NUREG/IA-0442

International Agreement Report

RELAP5/MOD3.3 analysis of steam generator tube rupture (SGTR) accident for NPP Krško

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U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

March 2014

Prepared as part of
The Agreement on Research Participation and Technical Exchange
Under the International Code Assessment and Maintenance Program (CAMP)

Published by
U.S. Nuclear Regulatory Commission

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NUREG/IA-0442

RELAP5/MOD3.3 analysis of steam generator tube rupture (SGTR) accident for NPP Krško

Manuscript Completed: December 2013
Date Published: March 2014

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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 authors have analyzed SGTR for NPP Krško (NEK) using RELAP5/MOD3.3 code for two basic scenarios; i.e. with and without offsite power available. The plant model has been updated taking into account the Resistance Temperature Detector Bypass Elimination (RTDBE) project realized during the 2013 outage. The actions from the standard Emergency Operating Procedures (EOPs) were modelled and the efficiency of operator actions to prevent radiological release to environment was evaluated. The time of the start of the operator action was selected as a critical parameter influencing occurrence of the release of the contaminated inventory (steam and liquid). In order to stop the steam release from the ruptured SG for the scenario with offsite power available the operator action has to be taken 15 minutes after transient begin, whereas the liquid solid condition and the liquid discharge can be prevented for operator action performed not later than 45 minutes after transient begin. For the scenario with offsite power not available the operator action has to be performed not later than 20 minutes to prevent the broken SG liquid solid condition and the liquid discharge. For both cases the operator action successfully stops the primary to secondary leakage and the inventory release to the environment.

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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 major concern for the SGTR event is the release of contaminated liquid through the secondary side relief valves to the atmosphere that may result in an increase of radiological doses. The primary-to-secondary leakage results in the RCS depressurization, which leads to an automatic reactor trip and Safety Injection (SI) actuation. Since the RCS pressure tends to stabilize at the value where the incoming SI flow rate equals the break flow rate, the operator must terminate the SI flow to stop the primary-to-secondary leakage and subsequent broken SG overfill and radioactive releases to the atmosphere. First, the operator is expected to determine that the SGTR has occurred and to identify and isolate the broken SG to minimize the contamination of the secondary side. The subsequent controlled RCS cooldown and depressurization are aimed firstly to achieve the conditions that satisfy the SI termination criteria and secondly to reduce the break flow. The goal of this part of the recovery procedure is to equalize the RCS and broken SG pressure in order to terminate the break flow whereas the RCS cooling is performed via intact SG using either steam dump or SG safety/or power operated relief valves. Finally, the plant cooldown and depressurization to hot and cold shutdown conditions with simultaneous depressurization of broken SG are performed.

The authors have analyzed SGTR for NPP Krško using RELAP5/MOD3.3 code for two basic scenarios; i.e. with and without offsite power available. The plant model has been updated taking into account the Resistance Temperature Detector Bypass Elimination (RTDBE) project realized during the 2013 outage. The actions from the standard Emergency Operating Procedures (EOPs) were modelled and the efficiency of operator actions to prevent radiological release to environment was evaluated. The time of the start of the operator action was selected as a critical parameter influencing occurrence of the release of the contaminated inventory (steam and liquid). In order to stop the steam release from the ruptured SG for the scenario with offsite power available the operator action has to be taken 15 minutes after transient begin, whereas the liquid solid condition and the liquid discharge can be prevented for operator action performed not later than 45 minutes after transient begin. For operator action performed in time period between 15 and 45 minutes a limited amount of steam is discharged through the ruptured SG. For the scenario with offsite power not available the operator action has to be performed not later than 20 minutes to prevent the broken SG liquid solid condition and the liquid discharge. For both cases the operator action successfully stops the primary to secondary leakage and the inventory release to the environment. In all the analyzed cases the operator performed the complete RCS cooldown & depressurization to Hot ShutDown (HSD) conditions when the Residual Heat Removal (RHR) system can be put in operation.
The report does not include the radiological consequences calculation, but based on the limited amount of the discharged fluid, they should be small.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from Krško Nuclear Power Plant and Croatian State Office for Nuclear Safety within CAMP program and continuous support from Croatian Ministry of science and education (project no. 036-0361590-1589). The RELAP5/MOD3.3 base input model was originally developed for Krško nuclear power plant. Special thank goes to M.Sc. Božidar Krajnc, director of engineering services division in Krško nuclear power plant, for expressing the need for such an analysis and for obtaining required plant data and permission to publish the results.

ABBREVIATIONS

ACC	accumulator
AFW	auxiliary feedwater
ANS	american nuclear society
BOL	beginning of life
CVCS	chemical and volume control system
EOP	emergency operating procedure
FER	Faculty of Electrical Engineering and Computing
HSD	hot shutdown
I&B	initial and boundary
MFIV	main feedwater isolation valve
MFW	main feedwater
MPa	megapascal
MSIV	main steam line isolation valve
NEK	nuclear power plant Krško
NPP	nuclear power plant
NR	narrow range
OPΔT	overpower delta T
OTΔT	overtemperature delta T
PORV	power operated relief valve
PRZ	pressurizer
PWR	pressurized water reactor
RCP	reactor coolant pump
RCS	reactor coolant system
RHR	residual heat removal
RPV	reactor pressure vessel
RSG	replacement steam generator
RTD	resistance temperature detector
RTDBE	resistance temperature detector bypass elimination
SB LOCA	small break loss of coolant accident
SG	steam generator
SGTR	steam generator tube rupture
SI	safety injection
SV	safety valve
US NRC	United States Nuclear Regulatory Commission

1. INTRODUCTION

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 major concern for the SGTR event is the release of contaminated liquid through the secondary side relief valves to the atmosphere that may result in an increase of radiological doses. The primary-to-secondary leakage results in the RCS depressurization, which leads to an automatic reactor trip (on low pressurizer pressure or overtemperature ΔT) and Safety Injection (SI) actuation. Since the RCS pressure tends to stabilize at the value where the incoming SI flow rate equals the break flow rate, the operator must terminate the SI flow to stop the primary-to-secondary leakage and subsequent broken SG overfill and radioactive releases to the atmosphere.

This technical report is prepared to demonstrate the capability of plant systems as well as adequacy of operator actions to prevent the discharge of contaminated inventory to the environment. First, the operator is expected to determine that SGTR has occurred and to identify and isolate the broken SG to minimize the contamination of the secondary side. The subsequent controlled RCS cooldown and depressurization are aimed to achieve the conditions that satisfy the SI termination criteria and also result in break flow reduction. The goal of this part of the recovery procedure is to equalize the RCS and the broken SG pressure in order to terminate the break flow whereas the RCS cooling is performed via intact SG using either steam dump or SG safety/or power operated relief valves. Finally, the plant cooldown and depressurization to hot and cold shutdown conditions with simultaneous depressurization of broken SG are performed.

The SGTR analysis for NPP Krško for the current plant configuration after Resistance Temperature Detector Bypass Elimination (RTDBE) and cycle 26 has been performed using RELAP5/MOD3.3 code. The SGTR analysis for the configuration before RTDBE and cycle 24 has been performed before and the results were published in Ref. 1. The SGTR analysis is aimed to estimate the efficiency of operator actions in preventing the release of contaminated inventory to the environment. Best estimate initial and boundary conditions as well as realistic operator actions were assumed in the analysis. The sensitivity study with various SGTR recovery scenarios regarding the availability of offsite power and subsequent operator actions was performed to determine the time for operator actions to prevent the steam and liquid discharge to the environment.

The time of the start of the operator action was selected as a critical parameter influencing occurrence of the release of the contaminated inventory (steam and liquid). The parameter is the time of begin of the first operator action (isolation of broken SG and the first cooldown as a preparatory action to fulfill the SI termination criteria). Following cases have been analyzed:

1) CASE 1: Offsite power available

CASE 1a: 15 minutes
The steam discharge from the broken SG is stopped after first operator action.

CASE 1b: 20 minutes
The small amount of steam is discharged after first operator action.

CASE 1c: 45 minutes
Only steam is discharged from the broken SG.

CASE 1d: 50 minutes
Broken SG becomes liquid solid and the liquid is discharged to the environment.

2) CASE 2: Offsite power not available

CASE 2a: 15 minutes
Maximal liquid fraction of the steam dome volume in the broken SG is less than 50%. Only steam is discharged after first operator action.

CASE 2b: 20 minutes
Broken SG becomes almost liquid solid but only steam is discharged to the environment.

CASE 2c: 25 minutes
Broken SG becomes liquid solid and also liquid is discharged.

2. COMPUTATION MODEL OF NPP KRŠKO

“Best estimate” code used for the analysis of the Steam Generator Tube Rupture (SGTR) for NPP Krško was RELAP5/MOD3.3, Microsoft Windows 98 version. RELAP5/MOD3.3 is the code developed for US NRC, for the modeling of complex thermohydraulic systems and is primarily intended to be used for the prediction of nuclear power plant behavior in the case of transients/accidents, Ref. 2.

For the purpose of NPP Krško (NEK) transient/accident analyses such model has been developed at the Faculty of Electrical Engineering and Computing (FER). The model is in compliance with Ref. 2, described in Ref. 3 and qualified on the steady-state level, Ref. 4. Base NEK nodalization for the analysis of SGTR for NPP Krško is presented in Figure 1. The plant model corresponds to the status after the Resistance Temperature Detector (RTD) Bypass Elimination (RTDBE) that has been carried out during the October 2013 outage. The RTD bypass manifold system for the narrow range (NR) RCS temperature measurement is removed and replaced with the fast-response RTDs that are embedded in the thermowell structure as a part of a pipe wall. The RTDBE project affects the RCS temperature measurement response time which is accounted for in reactor protection system setpoints as well as in plant control system settings.

The break is located at a bottom of one tube in the loop 1 (loop with pressurizer). The sensitivity analyses to identify the location of the break resulting in a maximum break flow were performed (the results are not presented here for brevity purposes). The outlet-cold side of the tube was found to have the maximum break flow, which is also confirmed by other analyses, e.g., Ref. 5. A doubled ended break was assumed having two sides as shown in Figure 2, i.e. the break side 1 at the tube sheet outlet and the break side 2 at the tube bottom, respectively. The broken U-tube is modeled separately with realistic tube cross sectional area and heat transfer area. The double ended break of U-tube is modeled by opening of the two valves (valves V1 and V2) connecting the break ends with the heat exchanger section on the SG secondary side, and closing the valve that connects the ends of tube before break occurrence (valve V3).

The RELAP5 model consists of 503 thermal-hydraulic volumes, 542 junctions, 398 heat structures with 2347 mesh points, 785 control variables and 217 variable and 249 logical trips. It includes major modifications related to the Krško modernization project as well as RTDBE project; e.g., the model of the replacement steam generator (RSG) based on data provided by the RSG designer (Siemens), power uprate, removal of the guide tubes plugs inside the core as well as changes to the protection and plant control systems. Also, the new steam generator (SG) level and the rod control system for the point kinetics model were introduced, together with the model of main feedwater (MFW) and auxiliary feedwater (AFW) lines to the SGs. A detailed steam dump system with realistic steam dump valves (valves 624 through 633 in Figure 1) has been introduced in the model. The valves are divided into four banks; bank A (valves 624 and 625), bank B (valves 626, 627 and 628), bank C (valves 629 and 630) and the bank D (valves 631, 632 and 633), respectively.

In order to accurately represent the NEK behavior, a considerable number of control variables and general tables are part of the model. They represent protection, monitoring and simplified control systems used only during steady state initialization, as well as main plant control systems:

- rod control system,
- pressurizer pressure control system,
- pressurizer level control system,
- SG level control system,
- steam dump.

The nominal core power has been fixed through the control variable input as described in Ref. 3. Also, primary heat losses were included in the model in order to represent actual plant status as close as possible.

Generally, each control system calculation is enabled through the associated trip and consists of associated trips, general tables and control variables.

Pressurizer pressure and level control system controls chemical and volume control system (CVCS) charging flow, pressurizer heaters power and spray control valves open area. As described in Ref. 3, pressurizer backup heaters are controlled by the pressurizer level and pressurizer pressure control systems. The rod control system calculates added reactivity from the integral rod worth versus steps withdrawn for banks d,c,b and a. SG level control system controls area of the feedwater control valve (FCV) in the MFW lines. Steam dump control system is modeled for three modes of operation, i.e., the load rejection and plant trip mode that control the RCS average temperature and the steam header pressure mode. The individual steam dump valve openings for each bank (A through D) are modeled by control variables taking into account all three modes of operation.

The RTDBE project affects the operation of automatic rod control system and pressurizer level control system as well, since these systems use the measured NR average temperature either as a controlled parameter (Automatic rod control system) or as an input to calculate the setpoint (pressurizer level). Automatic control rod system constants (gains and time constants) are affected by RTDBE and pressurizer control systems constants are not. The constants and control functions of the overtemperature delta T (OTΔT) and overpower delta T (OPΔT) protection as well as of steam dump system have also been changed due to RTDBE.

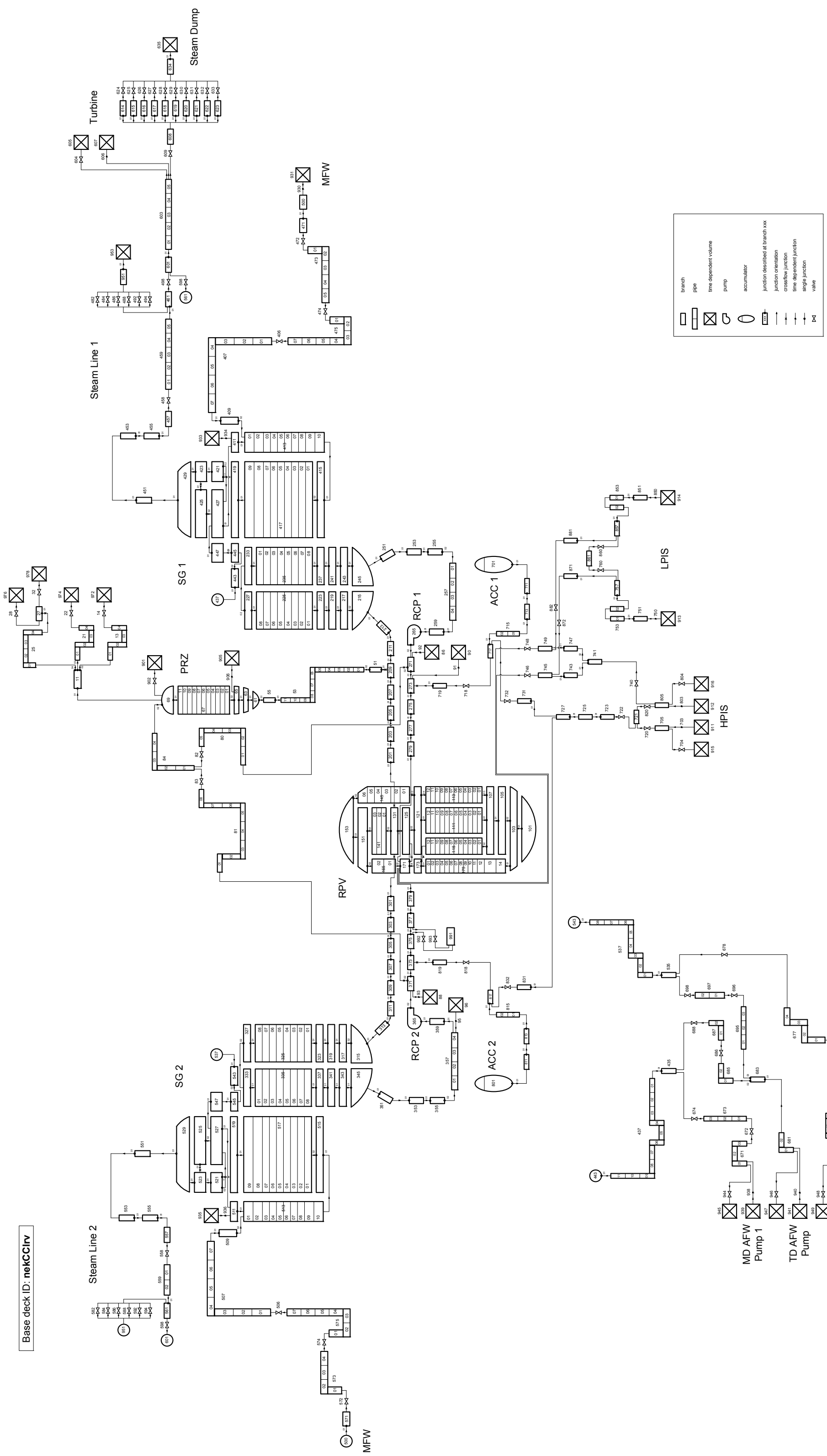

Figure 1 RELAP5/MOD3.3 nodalization scheme for NPP Krško

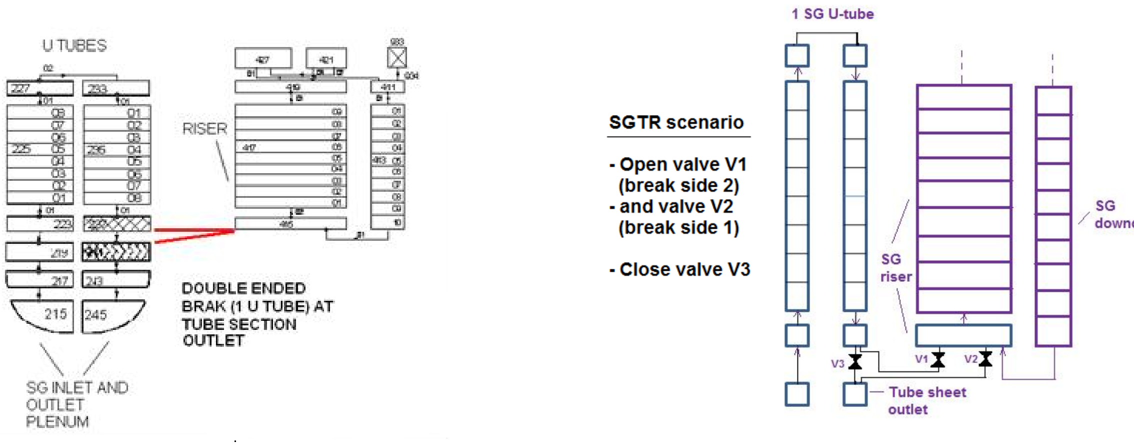

Figure 2 Nodalization scheme for SGTR scenario

3. TRANSIENT DESCRIPTION

The SGTR results in the primary-to-secondary leakage that exceeds the capacity of Chemical and Volume Control System (CVCS). The loss of coolant through the primary-to-secondary break causes the reactor coolant system (RCS) depressurization that leads to an automatic reactor trip (on low pressurizer pressure or overtemperature ΔT) and safety injection (SI) actuation. After SI actuation, the RCS pressure will tend to stabilize at the value where SI flow equals the break flow rate. Unlike other loss of coolant accidents an early operator involvement is necessary to prevent the radiological release to environment. If not terminated, the primary-to-secondary leakage causes the filling-up of the secondary side of the affected SG with contaminated liquid until the pressure rises above the SG PORV valve opening setpoint. First, the steam is discharged through the broken SG PORV and the liquid discharge follows if the operator has not stopped primary-to-secondary leakage. The operator actions were adopted from the NPP Krško Emergency Operating Procedure (EOP) E-3, Steam Generator Tube Rupture, Ref. 7. The operator actions can be divided into three basic steps:

1. The operator is expected to determine that a SGTR has occurred and to identify and isolate the broken SG by closing the main feedwater and the main steam isolation valve. The operator shall determine the accident occurrence by observing the difference between steam and feedwater flow (if detected before reactor trip) as well as by observing the increase of radiation level in the affected SG.

2. The operator shall terminate the break flow as soon as possible to prevent SG PORV opening and steam discharge to the atmosphere. If the operator action was not performed before reactor and the subsequent turbine trip and the steam dump is not available, SG PORV valve will open on both SGs. In this case the terminating of the primary-to-secondary leakage terminates the steam discharge on one side and on the other side it prevents the broken SG liquid filled condition and the subsequent liquid discharge. This is particularly important since the spillage of the liquid is more critical than the release of only steam.
In order to stop the primary-to-secondary leakage the operator has to terminate the SI flow. The prerequisites for SI termination are a sufficient RCS subcooling margin, the pressurizer level that accounts for pressurizer inventory loss due to outsurge after SI termination and the SG level in the intact SG that ensures heat sink. The first operator action that precedes the SI termination is the cooldown (1st cooldown) performed as fast as possible to the RCS temperature that should ensure the required RCS subcooling. The target core exit temperature is determined as a saturation temperature corresponding to the damaged SG pressure minus the RCS subcooling measurement uncertainty. As soon as the 1st cooldown has been performed, the operator should decrease the RCS pressure in order to decrease the break flow. The preferred way to perform the cooldown is the steam dump since it has larger capacity than the SG PORV and the cooldown can be performed fast. For depressurization, the operator should always use pressurizer spray if the RC pumps are in operation since the pressurizer spray recovers pressurizer inventory. Thereby, the operator regulates the pressurizer spray flow in order to prevent the pressurizer liquid solid conditions by maintaining the pressurizer level. On the secondary side, the operator should maintain the SG narrow range level of the intact SG not less than 20% in order to ensure the required heat sink. Finally, the operator terminates the SI flow. The inherent system behavior with pressurizer pressure setpoint set to the broken SG pressure tends to equalize the RCS and broken SG pressure. This leads to termination of the break flow and the stop of the filling of the broken SG.

3. Operator performs the actions to prepare the plant for SG inspection and repair. First, the cooldown & depressurization to hot shutdown (HSD) conditions (RCS pressure< 2.8 MPa, RCS average temperature < 177 °C) is performed when Residual Heat Removal (RHR) system can be put in operation. The goal of this action is twofold, i.e., to depressurize the broken SG and on the other side to prepare the plant for cooldown to cold shutdown conditions. At cold shutdown, the primary circuit is drained to mid-loop elevation, and the steam generators can be isolated for inspection and repair from the rest of the primary circuit.
The time of the start of the operator action was selected as a critical parameter influencing occurrence of the release of the contaminated inventory (steam and liquid). The parameter is the time of begin of the first operator action (isolation of broken SG and the first cooldown as a preparatory action to fulfill the SI termination criteria).
Following cases have been analyzed:

1) CASE 1: Offsite power available

CASE 1a: 15 minutes
The steam discharge from the broken SG is stopped after first operator action.

CASE 1b: 20 minutes
The small amount of steam is discharged after first operator action.

CASE 1c: 45 minutes
Only steam is discharged from the broken SG.

CASE 1d: 50 minutes
Broken SG becomes liquid solid and the liquid is discharged to the environment.

2) CASE 2: Offsite power not available

CASE 2a: 15 minutes
Maximal liquid fraction of the steam dome volume in the broken SG (volume 429 in Figure 1) is less than 50%. Only steam is discharged after first operator action.

CASE 2b: 20 minutes
Broken SG becomes almost liquid solid but only steam is discharged to the environment.

CASE 2c: 25 minutes
Broken SG becomes liquid solid and also liquid is discharged.

3.1 Initial and boundary conditions

The SGTR analyses were performed for Beginning Of Life (BOL), cycle 26, and nominal power (1994 MW). The initial and boundary conditions for SGTR analysis are summarized in Table 1 and Table 2, respectively. Best estimate initial and boundary conditions were assumed in the analysis with the exception of automatic rod control system that is not available. In the analysis it was assumed that the operator did not start any action before reactor trip or safety injection. The steam dump was assumed available first by controlled operator action, whereas an automatic steam dump following the reactor trip was disabled. The operator actions assumed in the analyses were adopted from the NEK EOP E-3 procedure, Steam Generator Tube Rupture, Ref. 7. The operator actions are performed in two steps:

1. Identification and isolation of the damaged SG (Main Steam Isolation Valve (MSIV) closure and isolation of main feedwater). Next, the operator performs the actions in order to terminate the primary-to-secondary leakage, i.e., the first cooldown performed as fast as possible followed by subsequent depressurization and finally the SI termination. The latter two actions are aimed to equalize the primary and secondary pressure thus stopping the leakage. The RCS cooldown is aimed to provide the required RCS subcooling after SI had been terminated. The target core exit temperature is determined according to NEK EOP recovery procedure, i.e., as the saturation temperature corresponding to the damaged SG pressure minus the RCS subcooling uncertainty. The realistic time for operator actions have been assumed; i.e., after closing the MSIV, the cooldown is initiated with 3 minutes delay and the depressurization 3 minutes after successful 1st cooldown.

2. RCS cooldown & depressurization to HSD conditions when RHR system can be put in operation. The maximum allowed RCS cooldown rate was limited to 55.6 °C/hour and the depressurization rate was adjusted to maintain the required RCS subcooling (19 °C).

During recovery procedure, the operator controls the charging and letdown flow to maintain the pressurizer level at 35% for the case with offsite power available and at 50% for the case without offsite power. This value was selected to ensure the minimum level for pressurizer pressure control during RCS cooldown. The pressurizer spray and PORV operation are defined in the pressurizer NR level range (50%, 60%) and (60%, 80%), respectively. These values were obtained as a result of performed sensitivity analyses resulting in the sufficient margin to pressurizer liquid solid condition and successful cooldown & depressurization to HSD conditions.

