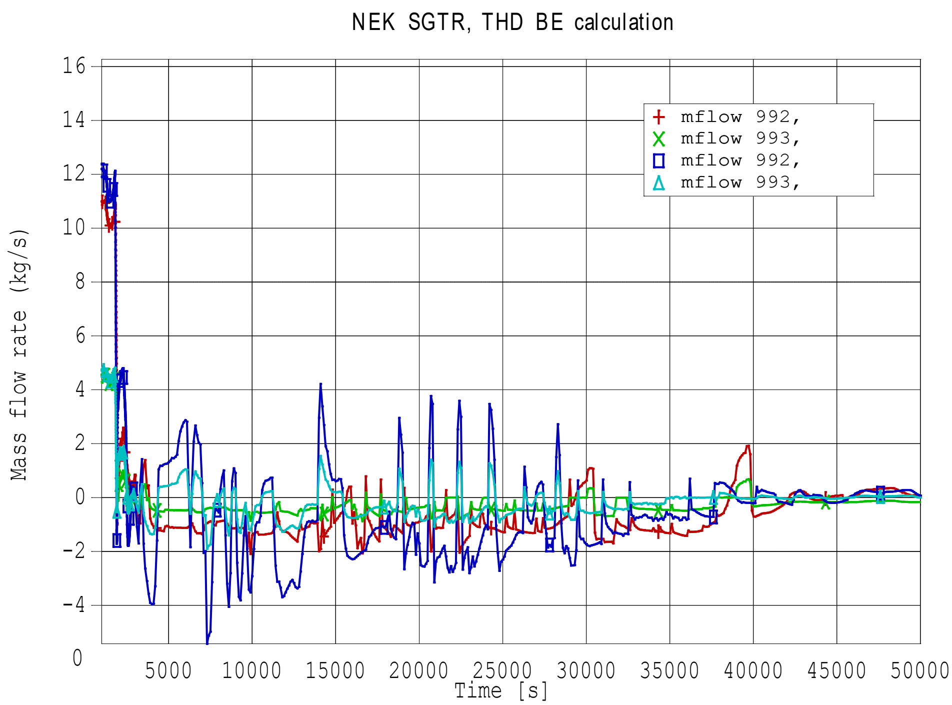

Figure 3-30 NEK SGTR, THD BE Analysis, Break Mass Flow Rate, RELAP5 and TRACE

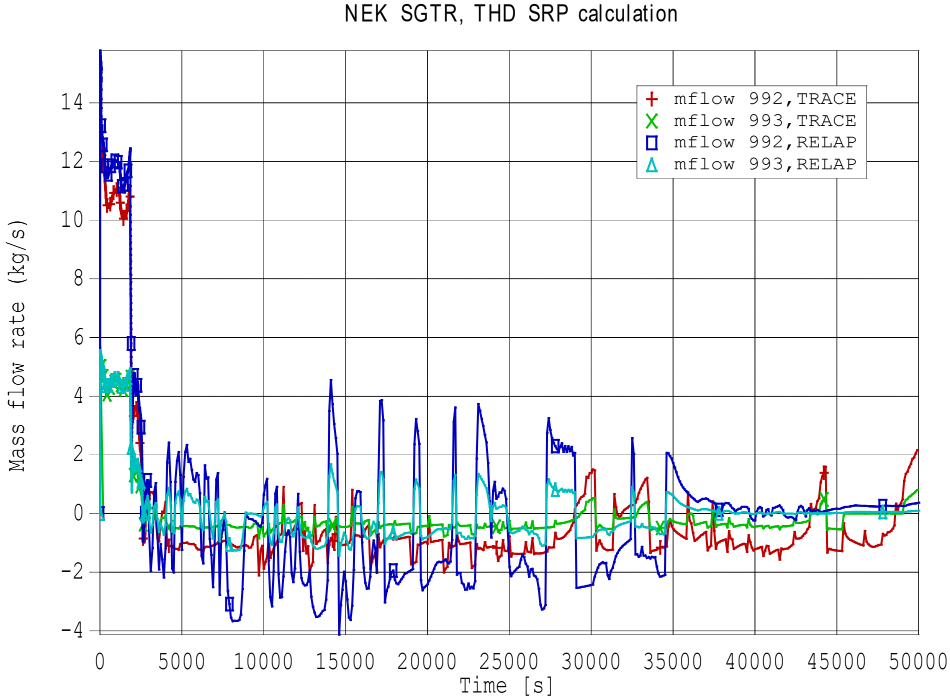

Figure 3-31 NEK SGTR, THD SRP Analysis, Break Mass Flow Rate, and RELAP5 TRACE

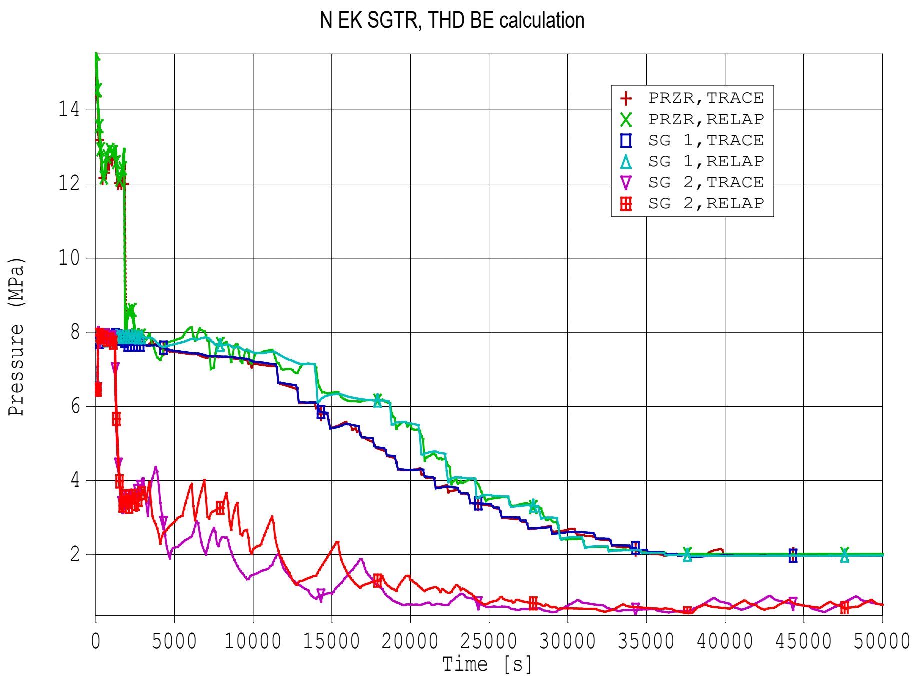

Figure 3-32 NEK SGTR, THD BE Analysis, Pressurizer and SG Pressure, RELAP5 and TRACE

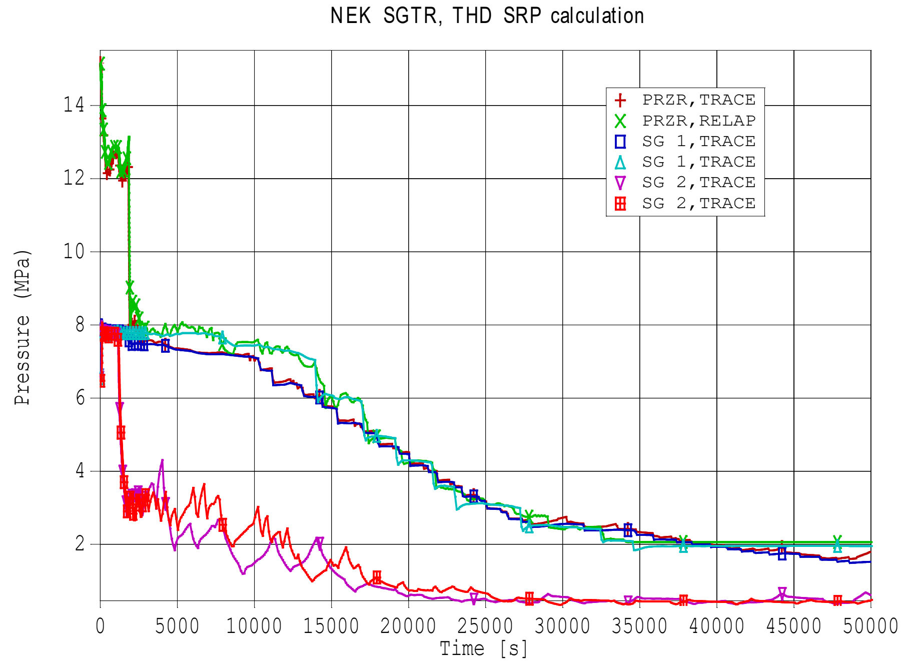

Figure 3-33 NEK SGTR, THD SRP Analysis, Pressurizer and SG Pressure, RELAP5 and TRACE

