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International Agreement Report

IJS Animation Model for Krško NPP

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ABSTRACT

This report presents the developed animation model for Krško nuclear power plant (NPP). For animations the Symbolic Nuclear Analysis Package (SNAP) was used. Krško NPP, which is a two-loop pressurized water reactor, Westinghouse type, before modernization in 2000 obtained plant specific full scope simulator. In the present study reference design basis calculations for Krško full scope simulator validation were analyzed with the latest RELAP5/MOD3.3 Patch 03 code to get the source data needed for development of animation model. In total six scenarios were analyzed: two scenarios of the Small Break Loss-of-Coolant Accident (LOCA), two scenarios of the Loss of Main Feedwater (LOFW), scenario of the Anticipated Transient Without Scram (ATWS), and scenario of the Steam Generator Tube Rupture (SGTR). Animation masks were created for the primary and the secondary system, important plant systems, the plant signals and the control systems. The use of SNAP for animation of Krško nuclear power plant analyses showed several benefits, especially better understanding of the calculated physical phenomena and processes. It can also be concluded that the use of such support tools to system codes significantly contributes to better quality of safety analysis.

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The authors acknowledge the financial support from Krško NPP and Slovenian Nuclear Safety Administration within CAMP program (project no. POG-3473) and from the state budget by the Slovenian Research Agency (program no. P2-0026). The RELAP5/MOD3.3 Krško NPP base input model is courtesy of Krško NPP. Special thanks also to undergraduate student (and scholar of NPP Krško) Martin Blazinšek for his help in drawing animation masks with SNAP.

ABBREVIATIONS

AFW	Auxiliary Feedwater
AMSAC	ATWS Mitigation System Actuation Circuitry
ATWS	Anticipated Transient Without Scram
CST	Condensate Storage Tank
CVCS	Chemical and Volume Control System
DEH	Digital Electro Hydraulic
ECCS	Emergency Core Cooling System
HPSI	High Pressure Safety Injection
IJS	Institut "Jožef Stefan"
LOFW	Loss of Feedwater
LPSI	Low Pressure Safety Injection
MD	Motor Driven
MFW	Main Feedwater
MPa	megapascal
MSIV	Main Steam Isolation Valve
NPA	Nuclear Plant Analyzer
NPP	Nuclear Power Plant
NR	Narrow Range
PORV	Power Operated Relief Valve
PRT	Pressurizer Relief Tank
PRZ	Pressurizer
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
s	second
SBLOCA	Small Break Loss-Of-Coolant Accident
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SI	Safety Injection
SNSA	Slovenian Nuclear Safety Administration
SV	Safety Valve
TD	Turbine Driven

1. INTRODUCTION

The Krško nuclear power plant (NPP), which is a two-loop pressurized water reactor, Westinghouse type, before modernization in 2000 obtained plant specific full scope simulator. With the RELAP5/MOD2 computer code reference calculations of some design basis accidents were performed for the verification of Krško Full Scope Simulator in 2000. In 2004 annual ANSI/ANS validation was performed using RELAP5/MOD3.3 computer code. In spring 2007 Slovenian Nuclear Safety Administration (SNSA) expressed interest to upgrade the Nuclear Plant Analyzer (NPA) of Krško nuclear power plant (NPP), developed for SNSA in 1997. The advantage of using NPA were developed masks, however the animation tool was rather obsolete. In addition, the RELAP5 input model including nodalization was changed after plant modernization in 2000 requiring modification of old masks. On the other hand, Symbolic Nuclear Analysis Package (SNAP) (Ref. 1) was modern tool still developing, but it use requires to start from scratch (no masks available). Therefore capabilities of SNAP version 0.27.3 were investigated first. SNAP besides animation offered also plotting through AptPlot. Due to these facts it was decided to make support to the analytical tools based on SNAP.

Motivation for developing the support tool based on SNAP was to prepare for the transition from RELAP5 to TRACE (RELAP5 to TRACE conversion, running codes, pre- and post-processing, generating input deck database etc.), better understanding of the calculated physical phenomena and processes, user friendly tool for understanding the nodalization and the detail of plant modeling, better presentation of the results, a tool to train new users of thermal-hydraulic code, and with modern tool to attract people to work with system codes. For verification of the animation models the source data were needed. SNAP tool is such that only calculated data support all animation features. Therefore it was decided to calculate the reference calculations (Refs. 3, 4, 5, 6) with the latest RELAP5/MOD3.3 Patch03 code (Ref. 2).

The RELAP5 input model of Krško NPP is very briefly described in Section 2. The scenarios for reference calculations of design basis accidents are described in Section 3. The developed animation masks are described in Section 4. Section 5 shows the results of RELAP5/MOD3.3 Patch 03 calculations, used as source data in SNAP. In addition, the RELAP5/MOD3.3 Patch 03 calculations are compared to RELAP5/MOD2 and RELAP5/MOD3.3 verified calculations. In Section 6 are given examples of the Krško NPP animation model use, while conclusions are given in Section 7.

2. INPUT MODEL DESCRIPTION

To perform these analyses, Krško NPP has provided the base RELAP5 input model, so called "Master input deck", which have been used for several analyses, including reference calculations for Krško full scope simulator verification (Refs. 7, 8, 9). The latest analyses were performed for uprated power conditions (2000 MWt) with new steam generators (SG) and core cycle 21 settings, corresponding to the plant state after outage and refueling in September 2004.

The model consists of 469 control volumes, 497 junctions and 378 heat structures with 2107 radial mesh points. Besides, 574 control variables and 405 logical conditions (trips) represent the instrumentation, regulation isolation, safety injection (SI) and auxiliary feedwater (AFW) triggering logic, steam line isolation, etc.

Modeling of the primary side without the reactor vessel and both loops includes the pressurizer vessel, pressurizer surge line, pressurizer spray lines and valves, two pressurizer power-operated relief valves (PORVs) and two pressurizer safety valves, chemical and volume control system (CVCS) charging and letdown flow, and RCP seal flow. The reactor vessel consists of the lower downcomer, lower head, lower plenum, core inlet, reactor core, core baffle bypass, core outlet, upper plenum, upper head, upper downcomer, and guide tubes. The primary loop is represented by the hot leg, primary side of the SG, intermediate leg with cold leg loop seal, and cold leg, separately for loop 1 and loop 2. Loops are symmetrical except for the pressurizer surge line and the chemical and volume control system connections layout. The primary side of the SG consists of the inlet and outlet plenum, tubesheet, and the U-tube bundle represented by a single pipe.

ECCS piping includes high-pressure safety injection (HPSI) pumps, accumulators, and low-pressure safety injection (LPSI) pumps. The hydrodynamic components representing HPSI and LPSI pumps are time-dependent junctions, while for accumulators the 'accum' hydrodynamic component was used. The ECCS connects to both cold legs and directly to the reactor vessel.

The secondary side consists of the SG secondary side (riser, separator and separator pool, downcomer, steam dome), main steamline, main steam isolation valves, SG relief and safety valves, MFW piping, and AFW piping from the header to the SG. The AFW injects above the SG riser. The main steam no. 1 has same volumes as main steam no. 2, but the geometry data differ depending on pipeline. Turbine valve is modeled by the corresponding logic, while turbine is represented by time dependent volume. MFW and AFW pumps are modeled as time dependent junctions, pumping water from time dependent volumes, representing the condensate storage tank. For AFW pumps, recirculation flow is modeled too.

The refueling water storage tank (RWST) is modeled as time dependent volume, similarly as the containment and the atmosphere. The break in the cold leg is modeled with two valves, giving possibility to model double ended guillotine break too.

In order to accurately represent the Krško NPP 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 the following main plant control systems: (a) rod control system, (b) PRZ pressure control system, (c) PRZ level control system, (d) SG level control system, and (e) steam dump. It must be noted that rod control system has been modeled for point kinetics. Present model can be used for transient analysis with two options: (a) with constant or predefined core power transient as function of time (including decay power calculation) or (b) with rod control system in auto or manual mode. The reactor protection system was based on trip logic and it generates various signals. It includes reactor trip signal, SI signal, turbine trip signal, steam line isolation signal, MFW isolation signal, and AFW start signal.

For the nodalization details of the above mentioned plant systems and components, plant signals and control systems schemes the reader can refer to Section 4.

3. SCENARIOS DESCRIPTION

In total six scenarios were analyzed: scenario of the Anticipated Transient Without Scram (ATWS), two scenarios of the Loss of Main Feedwater (LOFW), two scenarios of the Small Break Loss-of-Coolant Accident (SBLOCA), and scenario of the Steam Generator Tube Rupture (SGTR). Since the purpose of the analyses was to provide basis for Krško full scope simulator validation, NPP Krško has required a simplified, but phenomenologically clear scenarios to be simulated. In all cases the reactor power at transient start was at 100%.

3.1 <u>Anticipated Transient Without Scram Scenario</u>

In ATWS transient with ATWS Mitigation System Actuation Circuitry (AMSAC) available it is assumed that both trains of ECCS and both motor driven (MD) AFW pumps were available. The transient is initiated by a malfunction in main feedwater system, causing total loss of normal feedwater, which is followed by the steam generator liquid inventory boil-off. The reactor trip signal is renounced and control rods are not inserted into the core to shut down the reactor. The liquid level in both steam generators lowers rapidly below AMSAC trip setpoint causing turbine trip. Consequently, as the heat transfer to the secondary side is degraded and finally interrupted, the rise in reactor coolant system temperature and pressure follows. This causes the pressurizer to get fully filled with the liquid (solid pressurizer). Soon after that the pressurizer relief and safety valves open and the liquid-vapor mixture is discharged into the pressurizer relief tank (PRT). Eventually, the PRT rupture disk breaks due to PRT over-pressurization and the reactor coolant is released into the containment. The moderator density and Doppler temperature feedback effects suppress the reactor positive reactivity and reduce the core power in the absence of reactor scram. Primary pressure and temperature soon stabilize near or below the normal operating values. Meanwhile, on the secondary side, the AFW pumps start and both steam generators are gradually refilled with cold water. With reduced and stabilized core power the secondary system is able to transfer and release the energy through the steam dump or the SG PORVs, depending on whether steam line is isolated or not.

The most important parameter in this transient is the primary pressure, which should not exceed the ASME stress level C limit of 22.7 megapascals (MPa) (Ref. 10). For the purpose of pressure peak reduction AMSAC is incorporated into the safety logic (Refs. 11 and 8), in parallel to the reactor protection logic. The safety goal of the AMSAC system is to reduce the core power and maximize secondary inventory available for later plant cooldown. This is achieved by reduction of the steam extraction from the secondary side, which accelerates the primary temperature rise and the core inventory density reduction. The two above mentioned most important inherent feedback effects reduce the core power earlier what results in lower primary pressure peak.

3.2 <u>Loss of Feedwater Scenarios</u>

For LOFW two different scenarios were analyzed. The difference between the scenarios was, that in the first scenario both MD AFW pumps were available and operator was maintaining steam generator level at no-load conditions between 68 and 72 % narrow range (NR), while in the second scenario all AFW pumps were unavailable. It is assumed that both trains of ECCS are available, rod control system was in MANUAL mode (temperature feedback blocked) and operator action to trip the RCP is modeled. It is assumed that the loss of main feedwater flow is caused by malfunction in MWF system, therefore AFW system will not start on the MFW isolation signal, but will be delayed till one of the SG narrow range levels drops below low-low setpoint at 13 %. Main characteristic of LOFW transient is gradual emptying of steam generators, while heat transfer to secondary side is still possible. Heat transfer is soon degraded during partial uncovering of the U-tubes and finally interrupted with complete emptying of steam generators. The consequences of the loss of heat sink to the secondary side reflect in increasing average coolant temperature and pressure on the primary side. Due to increased primary pressure the pressurizer relief and safety valves open and part of the primary coolant is released into the PRT. If the AFW flow is established, there is no further threat to the core. The AFW inflow ensures sufficient secondary coolant resource to establish stable secondary heat sink either through steam dump, SG relief or SG safety valves. When no heat sink could be established on the secondary side and if no other operator intervention is assumed, the pressurizer relief and safety valves open and close between their set and reset pressures to remove the decay heat from the primary system. This is satisfactory only until the amount of the primary coolant lost is such that core uncovering occurs.

3.3 Small Break Loss-of-Coolant Accident Scenarios

For SBLOCA the 5.08 cm and 20.32 cm equivalent diameter break size scenarios were analyzed. For 5.08 cm cold leg break both trains of ECCS system were available and both MD AFW pumps. Each ECCS train consists of HPSI and LPSI pumps, and passive accumulators. For 20.32 cm cold leg break loss of off-site power was assumed and successful emergency diesel generator start. After the emergency diesel generator start one train of safety systems was available. No operator actions were specified in the scenarios except RCP trip per emergency operating procedures. In the case of 5.08 cm break rapid primary pressure drop after break opening causes the reactor trip on low pressurizer pressure signal at 12.99 MPa. The safety injection (SI) signal is generated on the low-low pressurizer pressure signal at 12.27 MPa. The SI signal actuates the ECCS and MD AFW pumps. On SI signal coinciding with high steam generator level signal also both MFW pumps are tripped. The RCPs are tripped manually on subcooling signal according to the emergency operating procedures allowing additional 60 seconds for operator actions. The accumulators start to inject at 4.93 MPa. In the case of 20.32 cm break simultaneous break opening and loss of offsite power is assumed. So the reactor trip, SI signal, both RCPs trip, MFW trip and turbine trip occur at 0 seconds.

3.4 Steam Generator Tube Rupture Scenario

In SGTR accident it is assumed that both trains of ECCS and both MD AF pumps were available and rod control system was in MANUAL mode (temperature feedback blocked). There were no operator actions assumed except isolation of the ruptured SG, when the NR liquid level difference between the intact and ruptured SG exceeds 5%, and maintaining of the SG liquid level at no load conditions between 68% and 72 % NR in the intact SG. After the tube rupture initiation similarly as in SBLOCA accident, pressure in the pressurizer starts decreasing. All pressurizer heaters are switched on trying to rebuild the primary pressure, while CVCS is trying to restore the primary coolant inventory (pressurizer level). However pressurizer pressure and level continue to decrease. When the pressurizer level drops below 18 %, the letdown is isolated and the pressurizer heaters are turned off. Following this event, more rapid pressure decrease causes the reactor trip and turbine trip. The reactor trip causes decreasing of the primary system average coolant temperature, while the primary pressure continues to decrease due to the rupture flow. Primary and secondary pressures start to equalize, so the rupture flow soon starts to decrease and turns from critical to pressure difference driven flow. The SI actuation setpoint is reached soon due to initial depressurization of the primary system. The HPSI pumps start to pump with the delay according to the SI triggering sequence after the SI signal is generated. On the secondary side immediately after the reactor trip, turbine is tripped and soon MFW is isolated. AFW pumps start shortly after MFW isolation. Due to the rupture flow from primary side, the mixture levels and pressure in both steam generators start to increase. The SG relief valves are expected to open when the secondary pressure reaches 7.5 MPa.

4. DESCRIPTION OF DEVELOPED ANIMATION MASKS

Animation masks were developed at Institut "Jožef Stefan (IJS) with the aim to present the RELAP5 input model, which is described in Section 2, in a user friendly way. Animation masks were developed for the plant systems and components, the plant signals and the control systems. The animation masks are shown with color maps for Display Bean animation mostly at time 0 second after which transients were simulated. The data shown at 0 second are steady state results of RELAP5 input model for Krško NPP at 100% power. Therefore, each Data Value on animation mask represents initial condition for the reference calculations performed for Krško full scope simulator validation.