The accident was further investigated regarding the major concern for SGTR event, i.e., the release of contaminated inventory through the damaged SG PORV. First, the less severe case (only steam release) was analyzed. The cases for the offsite power available (CASE 1) where steam is released through the damaged SG PORV (CASE 1b) after the first operator action and the case with no release after the first operator action (CASE 1a) were identified. For the CASE 2 (offsite power not available) the cases with only steam release were identified; CASE 2a (maximal liquid fraction in the steam dome volume in the broken SG less than 50%) and CASE 2b with broken SG steam dome volume almost liquid solid but with no liquid discharge. Furthermore, for the CASE 1 the maximum time for the first operator action was determined for relief of only steam (CASE 1c) and the time where liquid is discharged (CASE 1d), respectively. For the CASE 2 the release of liquid was analyzed in the CASE 2c. For all the analyzed cases (both with and without liquid discharge through the damaged SG PORV) the whole event with cooldown to HSD conditions was simulated.

The results of RELAP5 part of the steady state calculation after 1000 seconds are reported in the table below.

Table 1 Initial conditions for SGTR analysis for NPP Krško

Parameter	Unit	RELAP5 calculation
Nuclear power	MW	1994
Primary pressure	MPa	15.51
Secondary pressure	MPa	6.44/6.42
RCS average temperature	K	578.15/578.06
SG power	MW	996.6/1002.5
Primary volumetric flow rate	m^3/s	6.27/6.26
SG mass	kg	49092/48960
PRZR level	%	55.8
SG NR level	%	69.3/69.3
Steam mass flow rate	kg/s	541.27/544.39
Feedwater mass flow rate	kg/s	541.27/544.39
Circulation ratio	-	3.75/3.73

Table 2 Boundary conditions for SGTR analysis for NPP Krško

Boundary condition	CASE 1 (Offsite power available)	CASE 2 (Offsite power not available)
RCP trip	-	At a time of reactor trip
Type of RCS cooldown	Steam dump (not available before cooldown)	SG 2 PORV, Steam dump not available
RCS depressurization	Pressurizer spray	Pressurizer PORV
<u>1st operator action:</u> Isolation of broken SG (SG 1) and 1st cooldown (3 minutes delay)	Operator action stops steam release from SG 1 PORV: CASE a: 15 min after transient begin (operator action successful) CASE b: 20 min after transient begin (limited steam release) Operator action to prevent liquid discharge through SG 1 PORV: CASE c: 45 min after transient begin (operator action successful) CASE d: 50 min after transient begin (SG 1 PORV liquid fraction > 0.1)	 CASE a: 15 min after transient begin (SG 1 steam dome volume liquid fraction < 0.5, only steam release) Operator action to prevent liquid discharge through SG 1 PORV: CASE b: 20 min after transient begin (operator action successful) CASE c: 25 min after transient begin (SG 1 PORV liquid fraction > 0.1)
Start of operator action to depressurize and recover RCS after first cooldown	3 minutes after 1st cooldown: Operator adjusts pressurizer setpoint pressure 2 bar above SG 1 pressure	3 minutes after 1st cooldown: Operator adjusts pressurizer setpoint pressure 2 bar above SG 1 pressure
Operator turns off SI (3 minutes delay)	RCS depressurization finished RCS subcooling >19 °C PRZR level >15% NR level of intact SG>20%	RCS depressurization finished RCS subcooling >19 °C PRZR level >15% NR level of intact SG>20%
<u>2nd cooldown</u>: - Operator starts RCS depressurization & cooldown to hot shutdown (2.8 MPa, 177 °C) - Operator enables CVCS (two charging pumps available)	0.5 hours after SI termination PRZR level setpoint=35 %	0.5 hours after SI termination PRZR level setpoint=50 %
SG NR level setpoint for auxiliary feedwater operation	SG 1: cycling between 50 and 60% SG 2: cycling between 60 and 70%	SG 1: cycling between 50 and 60% SG 2: cycling between 60 and 70%
PRZ level setpoint for PRZ spray/PRZ PORV operation	PRZ spray operation for PRZ level < 60%; cycling: (50%, 60%)	PRZ PORV operation for PRZ level < 80%; cycling: (60%, 80%)
PRZ level setpoint for PRZ heaters (actuated to maintain PRZ pressure greater than 1.8 MPa)	- PRZ proportional heaters operation enabled for PRZ level >20%; cycling: (20%, 30%) - PRZ backup heaters disabled	- PRZ proportional heaters operation enabled for PRZ level >20%; cycling: (20%, 30%) - PRZ backup heaters disabled

4. RESULTS

4.1 Analysis and results, CASE 1: Offsite power available

The transient was initiated after 1000 seconds of steady state calculation by simultaneously opening of two break valves simulating the double ended break of one U-tube to the bottom of the SG 1 riser section and closing the valve connecting the U-tube ends. The main events are summarized in Table 3. The cases were identified regarding to the discharge through the broken SG PORV following the first operator action; i.e. the case without any discharge (CASE 1a), the case with only steam discharge (CASE 1b), the case for the latest operator action where only steam is discharged (CASE 1c) and the case where the operator action does not prevent the broken SG liquid discharge (CASE 1d). Here, the case with no discharge after first operator action (CASE 1a) is presented in a more detail. Due to loss of RCS inventory through the break, Figure 3, the pressurizer level, Figure 4, decreases thus reducing the primary pressure, Figure 5. The automatic reactor trip (162.2 s after transient begin) was actuated on OTΔT reactor trip signal (actuated due to primary pressure decrease), Figure 6, and the turbine trip is actuated immediately after reactor trip. Following reactor trip, the large negative scram reactivity is inserted, Figure 9, and nuclear power as well as core thermal power decrease to no-load value, Figure 7 and Figure 8. The cooldown following the reactor trip, Figure 10, causes decrease of coolant specific volume, which increases the outsurge flow from the pressurizer and the RCS pressure starts to decrease more rapidly. Finally, the SI on low-2 pressurizer pressure is actuated (at time=346.1 s), Figure 11. The SI adds the inventory to the RCS and increases the primary pressure which supports the primary-to-secondary leakage and the increase of the broken SG inventory, Figure 12. The main feedwater is isolated before SI actuation on low RCS average temperature signal in combination with reactor trip (at time=256.7 s). On the secondary side, the pressure increases after turbine trip, Figure 5, and the SG PORV valve opens on both SG 1 and SG 2, Figure 22. The secondary pressure decrease following the SG PORV operation continues even after closure of the SG PORVs due to condensation of steam after injection of cold auxiliary feedwater (AFW), Figure 13. This rather slow pressure decrease ends at 500 s. Due to the fact that the steam dump was assumed unavailable before first operator action (not before 1080 s in the CASE 1a, the secondary pressure increased after closing the AFW flow in both SGs. The first operator action consists of the isolation (closing of the main steam isolation valve (MSIV) of the broken SG) and the cooldown (1st cooldown) & depressurization performed as fast as possible to terminate the SI and stop the primary-to-secondary leakage. In order to perform the RCS cooldown the operator uses the steam dump in steam header pressure mode and sets the steam header pressure setpoint to the value that would result in the target core exit temperature. The target temperature is determined as a saturation temperature corresponding to the broken SG pressure at a time of the begin of the cooldown taking into account the subcooling measurement uncertainty and an additional subcooling uncertainty (11.11 °C). In the analysis, it was assumed that the operator has enabled the steam dump bank A having two valves (out of 10 valves for all the banks). This has resulted in the fast first cooldown that lasted 2 minutes and a few seconds. The secondary pressure of both SGs that were coupled via steam header, Figure 5, decouple after SG 1 isolation. The pressure of the intact SG that was very close to the broken SG pressure rapidly decreased after start of steam relief via steam dump. The broken SG pressure decreases, too, despite of MSIV isolation. The reason is in the strong RCS cooldown and heat flux reversal in the broken SG, Figure 8, that causes the broken SG temperature and pressure decrease. The pressure in the broken SG fell below the PORV opening setpoint and the release through the broken SG is thus stopped. The RCS pressure decreases during cooldown due to outsurge from the pressurizer. However, as soon as the

cooldown had been finished the RCS pressure rises again due to persisting SI flow. Three minutes after cooldown had been finished, the operator started the depressurization with target RCS pressure equal to broken SG pressure (plus 2 bar in order to account for the difference between pressurizer and the SG tube bottom) using the pressurizer spray, Figure 18. During the depressurization the operator has fully opened spray valves until the required pressure was reached. Thereafter, the pressurizer spray was controlled automatically. The pressurizer spray was closed when the pressurizer level increased above 60% in order to prevent the liquid solid condition. After closing the pressurizer spray the RCS pressure started to rise again due to persisting SI flow that has substantially increased due to RCS pressure decrease. During the spray operation the pressurizer inventory has recovered which was one of the prerequisites for SI termination. After finishing the RCS depressurization and with the required criteria fulfilled; i.e., pressurizer level greater than 15%, subcooling greater than 19 °C and NR level of intact SG greater than 20% the SI termination was performed with 3 minutes delay (at time=1729 s). The pressure difference between the primary and secondary side is sufficiently high to fill up the broken SG for about 20 minutes after SI termination. Gradually, the primary pressure decreases and approaches the broken SG pressure, whereas the resultant break flow decreases to zero and the primary-to-secondary leakage is stopped.

The safety injection has been identified to have the major role in supporting the primary-to-secondary leakage. Therefore, the time of the first operator action aimed to prepare the plant conditions for SI termination has been chosen as the parameter in sensitivity analyses aimed to determine the maximum time for the start of the first operator action to prevent steam and liquid discharge. In the analysis, the steam discharge after first operator action was obtained if the operator has performed the first action 20 minutes after transient begin, whereas for the 15 minutes there was no additional discharge, Table 3. If the operator action was not started in a due time to prevent the broken SG filled with liquid, liquid discharge would follow after steam had been discharged. The comparison of the results for the cases with and without discharge (Parameter is the time of the first operator action.) are shown in Figure 21 through Figure 25. The results are summarized below:

CASE 1a (15 min), no release after first operator action, total: 4972 kg

CASE 1b (20 min), discharged mass=74 kg of steam after first operator action (total 7307 kg)

CASE 1c (45 min), discharged mass=13952 kg of steam (no liquid)

CASE 1d (50 min), discharged mass=15745 kg (steam and also liquid discharge).

Here, the liquid fraction of the flow through the SG 1 PORV greater than 0.1 has been selected as a criteria for liquid discharge. For the CASE 1d the SG became liquid solid, (liquid fraction in the steam dome volume (volume 429) liquid fraction=1), whereas for the CASE 1c only steam is discharged despite of almost liquid solid condition in the broken SG (max. liquid fraction in the steam dome volume=97.1%). The duration of the discharge through the SG 1 PORV increases with increasing the delay for the first operator action; e.g., for the CASE 1b discharge lasts for 29 minutes, 33 minutes for the CASE 1c and 45 minutes for the CASE 1d, respectively. Thus, if not performed in due time to prevent any discharge, the operator actions have proven to be efficient in at least limiting the amount of discharged mass.

A half an hour after terminating the SI flow, the operator starts the final cooldown & depressurization to hot shutdown conditions. Also, the normal CVCS is actuated, Figure 20. In the analysis, the operator adjusts the steam header setpoint pressure (steam dump system) in

order to perform the cooldown to hot shutdown conditions, Figure 10. Similarly to the first cooldown, the operator has enabled the steam dump valves of the bank A (two valves) to perform the final cooldown. The resulting steam dump flow and the valve opening are shown in Figure 15 and Figure 16. The realistic valve model is used and the valve opening increases with decreasing SG 2 pressure in order to obtain the required flow. Along with the cooldown the RCS depressurization takes place aimed on one side to follow the RCS temperature during cooldown and on the other side to depressurize the broken SG. Pressurizer spray operation was determined by the pressurizer pressure setpoint and by the pressurizer level not greater than 60 % in order to prevent pressurizer liquid solid conditions, Figure 18. Along with the RCS depressurization, Figure 5, the back flow from the SG 1 to the RCS is established and the mass of broken SG decreases, Figure 12. By finishing the RCS depressurization approx. 3 hours after first operator action the net break flow from the two break sides is zero and the stable conditions both on primary as well as on secondary side are established. At the end of cooldown and depressurization the pressurizer pressure was equal to 1.8 MPa, whereas the RCS average temperature oscillated with a small amplitude around its target value (450 K). The RCS temperature oscillations are caused by the oscillatory behaviour of the steam header pressure which on the other side is affected by the ON/OFF injection of the auxiliary feedwater, Figure 14. The steam dump valve opening, Figure 16, that is controlled by the steam dump control in steam header pressure mode as well as steam dump flow oscillate as well. The cooldown to the HSD conditions was performed at around 53.4 °C/hour that is close to maximum allowed cooldown rate (55.6 °C/hour). It lasted for approximately 1 hour and 40 minutes for all the analyzed cases. At the end of depressurization the pressurizer pressure, Figure 5 is held slightly greater than broken SG pressure to maintain the constant SG inventory. On the other side the pressurizer pressure is maintained above the lower limit (1.8 MPa) that is determined by the RHR operation and subcooling requirement. The subcooling during the cooldown procedure was considerably larger than the limiting value (19 °C), Figure 24 and pressurizer level was maintained within the acceptable range (25%-60%), Figure 25. The primary side mass after the end of the cooldown to HSD conditions is affected by the normal CVCS charging and letdown flow aimed to maintain the programmed pressurizer level (35 %), Figure 12, Figure 4 and Figure 20.

Table 3 Time table of main events for NEK SGTR CASE 1 analysis; parameter: begin of first operator action

Event	CASE 1a (15 min)	CASE 1b (20 min)	CASE 1c (45 min)	CASE 1d (50 min)
Transient start	0 s	0 s	0 s	0 s
Reactor trip (OTΔT trip, loop 2)	162.2 s	162.2 s	162.2 s	162.2 s
Turbine trip (on reactor trip)	162.2 s	162.2 s	162.2 s	162.2 s
Main FW isolation (on low RCS average temperature & reactor trip)	256.7 s	256.7 s	256.7 s	256.7 s
SI actuation (on low-2 pressurizer pressure)	346.1 s	346.1 s	346.1 s	346.1 s
1st operator action: MSIV 1 isolation	900 s	1200 s	2700 s	3000 s
1st cooldown	1080 s	1380 s	2880 s	3180 s
Time to achieve target core exit temperature during first cooldown	1214 s (542.1 K)	1511 s (542.0 K)	3016 s (541.5 K)	3315 s (541.6 K)
1st RCS depressurization	1394 s	1691 s	3196 s	3495 s
Operator turns off SI (180 s delay)	1729 s	2016 s	3541 s	3852 s
End of primary-to-secondary leakage	2950 s	3334 s	5350 s	5670 s
Discharge through SG 1 PORV (after 1st operator action)	-	2525 s	3170 s	3470 s
SG 1 steam dome liquid fraction > 10%	-	-	3735 s	3040 s
Max. SG 1 steam dome liquid fraction	0.02% (197 s)	0.02% (197 s)	97.1% (5350 s)	100% (4525 s)
Liquid discharge - SG 1 PORV (voidfj > 0.1)	-	-	-	4600 s
End of discharge	1140 s	2960 s	4685 s	5690 s
Total discharged mass through SG 1 PORV after 1st operator action	0 kg	74 kg	372 kg	1165 kg
Total discharged mass through SG 1 PORV	4972 kg	7307 kg	13952 kg	15745 kg
2nd cooldown & depressurization to HSD; CVCS enabled, operator isolates accumulators	3529 s	3816 s	5341 s	5652 s
HSD conditions achieved, cooldown rate	9540 s (53.3 °C/hour)	9820 s (53.4 °C/hour)	11320 s (53.6 °C/hour)	11670 s (53.2 °C/hour)