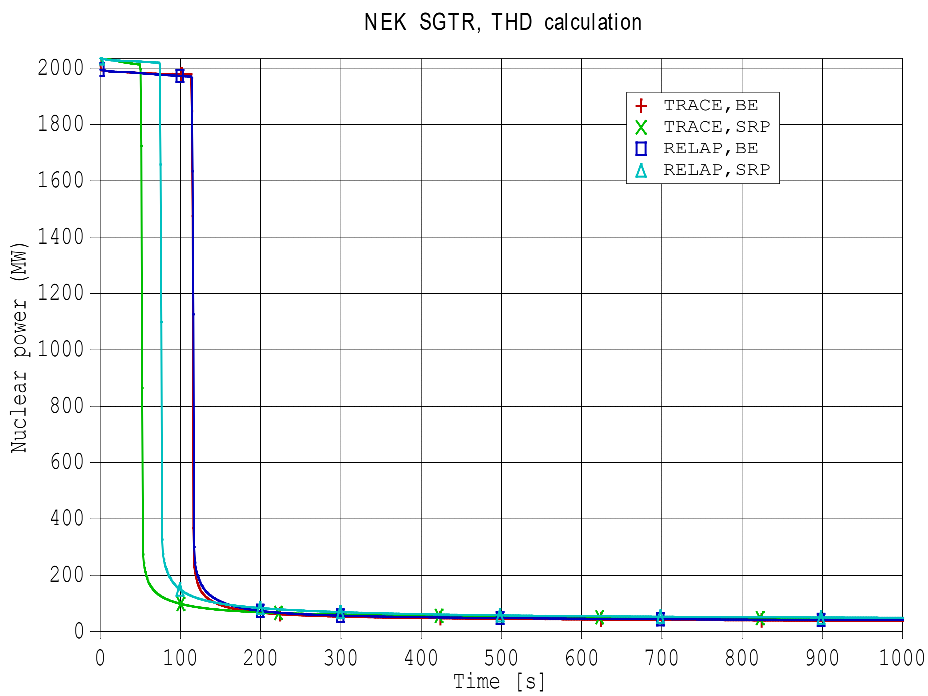

Figure 3-34 NEK SGTR, THD Analysis, Nuclear Power, RELAP5 and TRACE (0-1000s)