4.1 Animation Masks of Plant Systems and Components

Animation masks of systems and components were created for the primary and secondary system representing a plant, the reactor vessel, the pressurizer with pressurizer relief tank, the steam generator (primary and secondary side), the emergency core cooling system, the main steam system, the main feedwater and the auxiliary feedwater system.

4.1.1 General Plant Mask

The general plant mask showing primary and secondary system is shown in Figure 1. Shown is the detail of the primary and secondary system modeling. Shown are volumes, pumps and valves. Information on volume number can be very easily obtained when mask is displayed in SNAP Model Editor or from more detailed masks for reactor vessel, pressurizer, ECCS, main steam system and auxiliary feedwater system. Junctions and heat structure are not shown, with exception of valves and a few arrows created by Line Annotation. The arrows indicate the normal direction of flow. From Figure 1 it can be very easily seen the number of safety and relief valves on pressurizer and steam generators and their status. Status is given also for the pumps. Green color means open valve and running pump, and red the opposite. It can be seen that secondary side is modeled up to the turbine and steam dump system. Main feedwater, auxiliary feedwater and emergency core cooling system are shown in more detail in separate masks. There are several pumps shown, but reactor coolant pumps are the only pumps modeled by RELAP5 'pump' card. The other pumps are modeled by 'tmdpjun' cards as it is schematically shown in Figures 8 and 9 by volume and junction inside the SNAP Simple Pump component. SNAP component can be animated by different Color Maps. The selected color map for volumes in Figure 1 is Void Fraction Color Map. For core the Temperature Color Map was selected. SNAP offers a variety of color maps. However, the color map can be changed in one step for the same Plant Components and Indicators only. In our case the Single Volume, Plenum, Pipe Elbow and Polygon were used for hydrodynamic volumes.

In Figure 2 is shown plat mask for the fluid condition. One can very easily see that primary side is subcooled liquid, while on the secondary side there is saturated liquid and steam. Please note that due to simplification the steam generator downcomers are not shown. They are shown in more detailed SG masks (see Figures 5 and 6).

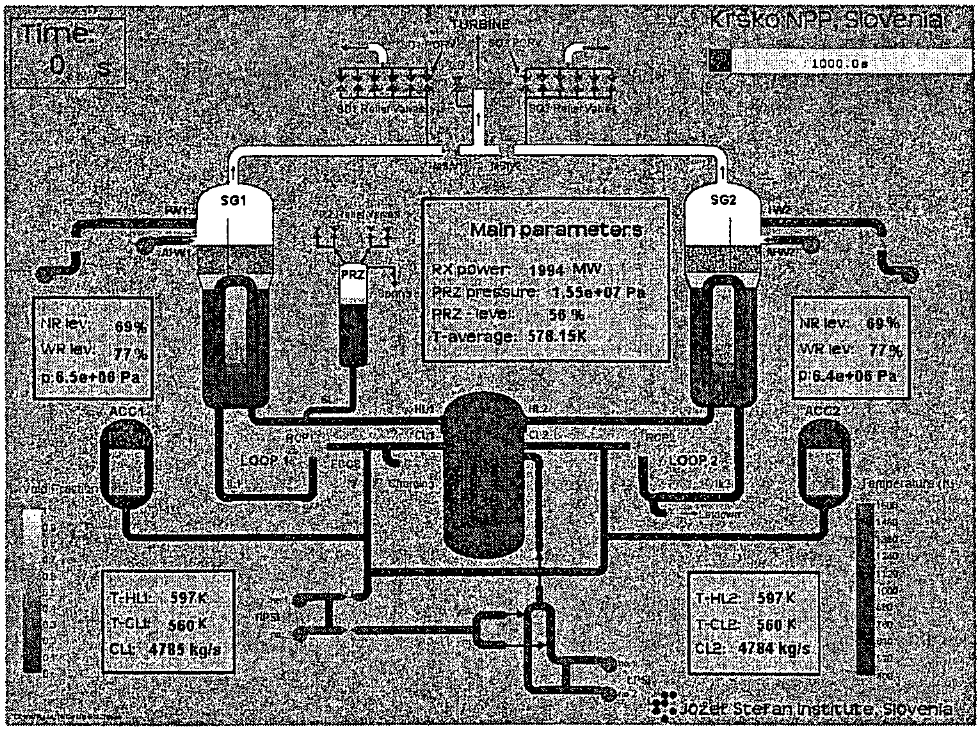


Figure 1 General plant mask after 1000 seconds of steady state – void color map

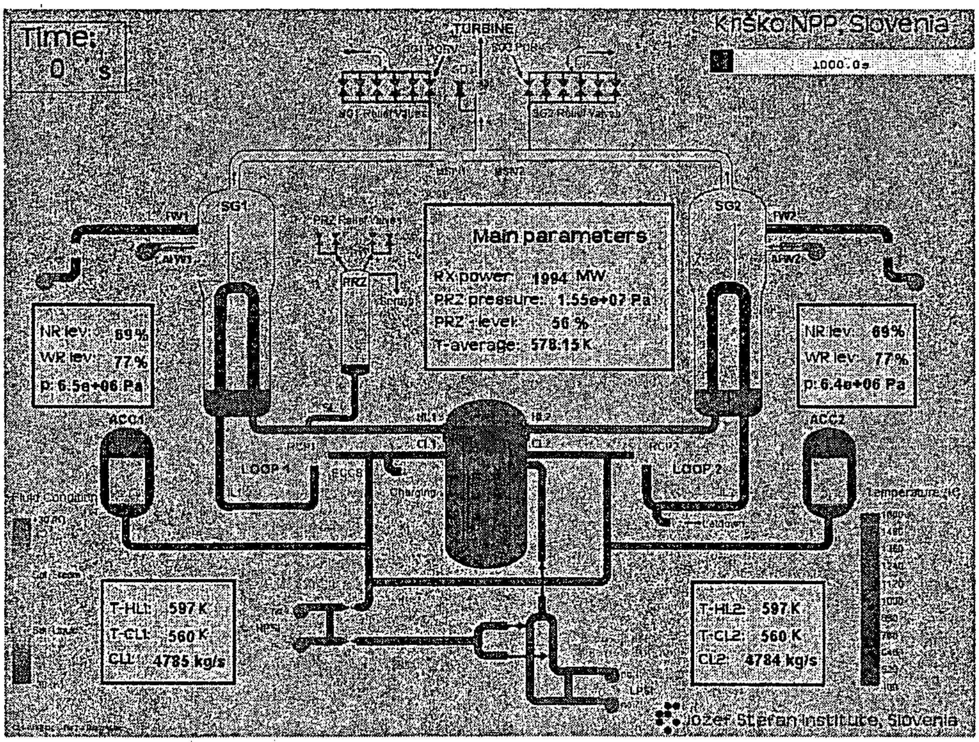


Figure 2 General plant mask after 1000 seconds of steady state – fluid condition color map

4.1.2 Reactor Vessel Mask

The reactor vessel mask gives details about the phenomena in the reactor vessel, especially during uncovery. First of all, the geometry of the reactor vessel is shown detailed comparing to the plant mask from which separate volumes are not seen. Besides, the directions of flows are also shown. When the flow direction changes, the color changes (in our case green color means normal flow and red the opposite direction). Core uncovery can be seen from Void Fraction Color Map and also from Fluid Level indicator. On the left side the reactor vessel like in the plant is drawn and described. The main parameters given are core power and heat transfer, pressure and temperature in the reactor head, and hot and cold leg flows. Finally, rod position is shown by Fluid Level indicator, where 609 steps mean fully withdrawn control rods and 0 steps reactor scram.

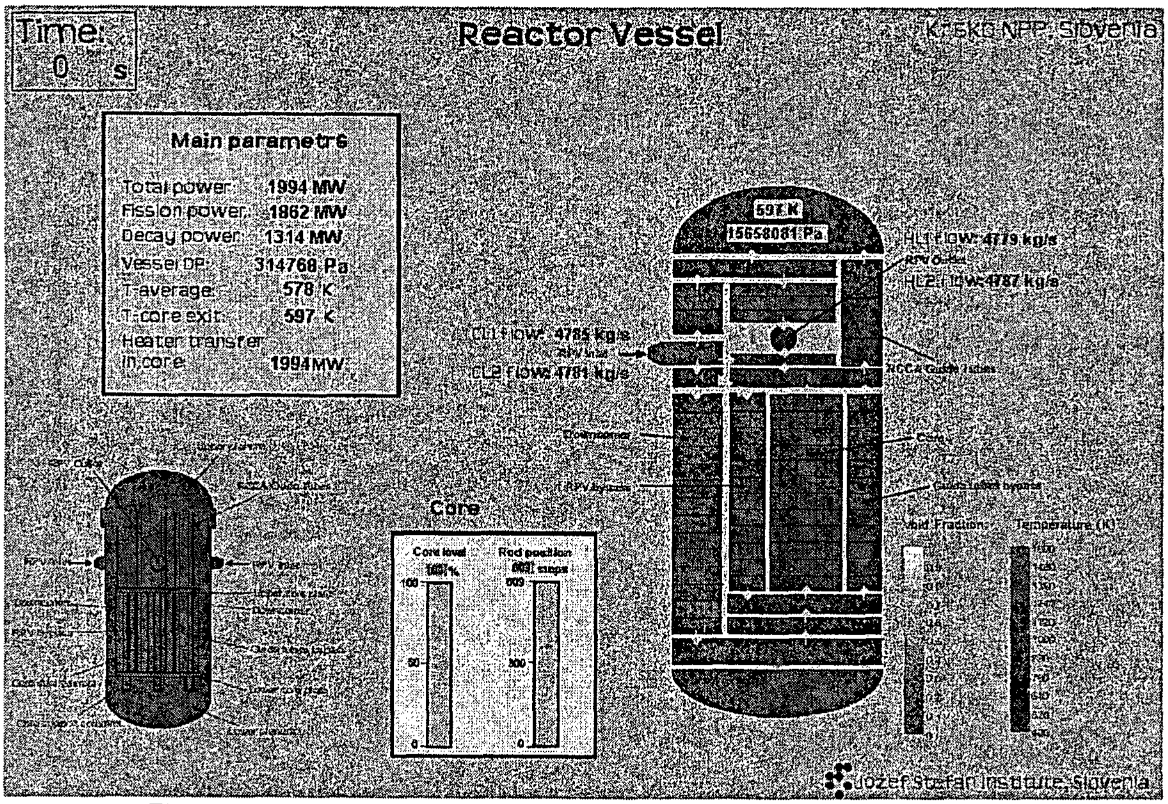


Figure 3 Reactor vessel mask after 1000 seconds of steady state

4.1.3 Pressurizer Mask

Pressurizer mask shows the reactor coolant system from surge line to pressurizer relief tank. Shown is pressurizer with electrical heaters and sprays, power operated relief valves and safety valves, and the associated piping. The pressurizer mask is important for pressurizer pressure and level control, and for transient with emptying and filling the pressurizer. One can clearly see the loop seal filled with the water before safety valves. From the main plant parameters are shown pressures, temperatures and flows. From flows are shown flow through surge line, sprays and PORVs and SVs. Shown is also pressurizer level as measured in the plant. The mask is useful especially for heatup events with overpressurization (e.g. ATWS).

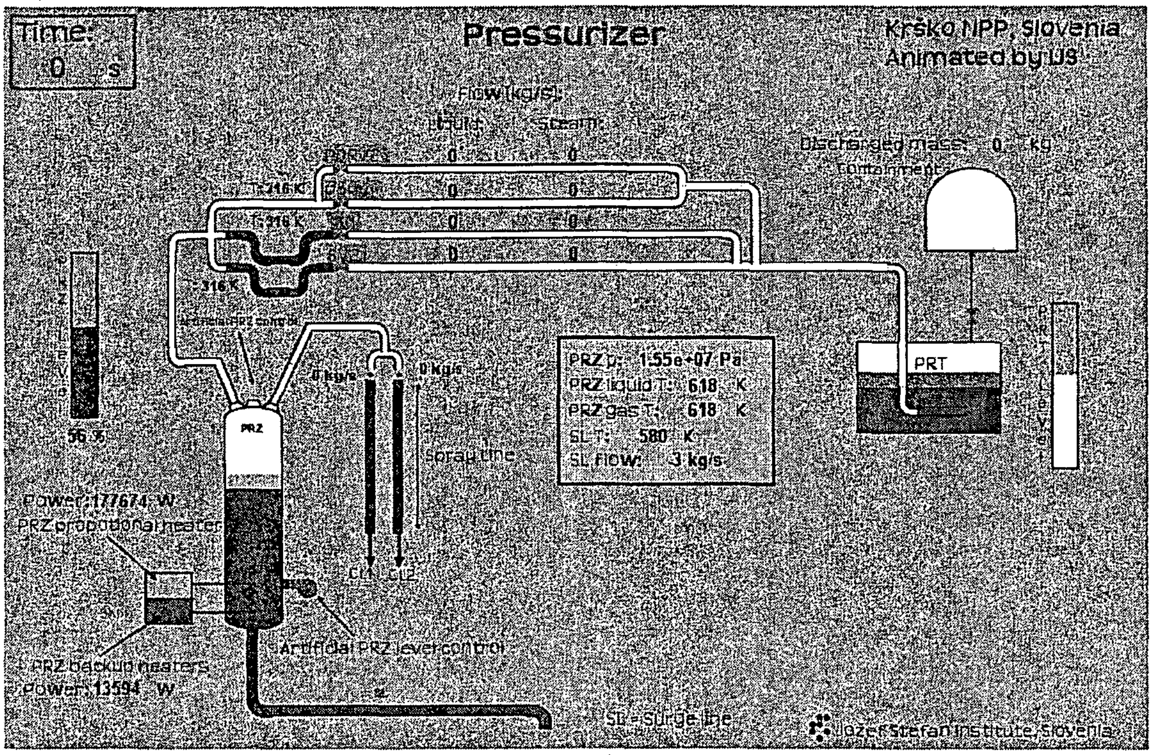


Figure 4 Pressurizer mask after 1000 seconds of steady state

4.1.4 Steam Generator Masks

There are two loops and each steam generator is on its own mask. Shown are the primary and the secondary side of the steam generator. On the primary side one can see the inlet and outlet plenum and U-tubes represented by a single pipe. On the secondary side there are downcomer and riser, the separators and the dryer. Shown are inlets for main feedwater and auxiliary feedwater flow and the piping inside the steam generator including J pipes and AFW injection above the separators. From the parameters are shown flows (cold and hot leg, SG downcomer and riser, main feedwater and auxiliary feedwater system, main steam system) and their temperatures. Shown are also SG parameters like pressure, wide and narrow range level, recirculation ratio, power and mass. Besides the mass in the steam generator is shown also the mass discharged through SG PORV and SG safety valves. The mask is very useful for transients with core cooling by the secondary side.