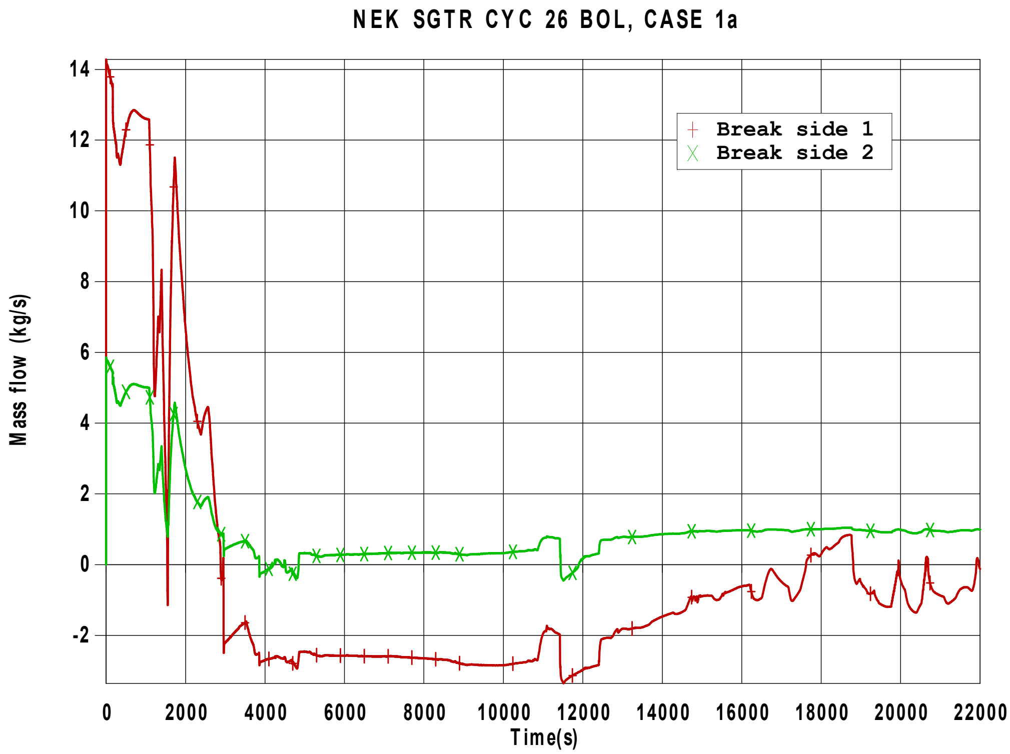

Figure 3 SGTR analysis, CASE 1a: Break mass flow rate

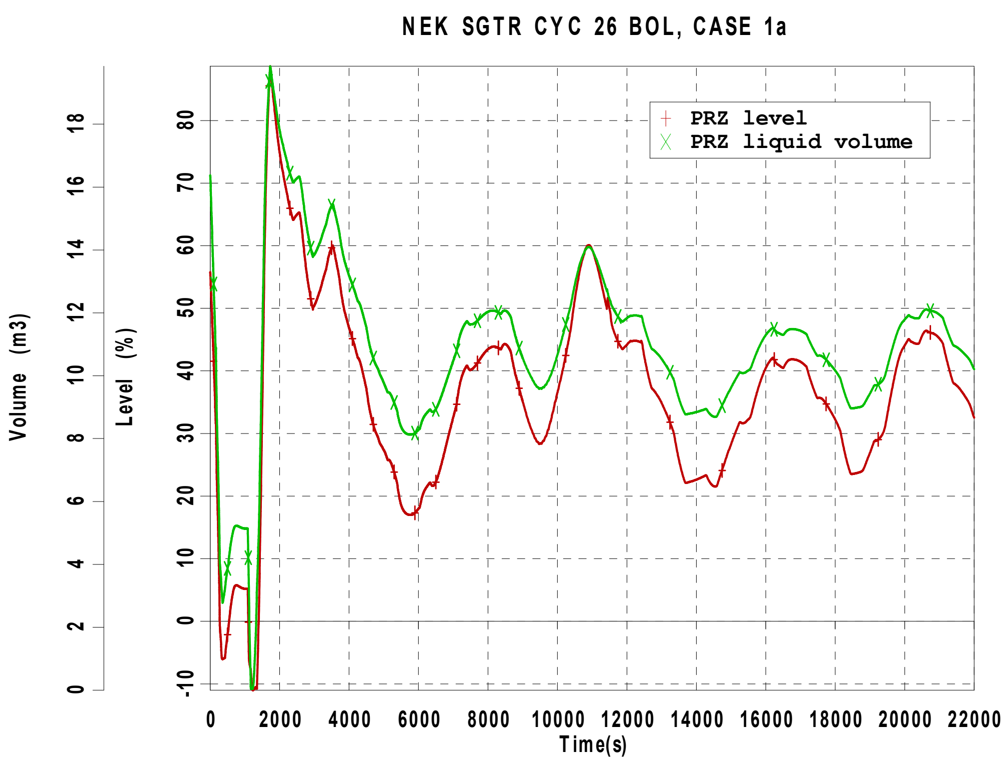

Figure 4 SGTR analysis, CASE 1a: Pressurizer NR level and liquid volume

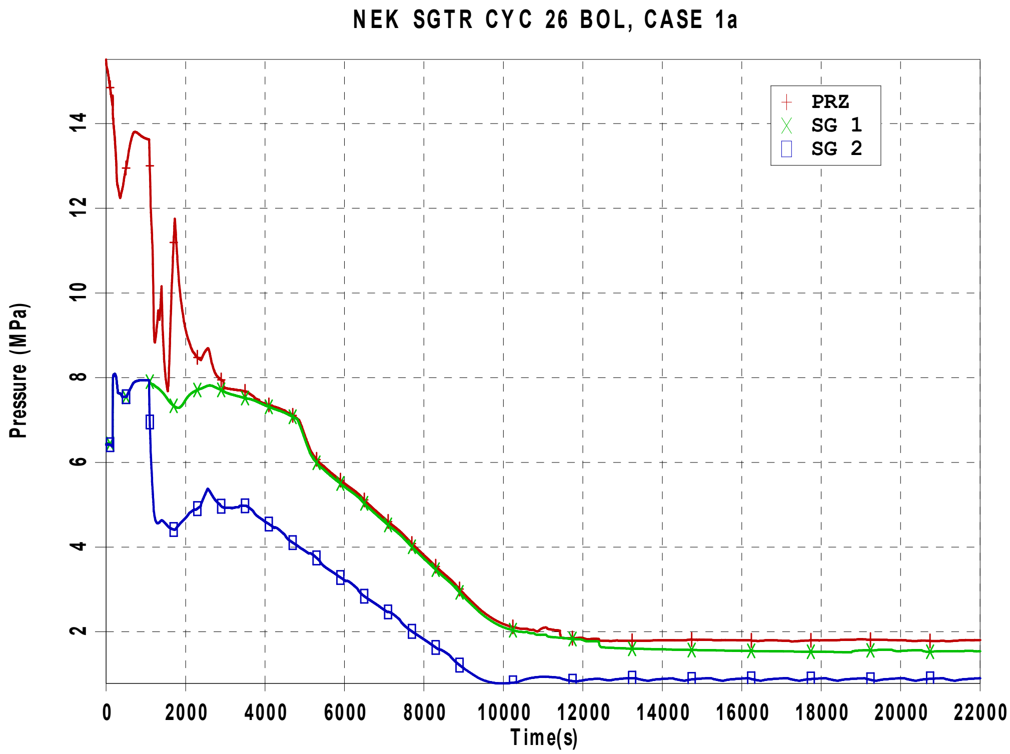

Figure 5 SGTR analysis, CASE 1a: Pressurizer and SG pressure

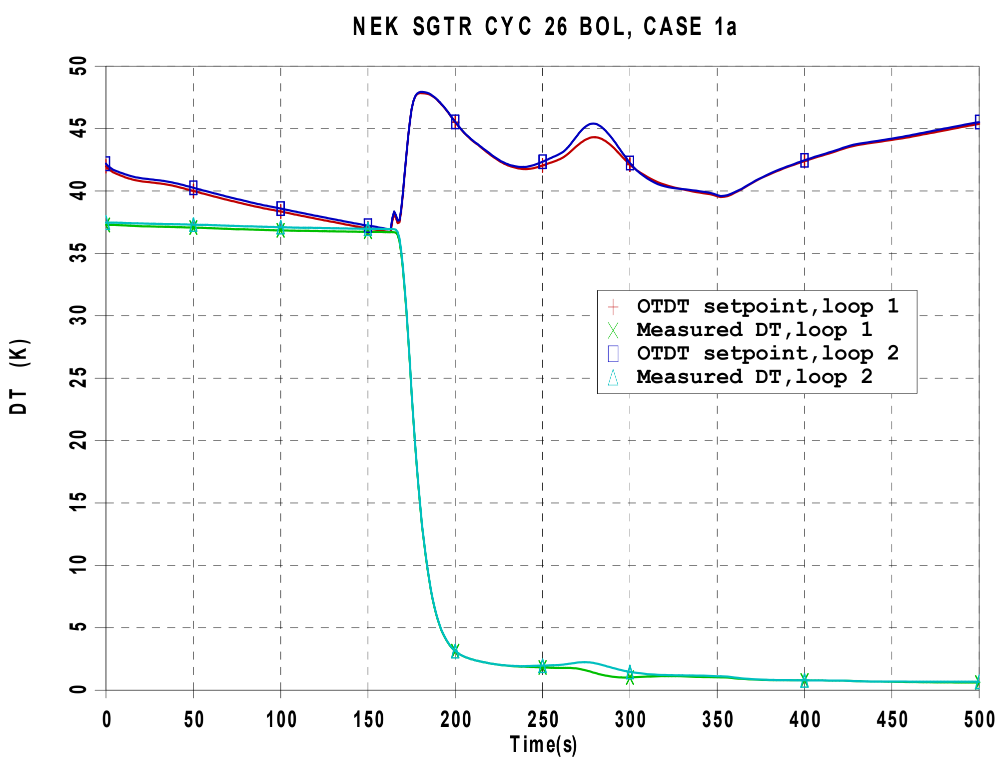

Figure 6 SGTR analysis, CASE 1a: Measured ΔT (compensated) and OTΔT setpoint

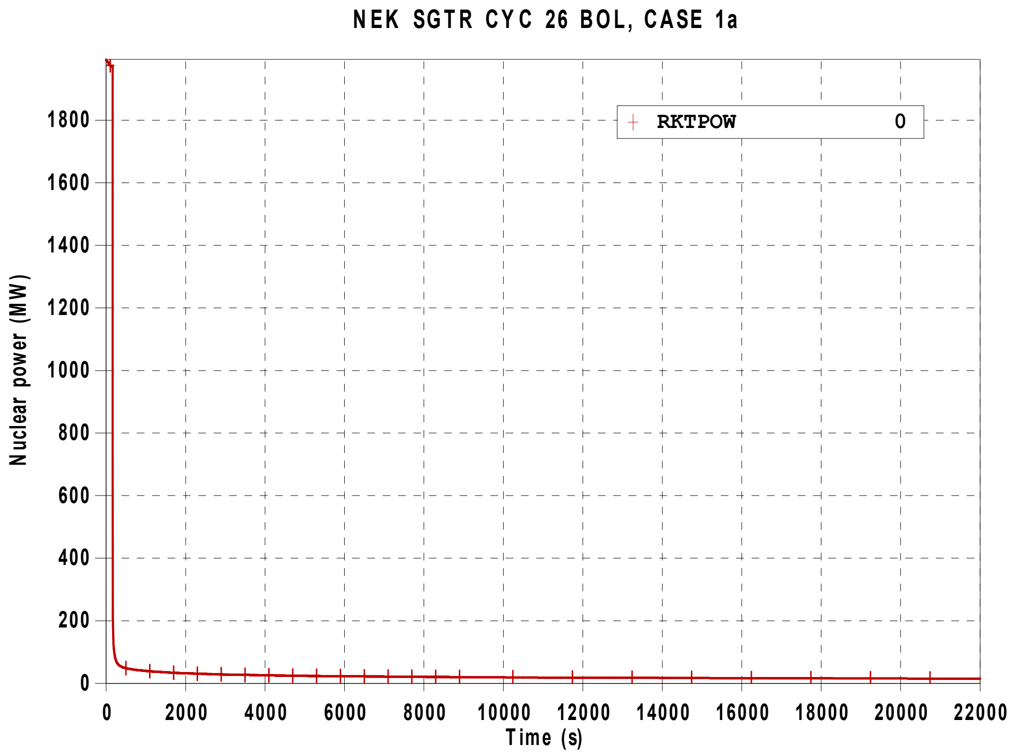

Figure 7 SGTR analysis, CASE 1a: Nuclear power

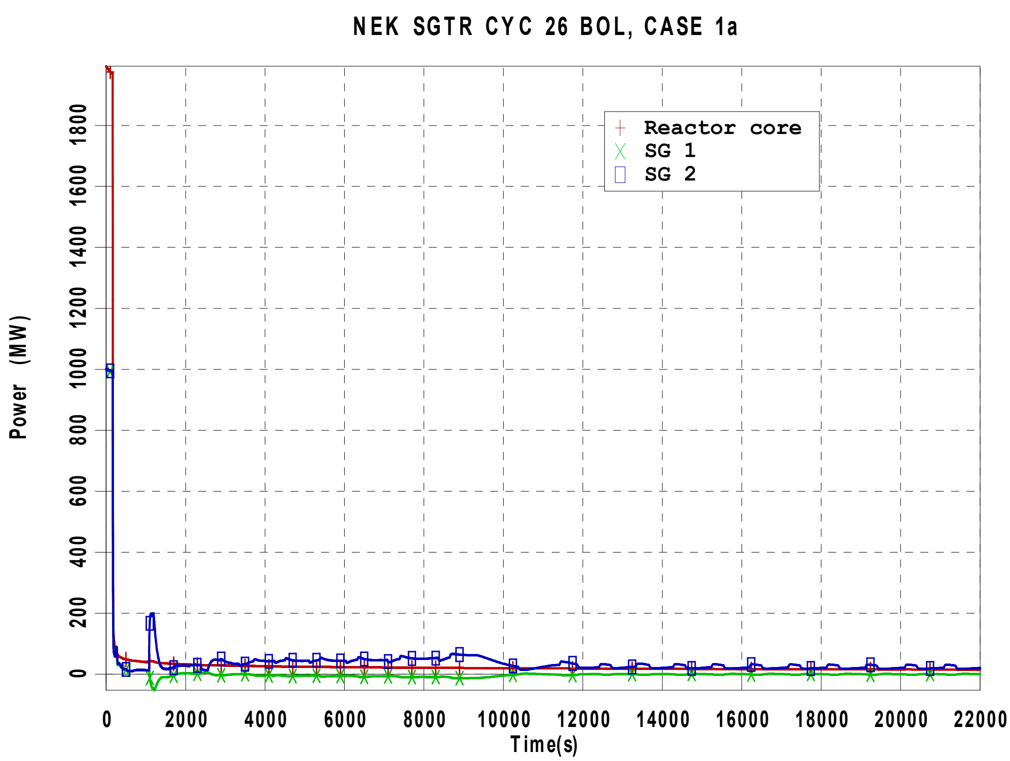

Figure 8 SGTR analysis, CASE 1a: Reactor core power and SG power

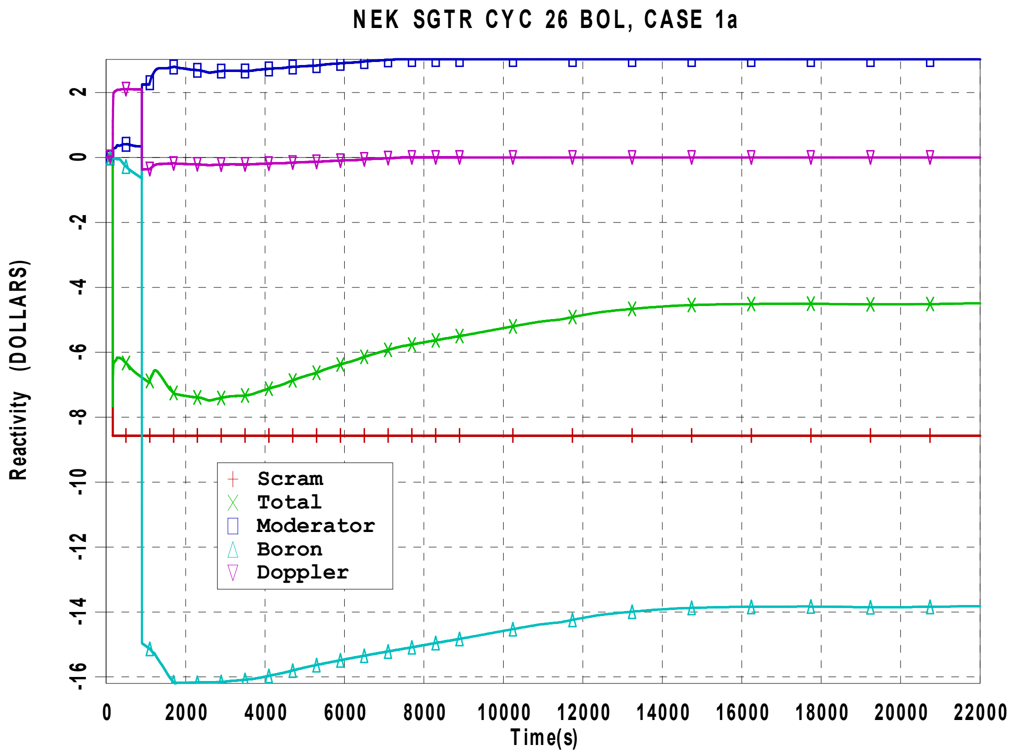

Figure 9 SGTR analysis, CASE 1a: Reactivity

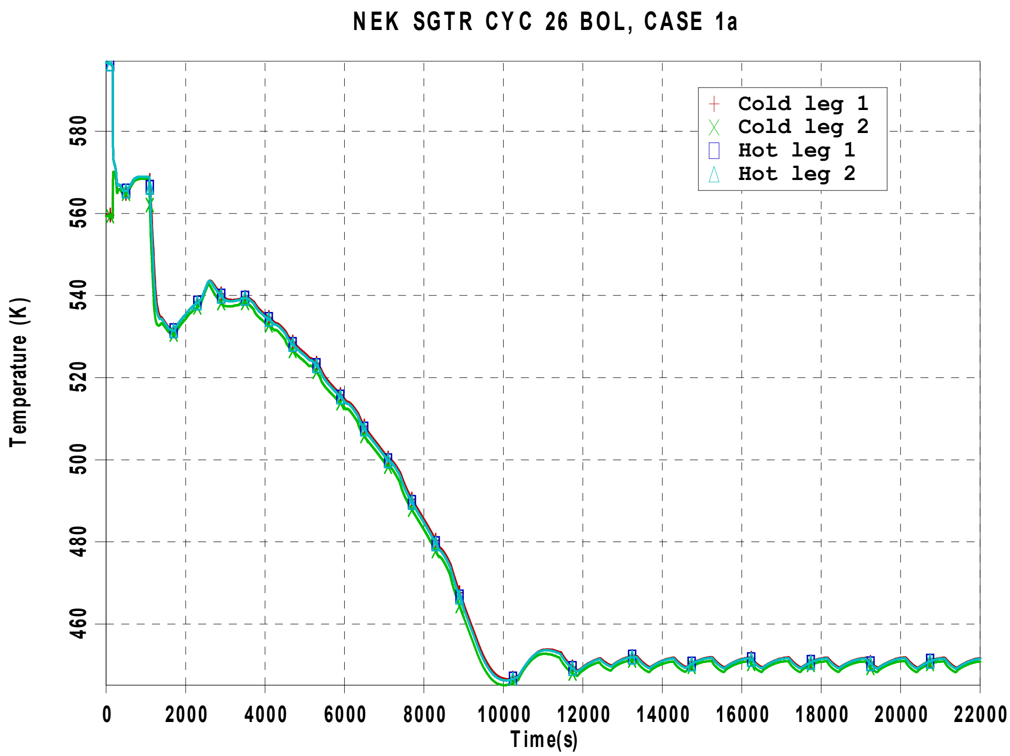

Figure 10 SGTR analysis, CASE 1a: RCS temperature

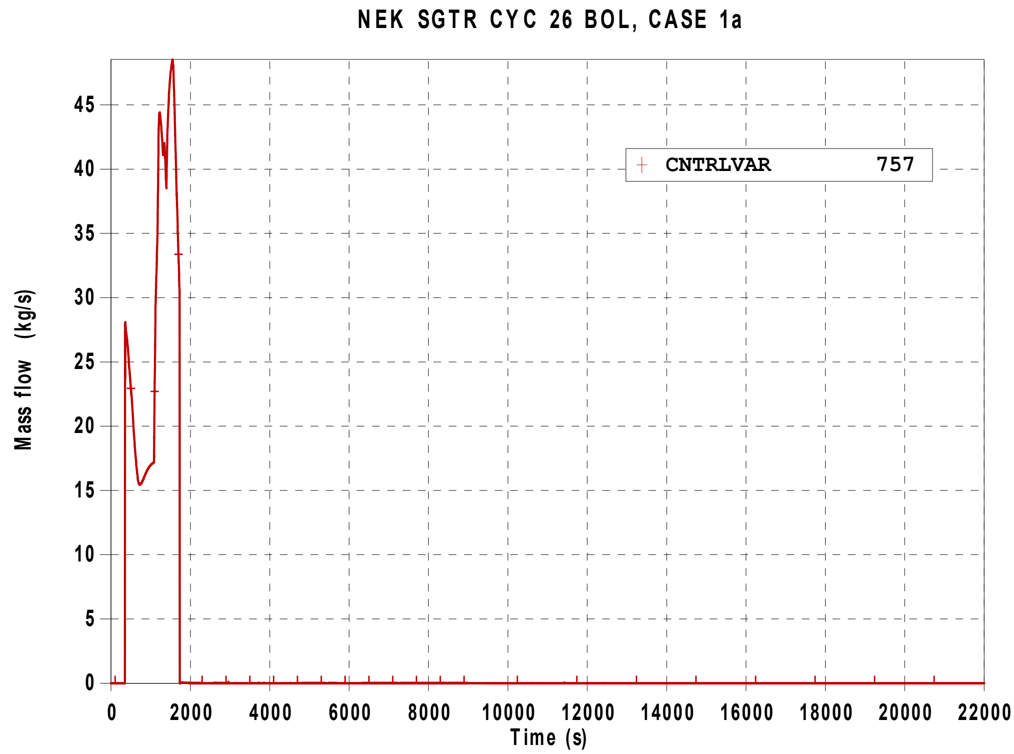

Figure 11 SGTR analysis, CASE 1a: Safety injection mass flow rate

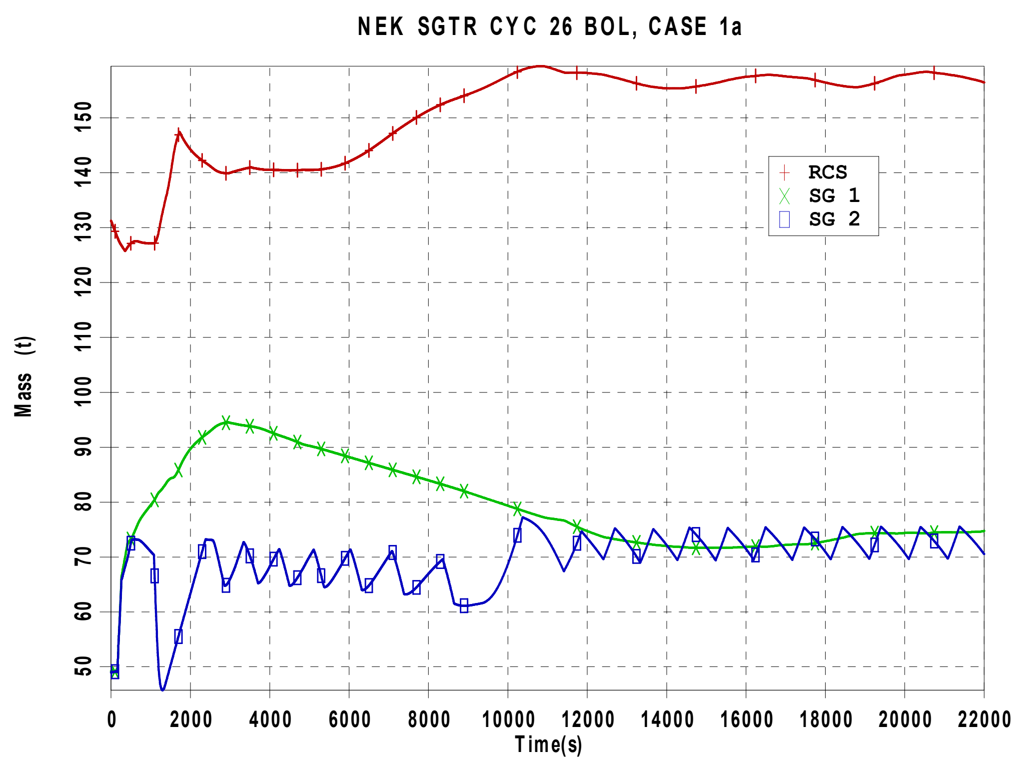

Figure 12 SGTR analysis, CASE 1a: RCS and SG mass

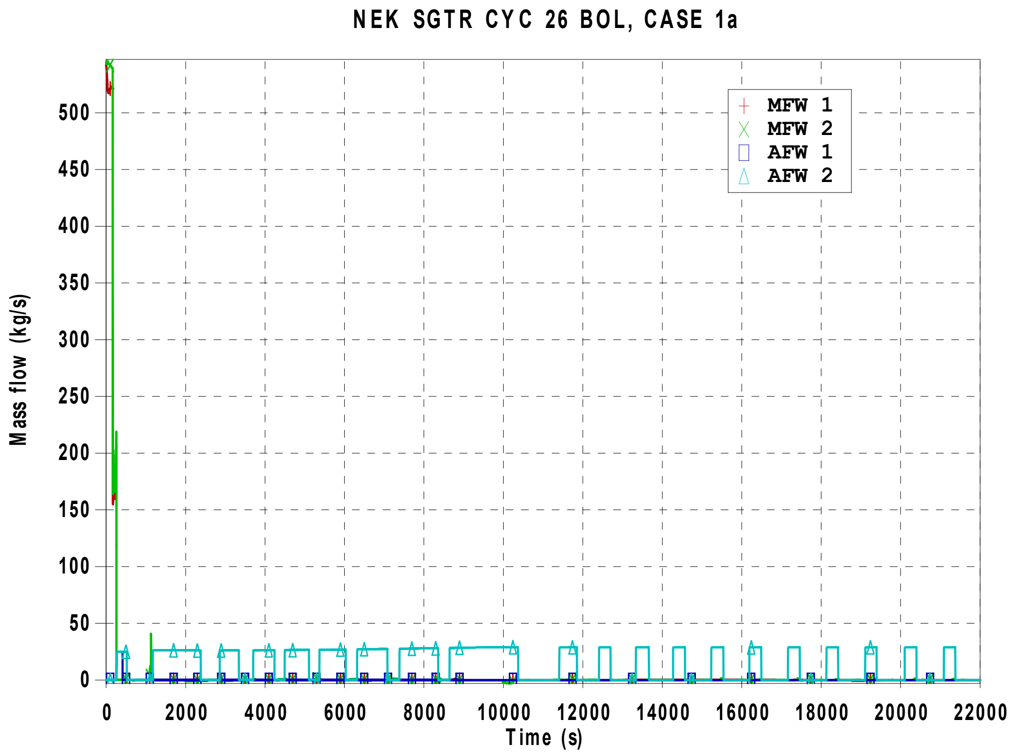

Figure 13 SGTR analysis, CASE 1a: Main and auxiliary feedwater flow

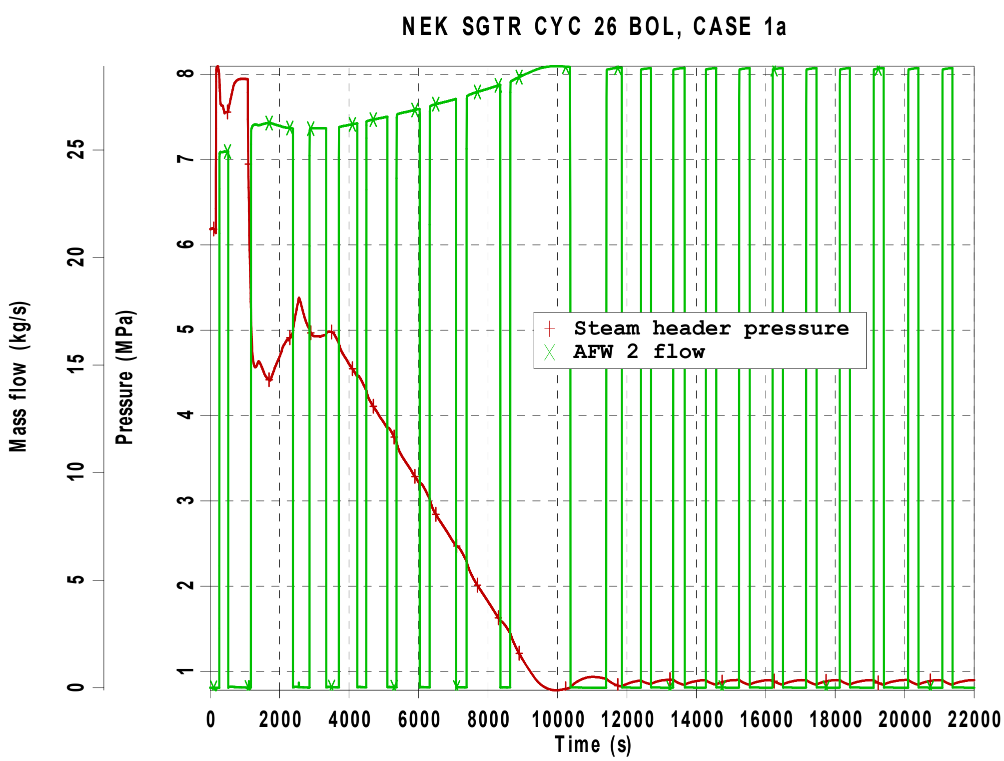

Figure 14 SGTR analysis, CASE 1a: Steam header pressure and SG 2 AFW flow

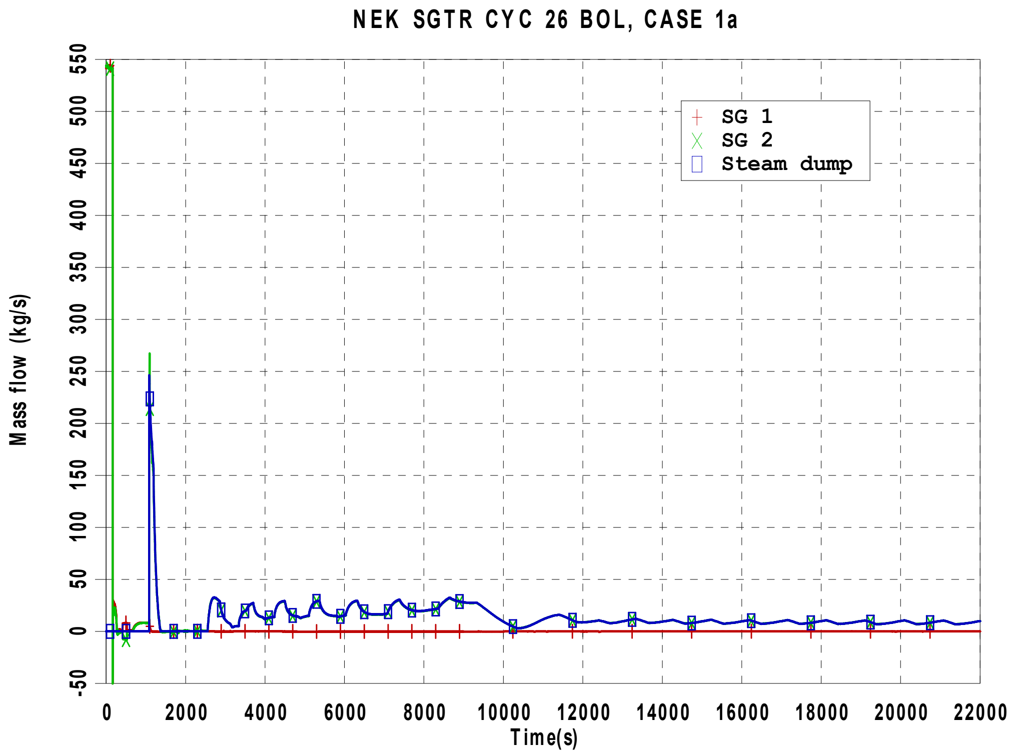

Figure 15 SGTR analysis, CASE 1a: Main steam flow and steam dump flow

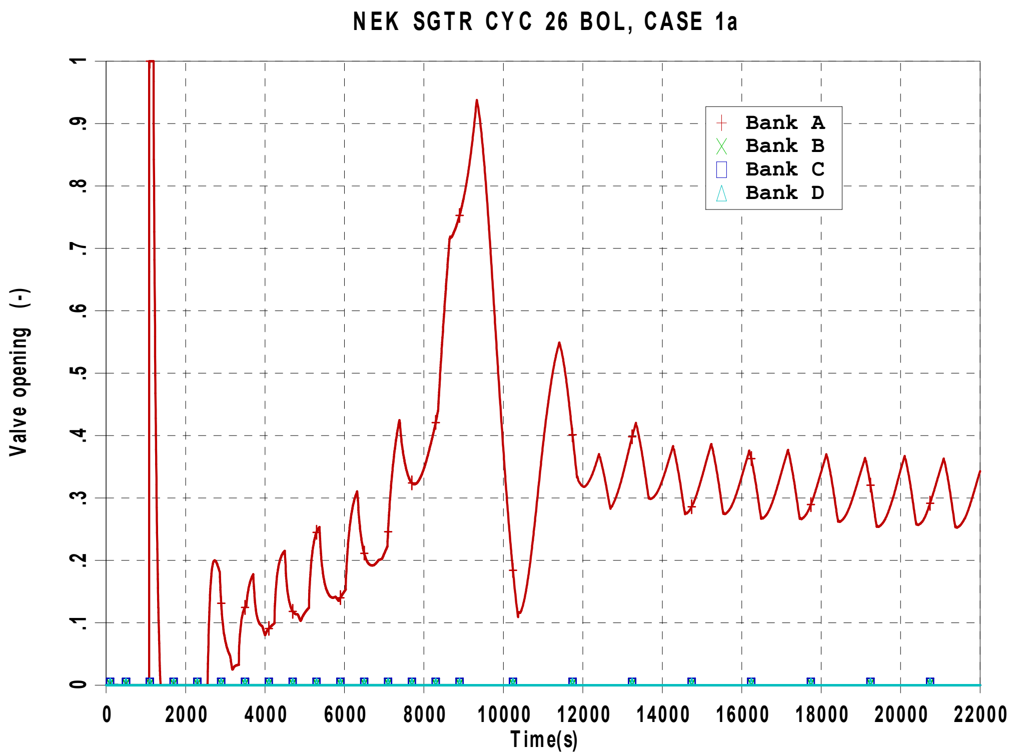

Figure 16 SGTR analysis, CASE 1a: Steam dump valve opening

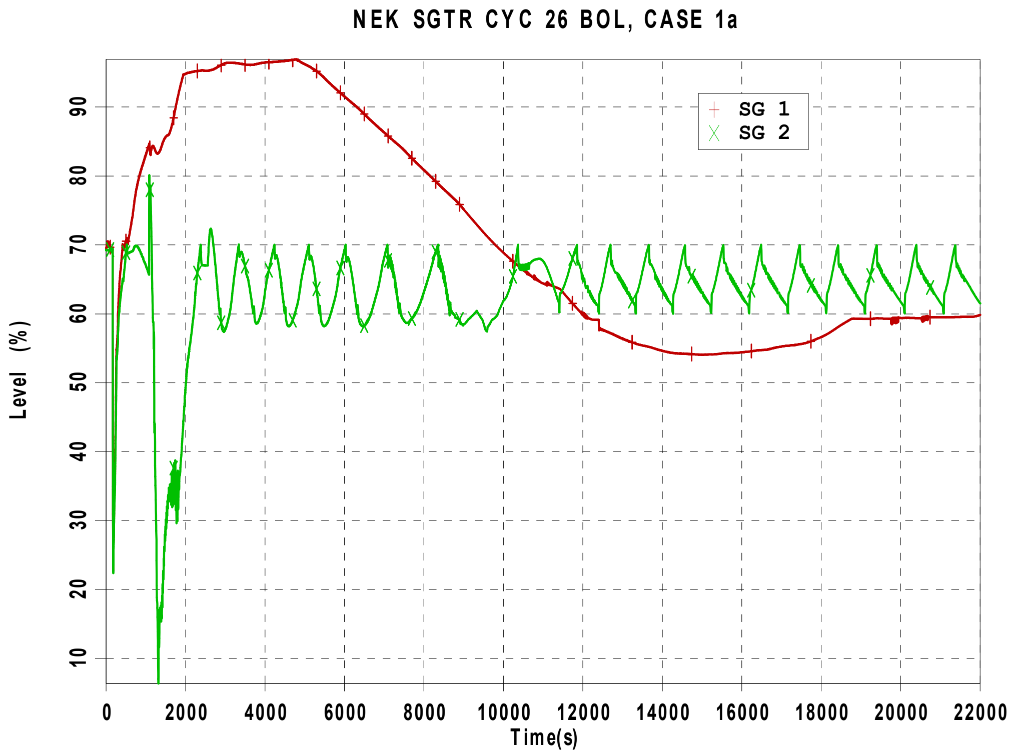

Figure 17 SGTR analysis, CASE 1a: SG NR level

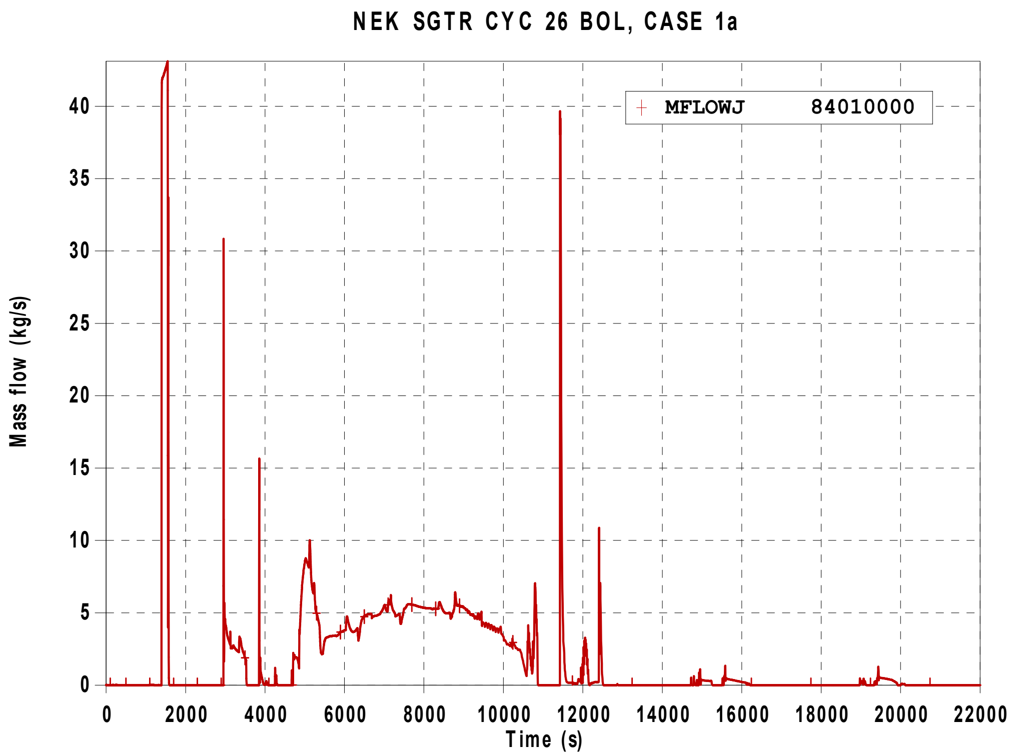

Figure 18 SGTR analysis, CASE 1a: Pressurizer spray mass flow rate

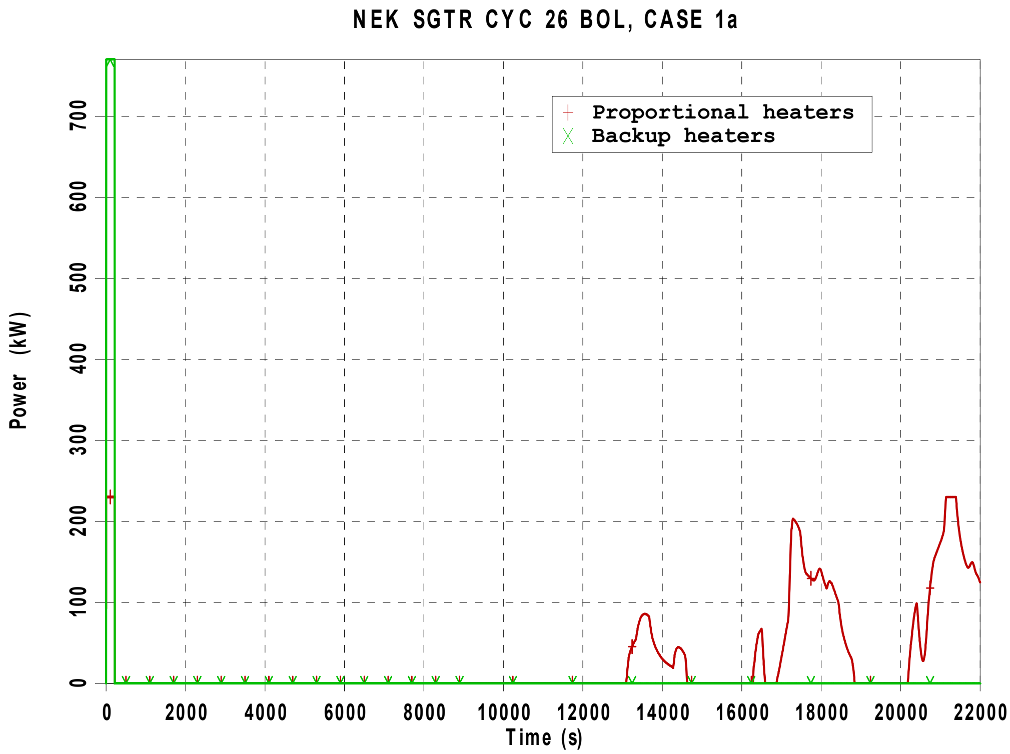

Figure 19 SGTR analysis, CASE 1a: Pressurizer heaters power

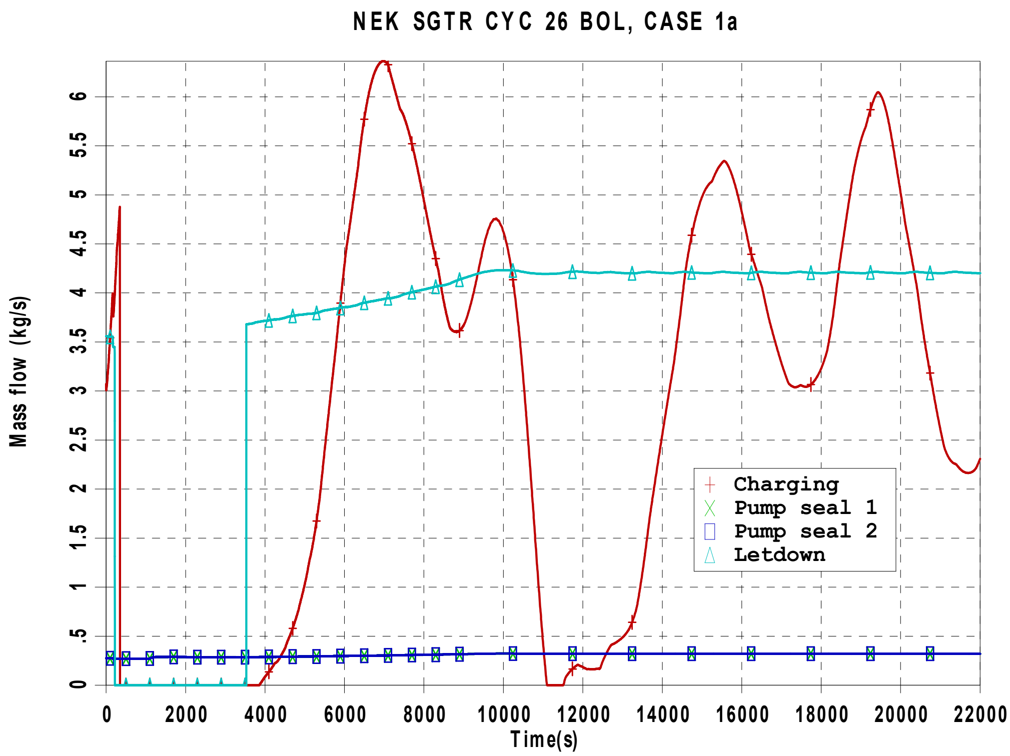

Figure 20 SGTR analysis, CASE 1a: CVCS mass flow rate

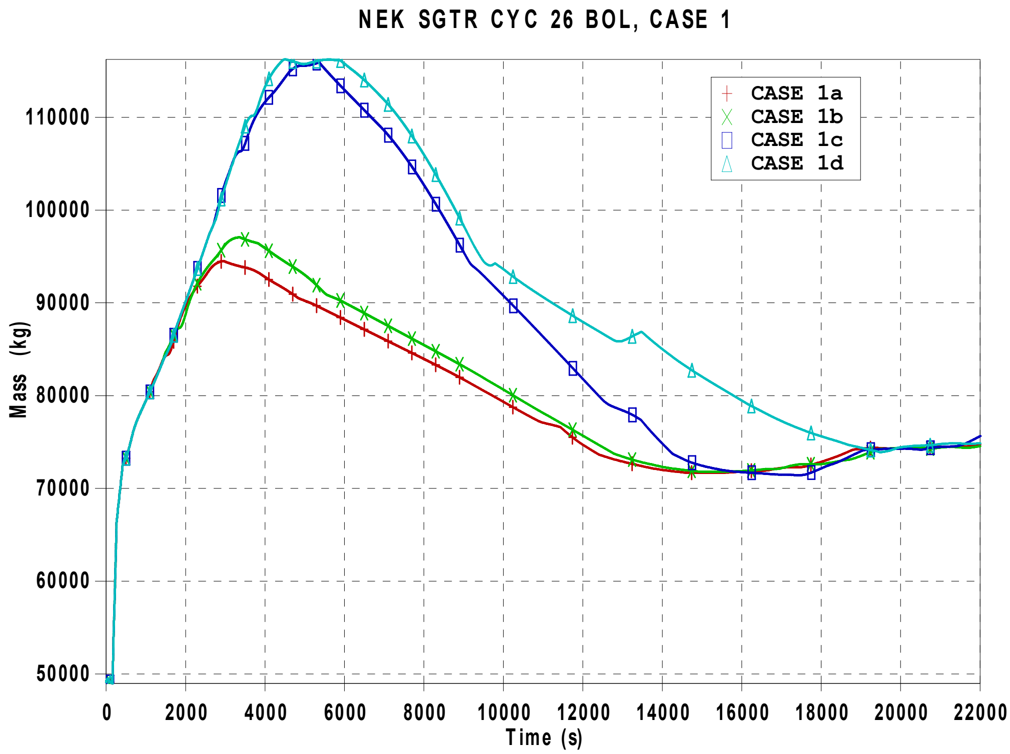

Figure 21 SGTR sensitivity analysis, CASE 1: Mass of broken SG (SG 1)

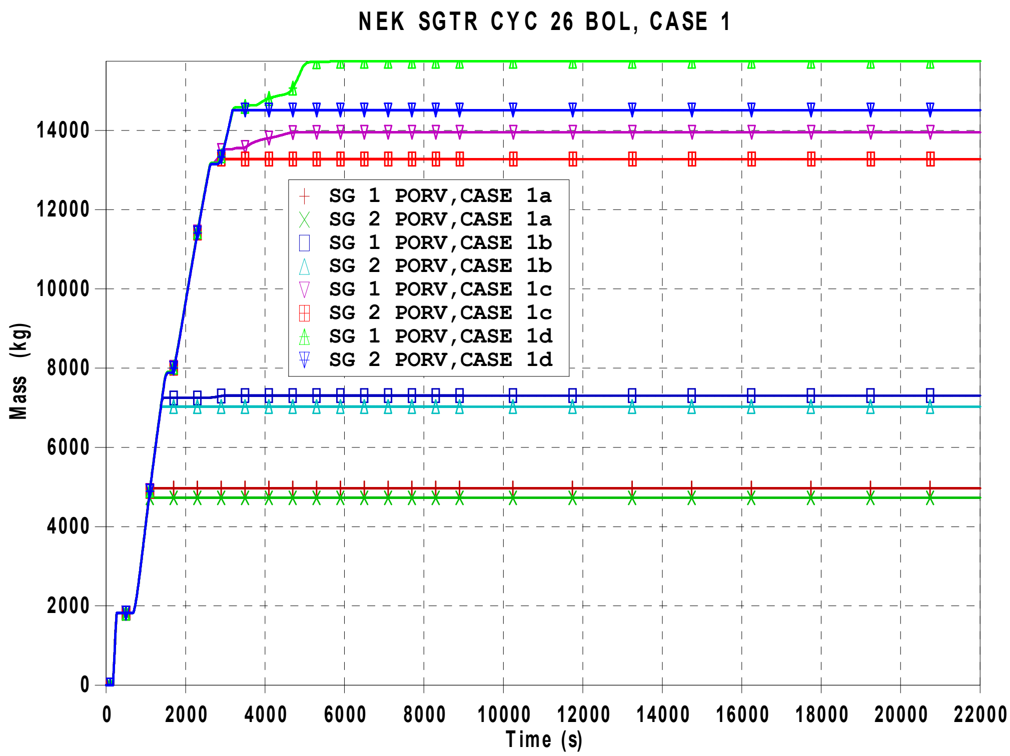

Figure 22 SGTR sensitivity analysis, CASE 1: Discharged mass through SG PORV

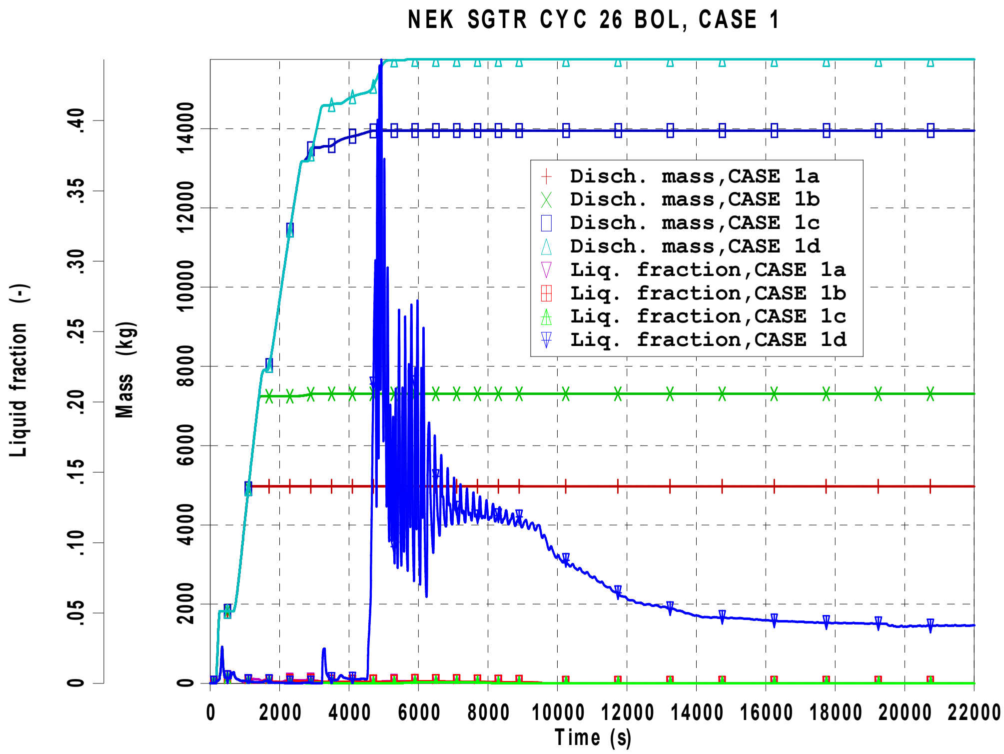

Figure 23 SGTR sensitivity analysis, CASE 1: Discharged mass through broken SG (SG 1) PORV and broken SG PORV flow liquid fraction

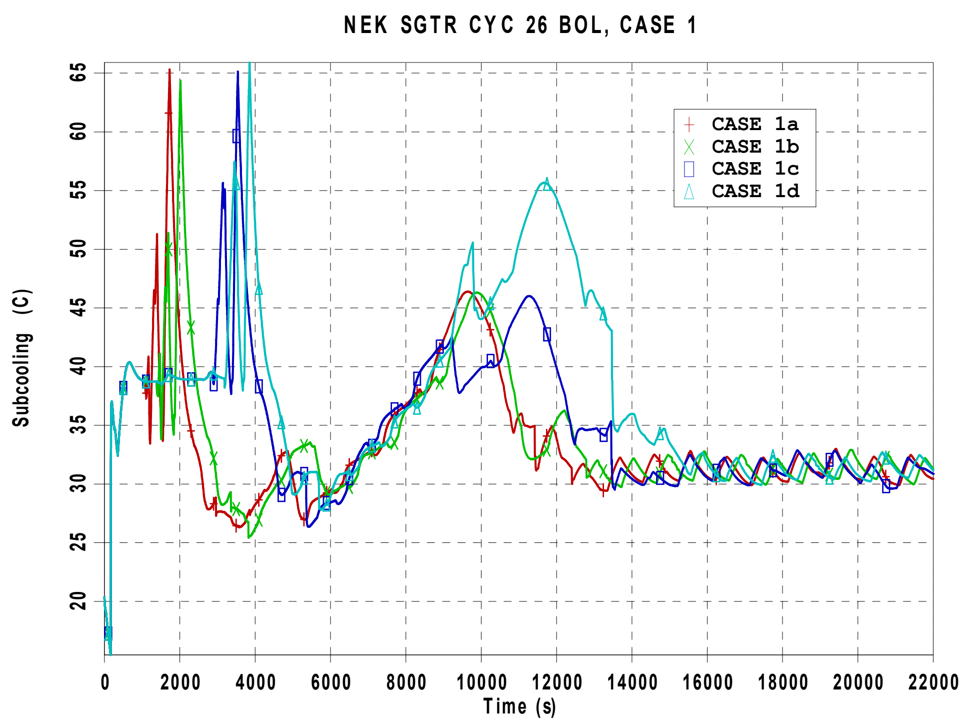

Figure 24 SGTR sensitivity analysis, CASE 1: RCS subcooling

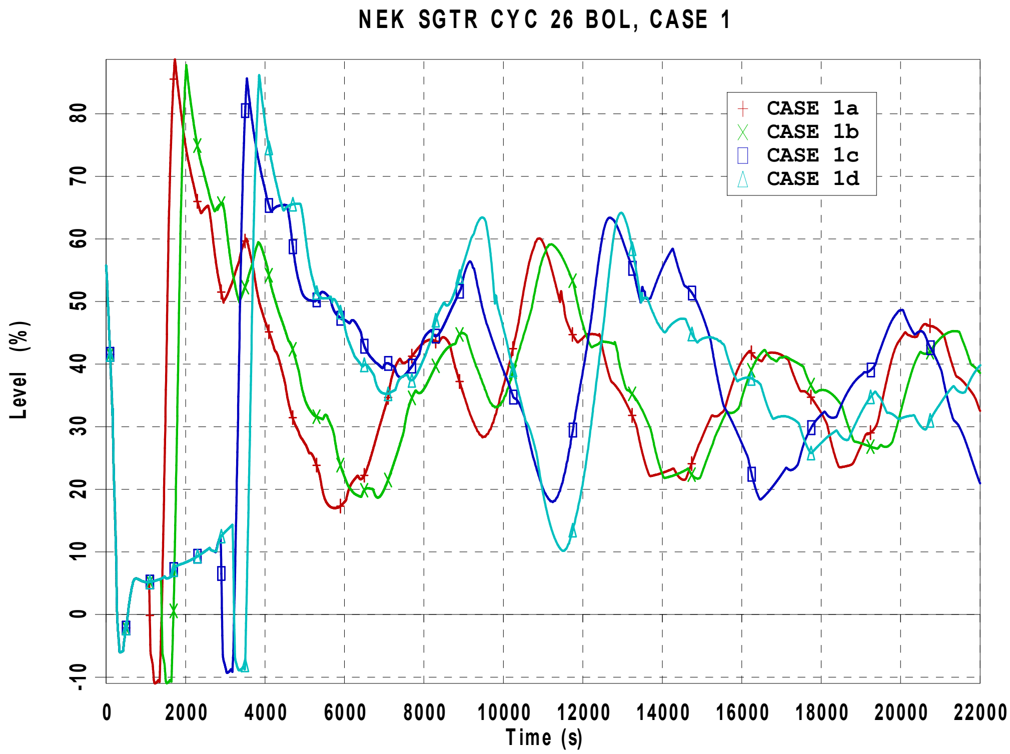

Figure 25 SGTR sensitivity analysis, CASE 1: Pressurizer NR level

4.2 Analysis and results, CASE 2: Offsite power not available

The transient was initiated after 1000 seconds of steady state calculation in the same manner as for CASE 1, i.e., the two break valves simulating the double ended break of one U-tube are open simultaneously with closing the valve that connects the U-tube ends before the break. The main events are summarized in Table 4. The results for the cases with steam (cases 2a and 2b) and also with liquid discharge (CASE 2c) through the broken SG PORV are summarized. The CASE 2 is identical to the CASE 1 until reactor trip when in the CASE 2 a loss of offsite power is assumed. Loss of offsite power results in a coastdown of both RCPs and automatic closure of steam dump valves. In reality, loss of offsite power would cause loss of main feedwater, but in the analysis it was conservatively assumed that the normal feedwater was in operation until either reactor trip in combination with low RCS average temperature or SI signal trip the feedwater pumps. The results are graphically presented in Figure 26 to Figure 51. Here, the case with only steam discharge and the steam dome volume of the broken SG filled with less than 50% with liquid (CASE 2a – 15 minutes for the first operator action) is presented in a more detail. Until reactor trip at 162.2 s after transient begin the transient is identical to the previously analyzed case (CASE 1). Immediately after reactor trip, loss of offsite power occurs resulting in a loss of forced RCS flow, Figure 27. The cooldown following the reactor trip, Figure 32, causes decrease of coolant specific volume, which increases outsurge flow from the pressurizer and the RCS pressure decreases more rapidly. Finally, the SI on low-2 