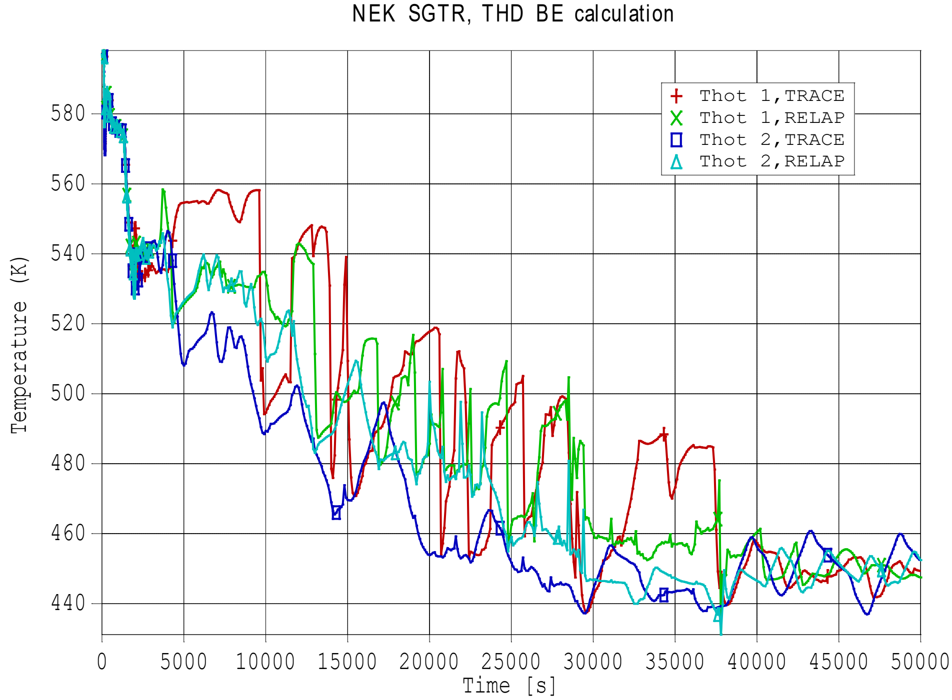

Figure 3-35 NEK SGTR, THD BE Analysis, Hot Leg Temperature, RELAP5 and TRACE

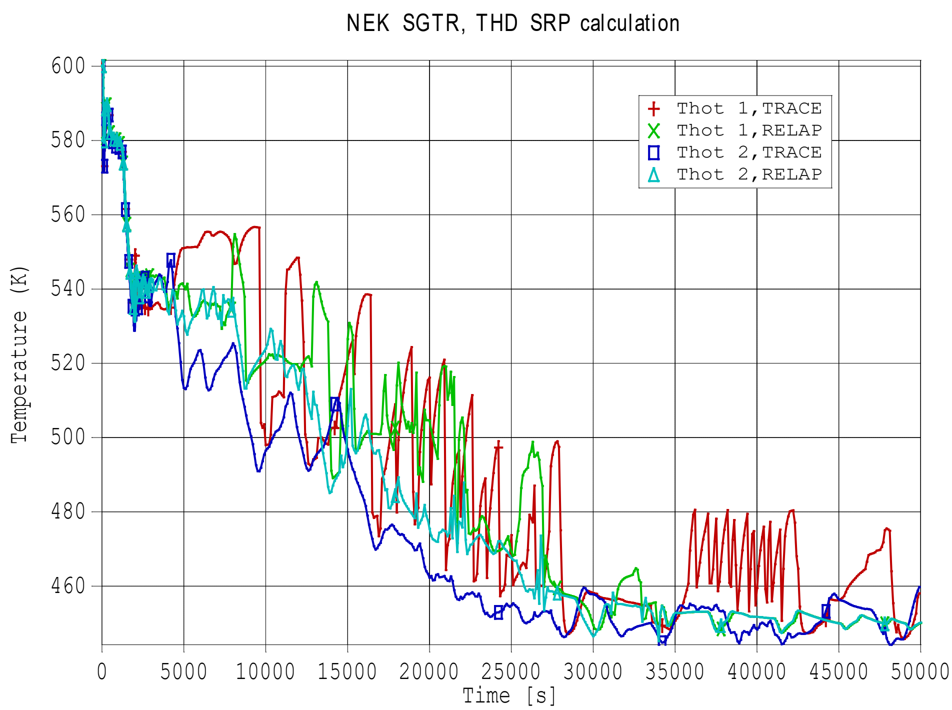

Figure 3-36 NEK SGTR, THD SRP Analysis, Hot Leg Temperature, RELAP5 and TRACE

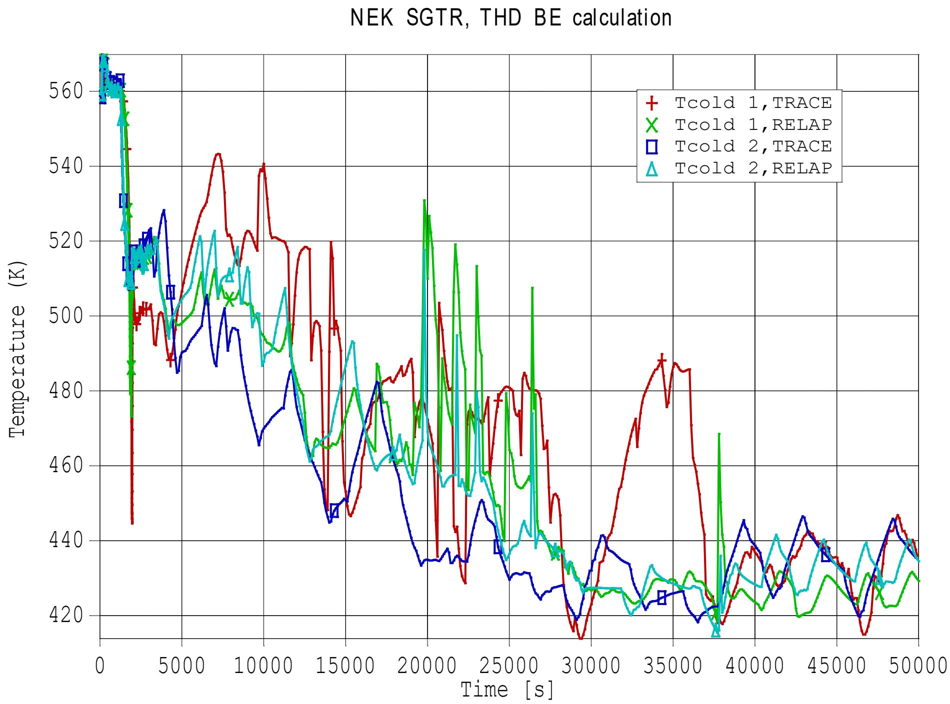

Figure 3-37 NEK SGTR, THD BE Analysis, Cold Leg Temperature, RELAP5 and TRACE

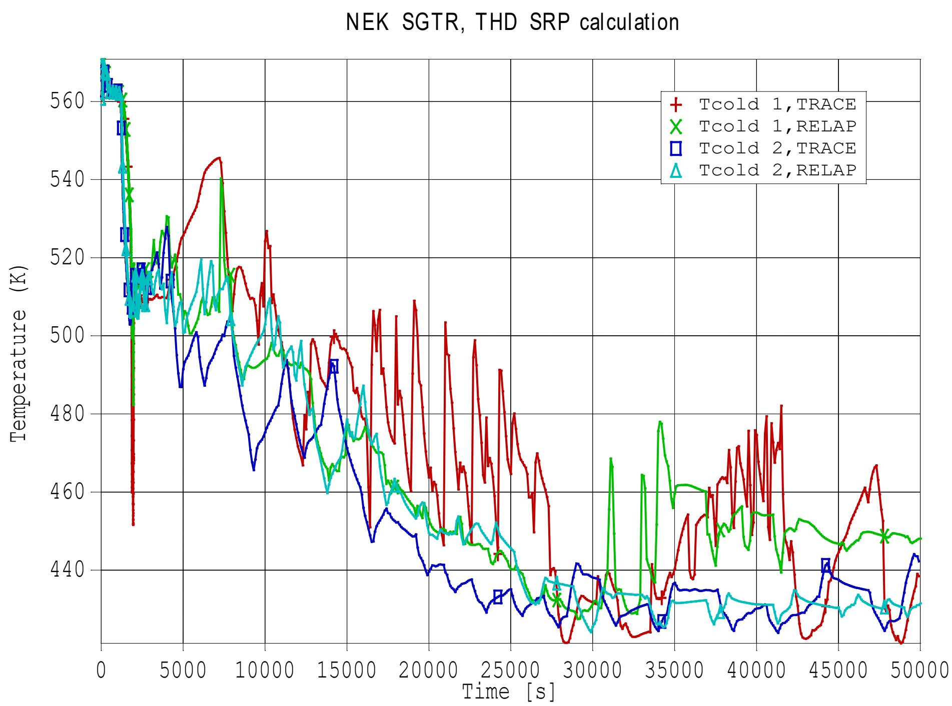

Figure 3-38 NEK SGTR, THD SRP Analysis, Cold Leg Temperature, RELAP5 and TRACE

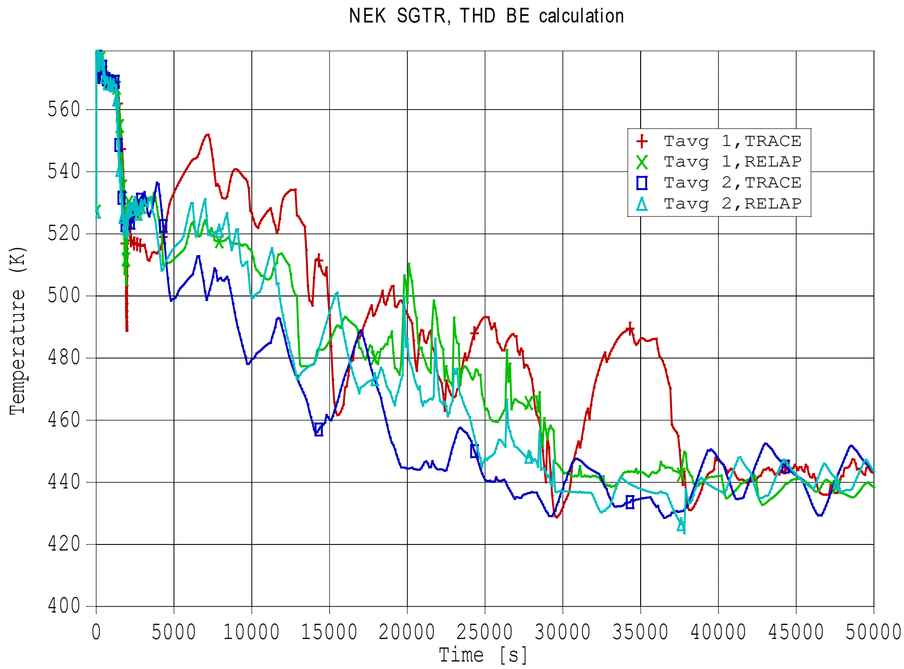

Figure 3-39 NEK SGTR, THD BE Analysis, RCS Average Temperature, RELAP5 and TRACE

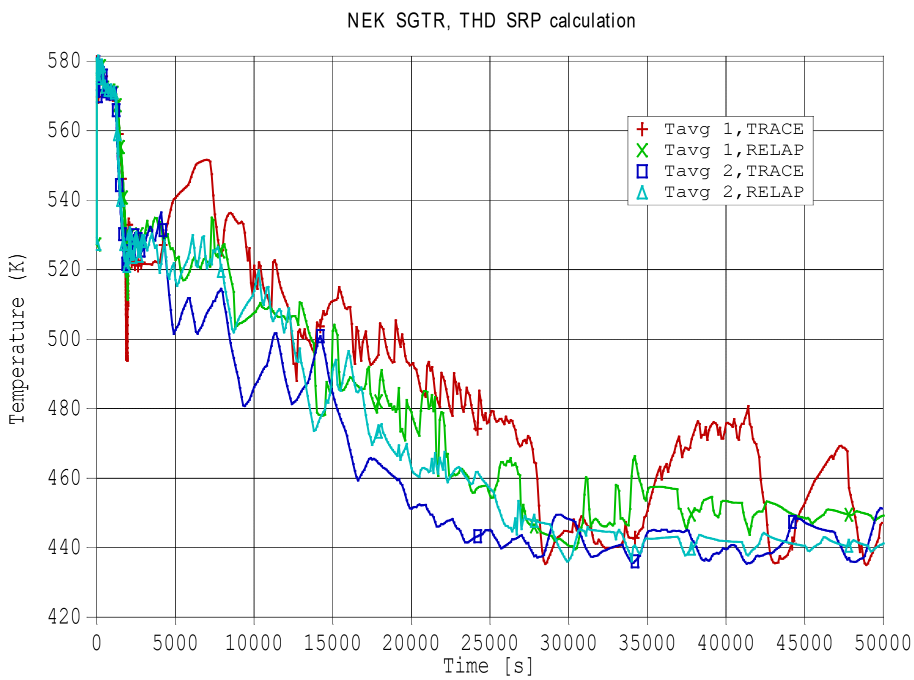

Figure 3-40 NEK SGTR, THD SRP Analysis, RCS Average Temperature, RELAP5 and TRACE