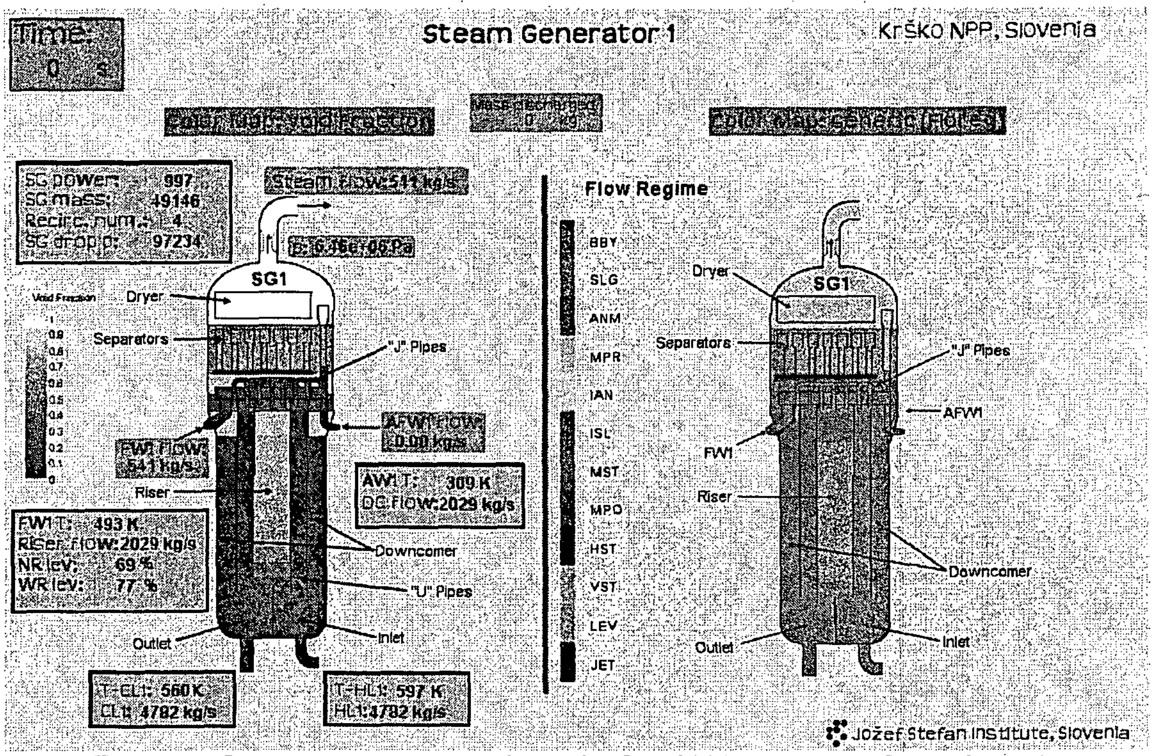


Figure 5 Steam generator no. 1 mask after 1000 seconds of steady state

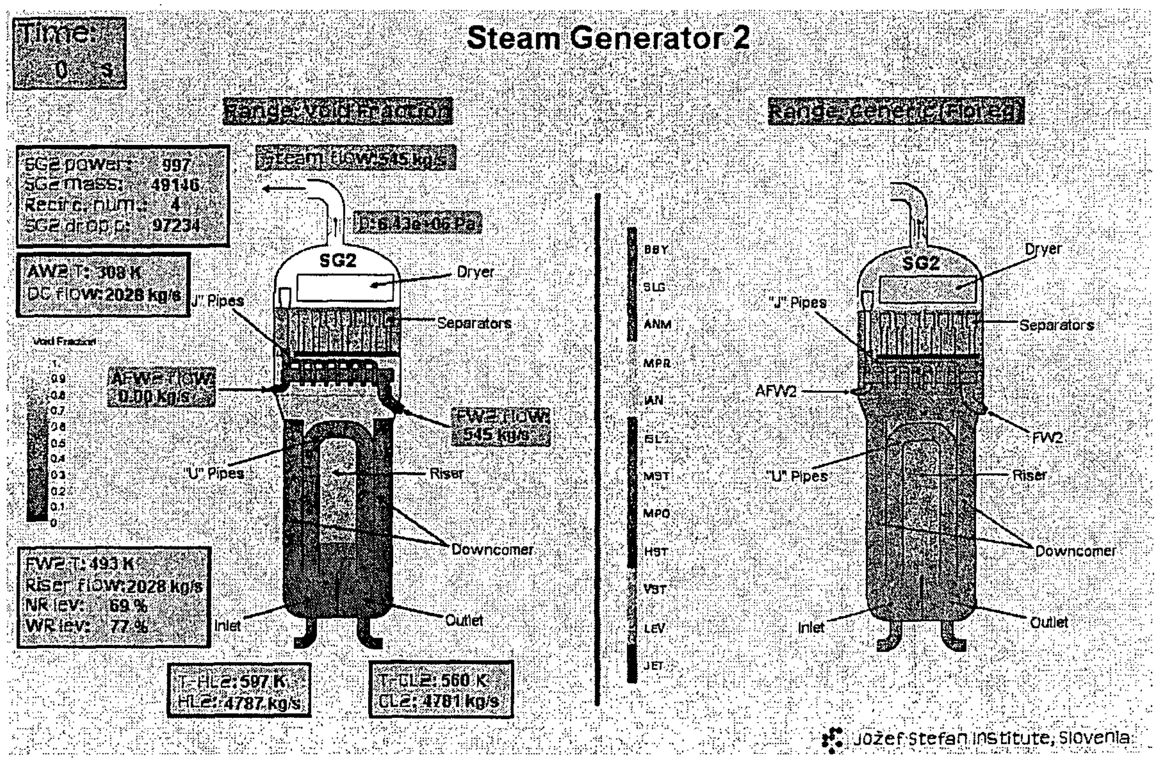


Figure 6 Steam generator no. 2 mask after 1000 seconds of steady state

4.1.5 Main Steam System Mask

The steam generator masks end on the secondary side, the main steam system mask starts. Shown are the main steamlines from the steam generator up to the turbine and steam dump system. Included are main steam isolation valves and SG PORVs and safety valves. For each relief valve the flow and mass discharged are shown. Other parameters shown are steam flows, turbine flow, feedwater flow, auxiliary feedwater flow and steam dump flow. For each steam generator are shown total mass discharged, pressure and level. Finally, turbine power is given.

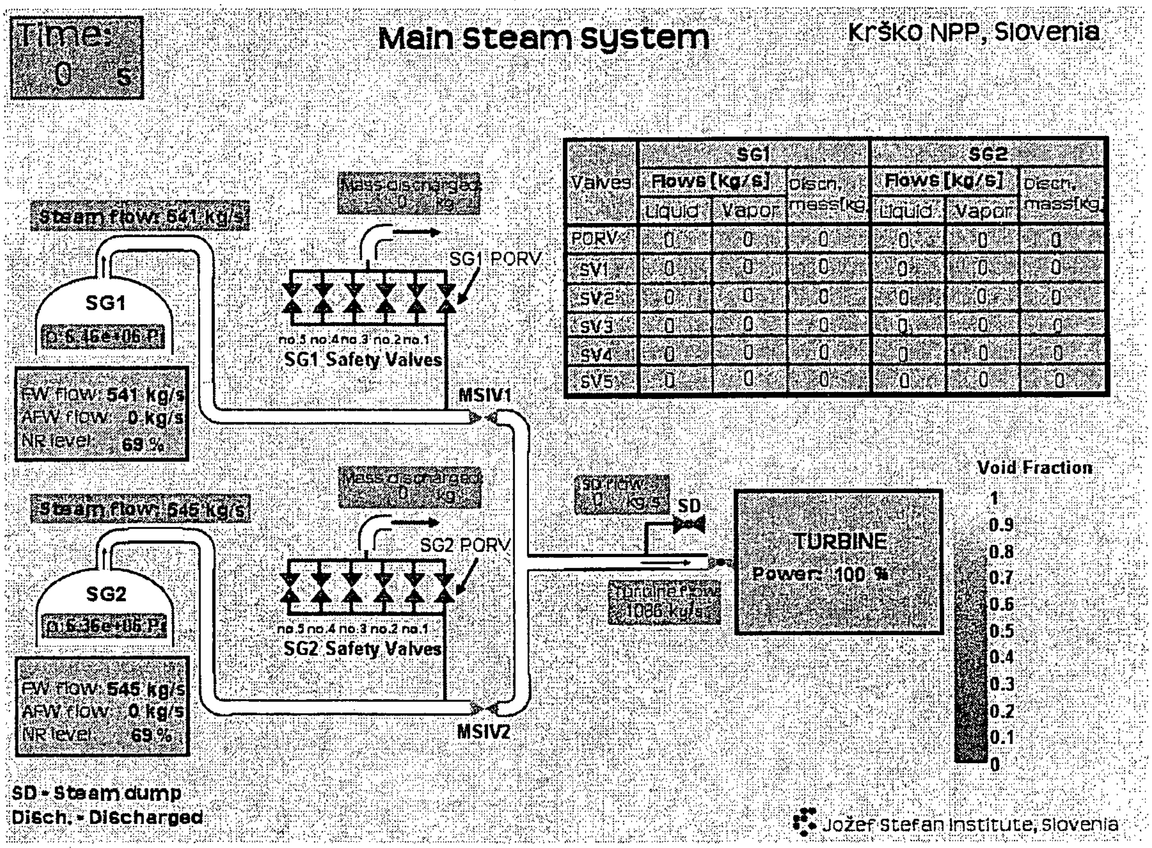


Figure 7 Main steam system mask after 1000 seconds of steady state

4.1.6 Main Feedwater System Mask

The main feedwater systems shows piping from the MFW pump modeled as time dependent junction to the J-ring tubes in the steam generator. Shown are the control and isolation valve with their status, green indicating open valve and red indicating closed valve. From parameters are shown MFW control valve area, flow and temperature. For each SG are shown main parameters like SG pressure and level, and steam flow. The mask is useful when we are interested on status of the feedwater system (pump running, control valve opening, status of feedwater isolations valves and the value and temperature of the flow).

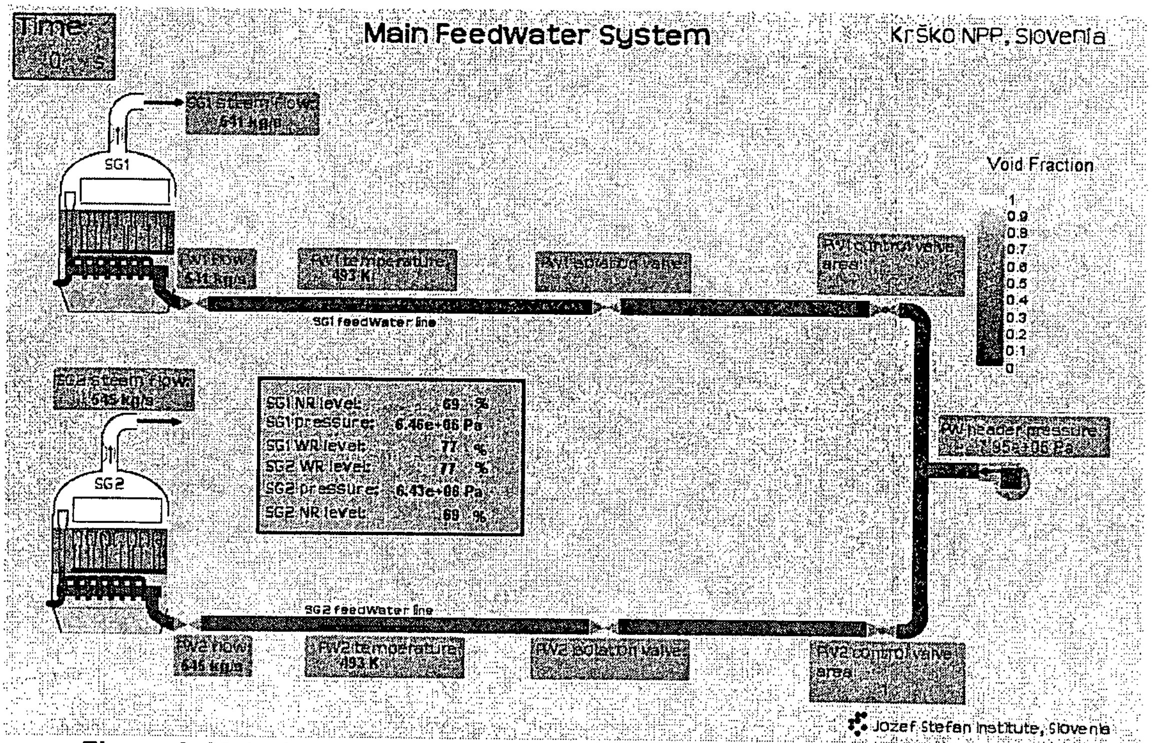


Figure 8 Main feedwater system mask after 1000 seconds of steady state

4.1.7 Auxiliary Feedwater System Mask

Similar information like for main feedwater is given also for auxiliary feedwater. From the mask shown in Figure 9 it can be seen that there are three AFW pumps. Two are motor driven AFW pumps each injecting into one steam generator and one is turbine driven (TD) AFW pump, injecting to both steam generators through header. Each pump is modeled by time dependent junction. Besides injecting flow path is modeled also recirculation flow path to condensate storage tank (CST). For each steam generators are given parameters on SG pressure and level, main feedwater flow and steam flow. For each AFW pump is given flow, temperature of the flow and integrated mass flow to each SG, recirculation flow and discharge pressure of the pumps.

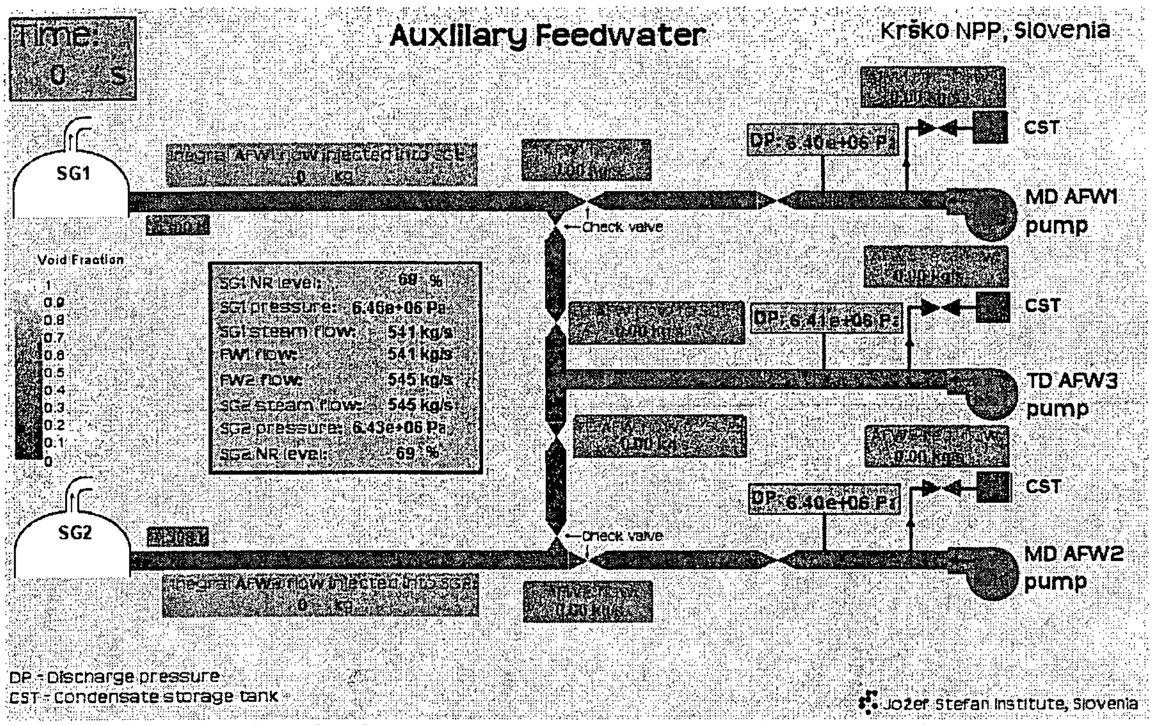


Figure 9 Auxiliary feedwater system mask after 1000 seconds of steady state

4.2 Animation Masks of Plant Signals

Various signals based on trip cards logic are included in the RELAP5 input model of Krško NPP. The following signals were presented on the animation masks:

- reactor trip signal,
- SI signal,
- turbine trip signal,
- steam line isolation signal,
- MFW isolation signal, and
- AFW start signal.