pressurizer pressure is actuated (at time=300 s), Figure 36. The SI adds the inventory to the RCS and increases the primary pressure which supports the primary-to-secondary leakage and the increase of the broken SG inventory, Figure 37. The main feedwater is isolated before SI actuation on low RCS average temperature signal in combination with reactor trip (at time=289.2 s). The secondary pressure increases after turbine trip, Figure 29, and the PORV valve opens on both intact and broken SG. The first operator action consists of the isolation (closing of the main steam isolation valve of the broken SG) and the cooldown (1st cooldown) followed by the depressurization with 3 minutes delay each. In order to perform the RCS cooldown the operator adjusts the SG 2 PORV setpoint pressure to the value that would result in the cooldown to the target core exit temperature. As for the previously analyzed case, the target core exit temperature is determined as a saturation temperature corresponding to the broken SG pressure at a time of the begin of the cooldown taking into account the subcooling measurement uncertainty (here for normal containment conditions) and an additional subcooling uncertainty (11.11 °C). The resulting SG 2 PORV mass flow rate is five times less than the steam dump flow (2 steam dump valves) in the CASE 1, Figure 41, Figure 15, even with fully open SG PORV valve, Figure 40. The secondary pressure of both SGs that were coupled via steam header before the isolation of the damaged SG, Figure 29, decouple after SG 1 isolation. However, the effect of the decoupling becomes significant first after start of the first cooldown when the pressure of the intact SG decreases at a fast rate and the broken SG pressure slowly decreases. Due to lower capacity of one SG PORV than the steam dump flow in the CASE 1, the cooldown to the target core exit temperature lasted significantly longer (about 12 minutes in the CASE 2 vs. 2 minutes in the CASE 1). The RCS pressure decreased during cooldown due to outsurge from the pressurizer. However, as soon as the cooldown had been finished the RCS pressure rises again due to persisting SI flow. Three minutes after finishing the cooldown, the operator starts the RCS depressurization using the pressurizer PORV, Figure 44 and Figure 45. Due to the loss of forced primary flow, the pressure difference between the cold leg and pressurizer spray nozzle is very low and the pressurizer spray flow is negligible despite of fully open pressurizer spray valve. During the depressurization the operator monitors the pressurizer level and closes the pressurizer PORV when the pressurizer level exceeds 80% in order to prevent the pressurizer liquid solid condition, Figure 28, Figure 44 and Figure 45. The RCS pressure started to rise again due to SI

flow. Finally, at time=2266 s, the operator has terminated SI with the required conditions fulfilled (RCS subcooling>19°C, PRZR level>15% and intact SG level>20%). After SI termination the primary pressure decreases and approaches the broken SG pressure. The break flow reverses, Figure 26, and the secondary-to-primary flow is established, thus decreasing the broken SG mass, Figure 37, whereas the RCS mass is subsequently increased. If primary-to-secondary leakage was not stopped in a due time, the broken SG fills up with liquid, Figure 47 and Figure 48. Similarly to the previously analyzed case the safety injection flow has been identified to have the major effect on filling the broken SG with the liquid and the subsequent liquid discharge. Consequently, the time of the operator actions that prepare the plant for the SI termination was selected as a major criteria for sensitivity analysis. The comparison of the results for the cases with and without liquid discharge (Parameter is the time of the first operator action.) are shown in Figure 47 through Figure 51. The results are summarized below:

CASE 2a (15 minutes), max. SG dome volume liquid fraction=47%, discharged mass=4558 kg of steam

CASE 2b (20 minutes), max. SG dome volume liquid fraction=96.8%, discharged mass=6084 kg of steam

CASE 2c (25 minutes), broken SG liquid solid, discharged mass=7811 kg of steam-liquid mixture.