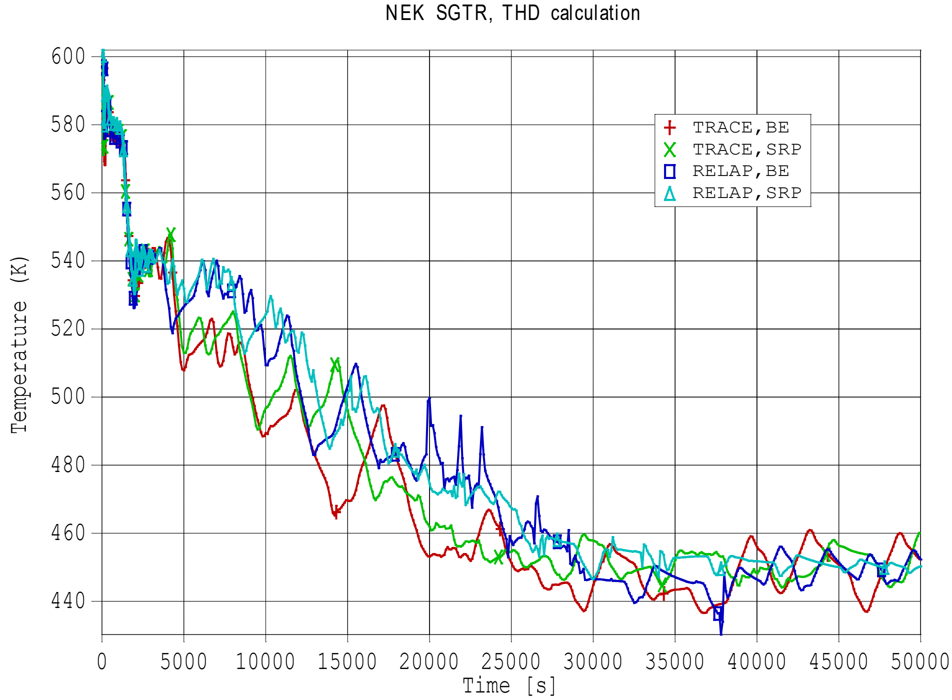

Figure 3-41 NEK SGTR, THD Analysis, Core Exit Temperature, RELAP5 and TRACE

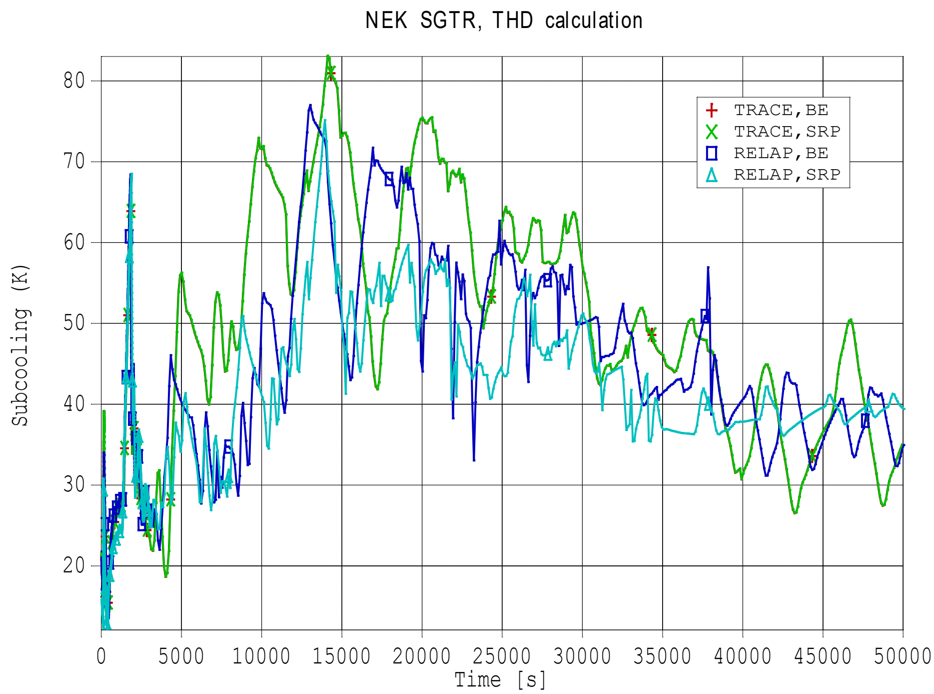

Figure 3-42 NEK SGTR, THD Analysis, RCS Subcooling, RELAP5 and TRACE

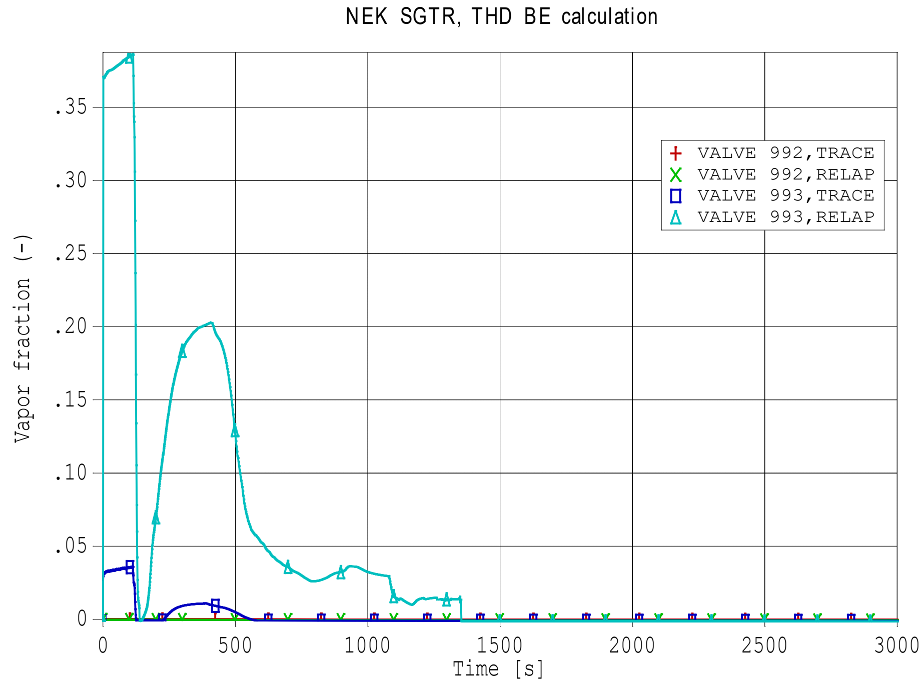

Figure 3-43 NEK SGTR, THD BE Analysis, Break Flow Vapor Fraction, RELAP5 and TRACE

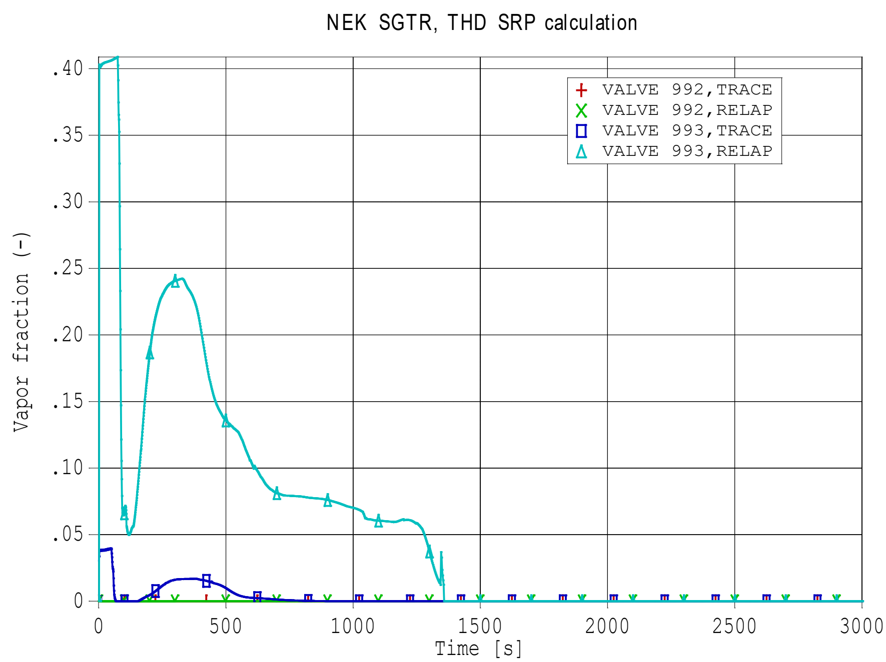

Figure 3-44 NEK SGTR, THD SRP Analysis, Break Flow Vapor Fraction, RELAP5 and TRACE