In addition, mask with main signals and sequence of events was created. SNAP RELAP5 plug-in offers all RELAP5 TRIP cards. However, the time when trip occurs is not available from restart-plot file. For the time being, no TRIP "time-of" plot variables were introduced in the RELAP5 input model. This information is available from the printed output file (trip time for trip number), but SNAP cannot use such data source. The only solution was therefore to use the Python data source. The trip times were determined from trip data time trends at times determined by plot frequency. The problem is when there is large number of time advances of plot data, since the trip times are not exact times, but rounded values.

4.2.1 Reactor Trip and Safety Injection Signal Mask

The reactor trip and safety injection signal presenting reactor protection system are shown in the same mask, each in its own table. For each reactor trip and safety injection signal is given trip setpoint (some are calculated, e.g. overtemperature delta T), status of the trip (0 indicating false and 1 indicating true), the time of the trip and the assumed delay of the signal. It should be noted that only the first reactor trip cause the reactor scram, while subsequent trips just reflect the conditions at which the trip would occur, but this is not physical because of the reactor scram after which the course of transient is completely changed. Nevertheless, this reflect the RELAP5 as in each time step each trip number is recalculated.

Reactor trip status 0.0 at 0 [s] Time: 0.0 s

Reactor trip signals	setpoint	trip	transient timing [s]	with assumed delay [s]
low pressurizer pressure	12.994 [MPa]	0	0	2
high pressurizer pressure	16.511 [MPa]	0	0	2
high pressurizer level	92.0 [%]	0	0	3
low SG 1 level	13.0 [%]	0	0	4
low SG 2 level	13.0 [%]	0	0	5
low loop 1 flow	5.71 m3/s	0	0	1
low loop 2 flow	5.71 m3/s	0	0	1
overtemperature dT loop 1	46.0 K	0	0	1
overtemperature dT loop 2	46.1 K	0	0	1
overpower dT loop 1	39.7 K	0	0	1
overpower dT loop 2	39.7 K	0	0	1
manual		0	0	0
SI signal		0	0	0
turbine trip		0	0	0

SI signal status 0.0 at 0 [s]

Safety injection signals	setpoint	trip	transient timing [s]	with assumed delay [s]
low - low pressurizer pressure	12.27 [MPa]	0	0	0
high containment pressure	0.129 [MPa]	0	0	0
low - low steam line 1 pressure	4.928 [MPa]	0	0	0
low - low steam line 2 pressure	0.0 [MPa]	0	0	0
manual		0	0	0

Figure 10 Reactor trip and safety injection signal mask after 1000 seconds of steady state

4.2.2 Turbine Trip and Feedwater Isolation Signal Mask

Second mask dealing with signals is for turbine trip and feedwater isolation. The turbine is tripped automatically on reactor protection signals, on any high SG level signal and AMSAC signal. In addition, it can be tripped manually.
Feedwater isolation occurs on similar signals as turbine trip with the exception that there must be coincidence between the reactor trip and low average RCS temperature signals and there is no AMSAC signal.

Turbine trip status 0.0 at 0 [s] Time: 0.0 s

Turbine trip signals	setpoint	trip	transient timing [s]	with assumed delay [s]
high SG 1 level	86.0 [%]	0	0	3
high SG 2 level	86.0 [%]	0	0	3
manual		0	0	0
SI signal		0	0	0
Reactor trip		0	0	0
AMSAC signal	8.0 [%]	0	0	15

Feedwater 1 isolation status 0.0 at 0 [s]

Feedwater 1 isolation signals	setpoint	trip	transient timing [s]	with assumed delay [s]
high SG 1 level	86.0 [%]	0	0	0
high SG 2 level	86.0 [%]	0	0	0
manual		0	0	0
SI signal		0	0	0
Reactor trip & low Tavg	568.8 [K]	0	0	0

Feedwater 2 isolation status 0.0 at 0 [s]

Feedwater 2 isolation signal	setpoint	trip	transient timing [s]	with assumed delay [s]
high SG 1 level	86.0 [%]	0	0	0
high SG 2 level	86.0 [%]	0	0	0
manual		0	0	0
SI signal		0	0	0
Reactor trip & low Tavg	568.8 [K]	0	0	0

Figure 11 Turbine trip and feedwater isolation signal mask after 1000 seconds of steady state

4.2.3 AFW Start Signal Mask

Auxiliary feedwater is also started automatically besides manual start. Both MD AFW pumps start on any low SG level, in case of both MFW pumps trip, on SI and AMSAC signal. The pumps can be started manually, too. Manual start is used also to simulate blackout sequence. TD AFW pump is started when both SG levels are low and on AMSAC signal. It can also be started manually. Manual AFW pump start is used also to simulate blackout sequence.

Time: 0.0 s

MD AFW start status 0.0 at 0 [s] (start with 25 s delay - 20 s for SI sequence and 5 s to reach full flow)

MD AFW start signal	setpoint	trip	transient timing [s]	with assumed delay [s]
low - low SG1 level	13 %	0	0	0
low - low SG2 level	13 %	0	0	0
trip of both main feedwater pumps		0	0	0
AMSAC signal		0	0	15
SI signal		0	0	0
manual		0	0	0

TD AFW start status 0.0 at 0 [s] (5 s for pump start)

TD AFW start signal	setpoint	trip	transient timing [s]	with assumed delay [s]
low - low SG1 and SG2 level	13 % / 13 %	0	0	0
AMSAC signal		0	0	15
manual		0	0	0

Figure 12 AFW start signal mask after 1000 seconds of steady state

4.2.4 MSIV Isolation and RCP Trip Signal Mask

The last signals simulated are MSIV no. 1 and MSIV no. 2 isolation signals, and RCP no. 1 and RCP no. 2 signals. Main steamline is isolated on high steam flow in any steamline when coincident with low-low average temperature and SI signal, high-high steamline flow in any steamline in coincident with SI signal, low steamline pressure in any steamline (permissible bypass if RCS pressure less than 13.89 MPa), high-high containment pressure and manual (operation either will operate both).

MSIV isolation 1 status 0 at 0 [s] — Time: 0.0 s

MSIV 1 isolation signals	setpoint	trip	transient timing [s]	with assumed delay [s]
high steam flow dp & low-low Tavg & SI signal	24.4 [kPa] 562.6 [K]	0	0	2
high - high steam flow dp & SI signal	115.8 [kPa] 117.0 [K]	0	0	0
low steam line pressure	4.928 [MPa]	0	0	0
high - high containment pressure	0.0 [MPa]	0	0	0
MSIV 1 manual trip		0	0	0

MSIV isolation 2 0 at 0 [s]

MSIV 2 isolation signals	setpoint	trip	transient timing [s]	with assumed delay [s]
high steam flow dp & low-low Tavg & SI signal	24.4 [kPa] 562.6 [K]	0	0	2
high - high steam flow dp & SI signal	115.8 [kPa] 117.0 [K]	0	0	0
low steam line pressure	4.928 [MPa]	0	0	0
high - high containment pressure	0.0 [MPa]	0	0	0
MSIV 2 manual trip		0	0	0

RCP 1 trip status 0 at 0 [s]

RCP 1 trip signal	setpoint	trip	transient timing [s]	with assumed delay [s]
pump 1 trip at reactor trip		0	0	1000000
pump 1 manual trip		0	0	1000000
pump's trip on HI cont. pressure	260.0 [kPa]	0	0	60
pump's trip on subcooling	11.0 [K] + SI signal	0	0	60

RCP 2 trip status 0 at 0 [s]

RCP 2 trip signal	setpoint	trip	transient timing [s]	with assumed delay [s]
pump 2 trip at reactor trip		0	0	1000000
pump 2 manual trip		0	0	0
pump's trip on HI cont. pressure	260.0 kPa]	0	0	60
pump's trip on subcooling	11.0 [K] + SI signal	0	0	60

Figure 13 MSIV isolation and RCP trip signal mask after 1000 seconds of steady state

4.2.5 Main Signals and Sequence of Events Mask

This mask shows the transient timing and status of the trip, 0 indicating false and 1 indicating true value. The signals shown are reactor trip, safety injection (SI) signal, turbine trip, steam line isolation, and main feedwater isolation. More detailed masks for these signals are given above. Sequence of events mainly consists of systems and components start times such as ECCS system, AFW system, CVCS system (charging and letdown) and steam dump system. For each ECCS subsystem it is shown when it is initialized (setpoint reached) and time at which started to inject. For additional information, injected flow or mass is shown. The reason for distinguishing the initialization time and injection time is, that pumps may be started; however the pressure might be higher than the pump head. Similarly it is done for AFW system. For reactor coolant pumps the trip times are shown, for charging and letdown the isolations times are given and finally, the start time of steam dump in case of plant trip.

Time: 0.0 s

SIGNALS	transient timing [s]	TRIP
Reactor trip signal generation	0	0
SI signal generation	0	0
turbine trip	0	0
steam line 1 isolation	0	0
steam line 2 isolation	0	0
MFW 1 isolation	0	0
MFW 2 isolation	0	0

EVENTS	transient timing [s]	TRIP		
accumulator no.1 initialization / isolation	0 / 0	0 / 0		
accumulator no.1 first injection	0	0	0.0	[kg]
accumulator no.2 initialization / isolation	0 / 0	0 / 0		
accumulator no.2 first injection	0	0	0.0	[kg]
LPSI pump no.1 initialization	0	0		
LPSI pump no.1 first injection	0	0	0.0	[kg]
LPSI pump no.2 injection	0	0		
LPSI pump no.2 first injection	0	0	0.0	[kg]
HPSI pump no.1 initialization	0	0		
HPSI pump no.1 first injection	0	0	0.0	[kg/s]
HPSI pump no.2 initialization	0	0		
HPSI pump no.2 first injection	0	0	0.0	[kg/s]
AF MD pump no.1 start	0	0		
AF MD pump no.2 start	0	0		
AF TD pump start	0	0		
RCP 1 trip	0	0		
RCP 2 trip	0	0		
charging isolation	0	0		
letdown isolation	0	0		
steam dump - plant trip	0	0		

Figure 14 Main signals and sequence of events mask after 1000 seconds of steady state

4.3 Animation Masks of Control Systems

The animation masks for the following control systems were developed:

- rod control system,
- pressurizer pressure control system,
- pressurizer level control system,
- steam generator level control system (both loops),
- turbine power control (artificial), and
- steam dump.

The animation models are not represented by control blocks available in SNAP animation plug-in. Rather, new blocks (just graphically) were created similar to Simulink and following the standard drawings of Westinghouse PWR control systems. The values are shown using Data Value indicator. This integrated view improves the understanding, how controls work and are much more suitable for the analyst and training purposes. It is not purpose to explain in detail how control systems works, but to present the layout of animated masks, and the data shown.

4.3.1 Rod Control System Mask

The animation mask for rod control system is shown in Figure 15. After 1000 seconds of steady state the reactor point kinetics model was introduced into the input model, what can be seen from the text annotation colored orange and labeled "Automatic rod control system active". This also means that rod control is not in manual. The steady state values of reactor and turbine power slightly deviates like the temperature. Nevertheless, the control rods are not moving. The rod control systems model includes power and temperature mismatch units giving the temperature error, which is input to rod speed program. The reactor control unit to generate rod speed program is in the RELAP5 modeled with a number of control blocks and trip logic. It converts the temperature error to rod speed. The rod speed program simulated the deadband, the lock-up, the minimum (8 steps/min.), proportional and maximum speed (72 steps/min.). The rod speed determines the rod position (609 steps mean fully withdrawn rods) and depending on the position the control rod reactivity is determined through table. Total reactivity is determined based on control rods and shutdown rods reactivity. By automatic positioning the control rods the control system maintains the programmed average temperature during power operations.

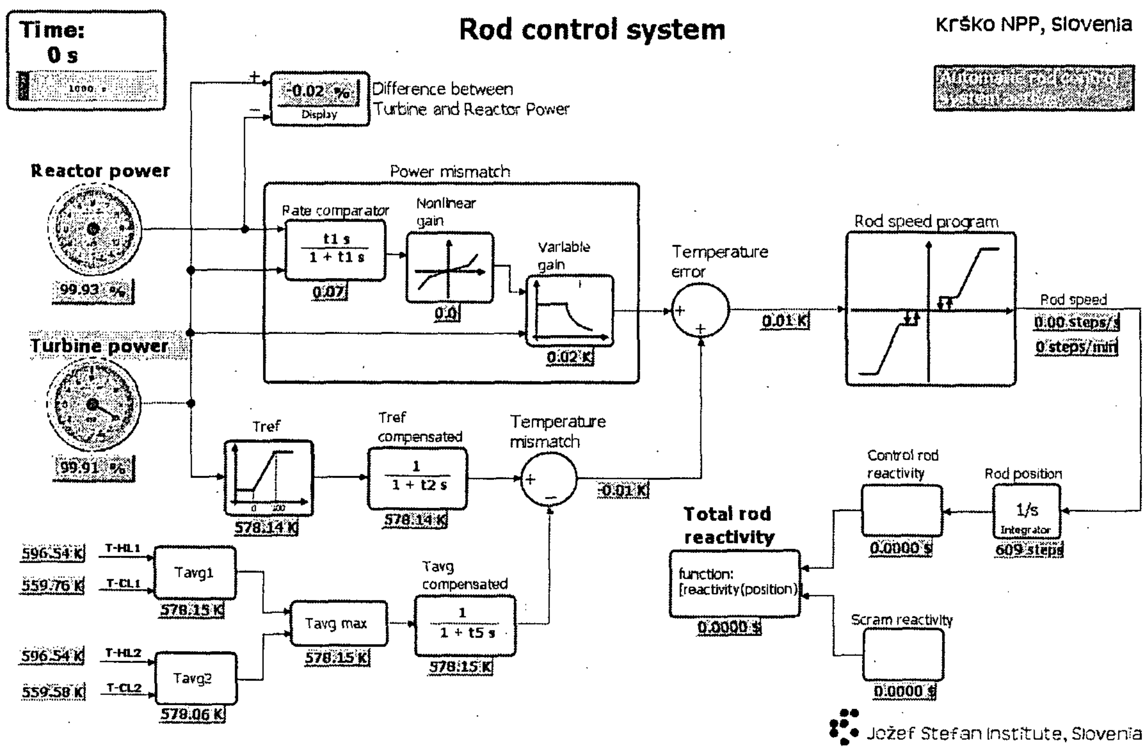


Figure 15 Rod control system mask after 1000 seconds of steady state

4.3.2 Pressurizer Pressure Control System Mask

The pressurizer pressure control system mask is shown in Figure 16. The control system controls the pressure of reactor control system at reference pressure, during both steady state and design transient conditions. In the selected 5.08 cm break size SBLOCA the pressure started to drop and after 1 second the pressure error is about 2 bars. This pressurizer pressure signal feeds proportional-plus integral (PI) controller before being used to control proportional and back-up heaters, spray valves and one of the two pressurizer PORVs. This compensated error signal is around 11 bars, what is more than sufficient to turn on the backup heaters. This can be also seen from information on the right side of Figure 16, as text box "Backup heaters ON (pressure deviation" is colored orange. The backup heaters could be switched on also in the case of 5% pressurizer level deviation. As pressurizer level is greater than 18%, the backup heaters are active. This mean they can operate when demanded. One can also see that in the case of low reactor coolant pump flow the backup heater control is disabled. This is operator correction in pressurizer control systems automatic operation due to low RCS flow causing dubious average temperature measurement with resistance temperature detectors.