Similarly to the CASE 1, the analyses have shown that the primary-to-secondary leakage as well as discharge through the broken SG (either steam or both steam and liquid) are successfully stopped about half an hour after SI termination, Table 4 and Figure 49.

A half an hour after terminating the SI flow, the operator starts the final cooldown & depressurization to hot shutdown conditions. Also, the normal CVCS is actuated, Figure 46. The begin of 2nd cooldown & depressurization has no influence on discharge through the broken SG PORV, since the discharge finishes before 2nd cooldown, Table 4, Figure 49. During 2nd cooldown the operator adjusts the intact SG PORV valve opening in order to perform the cooldown at maximum possible rate, Figure 40. However, due to decreasing difference between the SG 2 and atmospheric pressure, the SG 2 PORV flow is very low when compared with the steam dump flow in the CASE 1. Consequently, the low RCS cooldown rate, Figure 32, was obtained (approximately 5.7 °C/hour) and the cooldown to hot shutdown conditions lasted for about 14 hours that is much longer than the cooldown for the CASE 1 (1 hour and 40 minutes). Along with the RCS cooldown, the pressurizer pressure was reduced from 8 MPa to 1.9 MPa. In order to prevent the loss of RCS subcooling, the pressurizer pressure setpoint was adjusted to follow the actual cooldown rate, Figure 29 and Figure 50. Pressurizer PORV operation was determined by the pressurizer pressure setpoint and by the pressurizer level not greater than 80% in order to prevent pressurizer liquid solid condition, Figure 28. Due to loss of forced RCS flow after reactor trip, the temperature difference between the hot and cold leg is much higher (not less than 20 ^{o}C), Figure 32, throughout the transient when compared with the CASE 1. Whereas in the intact loop a low positive flow was established and almost constant temperature difference between the hot and cold leg was maintained, in the broken loop the fluid was almost stagnant, Figure 27 and the temperatures were greatly influenced by the break flow. During the SI injection the cold leg temperature in the broken loop is also affected by the injection of the cold SI flow and stagnant conditions due to break. In the period of the intensive back flow from the secondary to primary side that lasted until approx. 14100 s, the cold leg temperature in the broken loop was dominantly influenced by the incoming secondary flow and it was greater than the hot leg temperature. First after secondary to primary flow was terminated, the fluid in the

broken SG moved from the hot to the cold leg thus reversing the hot to cold leg temperature difference. During the cooldown and depressurization the SG level in the broken SG fell below 50% and the AFW flow was actuated. The condensation on the cold AFW water causes the broken SG pressure decrease which on the other side causes the primary-to-secondary leakage. Due to ON/OFF opening of the AFW flow in the broken SG, Figure 38, that controls the broken SG level in the range (50%, 60%) the periodic oscillations of the break flow results. This causes further oscillation behaviour for a number of parameters, e.g., RCS and broken SG pressure and mass as well as the RCS temperature in the broken loop, Figure 34. On the other side, the periodic ON/OFF operation of the AFW flow in the intact loop causes the temperature oscillations in that loop only due to oscillations of the transferred heat. The heat transferred in the broken loop is negligible throughout the transient due to the fact that the broken SG is isolated as well as due to the stagnant flow conditions on its primary side. The maximum average temperature (out of two loops) was monitored as criteria for ending the cooldown to HSD conditions (177 °C). Finally, the successful cooldown & depressurization to hot shutdown conditions was performed with RCS subcooling larger than the limiting value (19 °C), Figure 50 and pressurizer level within the acceptable range (20%-80%), Figure 51. One hour after the HSD conditions had been achieved the operator has turned ON the PRZ proportional heaters in order to prevent the primary pressure decrease below 1.8 MPa as well as the loss of RCS subcooling, Figure 35. Thereby, the pressurizer pressure stabilizes, which on the other side instigates the primary to secondary leakage, Figure 37. This urges the operator to switch to RHR operation and initiate the cooldown to cold shutdown conditions.

Table 4 Time table of main events for NEK SGTR CASE 2 analysis; parameter: begin of first operator action

Event	CASE 2a (15 min)	CASE 2b (20 min)	CASE 2c (25 min)
Transient start	0 s	0 s	0 s
Reactor trip (OTΔT trip, loop 2)	162.2 s	162.2 s	162.2 s
Turbine trip (on reactor trip)	162.2 s	162.2 s	162.2 s
RCP trip (1 sec delay)	163.2 s	163.2 s	163.2 s
Main FW isolation (on low RCS average temperature & reactor trip)	289.2 s	289.2 s	289.2 s
SI actuation (on low-2 pressurizer pressure)	300.0 s	300.0 s	300.0 s
1st operator action: MSIV 1 isolation	900 s	1200 s	1500 s
1st cooldown	1080 s	1380 s	1680 s
Time to achieve target core exit temperature during first cooldown	1845 s (541.8 K)	2100 s (541.8 K)	2365 s (541.7 K)
1st RCS depressurization	2025 s	2280 s	2545 s
Operator turns off SI (180 s delay)	2266 s	2518 s	2782 s
End of primary-to-secondary leakage	4000 s	4320 s	4585 s
SG 1 steam dome liquid fraction > 10%	2027 s	2100 s	2115 s
Max. SG 1 steam dome liquid fraction	47.0% (3970 s)	96.8% (4315 s)	100% (3010 s)
Liquid discharge - SG 1 PORV (voidfj > 0.1)	-	-	-
End of discharge	3945 s	4290 s	4560 s
Total discharged mass through SG 1 PORV	4558 kg	6084 kg	7811 kg
2nd cooldown & depressurization to HSD; CVCS enabled, operator isolates accumulators	4066 s	4318 s	4582 s
HSD conditions achieved, cooldown rate	54350 s (5.7 °C/hour)	55530 s (5.7 °C/hour)	56000 s (5.7 °C/hour)