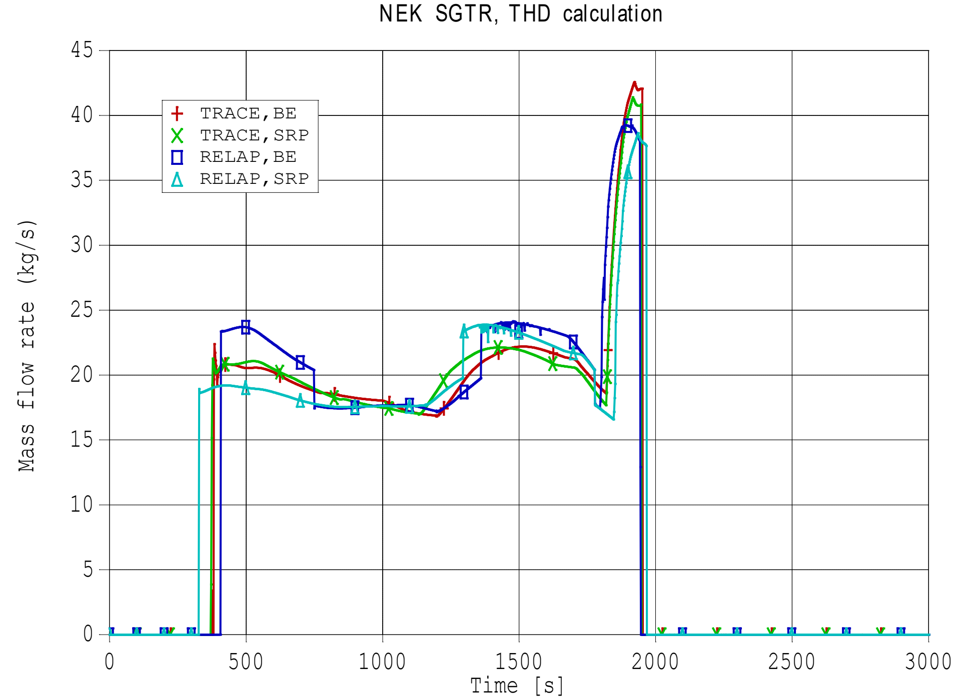

Figure 3-45 NEK SGTR, THD Analysis, ECCS Flow, RELAP5 and TRACE

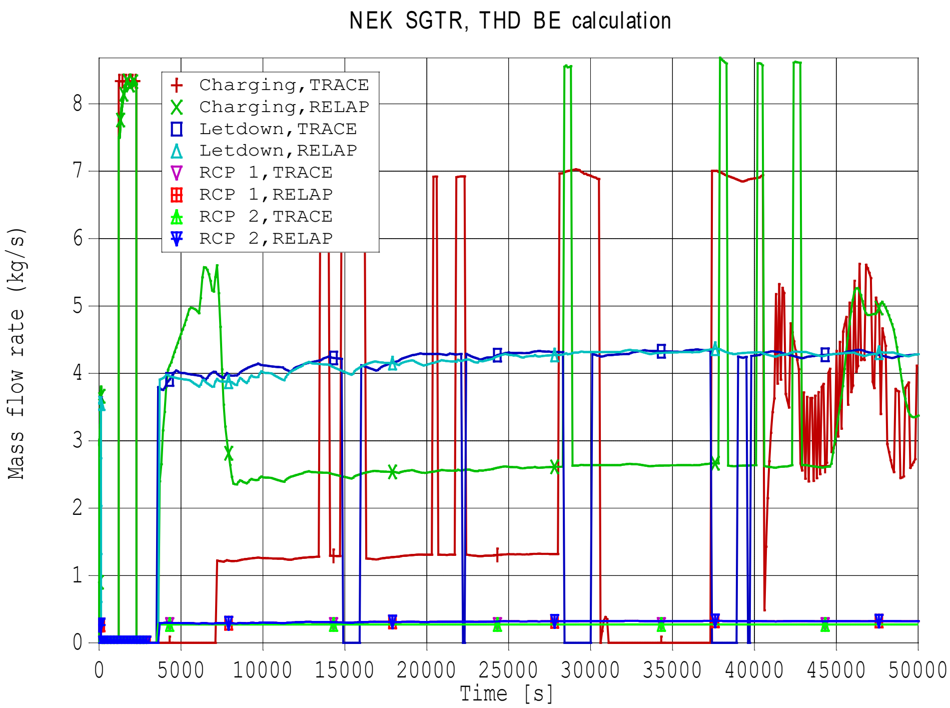

Figure 3-46 NEK SGTR, THD BE Analysis, CVCS Flow, RELAP5 and TRACE

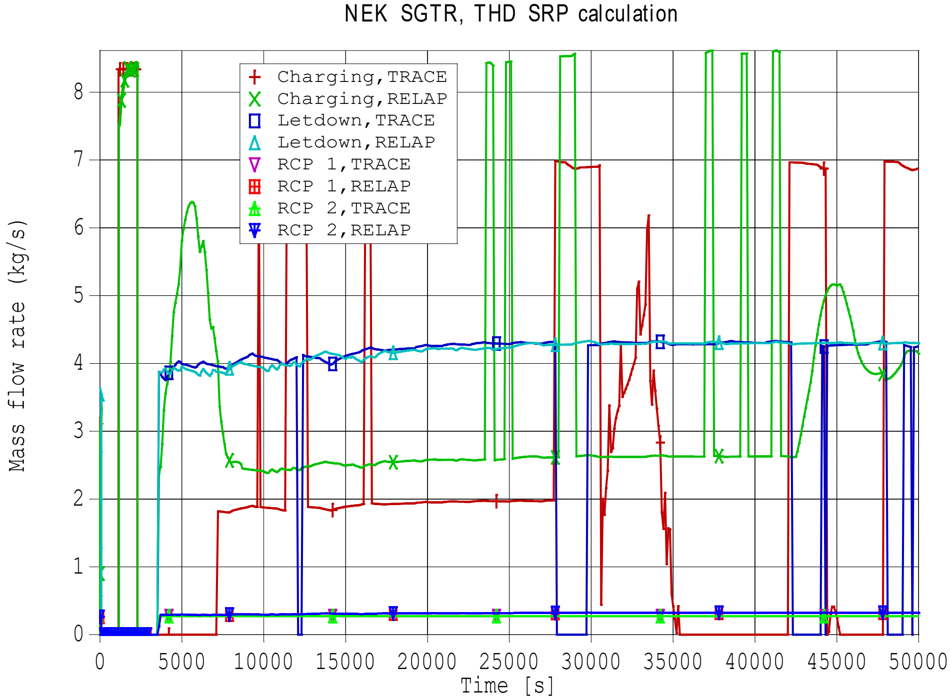

Figure 3-47 NEK SGTR, THD SRP Analysis, CVCS Flow, RELAP5 and TRACE

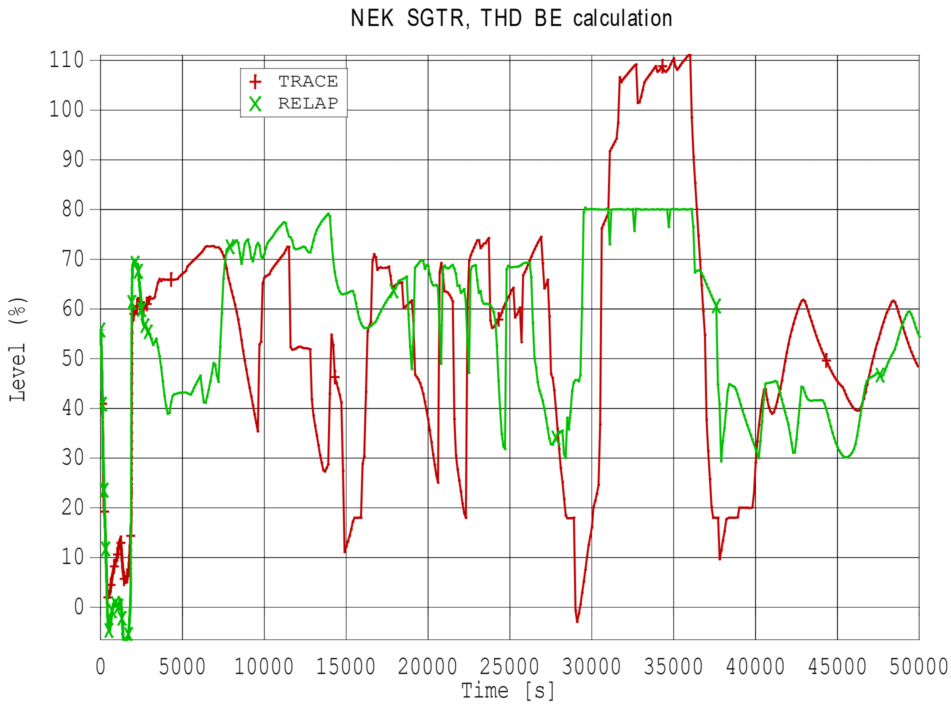

Figure 3-48 NEK SGTR, THD BE Analysis, Pressurizer Level, RELAP5 and TRACE

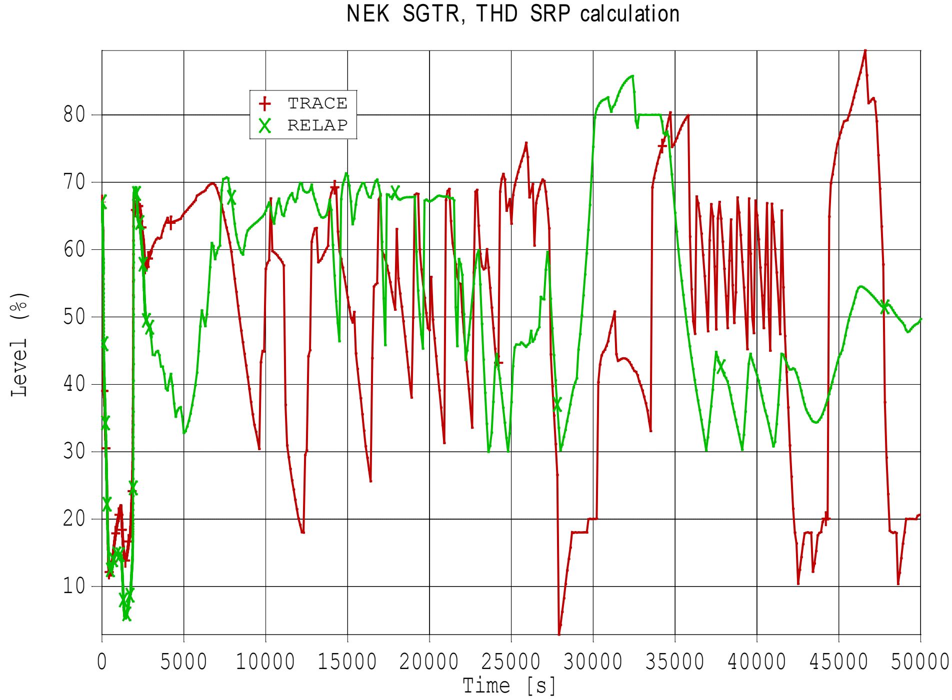

Figure 3-49 NEK SGTR, THD SRP Analysis, Pressurizer Level, RELAP5 and TRACE

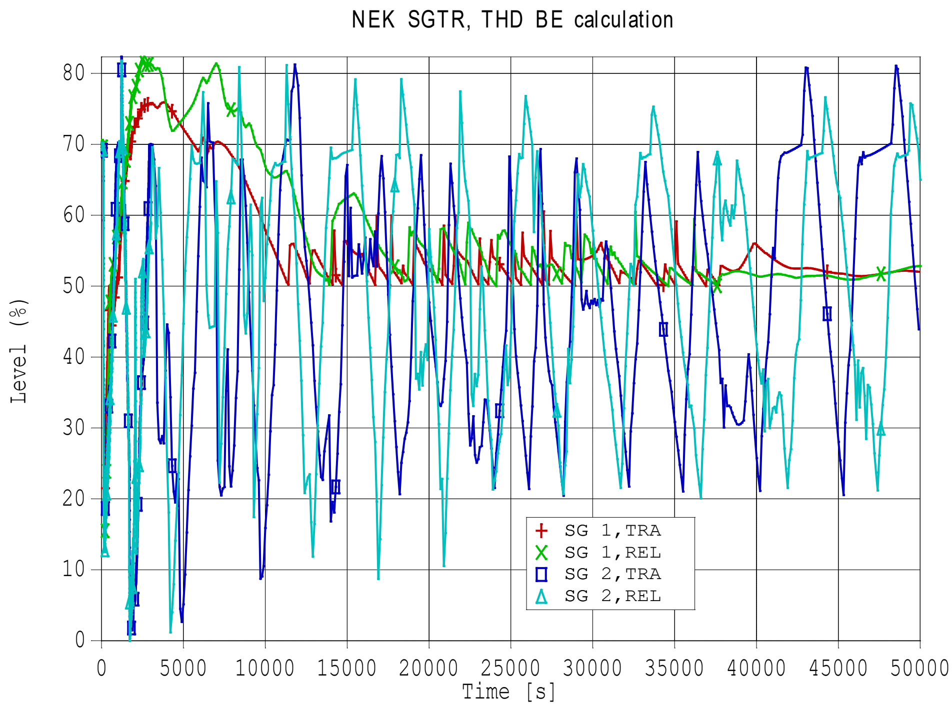

Figure 3-50 NEK SGTR, THD BE Analysis, SG NR Level, RELAP5 and TRACE

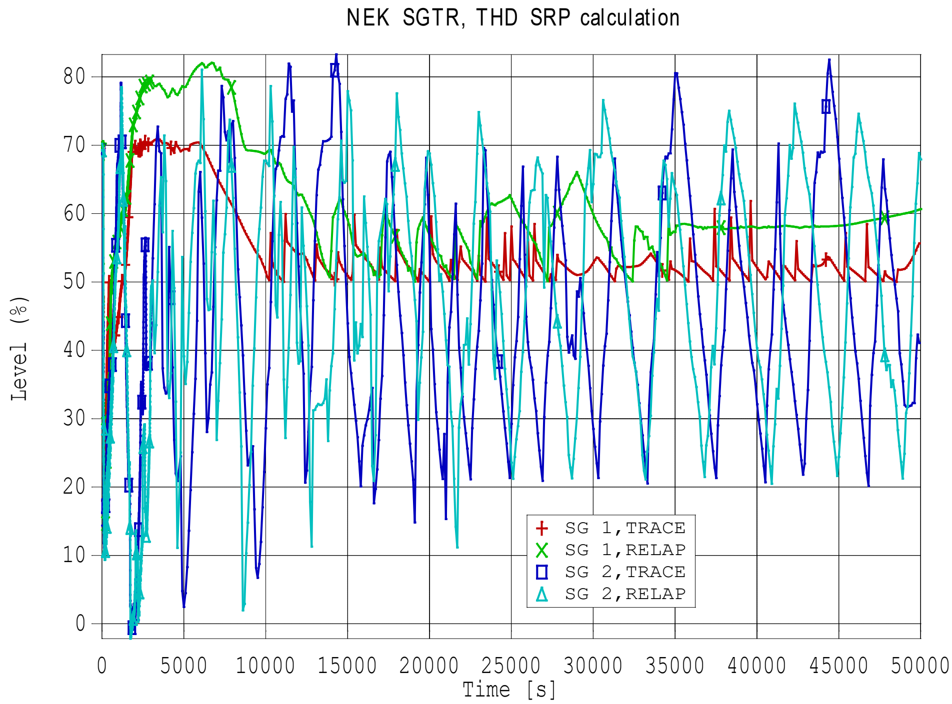

Figure 3-51 NEK SGTR, THD SRP Analysis, SG NR Level, RELAP5 and TRACE

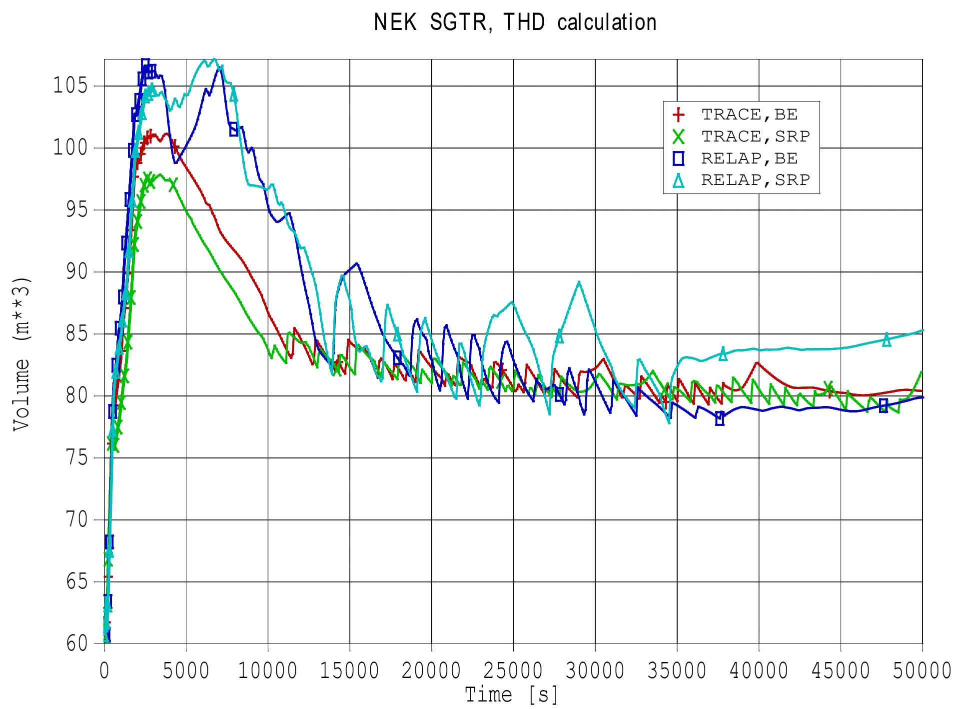

Figure 3-52 NEK SGTR, THD, SG 1 Liquid Volume, RELAP5 and TRACE

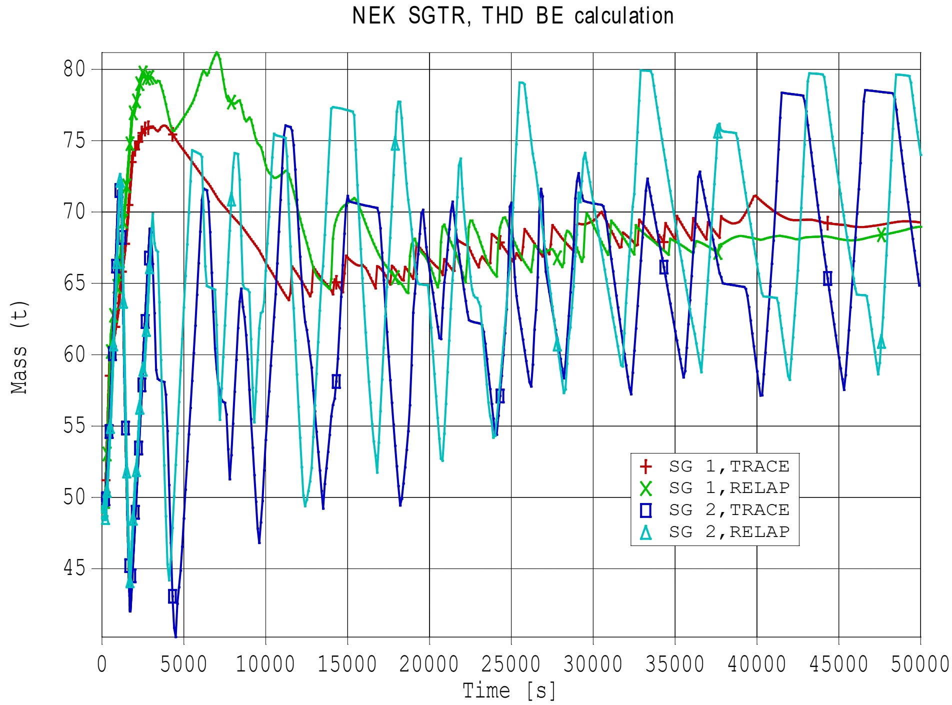

Figure 3-53 NEK SGTR, THD BE Analysis, SG Mass, RELAP5 and TRACE

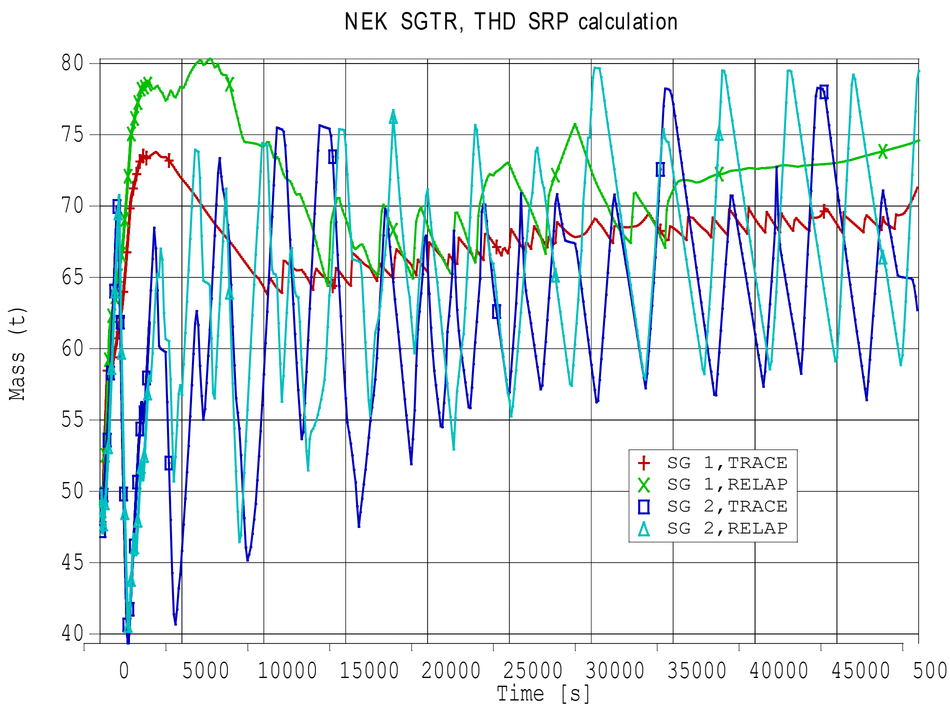

Figure 3-54 NEK SGTR, THD SRP Analysis, SG Mass, RELAP5 and TRACE

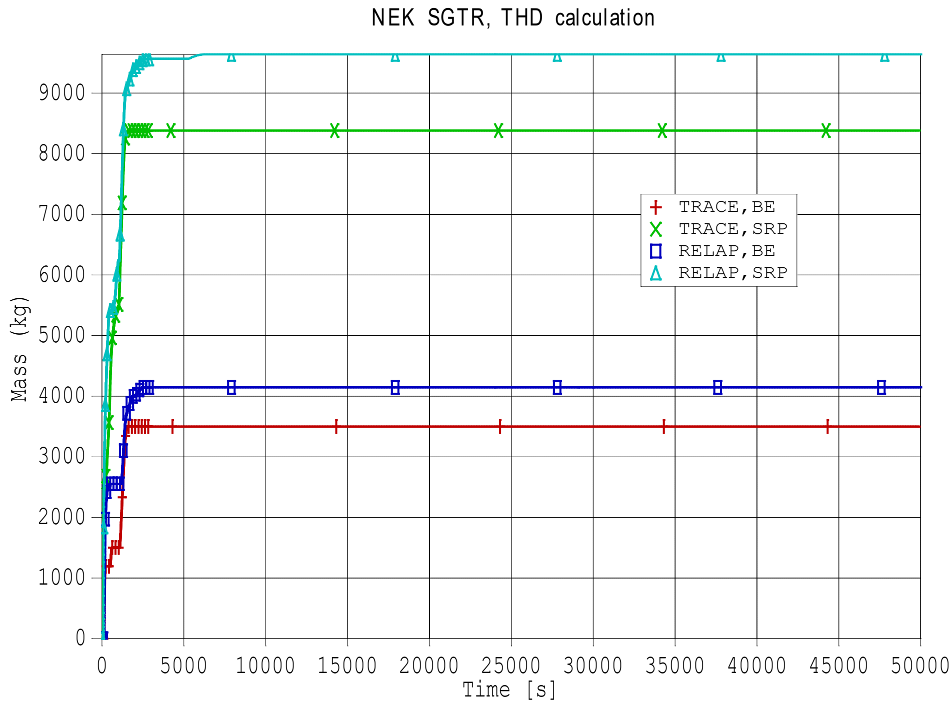

Figure 3-55 NEK SGTR, THD Analysis, Integrated SG 1 PORV TFlow, RELAP5 and RACE

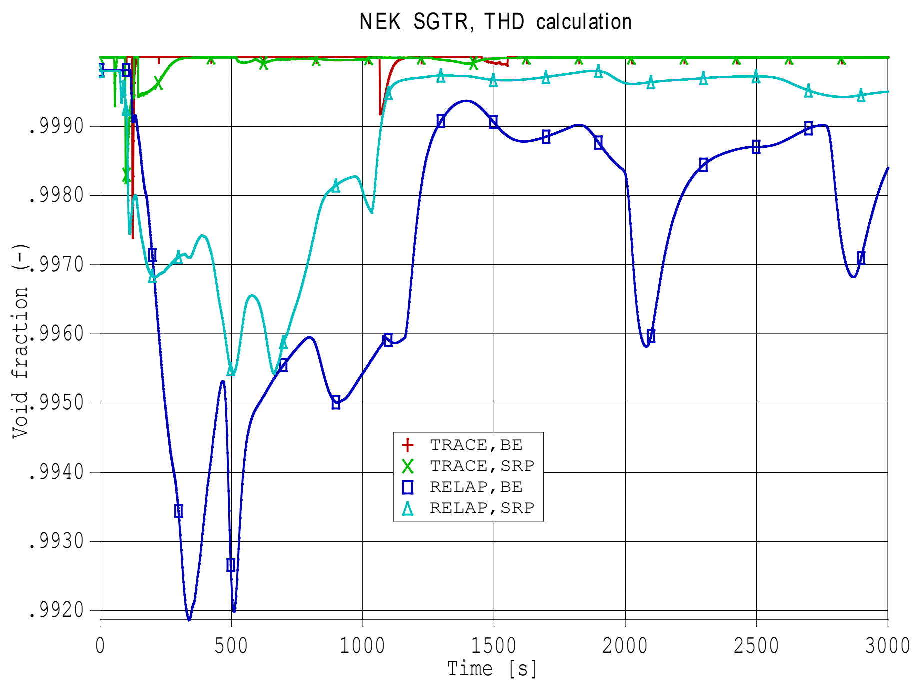

Figure 3-56 NEK SGTR, THD Analysis, SG 1 PORV Flow Void Fraction

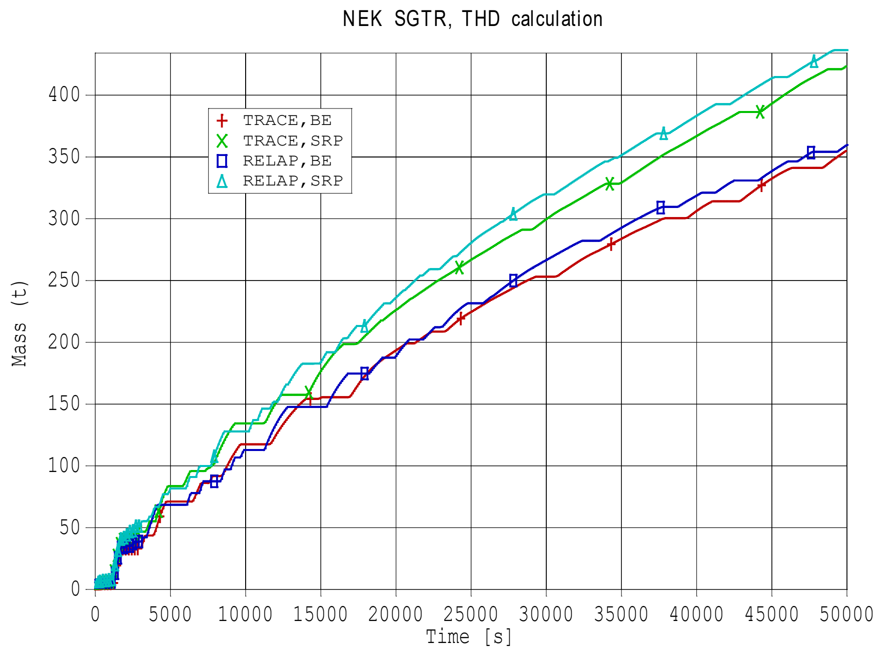

Figure 3-57 NEK SGTR, THD Analysis, Integrated SG 2 PORV Flow, RELAP5 and TRACE

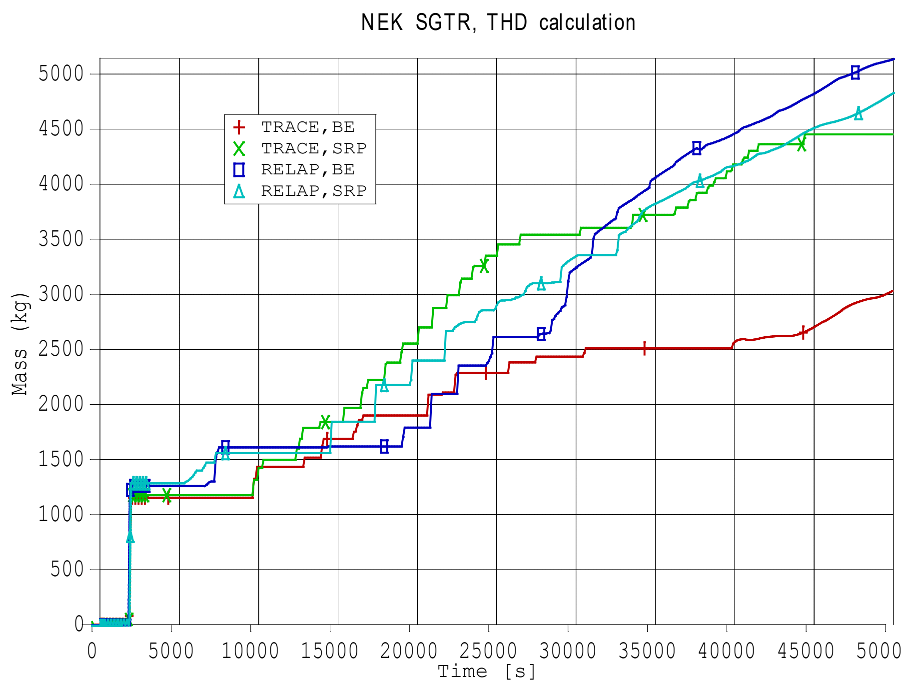

Figure 3-58 NEK SGTR, THD Analysis, Integrated Pressurizer PORV Flow, RELAP5 and TRACE

4 CONCLUSIONS