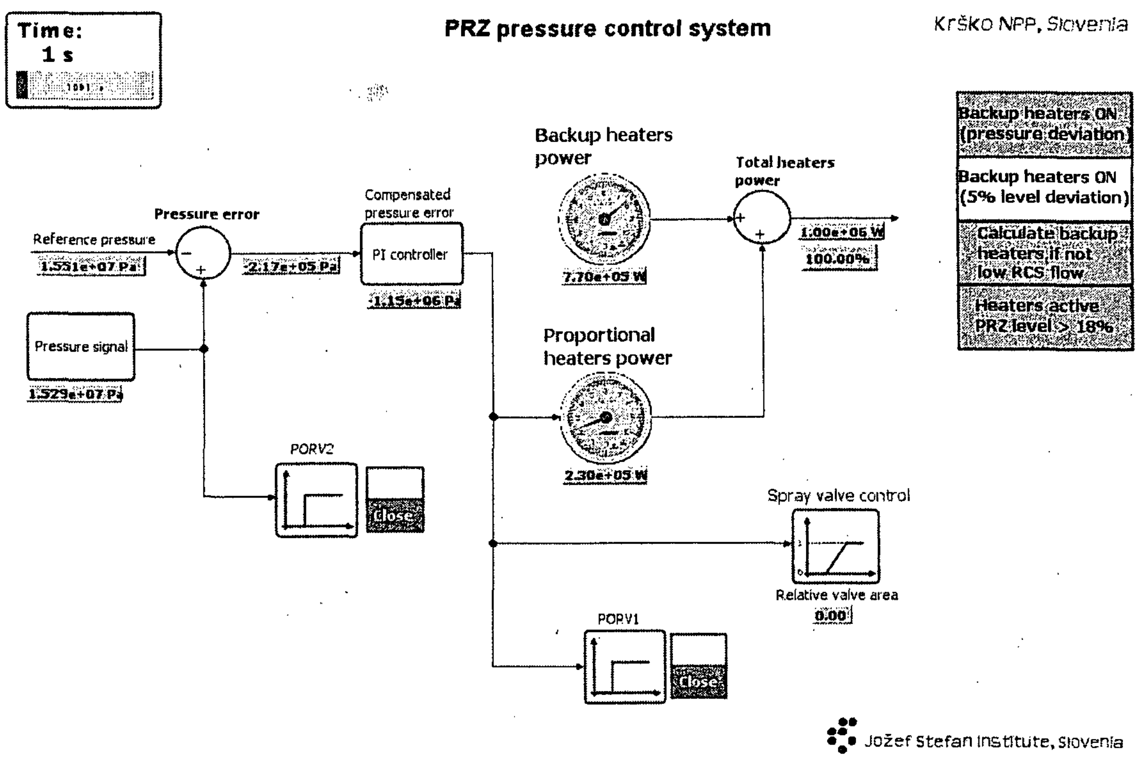


Figure 16 Pressurizer pressure control system mask after 1 second for 5.08 cm break size SBLOCA

4.3.3 Pressurizer Level Control System Mask

The pressurizer level control system mask is shown in Figure 17. The control system controls the charging flow to maintain the programmed level in the pressurizer. As can be seen the charging flow is modeled by time dependent junction. The level signal is a simulation of the differential pressure measurement, taking into account calibration (based upon pressurizer temperature). The simulated measured level signal is compared to the programmed level, depending on the average temperature (maximum from the two loops). The resulting level error signal feeds PI controller, which controls the CVCS charging flow. This is done through comparing flow signal based on compensated level error with the charging flow signal. Also level error signal feeds the PI controller. The "fixed letdown flow" is zero when pressurizer level control is ON; otherwise it is equal to letdown flow. The resulting charging flow in % then determines the actual charging flow, modeled by time dependent junctions. In addition, it is used to calculate the charging flow signal. In Figure 17, showing conditions 15 seconds after 5.08 cm break size SBLOCA occurence, it can be seen that pressurizer level control is on, therefore fixed letdown flow is zero. The letdown system is also on. The charging flow is larger than letdown flow, because the level is below the programmed level. Additional information is also given on the status of charging and letdown flow (ON/OFF) to be promptly alarmed. Finally, as can be seen in Figure 17, the uncompensated level error is input to the pressurizer control system in order to switch on backup heaters when pressurizer level is 5% higher than the programmed level.

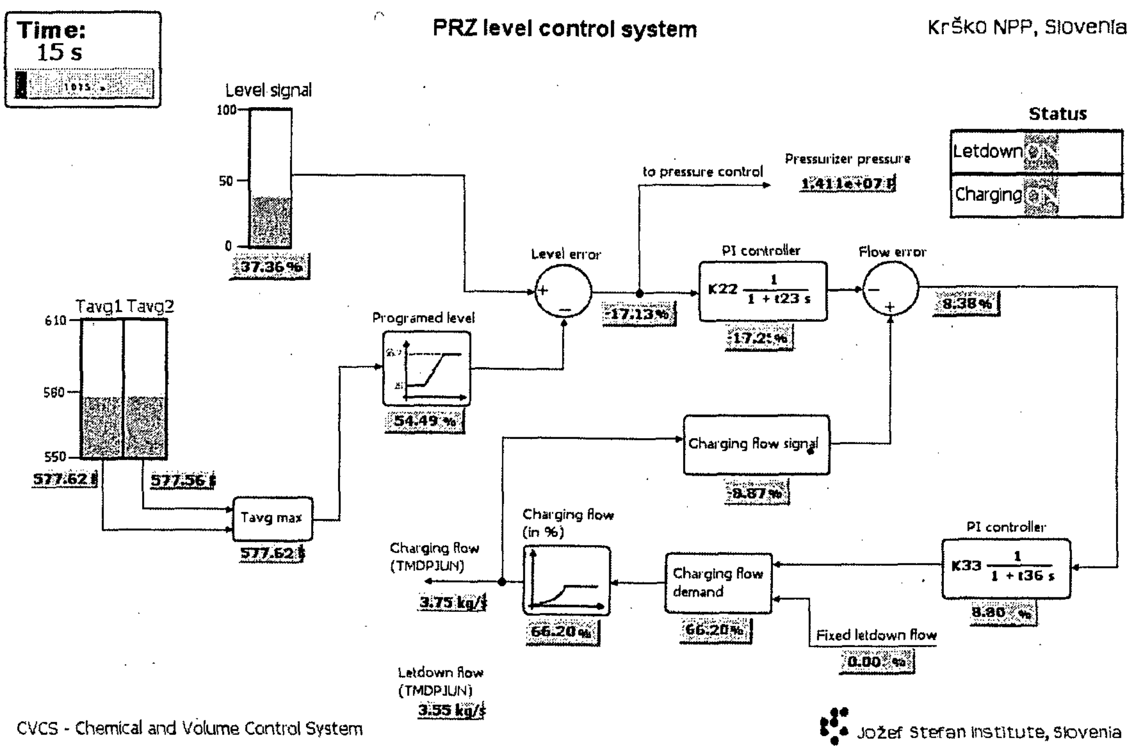


Figure 17 Pressurizer level control system mask after 15 seconds for 5.08 cm break size SBLOCA

4.3.4 Steam Generator Level Control System Masks

The steam generator level control system masks for loop 1 and 2 are shown in Figure 18 and Figure 19, respectively. The main purpose of the steam generator water level is to control the feedwater flow to maintain a programmed level in the steam generators. Each steam generator has its own controller. First the actual level signal, sent through a lag unit to dampen out any oscillations in the signal, is compared to the programmed level. The level error is then sent to PI controller where it is converted into an equivalent flow error. This flow error signal is then combined with steam flow and feedwater flow to produce a total error in the PI controller. This signal is then used to position the main feedwater control valve.

Figure 18 shows the condition at the end of steady state for SG 1 level control. It can be seen that artificial control to achieve steady state is on and that desired level is achieved. Besides level also steam and feedwater flow are balanced, therefore there is no valve area change needed.

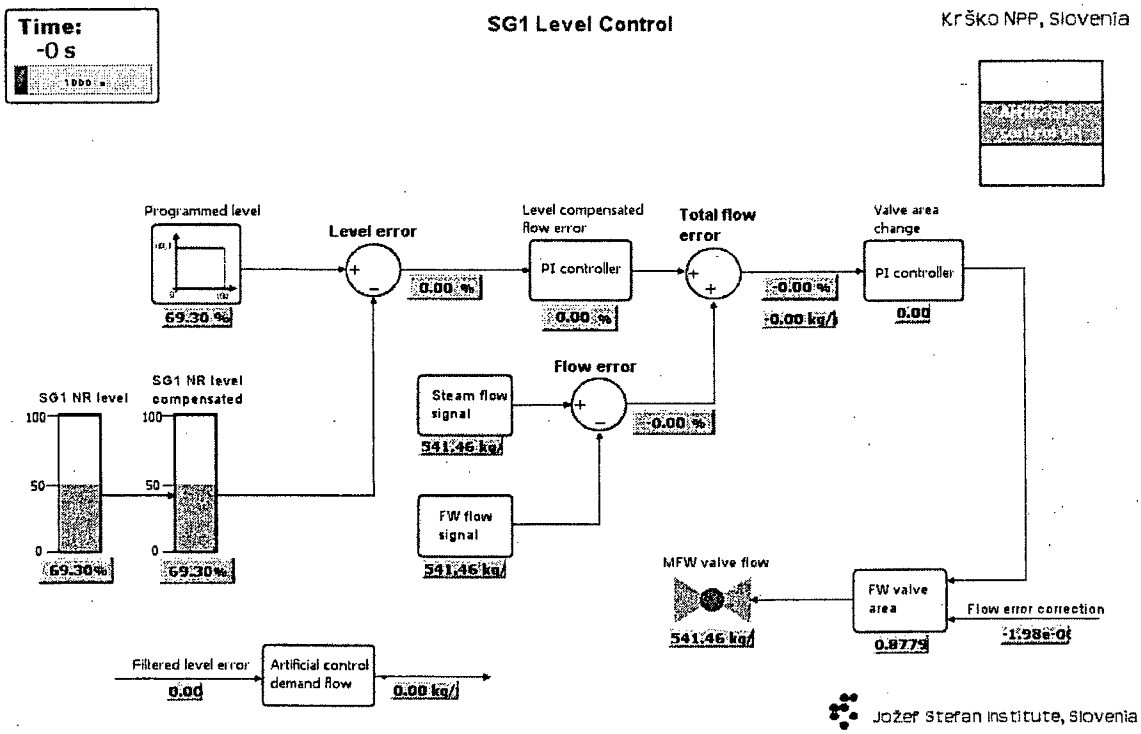


Figure 18 Steam generator no. 1 level control system mask after 1000 seconds of steady state

Figure 19 shows the conditions after 8 seconds of LOFW accident for SG 2 level control. It can be seen that at 8 second MFW valve is closed (closure time is 7 seconds). In order to simulated LOFW accident by assumption the MFW control valve started to close at 0 second.

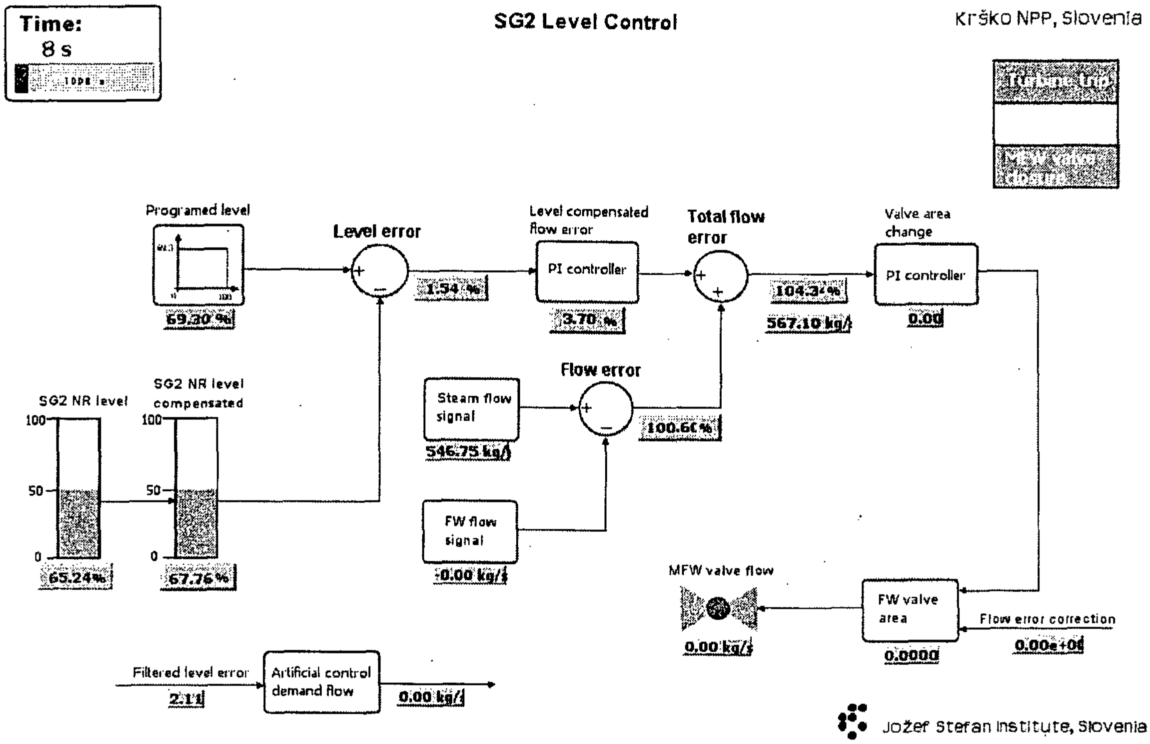


Figure 19 Steam generator no. 2 level control system mask after 8 seconds of LOFW scenario 1

4.3.5 Turbine Power Control Mask

To control the operation of the turbine the digital electro hydraulic (DEH) control system was designed in Krško NPP (in 2009 was replaced by programmable DEH). In the RELAP5 model the secondary side was modeled up to the turbine control valves. To simulate the turbine and power control the artificial turbine power control was introduced into the RELAP5 input model. The animation mask of artificial turbine power control is shown in Figure 20.

To understand how this control works, it must be explained that the turbine flow is modeled by control valve discharging to time dependent volume. In addition, in the case of turbine runback or external perturbation (load function defined by RELAP5 user), the turbine flow (see upper part of Figure 20) is established through the time dependent junction. In the case of turbine trip or demanded constant flow the flow is regulated by the turbine valve. Demand on the turbine valve area change is by assumption such that control of turbine governor valve preserves constant mass flow through the turbine (mass flow through the turbine after the end of steady state). Scaling factor for error in mass flow and lag constant were based on the engineering judgment. The part with temperature error is just to compensate average temperature error during steady state calculation. Calculation of this error is enabled only during steady state calculation (artificial control ON – value 1). During steady state calculation turbine governor valve area regulates SG pressure to achieve desired RCS T_{hot} temperature. Following the end of steady state calculation, control system regulates turbine valve area to preserve constant mass flow to turbine as already mentioned.