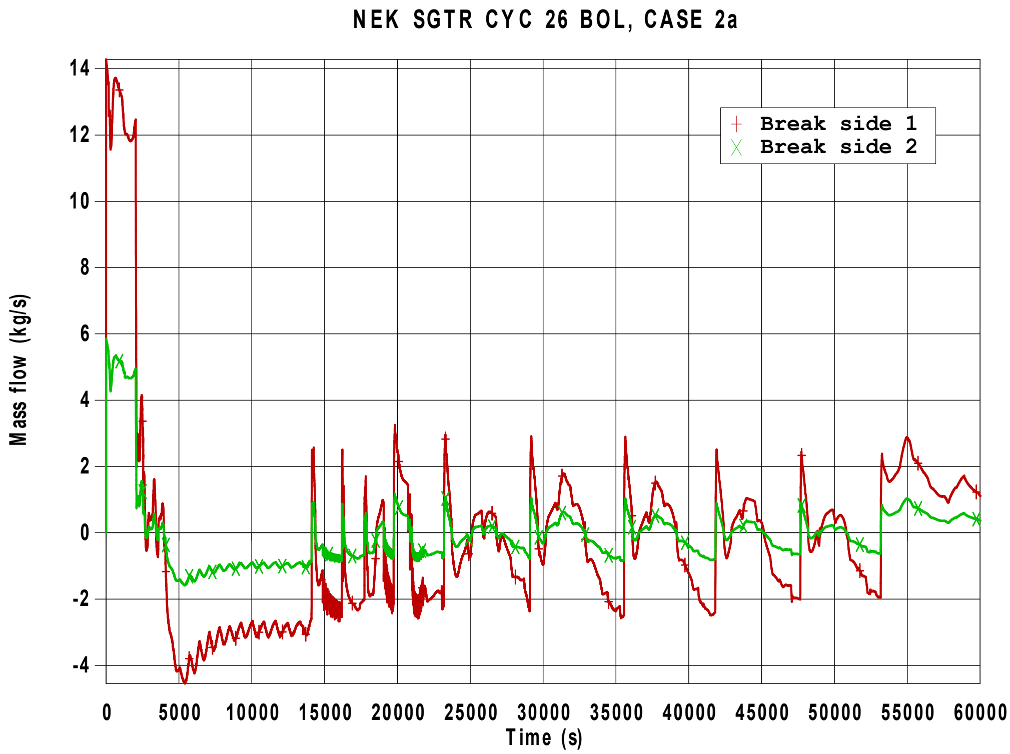

Figure 26 CASE 2a analysis: Break mass flow rate

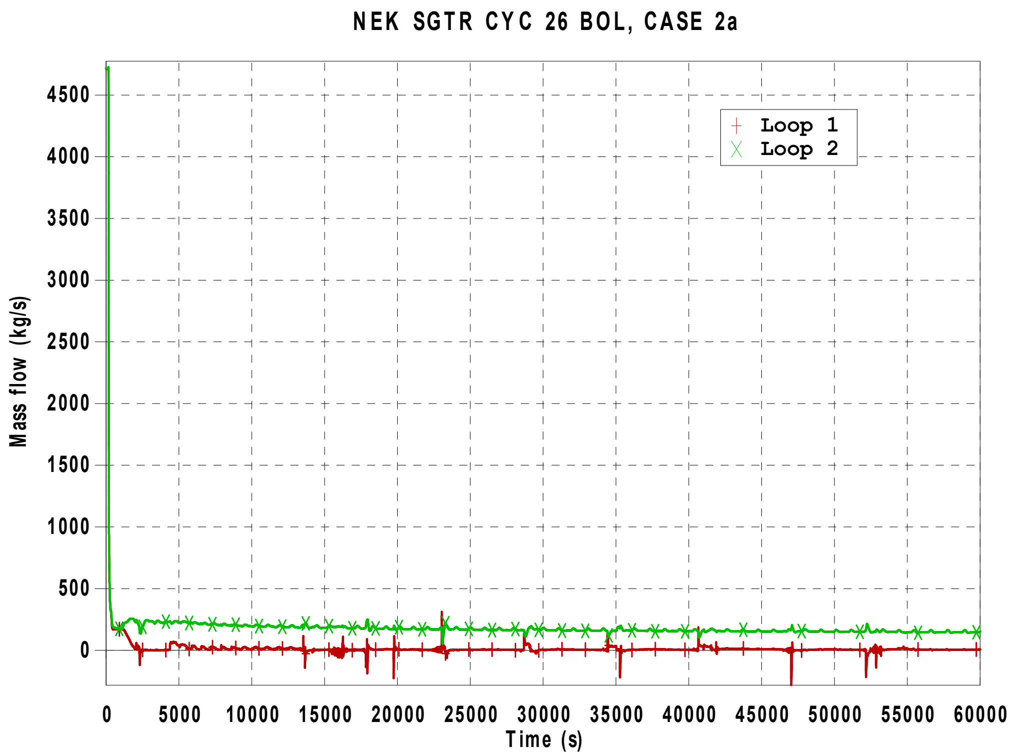

Figure 27 CASE 2a analysis: RCS mass flow rate

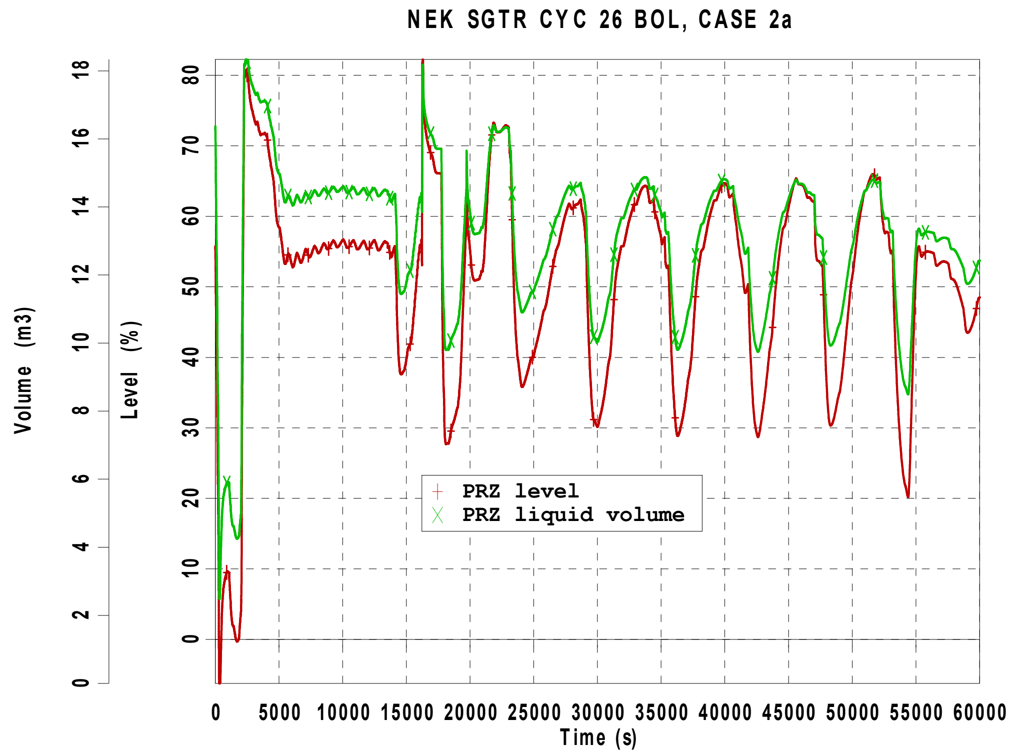

Figure 28 CASE 2a analysis: Pressurizer NR level and liquid volume

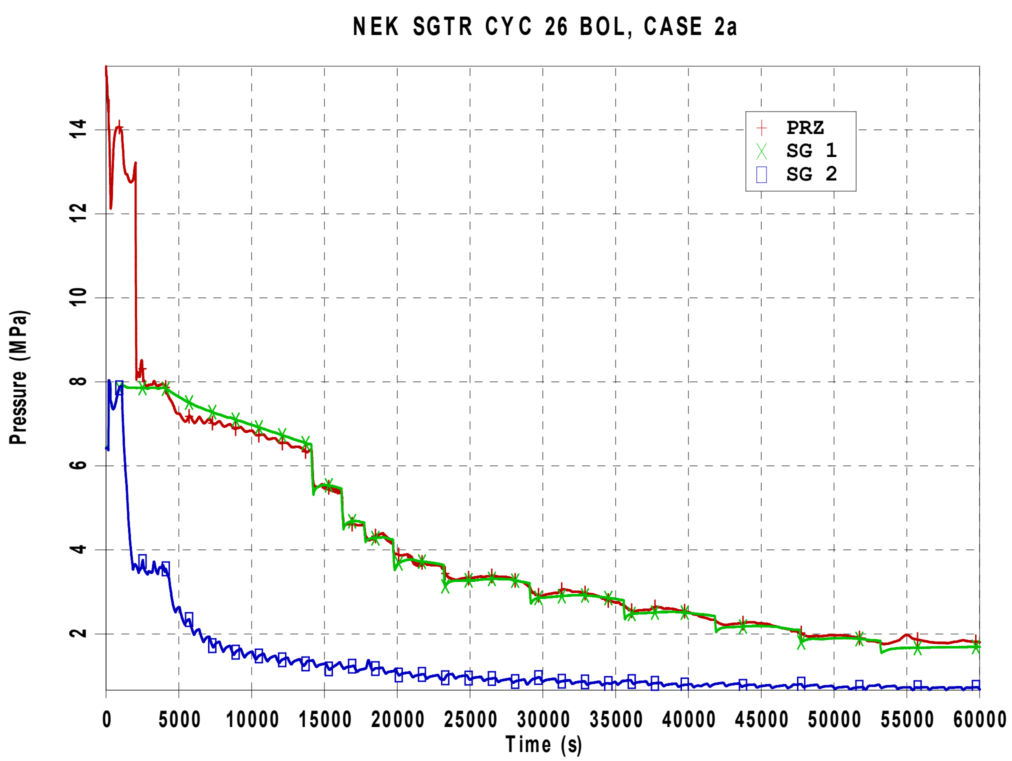

Figure 29 CASE 2a analysis: Pressurizer and SG pressure

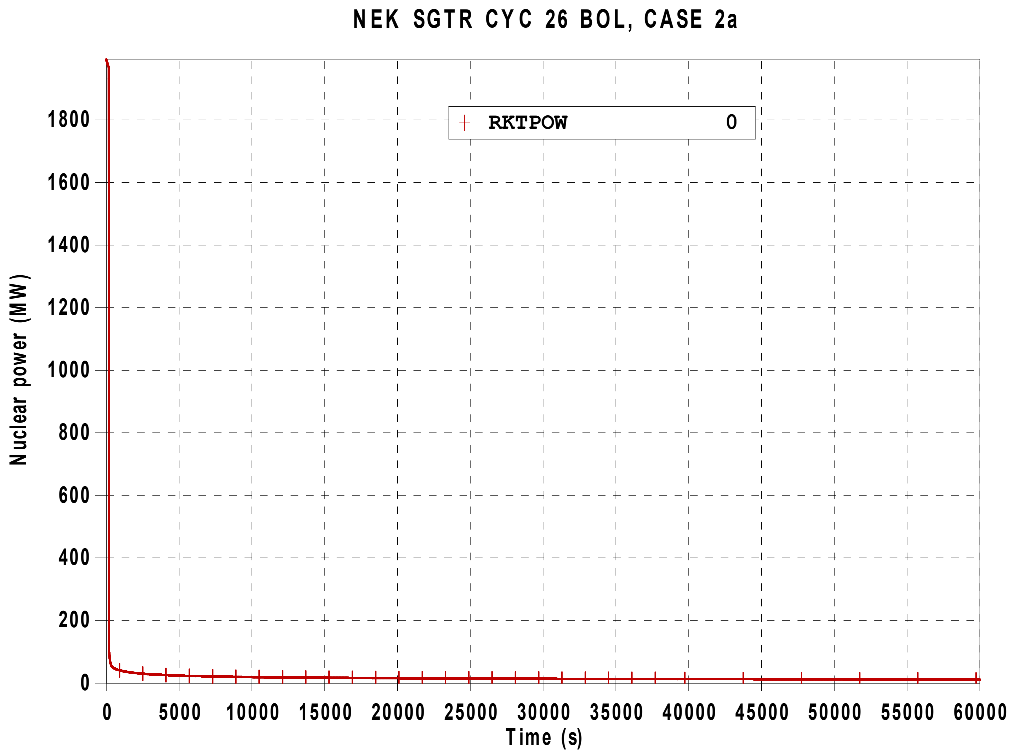

Figure 30 CASE 2a analysis: Nuclear power

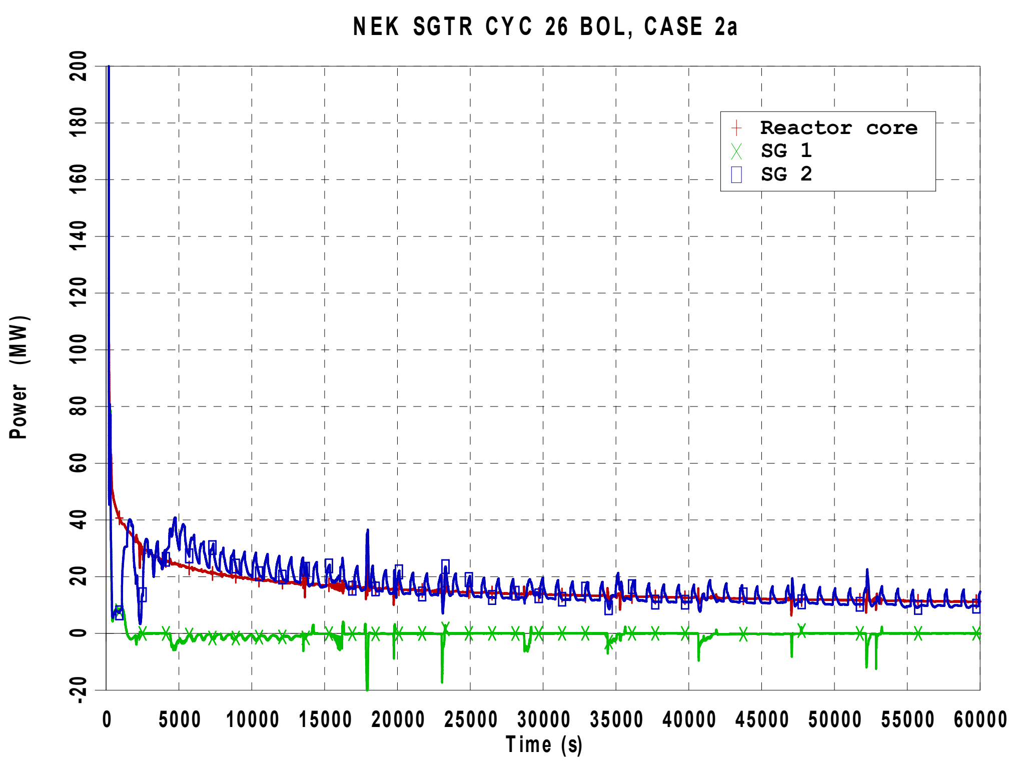

Figure 31 CASE 2a analysis: Reactor core and SG power

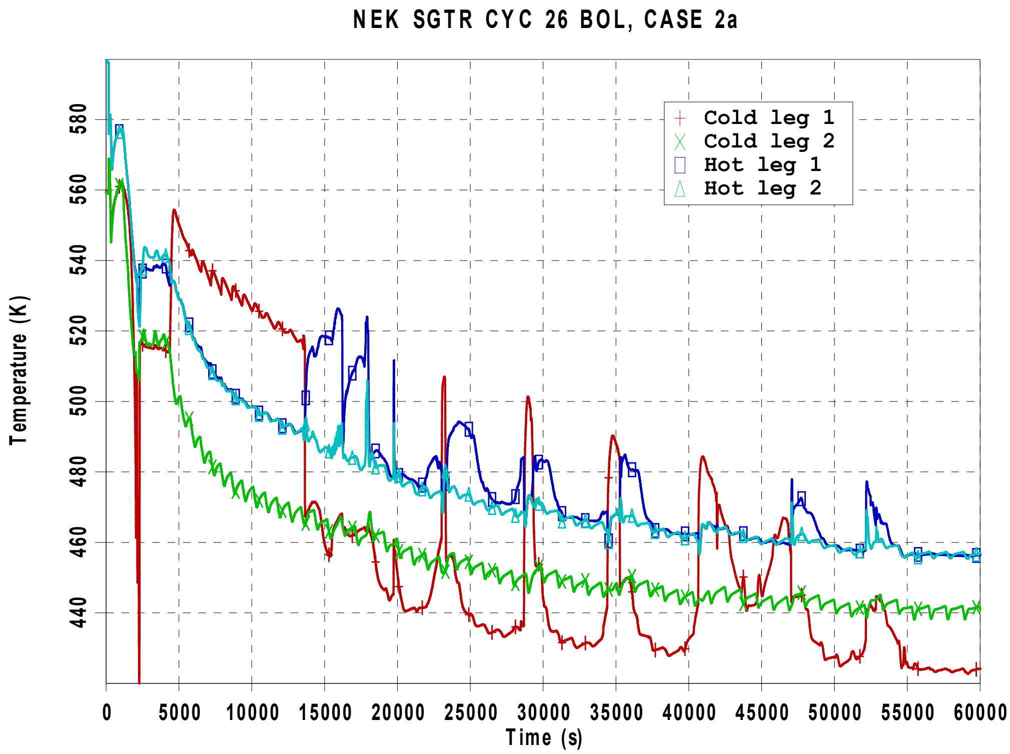

Figure 32 CASE 2a analysis: RCS temperature

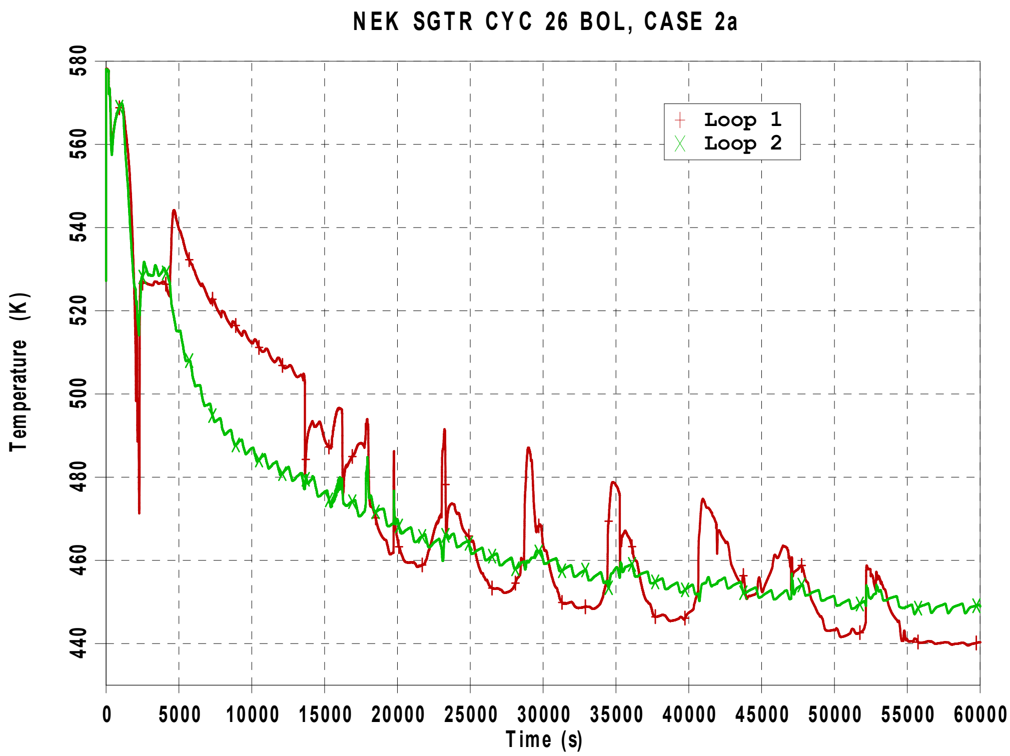

Figure 33 CASE 2a analysis: RCS average temperature

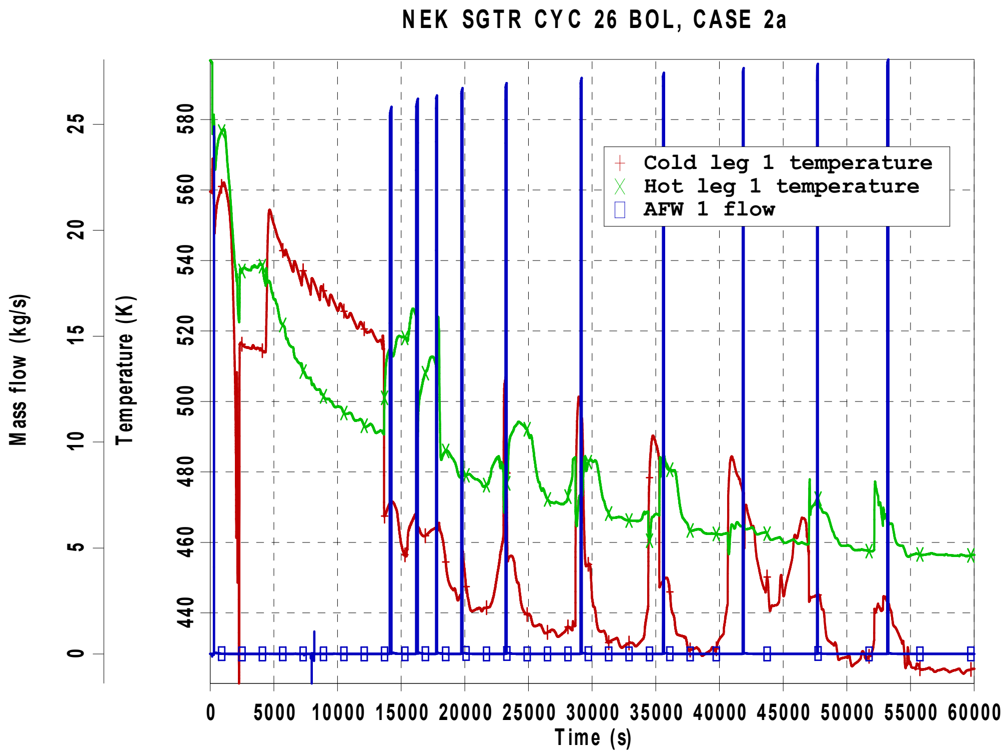

Figure 34 CASE 2a analysis: Loop 1 temperature and SG 1 auxiliary feedwater flow

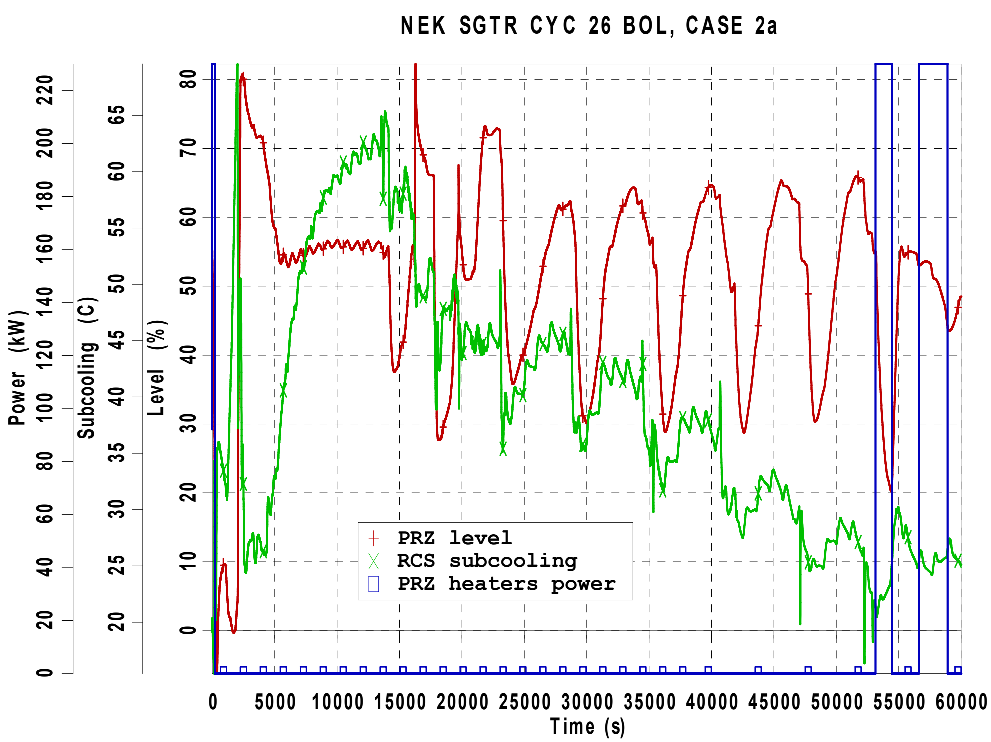

Figure 35 CASE 2a analysis: RCS subcooling, pressurizer level and pressurizer heaters power

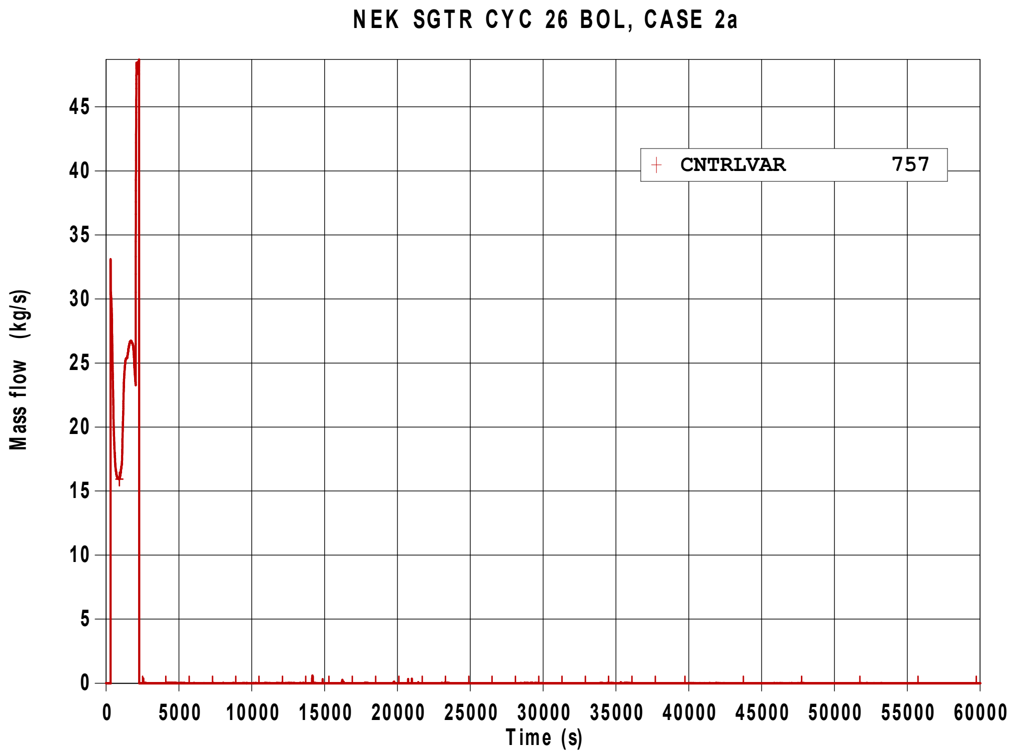

Figure 36 CASE 2a analysis: Safety injection flow

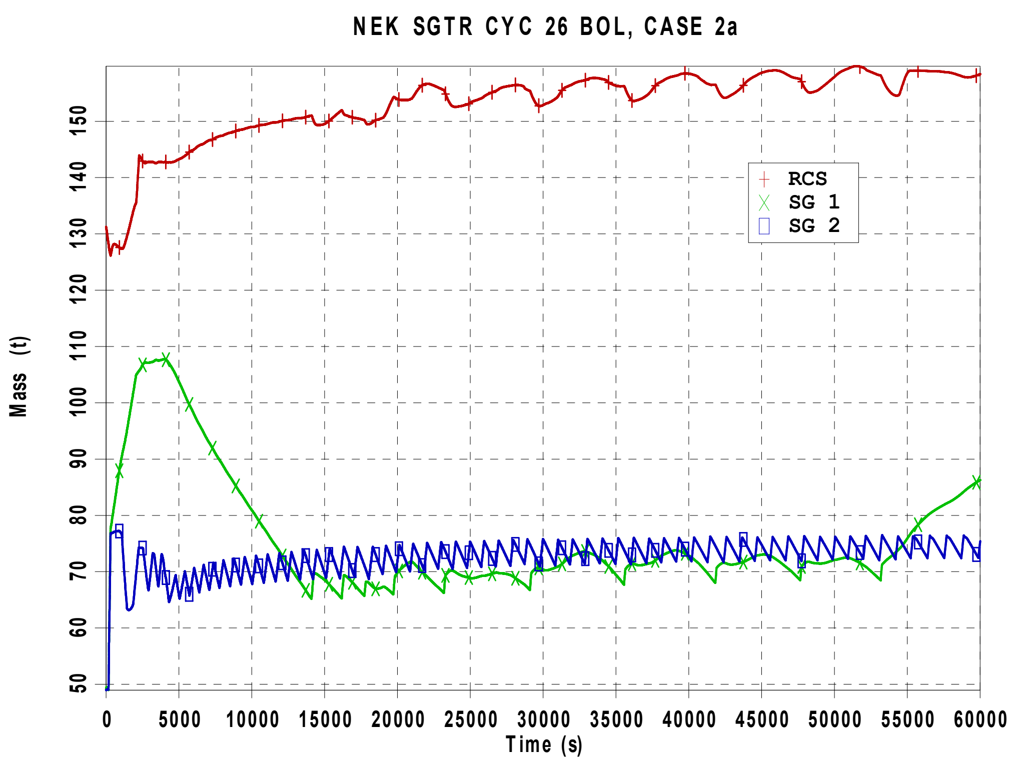

Figure 37 CASE 2a analysis: RCS and SG mass

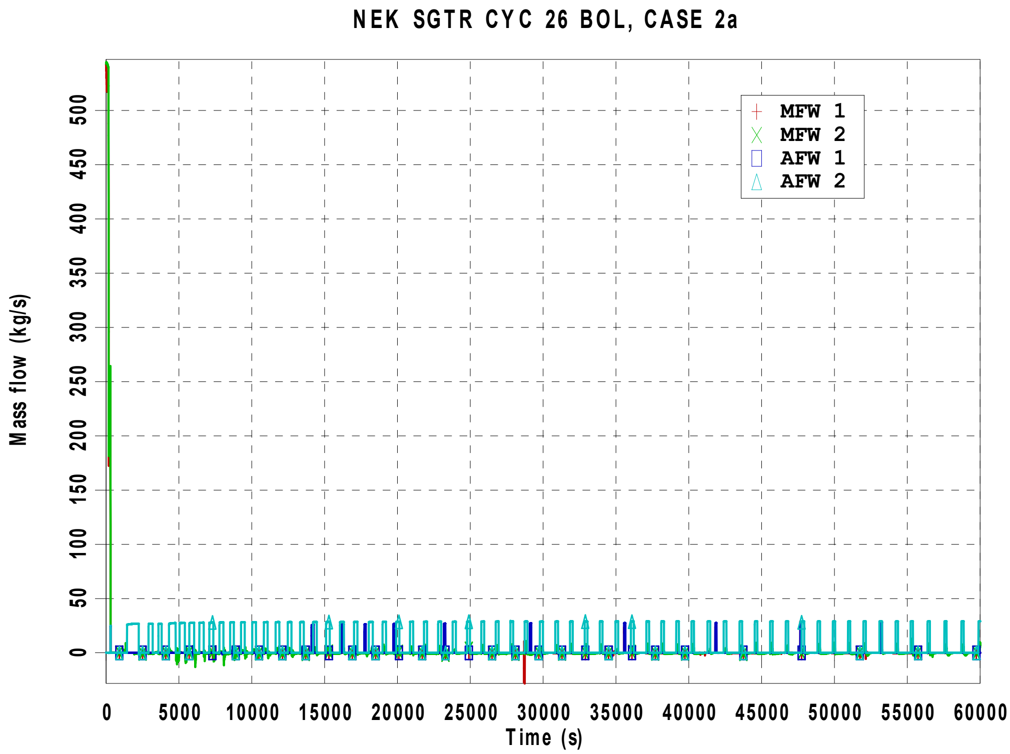

Figure 38 CASE 2a analysis: Main and auxiliary FW mass flow rate

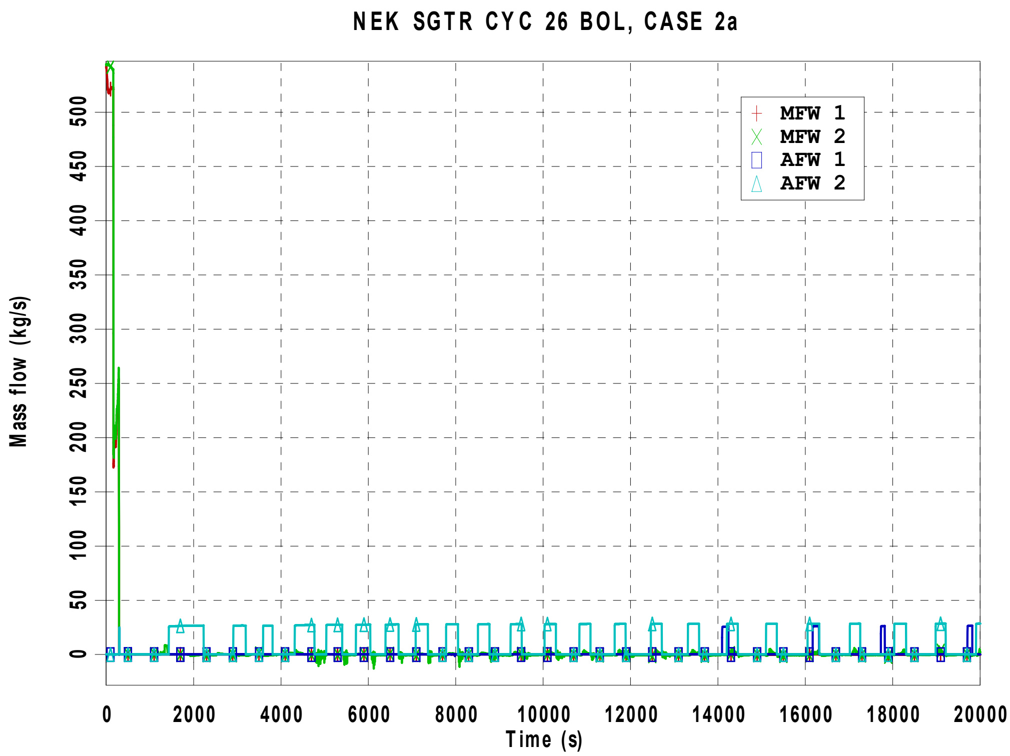

Figure 39 CASE 2a analysis: Main and auxiliary FW mass flow rate, time (0-20000 s)