The Steam Generator Tube Rupture (SGTR) accident was analyzed for NPP Krško using TRACE 5.0p5 and RELAP5/MOD 3.3 codes. Operator actions aimed to stop the primary-to-secondary leakage were included in the analyses. Both best-estimate (BE) and conservative (Standard Review Plan – SRP) analyses were performed. Two groups of analyses have been performed, i.e., the Margin to Overfill (MTO) analyses with assumptions that would lead to the minimum margin to ruptured SG liquid solid conditions and Thermal Hydraulic conditions for radiological Dose calculation (THD) analyses that would lead to largest voiding at the break and most conservative results regarding the release of airborne iodine into environment. Following conclusions can be drawn from the presented analyses.

Steady state calculation has been performed for 1000 seconds. Very small differences for relevant physical parameters between calculated data for both RELAP5 and TRACE and the plant referent data were obtained.

1. For MTO analyses the primary-to-secondary leakage was stopped around 31 minutes after transient begin. In general, the break flow for both sides of the broken tube was somewhat larger for RELAP5 than for TRACE but the differences between the two codes for most variables are small. The maximum liquid volume was not larger than 125.1 m^3 which is much smaller than the total SG volume (152.7 m^3). A small amount of steam was discharged through the ruptured SG PORV, i.e., 1941.3 kg for RELAP5 BE, 1443.1 kg for TRACE BE, 446.5 kg for RELAP SRP and 127.4 kg for TRACE SRP calculation, respectively. The smaller amount of discharged mass in SRP analyses were obtained due to smaller initial SG secondary side pressure.

2. For THD calculation similar results for the duration time of operator actions (e.g., cooldown termination, SI flow stop, termination of primary-to-secondary leakage were obtained when compared to MTO analyses. THD calculation was conservative regarding the flashing of break flow and the amount of discharged mass through the