Figure 20 shows conditions 2 seconds after transient start. In this case artificial control is OFF and turbine valves are opened. The flow error between turbine flow and turbine flow at the end of steady state is very small; therefore the turbine valve area not changes much. In the bottom part of artificial turbine power control system the power is determined based on turbine mass flow. There are four contributors to power: power at turbine trip, power at turbine runback, power at external perturbation, and power when all these trips are off. From them the final turbine power is determined. The feedback is turbine mass flow. In the case of turbine runback and external perturbation it is simulated by time dependent junction. When neither turbine runback nor external perturbation is present, turbine valve area is changed. In the case of turbine trip the turbine valve closure is simulated. When none of the three trips is present, the constant mass flow is maintained.

The status of turbine stop valves and the above mentioned trips is shown at top on the right in Figure 20. Orange color means that value is true. White value means the value is false (as font color is white the text is not visible). At present the turbine stop valves are closed. This also means that there is no turbine trip (second box from top). Third box indicates there is no external perturbation. Fourth box indicates there is no turbine runback.

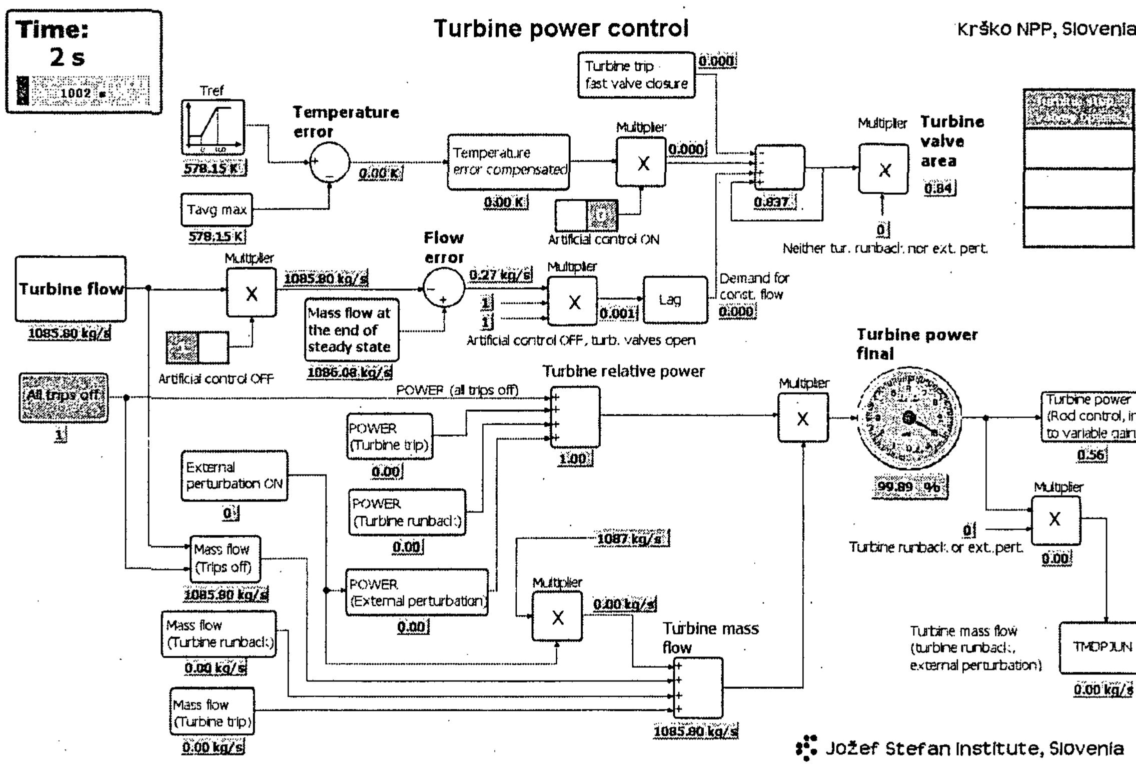


Figure 20 Turbine power control system mask after 2 seconds of LOFW scenario 1

4.3.6 Steam Dump Control Mask

Steam dump model is represented by simplified time dependent junction and its flow is calculated by steam dump control system shown in Figure 21. Steam dump control system consists of steam dump Tavg control for load follow and turbine trip, as well as steam header pressure control. The corresponding controllers are load rejection controller, turbine trip controller and steam pressure controller. One mode of operation can be selected at a time: Tavg mode and pressure mode. During normal power operations generally greater than 15% thermal power, the steam dump is placed in the Tavg mode. Until turbine trip, loss of load controller is automatically selected. When turbine trip occurs, loss of load controller is disconnected and turbine trip controller is enabled. The two controllers differ according to their functions. The function of loss of load controller is to provide alternate heat sink until rod control system reduces reactor power to match turbine power. Therefore the load reduction controller has a deadband to allow for control rod motion before the steam dump valves begin to open. The function of the turbine trip controller is to remove decay heat and stored energy to return Tavg to its no load value. There are ten valves which are divided into four groups. Each valve has 10% capacity. In group a are two valves, in group b three valves, in group c two valves and in group d three valves. To arm the loss of load, there are two interlocks, one set to 10% sudden load loss and the other 50% sudden load loss. In the case of 10% sudden loss load, only first half of valves will be armed (groups a, b). When sudden loss load is greater than 50% step, second group is also armed (groups c, d). In the case of turbine trip only the first half of valves are armed (groups a, b). The temperature difference modulates open steam dump valves. When this difference originally is higher than the controller can handle, first group of valves is fully opened. If the temperature error continues increasing, second group is fully opened. The bistable trip setpoints for turbine trip controller are higher than those for loss of load controller.

Figure 21 shows steam dump system operated in Tavg mode during LOFW scenario no. 1. Load rejection controller is enabled and first two groups are armed. As temperature difference is below trip bistables setpoints, the steam dumps valves are modulated open. Total steam dump (SD) flow is calculated from the contributions from the three above mentioned controllers, with only loss of load controller contributing. There is no main steam isolation valve closure or RCP trip. In such cases the steam dump flow is not calculated. When steamlines are isolated the steam flow is not feasible. In the case of RCP trip the reason for not calculating steam dump flow is dubious Tavg measurement, and steam dump can be put to manual.

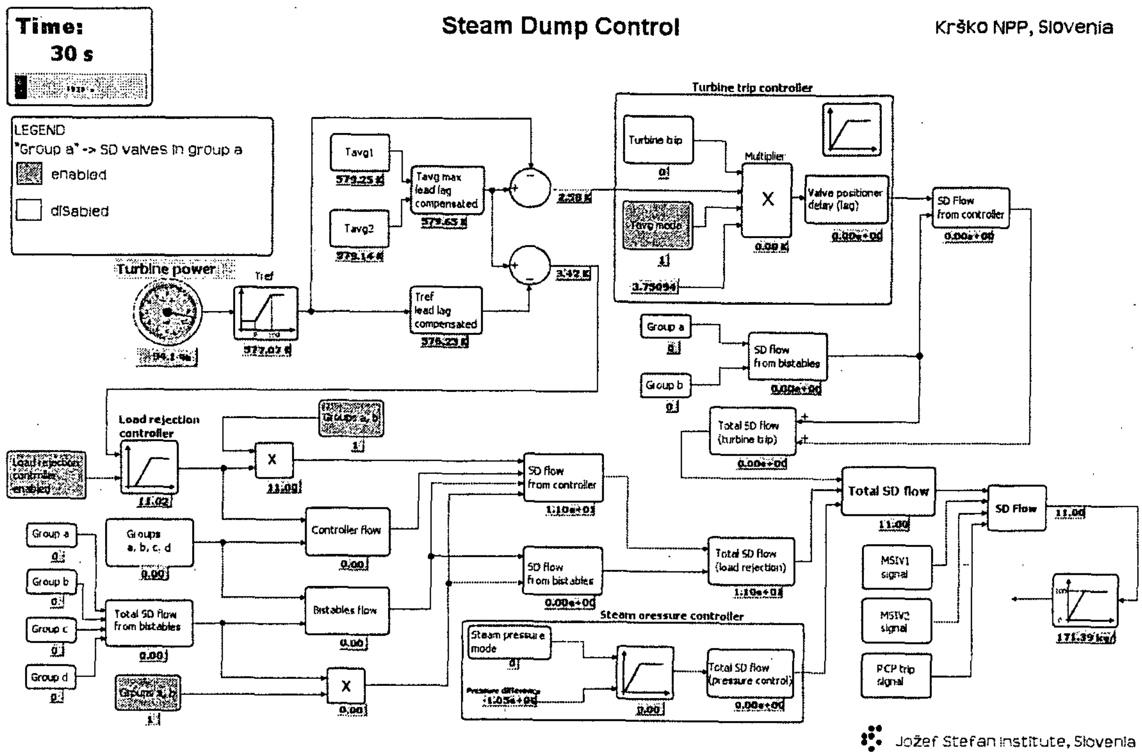


Figure 21 Steam dump control system mask after 30 seconds of LOFW scenario 1

5. RESULTS OF RELAP5 CALCULATIONS

The calculated results of scenarios for ATWS, LOFW, SBLOCA and SGTR, described in Section 3, are presented. Compared are RELAP5/MOD2 (input model for cycle 17), RELAP5/MOD3.3 (input model for cycle 19), RELAP5/MOD3.3 (input model for cycle 21) and RELAP5/MOD3.3 Patch 03 (input model for cycle 21). The RELAP5/MOD2 is the last, frozen computer code version 36.05 from 1989. The RELAP5/MOD3.3 is computer code version 3.3bf from February 2002 and RELAP5/MOD3.3 Patch 03 is computer code version 3.3gl from March 2006. The calculations with RELAP5/MOD3.3 and RELAP5/MOD3.3 Patch 03 computer codes were performed using same initial conditions and models. In general, the differences for the indicated variables are small. Besides different initial conditions (reactor kinetics feedbacks, initial pressurizer level, initial SG level, different SG level regulation, consideration of pump seal flow) important difference between RELAP5/MOD2 and RELAP5/MOD3.3 calculations was the break flow model used (Ransom-Trapp versus Henry-Fauske). As can be seen, the cycle 21 calculation with RELAP5/MOD3.3 Patch 03 is just reanalysis and results in principle should be the same except for code improvements influence. The main aim of reanalysis was to prepare the source data for SNAP animation model with the latest RELAP5 and not to compare RELAP5 calculations with different versions. Nevertheless, the comparison was done with previous versions in order to be sure that the calculated data are comparable to the previously verified reference calculations. The reasons for discrepancies are also explained.

For each scenario the sequence of events for RELA5/MOD3.3 Patch 03 is given, created by SNAP animation model. In addition, a few important variables are shown and described to understand the transient. This will help the user of the Krško NPP animation model to understand the transients when animating the SNAP masks with the source data of reference calculations.

5.1 Anticipated Transient Without Scram Results

The results for ATWS are shown in Table 1 and Figures 22 through 30. ATWS transient started at simulation time 0 s, when both main feed water lines to the steam generators were closed due to malfunction in the main feed system. Initially, absence of the subcooled main feedwater flow into the steam generators slowed down the recirculation and caused increased steam production in the saturated secondary liquid-vapor mixture. The low-low SG level alarm (NR level < 13 %) started the AFW pumps around 56 second. Due to degraded SG ability to remove the heat produced in the core (fission + decay) the secondary pressure started to increase as shown in Figure 22. At the same time the AFW flow was insufficient to refill the SG. This resulted in secondary pressure initial rise. Before the turbine trip the steam from the steam generators was released through the condenser via turbine at 100 % mass flow rate. Since the SG inventory was discharged (Figure 23), the steam line pressure soon started to decrease, which produced SI signal at time 97 seconds. That caused the turbine trip, steam line isolation (Figure 24) and also disabled steam dump operation. Meanwhile, due to SG PORV and safety valves opening, SG water level is further decreasing till the steam generators dry out at time around 91 seconds (SG NR level below 1 %). After the turbine trip the steam produced in steam generators is released through SG PORVs. Shortly after that (within the next 100 seconds) steady state was reached on the secondary side and the SG PORVs steam release was balanced by the cold water delivered from the AFW system.

Table 1 Main plant signals and sequence of events - ATWS

Time: 10000.1 s

SIGNALS	transient timing [s]	TRIP		
Reactor trip signal generation	0	0		
SI signal generation	97	1		
turbine trip	69	1		
steam line 1 isolation	97	1		
steam line 2 isolation	97	1		
MFW 1 isolation	1	1		
MFW 2 isolation	1	1		
EVENTS	**transient timing [s]**	**TRIP**		
accumulator no.1 initialization / isolation	0 / 0	0 / 0		
accumulator no.1 first injection	0	0	0.0	[kg]
accumulator no.2 initialization / isolation	0 / 0	0 / 0		
accumulator no.2 first injection	0	0	0.0	[kg]
LPSI pump no.1 initialization	107	1		
LPSI pump no.1 first injection	0	1	2.4077497	[kg]
LPSI pump no.2 injection	107	1		
LPSI pump no.2 first injection	0	1	2.3508828	[kg]
HPSI pump no.1 initialization	102	1		
HPSI pump no.1 first injection	102	1	6.4987364	[kg/s]
HPSI pump no.2 initialization	102	1		
HPSI pump no.2 first injection	102	1	6.4987364	[kg/s]
AF MD pump no.1 start	56	1		
AF MD pump no.2 start	56	1		
AF TD pump start	0	0		
RCP 1 trip	0	0		
RCP 2 trip	0	0		
charging isolation	97	1		
letdown isolation	278	1		
steam dump - plant trip	69	1		

According to the NPP Krško Technical Specification the reactor trip signal is not produced therefore the reactor remains at full power 2000 MWt after the closure of the feedwater lines. Since low SGs water level disabled the heat extraction from the primary side, the primary pressure and coolant temperature started to increase. This caused primary coolant expansion. The pressurizer, which is compensating transient consequences, started to fill with liquid and the liquid level reached the top (solid pressurizer). At increased primary pressure above 17.2 MPa (Figure 25), PRZ PORVs and safety valves opened. The primary coolant average temperature increase has negative feedback effect on core reactivity. During the initial steady state operation reactivity was kept around 0 (Figure 26). It started to decrease in the beginning of the primary coolant average temperature increase (Figure 27) and reached its minimum value around 150 seconds. The reactor core power was decreased to minimum around 300 seconds (Figure 30) what resulted from negative feedback effects caused by primary coolant average temperature increase. Before AMSAC intervention steam extraction from both steam generators increased, causing primary coolant average temperature decrease and consequently positive feedback effects. A short return to power was observed after that, at around 400 second. Later in the transient (after 2000 seconds), steady state was reached.

The root cause for slight differences between RELAP5/MOD3.3 and RELAP5/MOD3.3 Patch 03 was the mass flow through PRZ PORVs. In the case of RELAP5/MOD3.3 Patch 03 more mass was discharged through PRZ PORVs comparing to RELAP5/MOD3.3 as can be seen in Figures 29 and 30 (flow is shown in the period from 0 to 500 seconds). The PRZ PORVs were modeled by motor valve. PRZ PORVs were initially opened approximately in the period between 70 and 200 second. Therefore in the RELAP5/MOD3.3 Patch 03 calculation pressure drops 14 seconds faster below the HPSI pump shutoff head than in the RELAP5/MOD3.3 calculation. Earlier injection caused further pressure decrease causing higher injection flow and the time difference in HPSI flow termination at around 700 seconds was already 50 seconds. As the pressures at that time were very close to the shutoff head, and due to the fact that injection initially also helps to further reduce the pressure, in RELAP5/MOD3.3 Patch 03 calculation the injection after 800 seconds lasted approximately 300 seconds longer than in the RELAP5/MOD3.3 calculation, and that causes differences in the primary pressure, in spite of the fact that flow was only a few kg/s. The primary pressure further influences the primary coolant average temperature. In the case with more injected water the temperature drops more. The other parameters agree rather well.