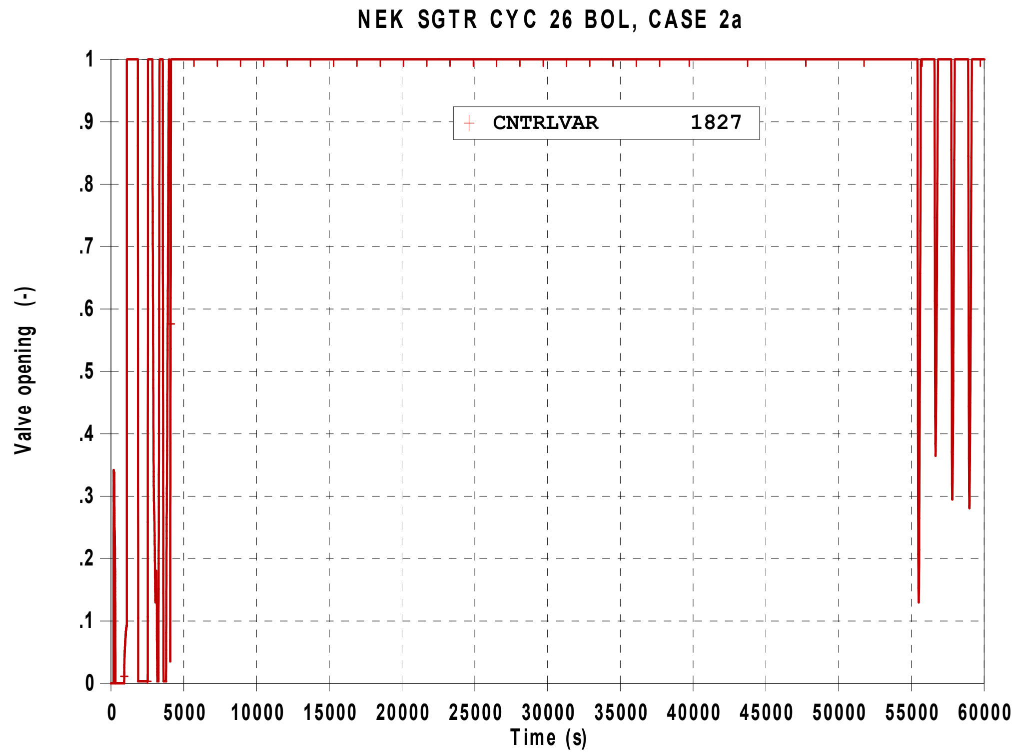

Figure 40 CASE 2a analysis: SG 2 PORV opening

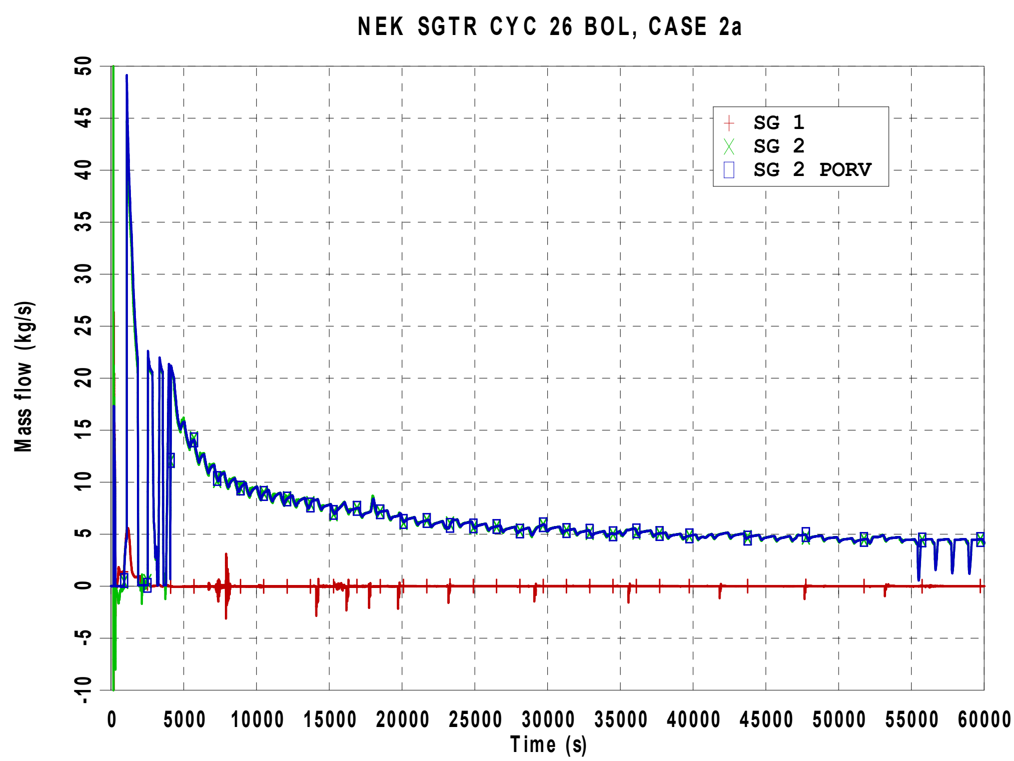

Figure 41 CASE 2a analysis: Main steam and SG 2 PORV mass flow rate

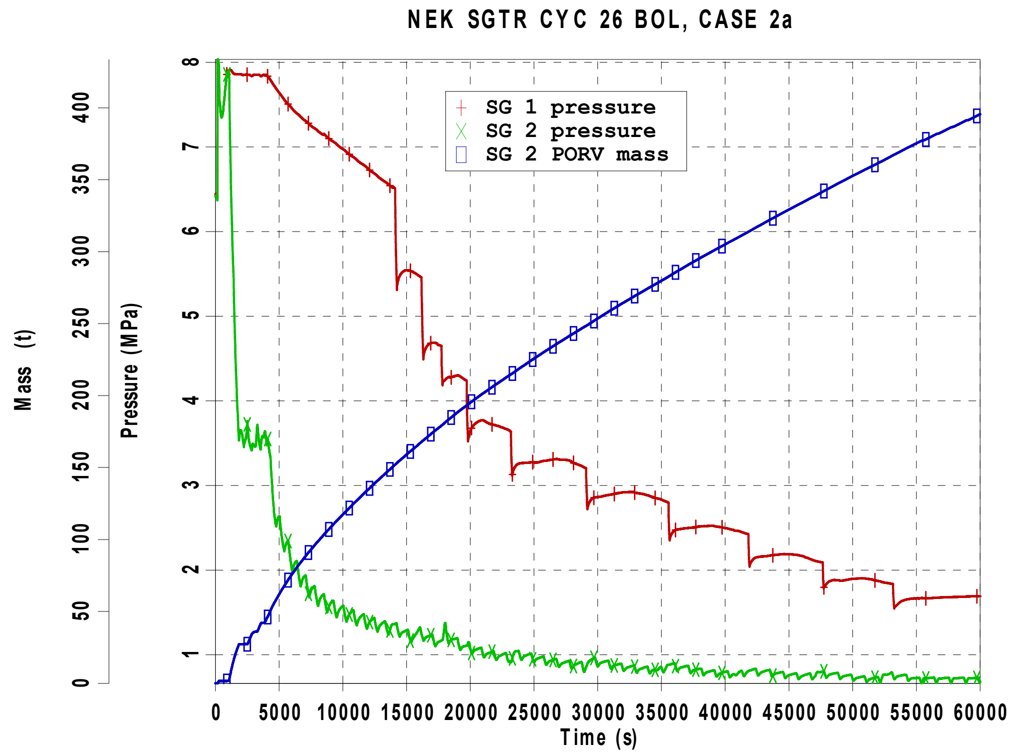

Figure 42 CASE 2a analysis: SG pressure, integrated flow through SG PORV

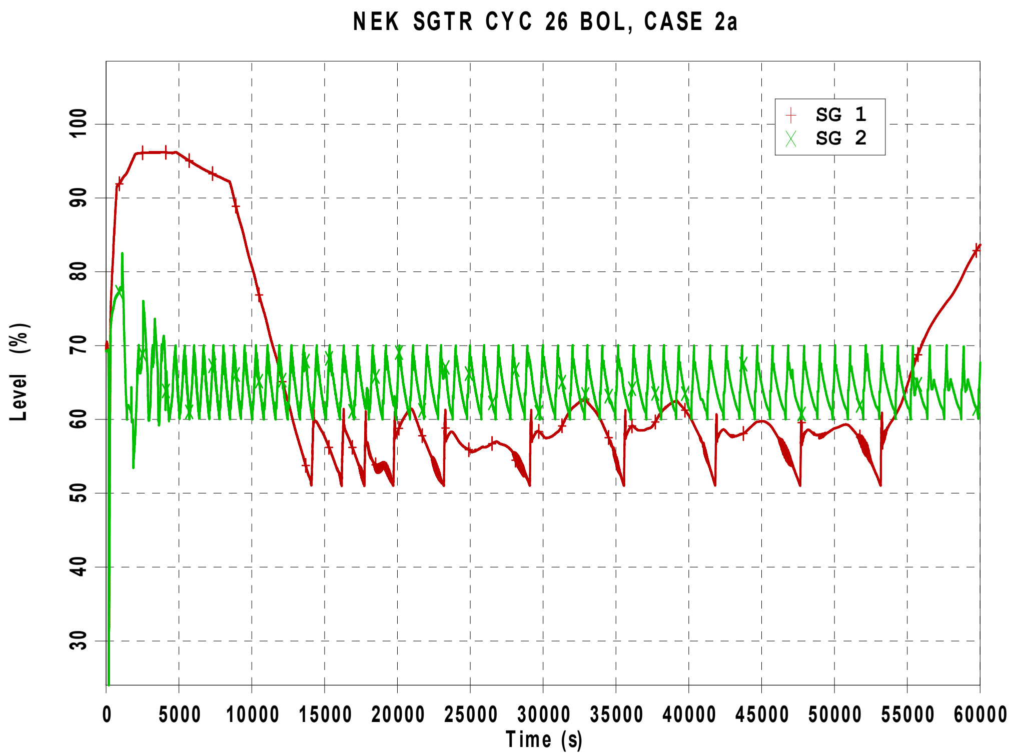

Figure 43 CASE 2a analysis: SG NR level

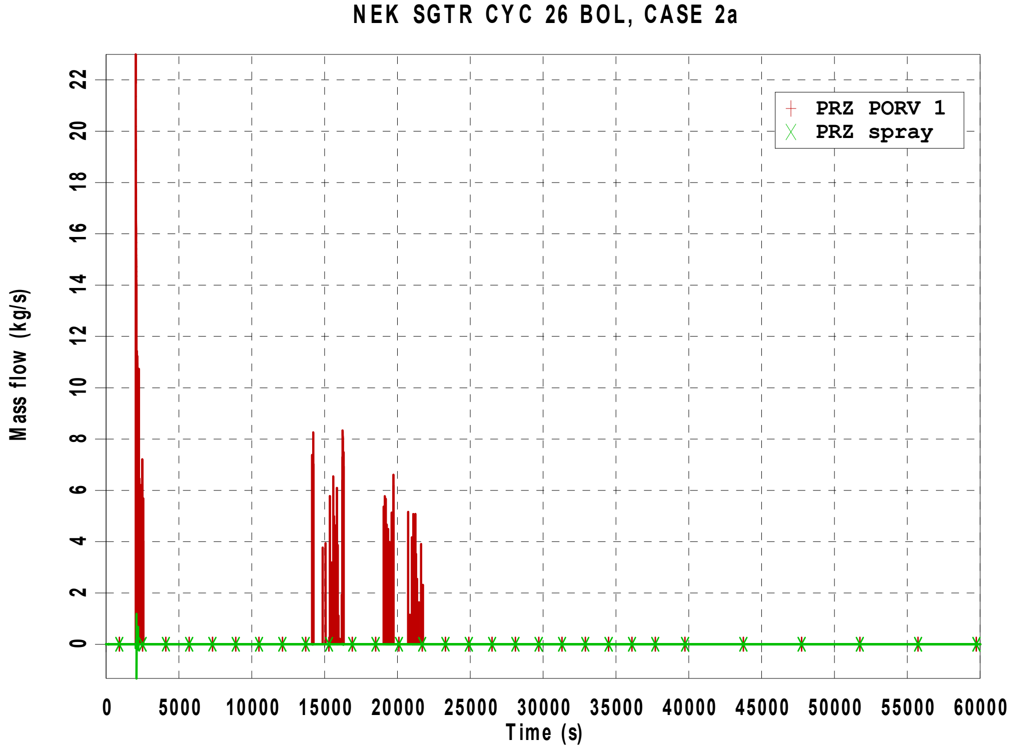

Figure 44 CASE 2a analysis: Pressurizer PORV 1 and spray mass flow rate

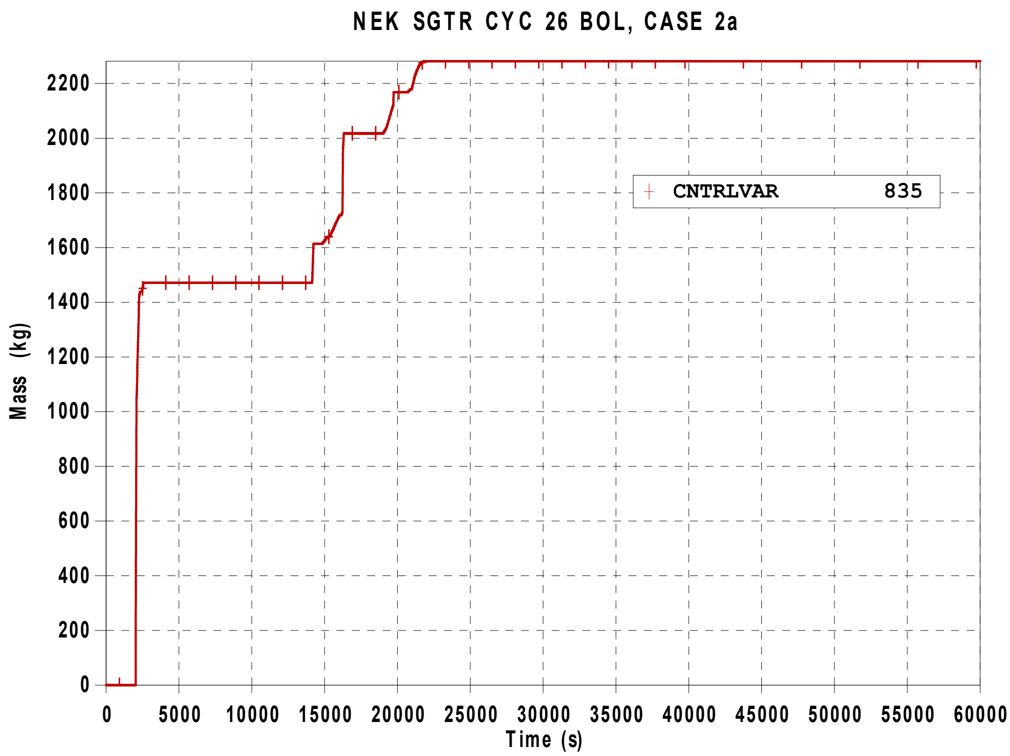

Figure 45 CASE 2a analysis: Integral of pressurizer PORV 1 mass flow rate

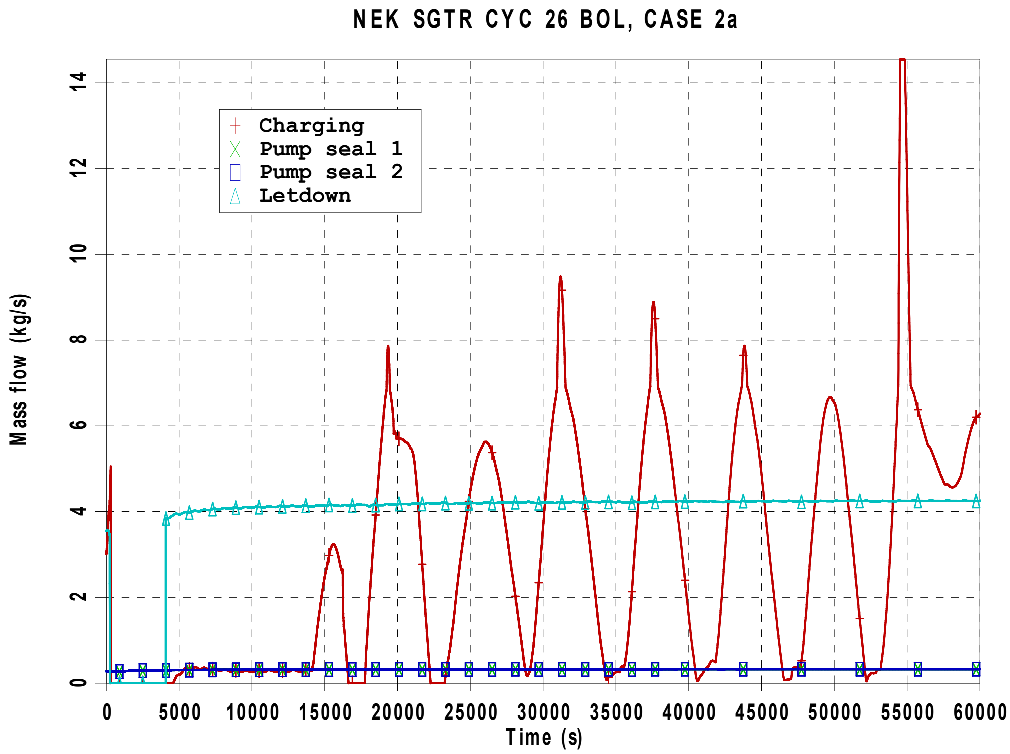

Figure 46 CASE 2a analysis: CVCS mass flow rate

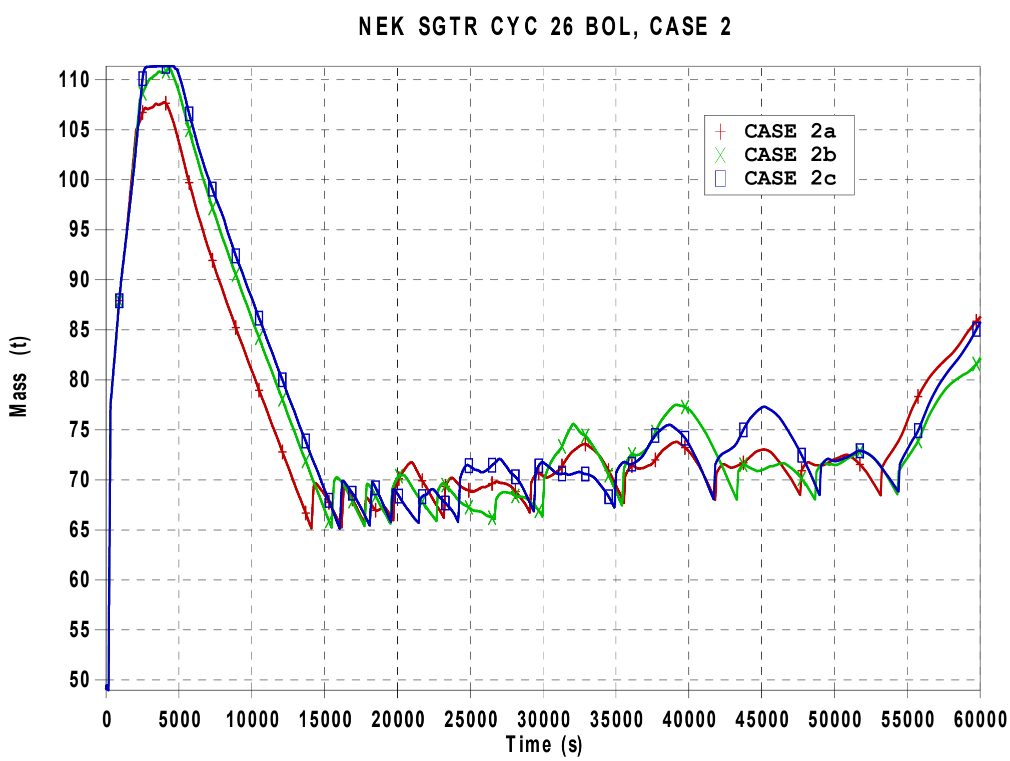

Figure 47 CASE 2 analysis: Mass of broken SG (SG 1)

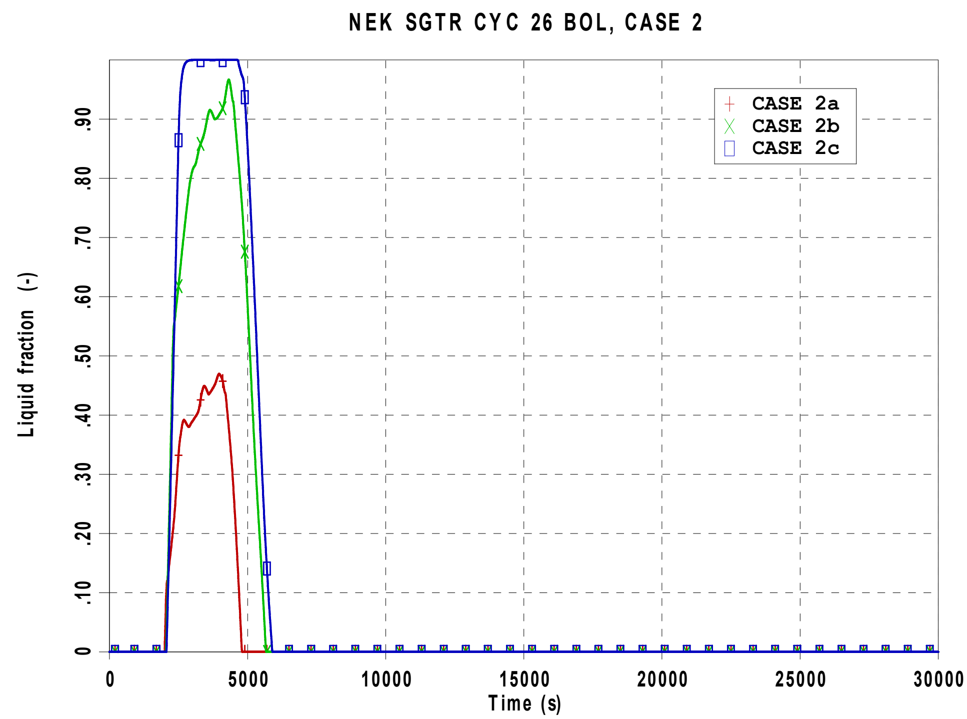

Figure 48 CASE 2 analysis: Broken SG (SG 1) steam dome volume liquid fraction

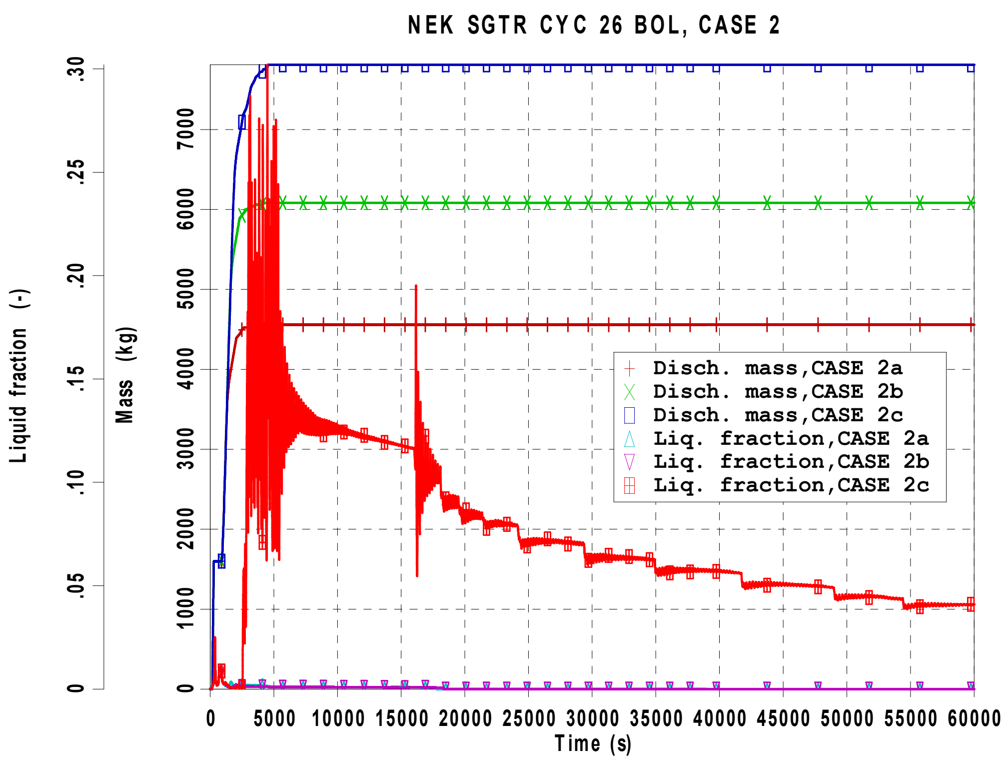

Figure 49 CASE 2 analysis: Discharged mass through broken SG (SG 1) PORV, broken SG PORV liquid fraction

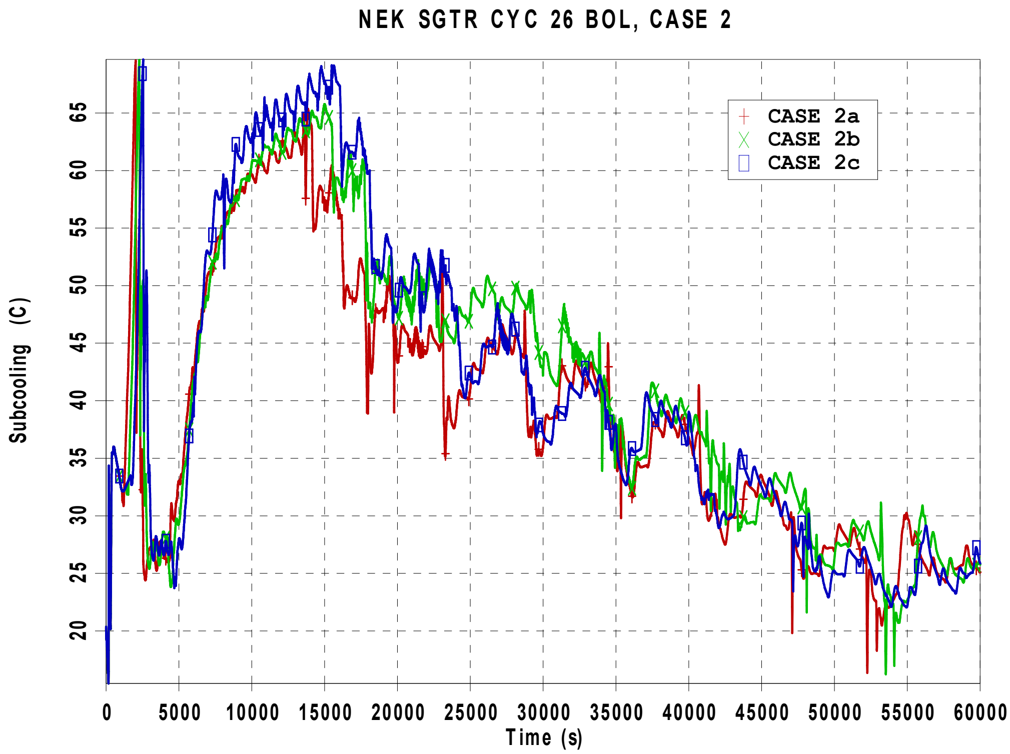

Figure 50 CASE 2 analysis: RCS subcooling

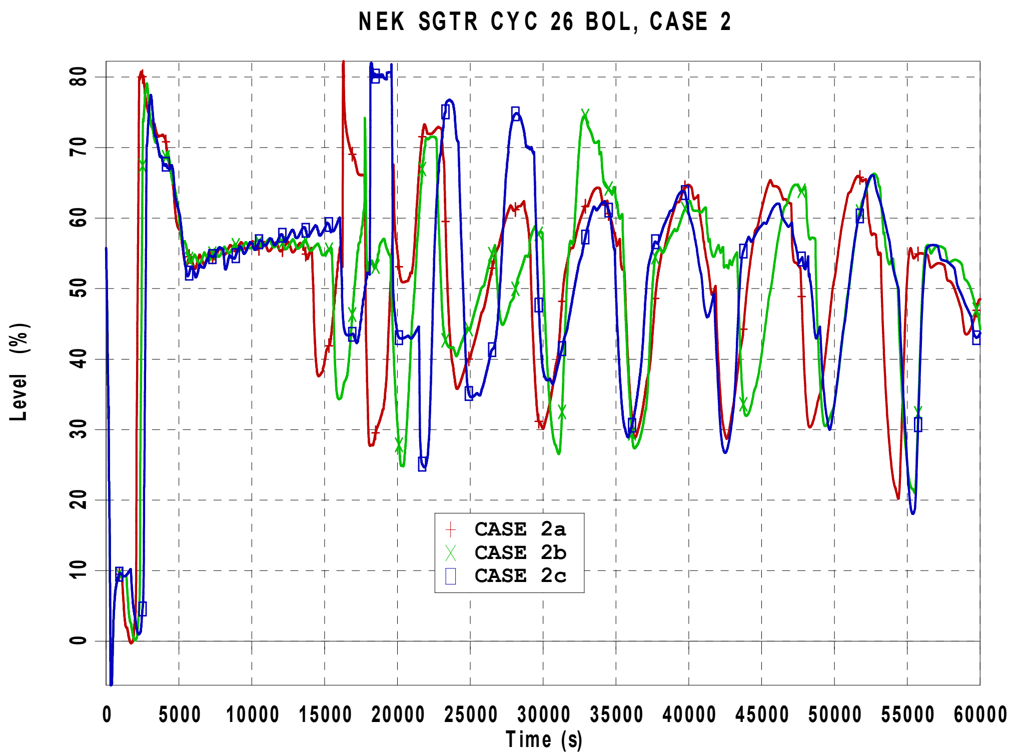

Figure 51 CASE 2 analysis: Pressurizer level

4.3 Discussion of differences between CASE 1 and CASE 2 analysis

Here, the major differences between the CASE 1 and CASE 2 will be discussed. The comparison between the two cases is presented in Table 5 and Figure 52 to Figure 59. In general, an earlier operator action is required for the CASE 2 than for the CASE 1 to both stop the steam discharge and to prevent the broken SG liquid solid condition. However, the analyses have shown that for the CASE 1 the larger amount of inventory was discharged through the broken SG than for the CASE 2 (e.g., 4972 kg and 4558 kg for 15 minutes and 7307 kg and 6084 kg for 20 minutes, respectively). On the other side, after the first operator action discharge was stopped earlier for the CASE 1 than for the CASE 2. In general, a more efficient heat transfer from primary to secondary side in the CASE 1 due to forced RCS flow causes higher secondary pressure in the broken SG than for the CASE 2, Figure 53, Figure 57 and Figure 59. Therefore, for the same delay for the first operator action the higher amount of discharged inventory was obtained for the CASE 1 than for the CASE 2. The difference for the transferred heat between the two cases has been increased at a time of the start of the cooldown. The steam dump valves (CASE 1) have significantly higher capacity than one SG 2 PORV valve (CASE 2), Figure 52. Immediately after start of the 1st cooldown the heat removed by the intact SG in the CASE 1 increases rapidly, Figure 52 and Figure 53. The RCS temperature decreases, Figure 54 and Figure 55 and the pressurizer outsurge flow increases due to coolant shrinkage, Figure 56. Consequently, the primary pressure decreases thus resulting in the reduction of the break flow as well, Figure 57. On the contrary, for the CASE 2 the transferred heat in the intact SG is much lower than in the CASE 1. The primary pressure decreased only slightly following the first cooldown. The break flow remains relatively high and the broken SG fills with liquid. First after the RCS depressurization (at 2025 s for the CASE 2a and at 2280 s for the CASE 2b) the primary pressure and the break flow are reduced. The high break flow together with the less amount of the discharged steam in the CASE 2 than in the CASE 1 lead to the faster accumulation of the liquid in the former case. The same trend is illustrated in Figure 59 where the CASE 1c (45 minutes for the operator action) and the CASE 2c (25 minutes) are compared. In the CASE 1c the broken SG has not become liquid solid but the amount of the discharged inventory is significantly larger (13952 kg vs. 7811 kg) than for the CASE 2 (broken SG liquid solid). The more efficient heat transfer from primary to the secondary side has also resulted in an earlier end of the discharge after first operator action in the CASE 1 (4 minutes and half an hour for the CASE 1 vs. 50 and 51 minutes for the CASE 2, Table 5 and Figure 58). Due to very intensive heat removal and RCS cooldown in the CASE 1 the broken SG pressure decreases below the SG PORV setpoint and the discharge is thus quickly stopped. Contrary to the CASE 1 in the CASE 2 the broken SG remains unaffected by the RCS cooldown primarily due to stagnant RCS flow conditions. The broken SG pressure decreases slowly and the discharge lasts longer than in the CASE 1.