ruptured SG relief valve. The differences for the maximum vapor fraction of break flow between MTO and THD case are however small when the same code was used (e.g., for THD case the maximum break flow vapor fraction is equal to 40.9% for RELAP5 and 4% for TRACE while for MTO case the corresponding values for RELAP5 and TRACE were equal to 39.9% and 3.7%, respectively). The difference for the discharged mass through the ruptured SG relief valve between MTO and THD case was larger, i.e., for THD case the maximum discharged mass for RELAP5 and TRACE were equal to 9637.3 kg and 8432.5 kg (1941.3 kg and 1443.1 kg for MTO case). On the other side, the maximum liquid volume was smaller in THD than in MTO case due to less amount of injected AFW flow in THD calculation. In general, more conservative results regarding the maximum break flow vapor fraction as well as discharged mass through the ruptured SG relief valve were obtained for RELAP5 than for TRACE. At least a part of the obtained differences between RELAP5 and TRACE can be assigned to the difference in calculated break flow that is somewhat larger in RELAP5 than in TRACE throughout the calculation.

3. For THD case the analysis with cooldown and depressurization to HSD condition (RCS pressure less than 2.8 MPa and RCS average temperature less than 450.15 K) was performed. In general, the cooldown and depressurization caused the back flow from the ruptured SG to the primary side on one side and decrease of pressurizer level on the other

side. 30000 seconds after transient begin the hot shutdown conditions were fulfilled for both RELAP5 calculations. For TRACE BE calculation, the RCS average temperature setpoint was reached 37500 seconds and the setpoint for RCS pressure was reached 30000 seconds after transient begin, respectively. For TRACE SRP