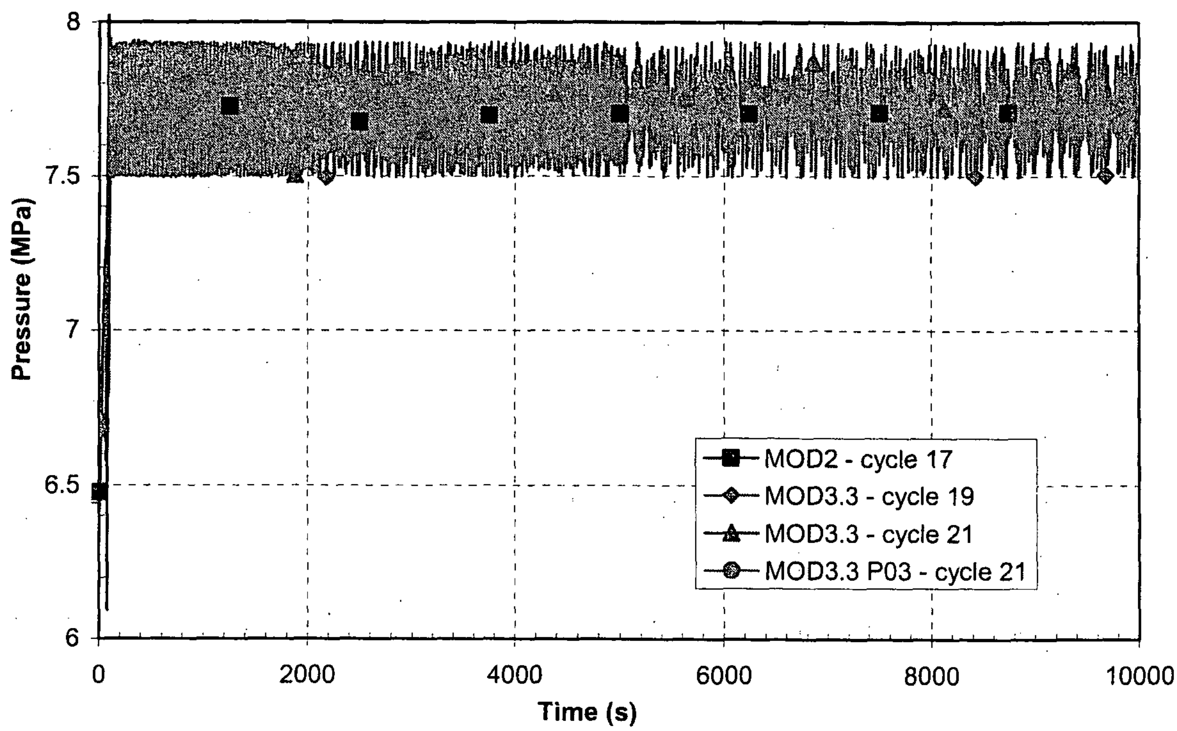


Figure 22 Steam generator no. 1 pressure – ATWS

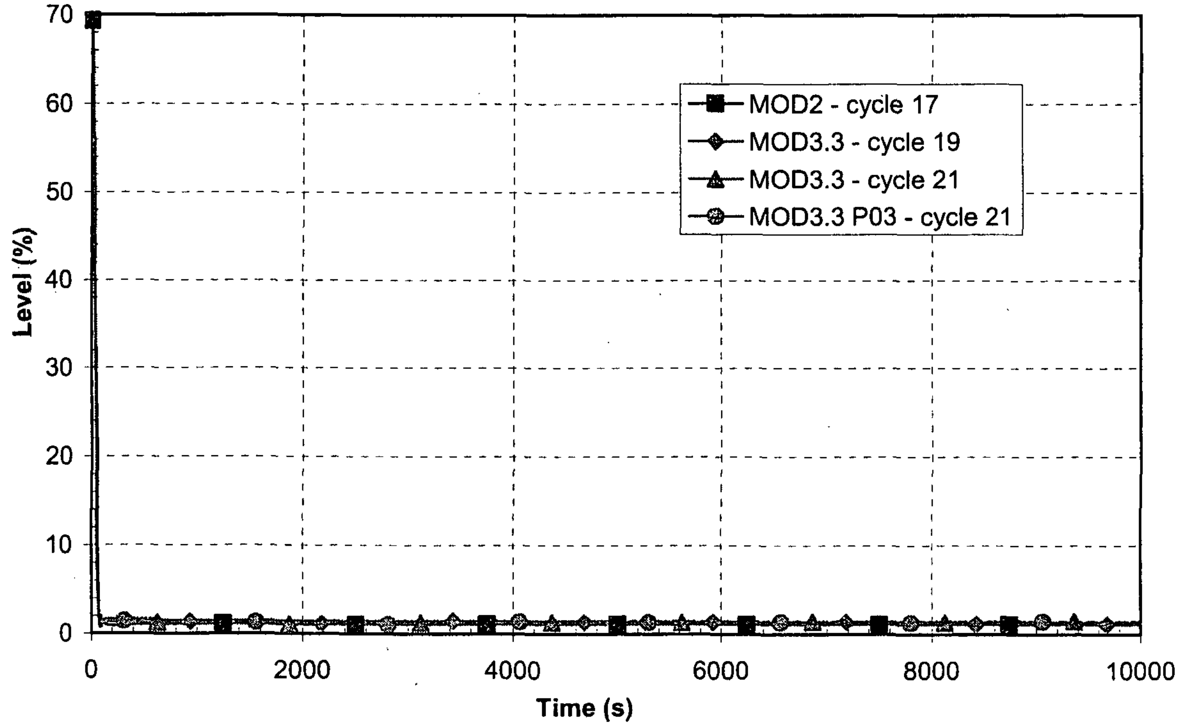


Figure 23 Steam generator no. 1 narrow range level – ATWS

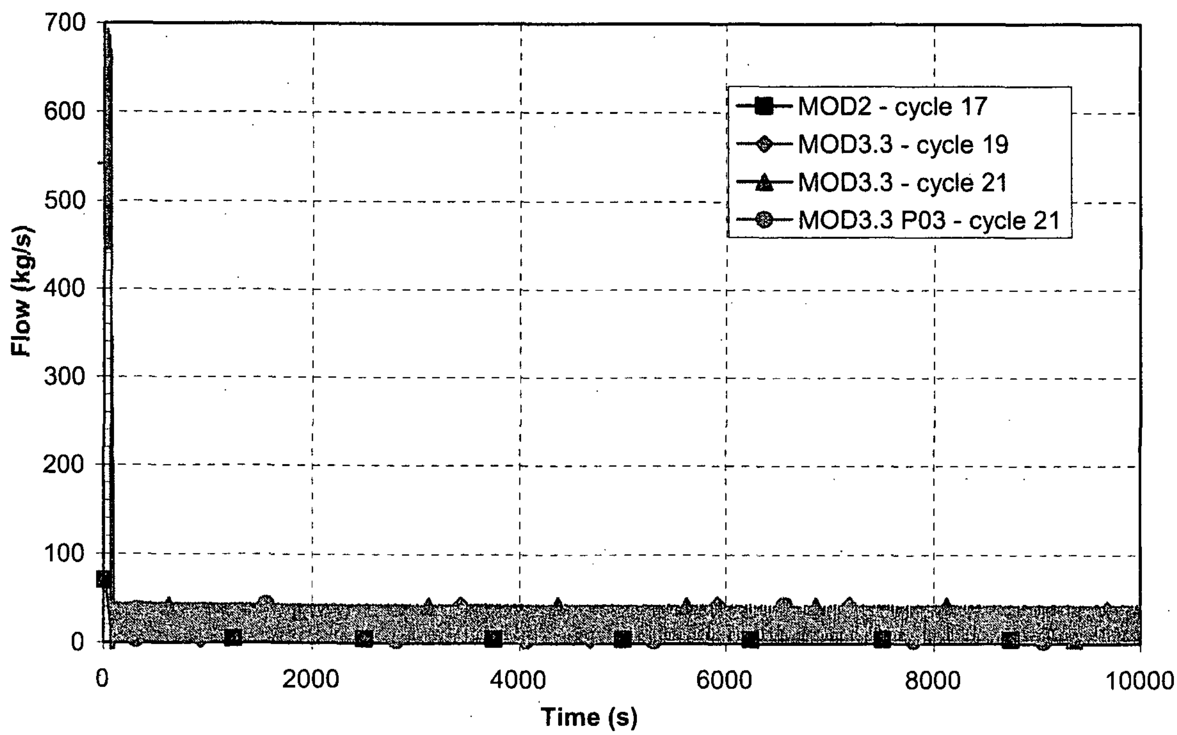


Figure 24 Main steamline no. 1 flow – ATWS

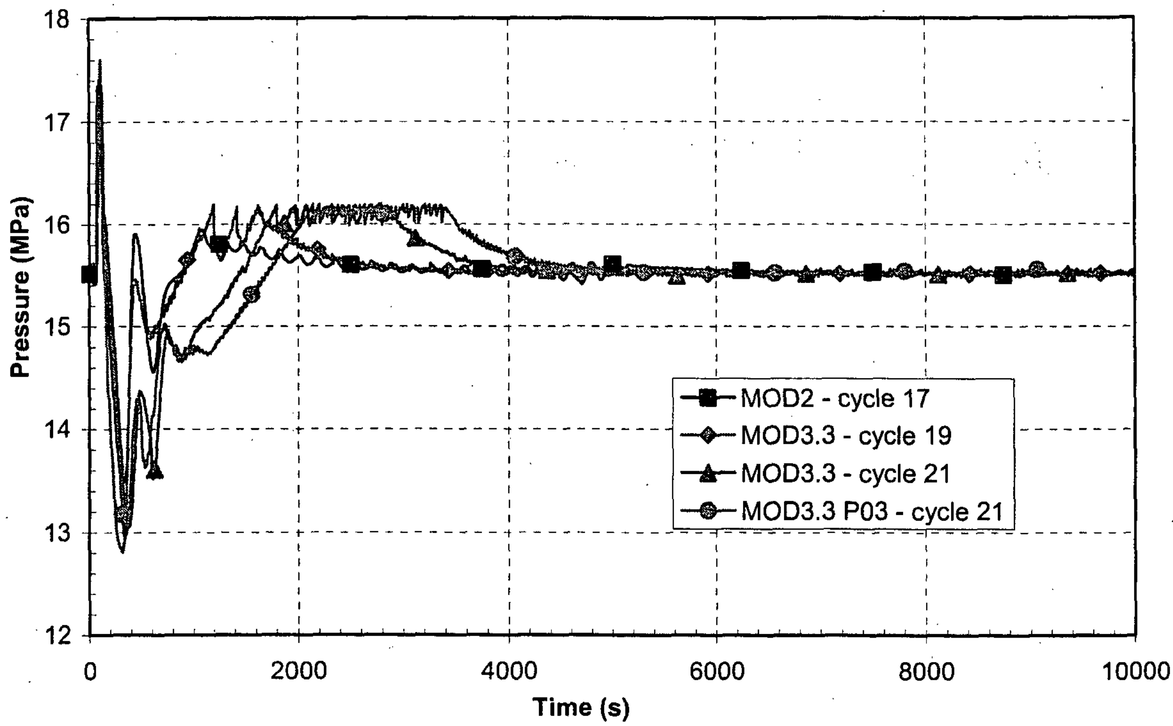


Figure 25 Primary pressure – ATWS

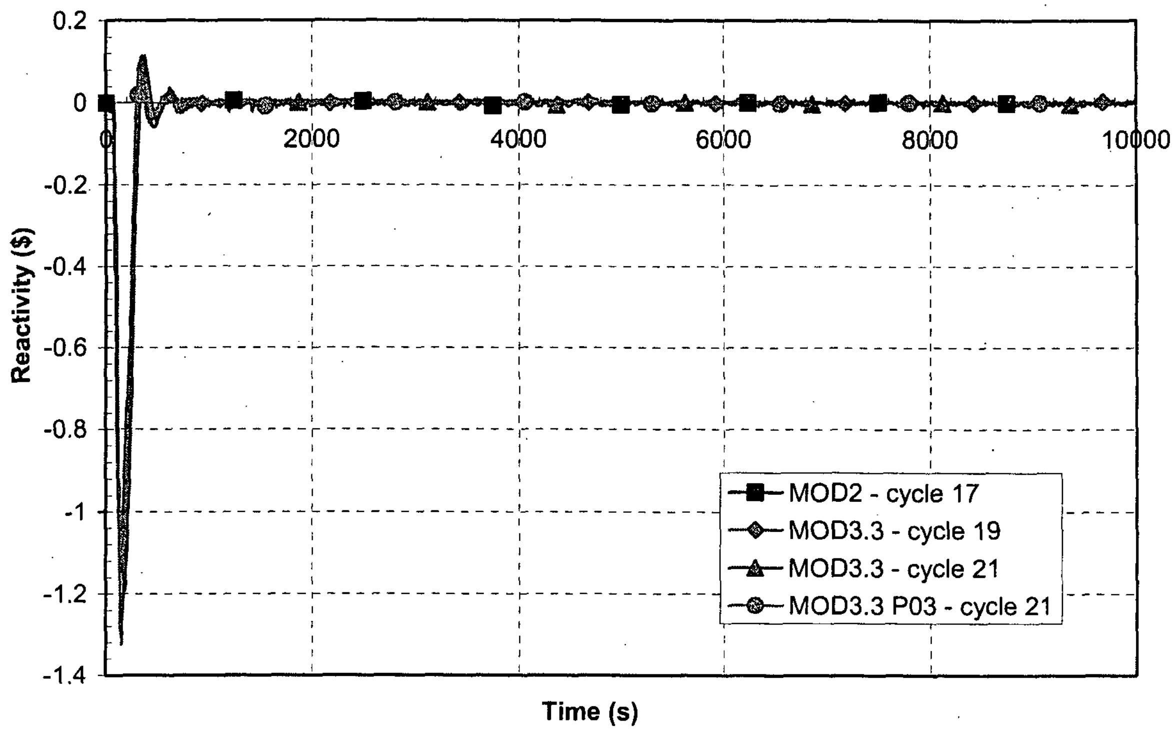


Figure 26 Reactivity – ATWS

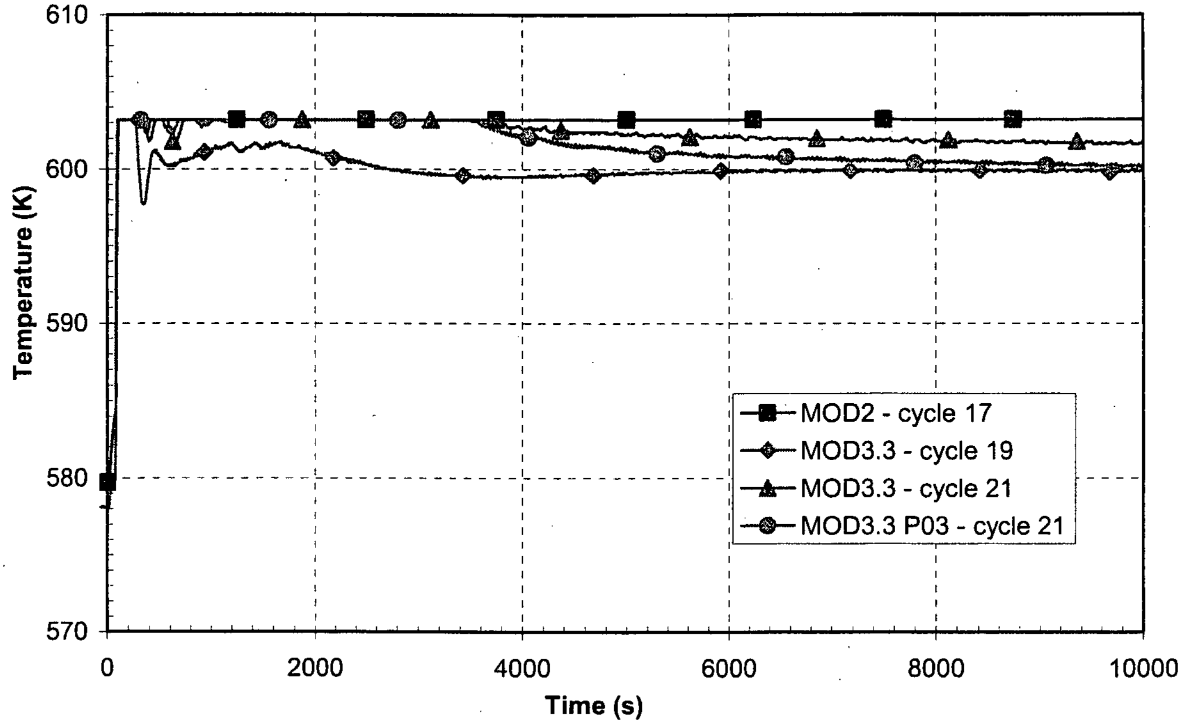


Figure 27 Primary coolant average temperature – ATWS

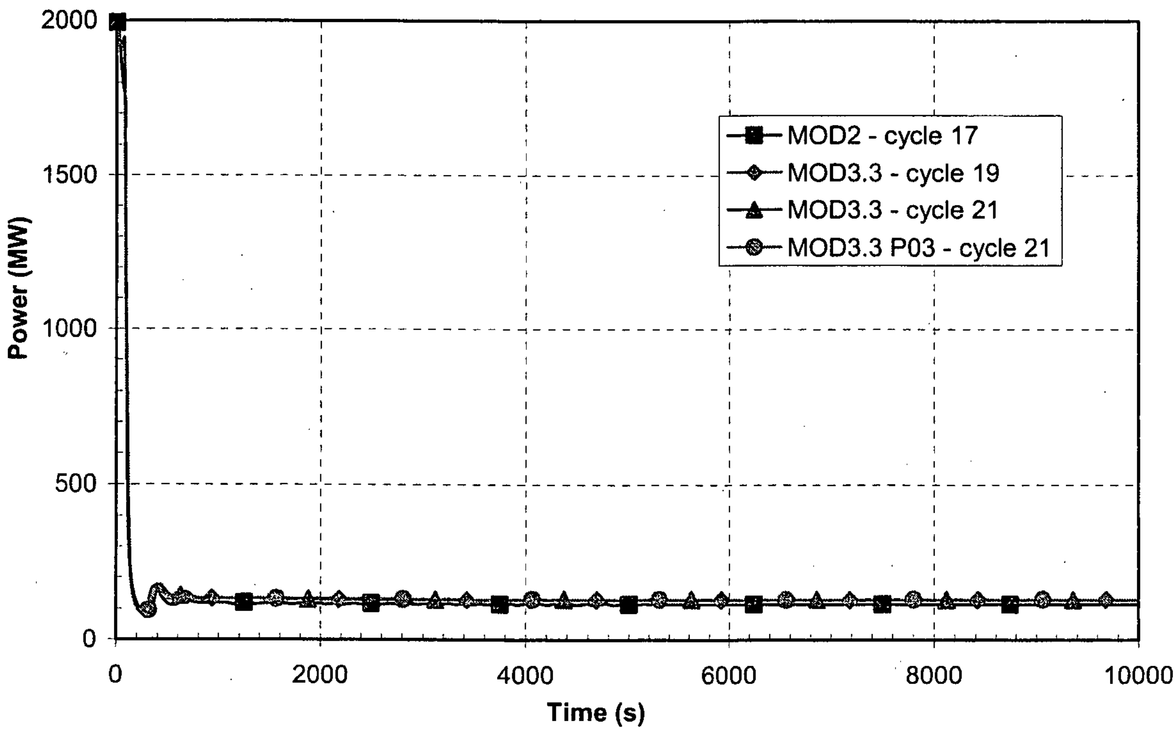


Figure 28 Core power – ATWS

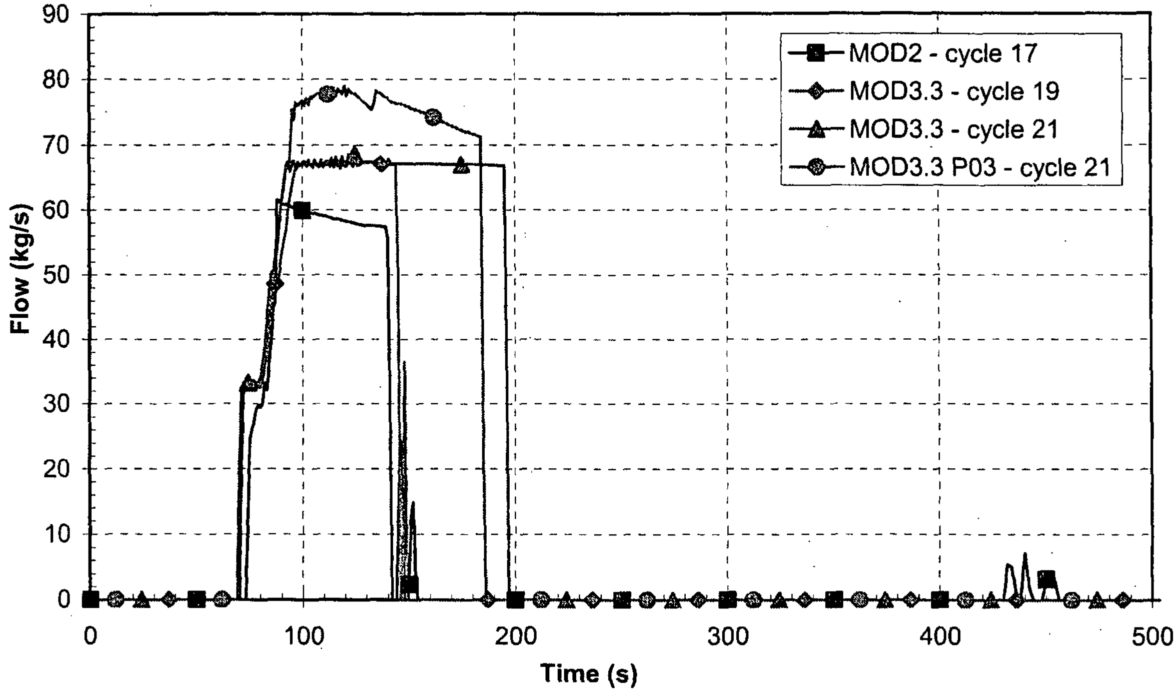


Figure 29 Pressurizer PORV no. 1 mass flow – ATWS

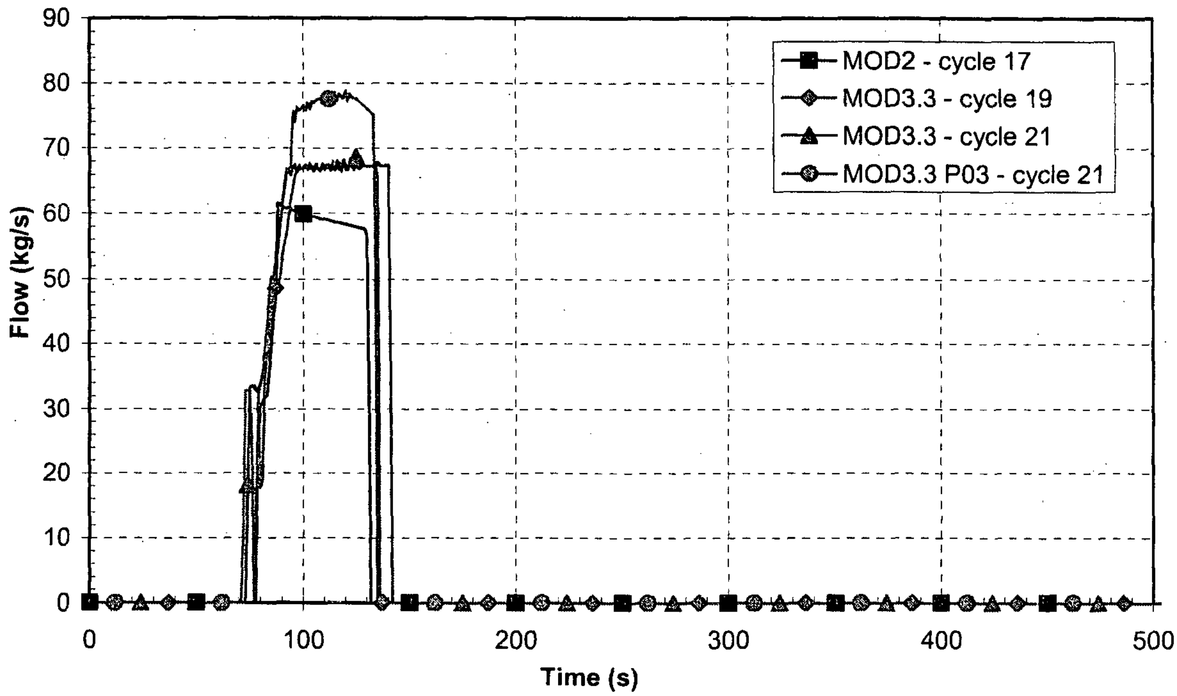


Figure 30 Pressurizer PORV no. 2 mass flow – ATWS

5.2 Loss of Feedwater Results

5.2.1 Loss of Feedwater with Auxiliary Feedwater Available Results

The results for LOFW with AFW available are shown in Table 2 and Figures 31 through 36. Due to unavailability of all data for RELAP5/MOD3.3 calculation of cycle 21 only three calculations were compared. Table 2 shows main sequence of events for the LOFW scenario, as calculated by RELAP5/MOD3.3 Patch 03 code. The triggering time for each event is given. The loss of feedwater leads to reactor trip after reaching low-low level setpoint in the steam generator (Figure 31), set to 13 % NR span. This consequently caused turbine trip. The primary pressure decreased (Figure 32) due to the reactor trip, while the secondary pressure increased due to the turbine trip (Figure 33).

Table 2 Main plant signals and sequence of events – LOFW with AFW available

Time: 9999.9 s

SIGNALS	transient timing [s]	TRIP		
Reactor trip signal generation	53	1		
SI signal generation	0	0		
turbine trip	53	1		
steam line 1 isolation	0	0		
steam line 2 isolation	0	0		
MFW 1 isolation	1	1		