Table 5 NEK SGTR analysis; comparison of CASE 1 and CASE 2 analysis

Event	CASE 1a (15 min)	CASE 2a (15 min)	CASE 1b (20 min)	CASE 2b (20 min)
1st cooldown	1080 s	1080 s	1380 s	1380 s
1st RCS depressurization	1394 s	2025 s	1691 s	2280 s
End of primary-to-secondary leakage	2950 s	4000 s	3334 s	4320 s
SG 1 steam dome liquid fraction > 10%	-	2027 s	-	2100 s
Max. SG 1 steam dome liquid fraction	0.02%	47.0%	0.02%	96.8%
Liquid discharge - SG 1 PORV (voidfj > 0.1)	-	-	-	-
End of discharge	1140 s	3945 s	2960 s	4290 s
Total discharged mass through SG 1 PORV	4972 kg	4558 kg	7307 kg	6084 kg

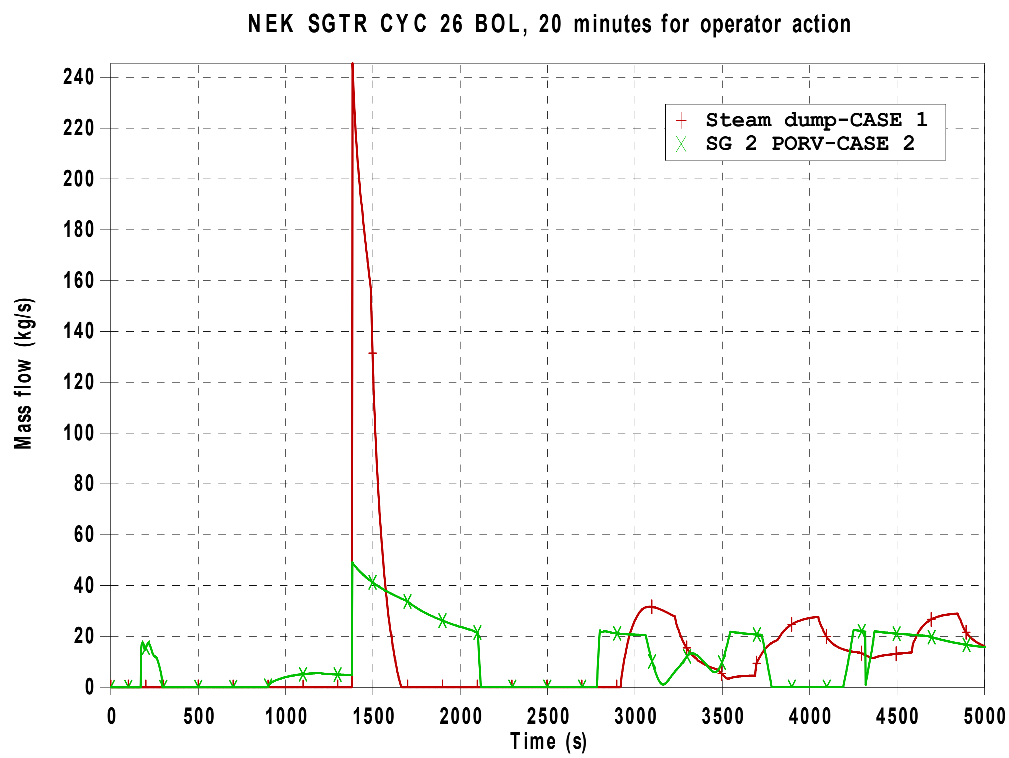

Figure 52 CASE 1 vs. CASE 2: 20 min for operator action: Steam dump (CASE 1) and SG 2 PORV mass flow rate (CASE 2)

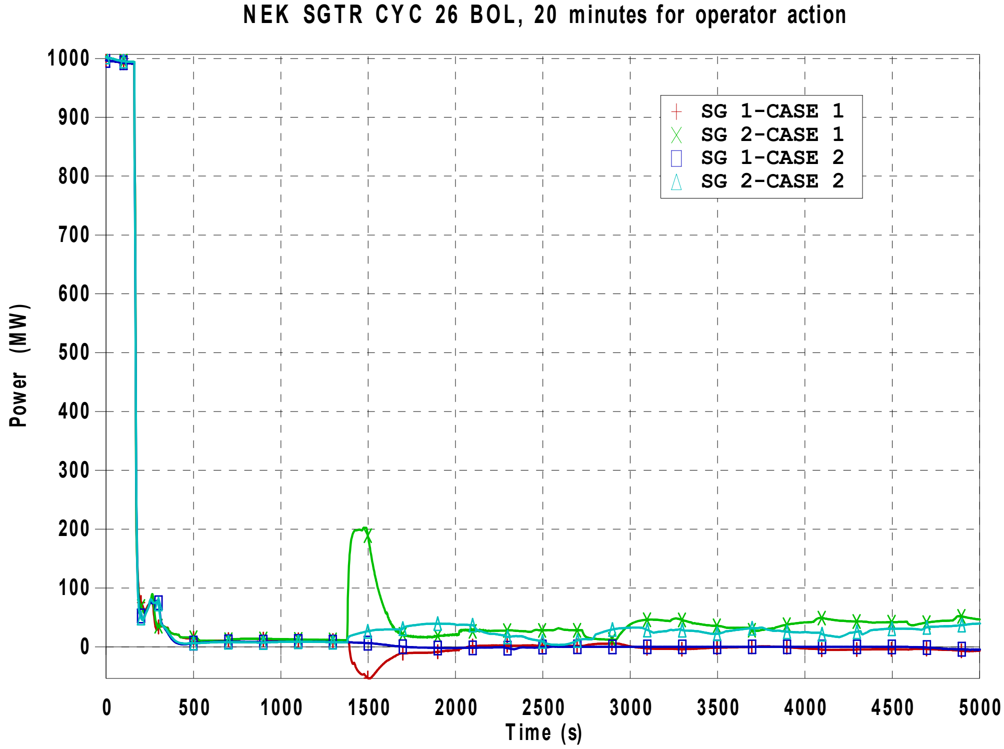

Figure 53 CASE 1 vs. CASE 2: 20 min for operator action: SG power

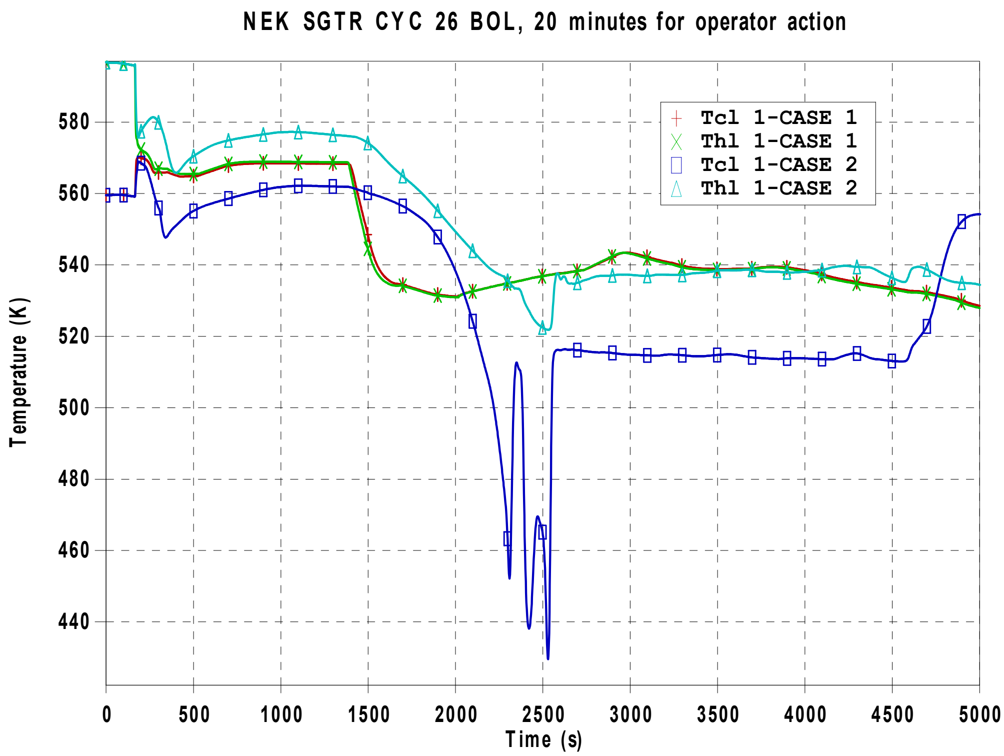

Figure 54 CASE 1 vs. CASE 2: 20 min for operator action: Loop 1 temperature

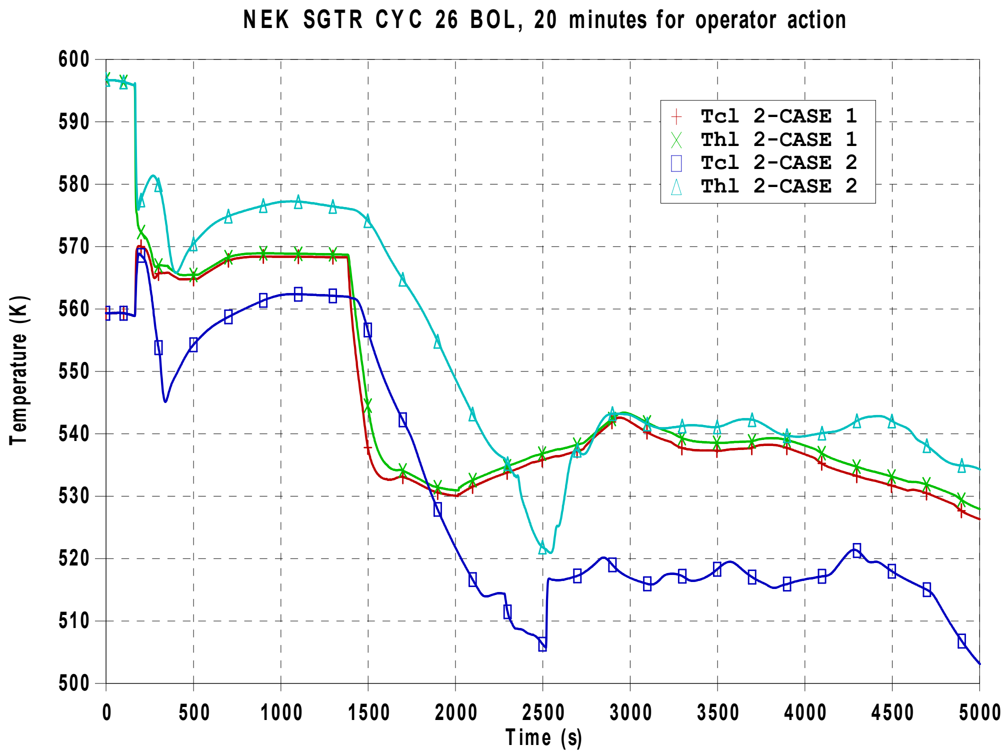

Figure 55 CASE 1 vs. CASE 2: 20 min for operator action: Loop 2 temperature

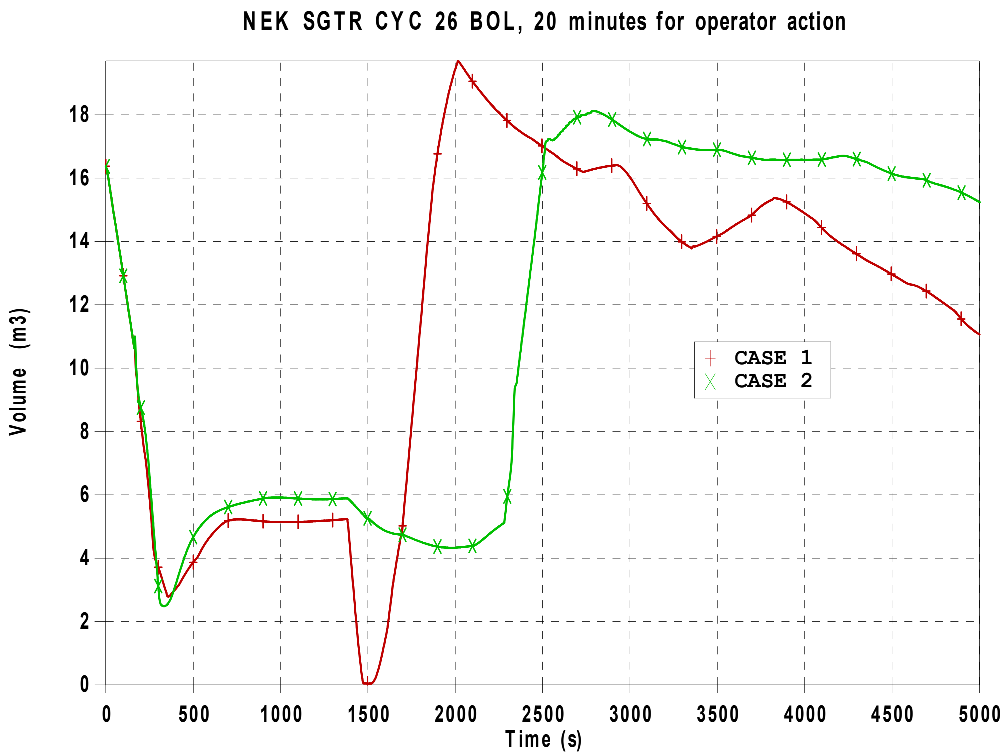

Figure 56 CASE 1 vs. CASE 2: 20 min for operator action: Pressurizer liquid volume

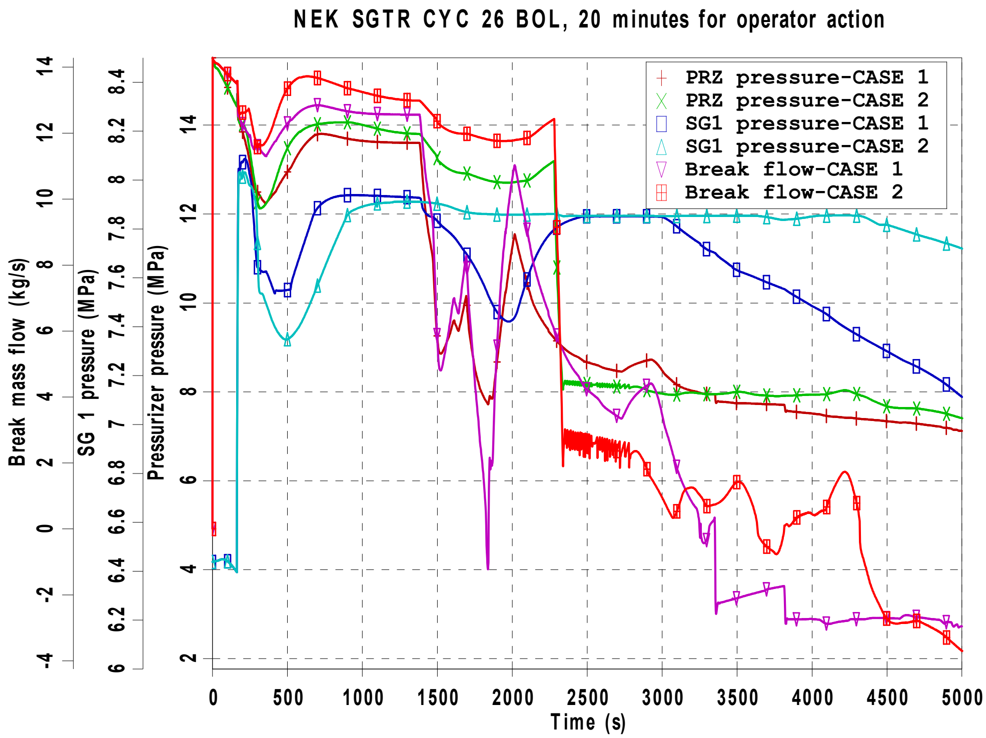

Figure 57 CASE 1 vs. CASE 2: 20 min for operator action: Pressurizer pressure, SG 1 pressure and break (side 1) mass flow rate

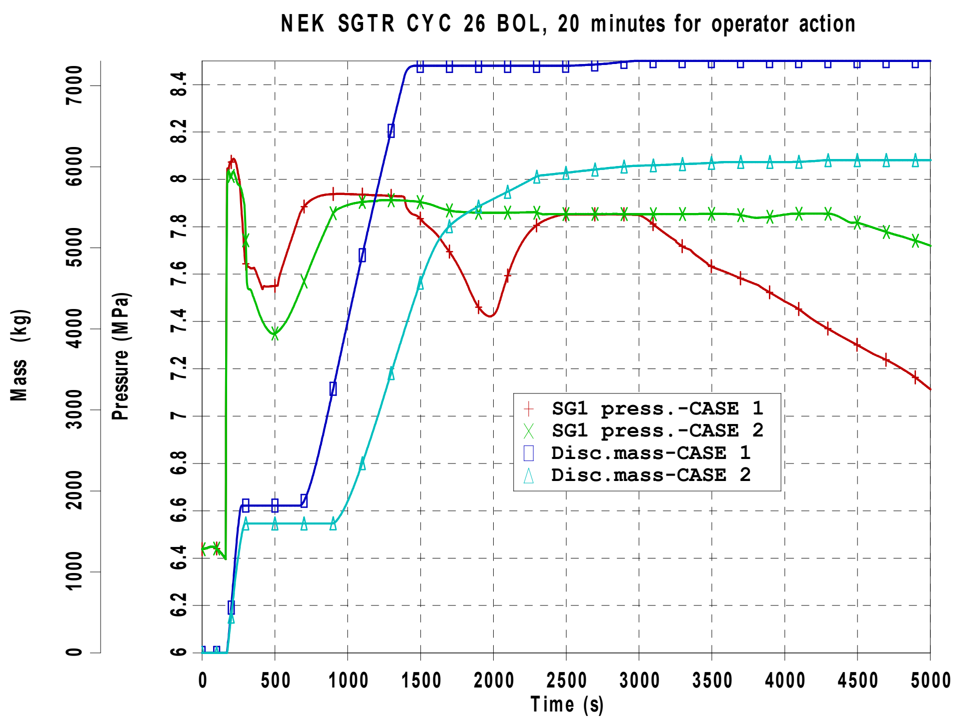

Figure 58 CASE 1 vs. CASE 2: 20 min for operator action: SG 1 pressure and discharged mass through SG 1 PORV

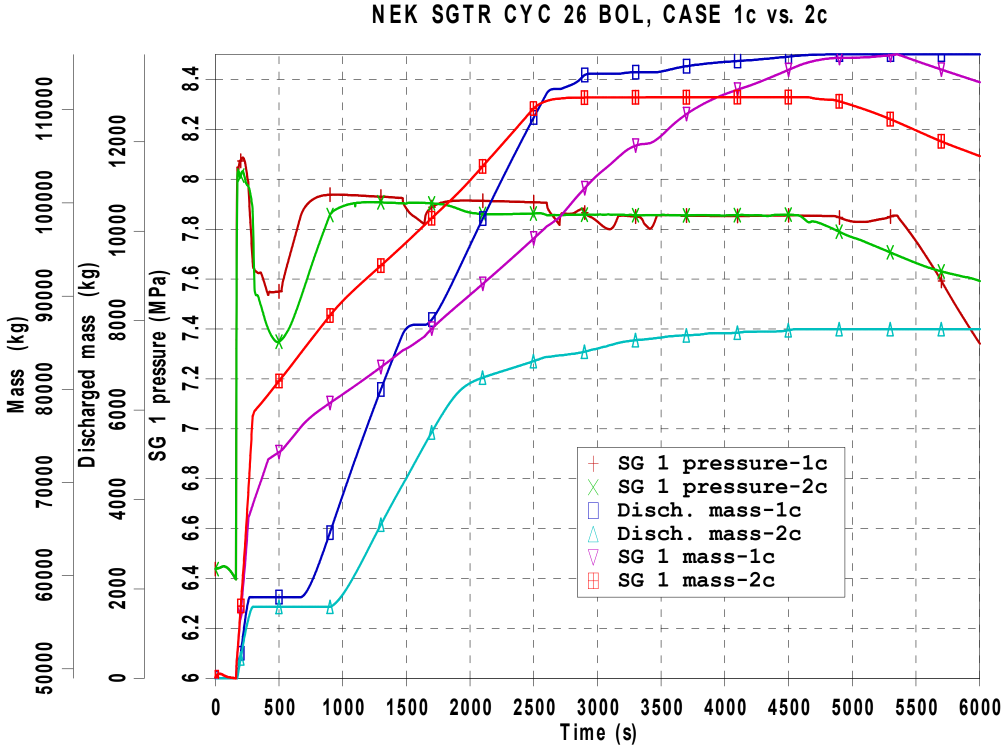

Figure 59 CASE 1c (45 min for operator action) vs. CASE 2c (25 min for operator action): SG 1 pressure, discharged mass through SG 1 PORV and SG 1 mass

5. CONCLUSIONS

The results of SGTR analysis for NPP Krško are presented. The guidelines from the NPP Krško EOP procedures for recovery following the SGTR event were applied for the modelling of operator actions. The analyses were primarily performed to demonstrate the capability of the plant systems as well as adequacy of operator actions to prevent the discharge of the contaminated inventory to the environment. Also the plant conditions during cooldown & depressurization to hot shutdown conditions were monitored to ensure the safe operation, i.e., the adequate RCS subcooling margin, pressurizer level and intact SG inventory for heat removal. The performed analyses did not include the radiological consequences calculation, but based on the limited amount of the mass of the discharged fluid, they should be small. Following conclusions can be drawn from the presented analyzed cases:

1. The analyses have been performed for different times for the operator action aimed to stop the primary-to-secondary leakage and the subsequent discharge of the contaminated inventory to the environment. The operator actions are primarily aimed to isolate the broken SG and to terminate the safety injection that has the major influence on filling the ruptured SG with liquid. The SI can be terminated first after successfully finishing the first cooldown & depressurization initiated by the operator.

2. The analyses have shown that an earlier operator action is required in the case without offsite power (CASE 2) than in the case with offsite power available (CASE 1) to both stop the steam discharge and to prevent the broken SG liquid solid condition. On the other side, for the same delay for the first operator action the total amount of the discharged inventory is larger in the CASE 1 than in the CASE 2. The differences in the heat transferred in both the broken and intact SG are responsible for the different transient outcome for the two cases. Due to better heat transfer in the broken SG, the higher broken SG pressure and the higher amount of the discharged inventory were obtained for the CASE 1 than for the CASE 2. On the other side, the more efficient cooldown in the CASE 1 when compared with the CASE 2 has two important consequences, i.e., an earlier stop of the break flow and an earlier stop of the discharge through the broken SG PORV.

3. Discharge through the broken SG PORV can be stopped immediately if the first operator action is initiated not later than 15 minutes after transient begin for the CASE 1 and the small amount of steam is discharged for 20 minutes. In order to prevent liquid discharge the first operator action must be initiated not later than 45 minutes for the CASE 1 and not later than 20 minutes for the CASE 2, respectively. In all the analyzed cases (also with liquid discharge) the operator can successfully stop the primary-to-secondary leakage and the discharge through the broken SG PORV.
The complete RCS cooldown & depressurization to hot shutdown conditions has been performed for all the analyzed scenarios. The procedure lasted about 1 hour and 40 minutes for the CASE 1 (steam dump available) with the cooldown rate equal to around 53.4°C/hour that is close to the maximum allowed (55.6 °C/hour). In the CASE 2 due to low capacity of one SG PORV, the cooldown lasted very long (14 hours) with the cooldown rate equal to around 5.7°C/hour.

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NRC FORM 335
(9-2004)
NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)
NUREG/IA-0442

2. TITLE AND SUBTITLE
RELAP5/MOD 3.3 analysis of steam generator tube rupture (SGTR) accident for NPP Krško

3. DATE REPORT PUBLISHED

MONTH	YEAR
March	2014

4. FIN OR GRANT NUMBER

5. AUTHOR(S)
V. Benčik, D. Grgić

6. TYPE OF REPORT
Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*
University of Zagreb, Faculty of Electrical Engineering and Computing Unska 3 10000 Zagreb, Croatia

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*
Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES
K. Tien, 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 authors have analyzed SGTR for NPP Krško (NEK) using RELAP5/MOD 3.3 code for two basic scenarios; i.e. with and without offsite power available. The plant model has been updated taking into account the Resistance Temperature Detector Bypass Elimination (RTDBE) project realized during the 2013 outage. The actions from the standard emergency operator procedures were modelled and the efficiency of operator actions to prevent radiological release to environment was evaluated. The time of the start of the operator action was selected as a critical parameter influencing occurrence of the release of the contaminated inventory (steam and liquid). In order to stop the steam release from the ruptured SG for the scenario with offsite power available the operator action has to be taken 15 minutes after transient begin, whereas the liquid solid condition and the liquid discharge can be prevented for operator action performed not later than 45 minutes after transient begin. For the scenario with offsite power not available the operator action has to be performed not later than 20 minutes to prevent the broken SG liquid solid condition and the liquid discharge. For both cases the operator action successfully stops the primary to secondary leakage and the inventory release to the environment.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*
RELAP
Steam Generator Tube Rupture(SGTR)
NPP Krsko
Loss of Offsite Power
Code Application & Maintenance Program (CAMP)
Emergency Operator Procedure (EOP)

13. AVAILABILITY STATEMENT
unlimited

14. SECURITY CLASSIFICATION
(This Page)
unclassified
(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

NUREG/IA-0442

RELAP5/MOD 3.3 Analysis of Steam Generator Tube Rupture (SGTR) Accident for NPP Krško

March 2014