calculation, the setpoint for RCS average temperature was reached earlier (35000 seconds after transient begin) and the setpoint for RCS pressure was reached 30000 seconds after transient begin. The RCS subcooling remained greater than 20 K during controlled cooldown and the ruptured SG liquid inventory was less than 91 m^3.

4. The report demonstrated that both codes are able to simulate complex operator actions during the accident and during long term stabilization of plant conditions.

5. The radiological consequences calculation was not performed, but based on limited amount of discharged fluid, the doses to the environment are expected to be small.

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10. SUPPLEMENTARY NOTES

A. Hsieh, NRC Project Manager

11. ABSTRACT (200 words or less)

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). Unlike other loss of coolant accidents, an early operator action is necessary to prevent radiological release to environment. The SGTR for NPP Krško (NEK) was analyzed using TRACE 5.0p5 and RELAP5/MOD3.3 codes. Two groups of analyses, aimed to determine the Margin To ruptured SG Overfill (MTO) as well as Thermal Hydraulic conditions for radiological Dose (THD) calculation, have been performed. For each group two analyses were done; the analysis based on initial conditions resulting in most adverse outcome and the analysis based on best-estimate initial conditions. Transient scenario and operator actions were taken from NPP Krško Emergency Operating Procedure (EOP) E-3, Steam Generator Tube Rupture, ref./7/. For THD analysis, cooldown and depressurization to Hot Shut Down (HSD) conditions (2.8 MPa, 450.15 K) have been performed. At that point Residual Heat Removal (RHR) system can be put in operation.

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