MFW 2 isolation	1	1		
EVENTS	**transient timing [s]**	**TRIP**		
accumulator no.1 initialization / isolation	0 / 0	0 / 0		
accumulator no.1 first injection	0	0	0.0	[kg]
accumulator no.2 initialization / isolation	0 / 0	0 / 0		
accumulator no.2 first injection	0	0	0.0	[kg]
LPSI pump no.1 initialization	0	0		
LPSI pump no.1 first injection	0	0	0.0	[kg]
LPSI pump no.2 injection	0	0		
LPSI pump no.2 first injection	0	0	0.0	[kg]
HPSI pump no.1 initialization	0	0		
HPSI pump no.1 first injection	0	0	0.0	[kg/s]
HPSI pump no.2 initialization	0	0		
HPSI pump no.2 first injection	0	0	0.0	[kg/s]
AF MD pump no.1 start	56	1		
AF MD pump no.2 start	56	1		
AF TD pump start	0	0		
RCP 1 trip	0	0		
RCP 2 trip	0	0		
charging isolation	0	0		
letdown isolation	1310	0		
steam dump - plant trip	53	1		

When the auxiliary feedwater was activated, it started to fill steam generators. Pressurizer pressure rate sensitive PORV no.1 discharged briefly (see pressure spike in Figure 33) around 55 second, while no secondary coolant was discharged through SG PORVs into the atmosphere. During the initial transient stage and later the steam dump provided the continuous heat sink (Figure 34). The second PRZ PORV has never opened. As it can be seen from Figure 31, the auxiliary feedwater refilled the steam generator no. 1, so the accident consequences were successfully mitigated. CVCS pumps have successfully recovered primary inventory (Figure 35), so the core was never uncovered (Figure 36) and thus fuel rods never over-heated.

The results showed that practically there are no differences between RELAP5/MOD3.3 (cycle 19) and RELAP5/MOD3.3 Patch 03 (cycle 21). This means that LOFW transient with AFW available is not very much sensitive to fuel cycle.

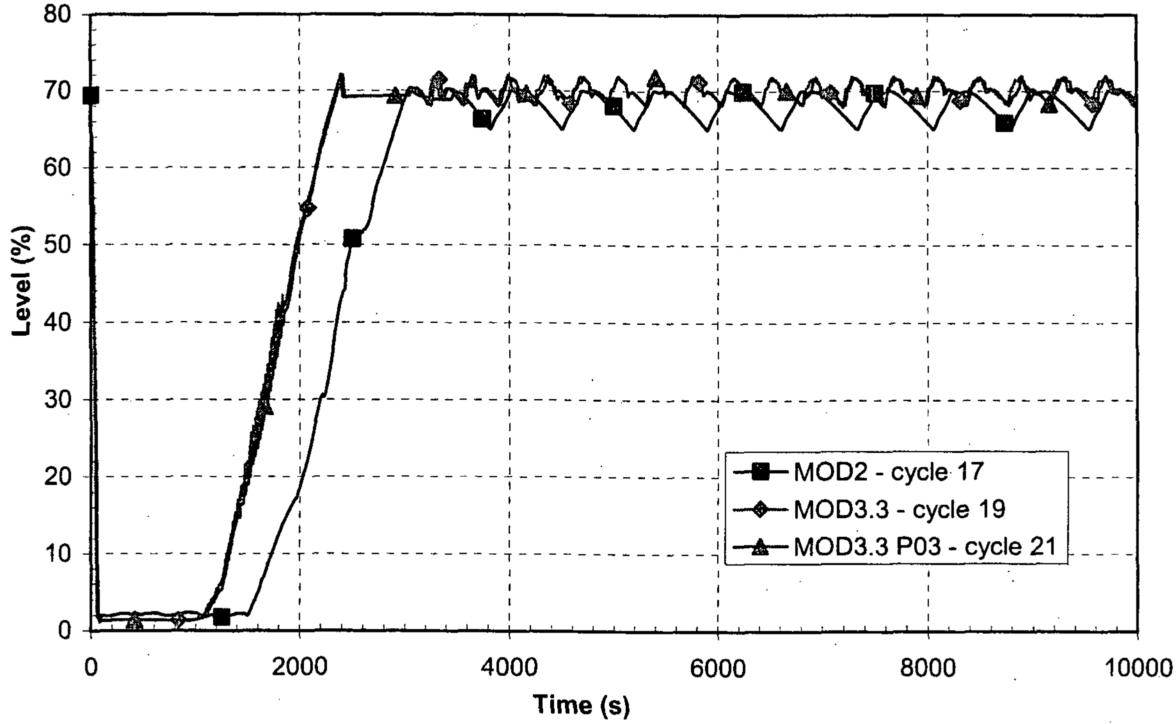


Figure 31 Steam generator no. 1 narrow range level – LOFW with AFW

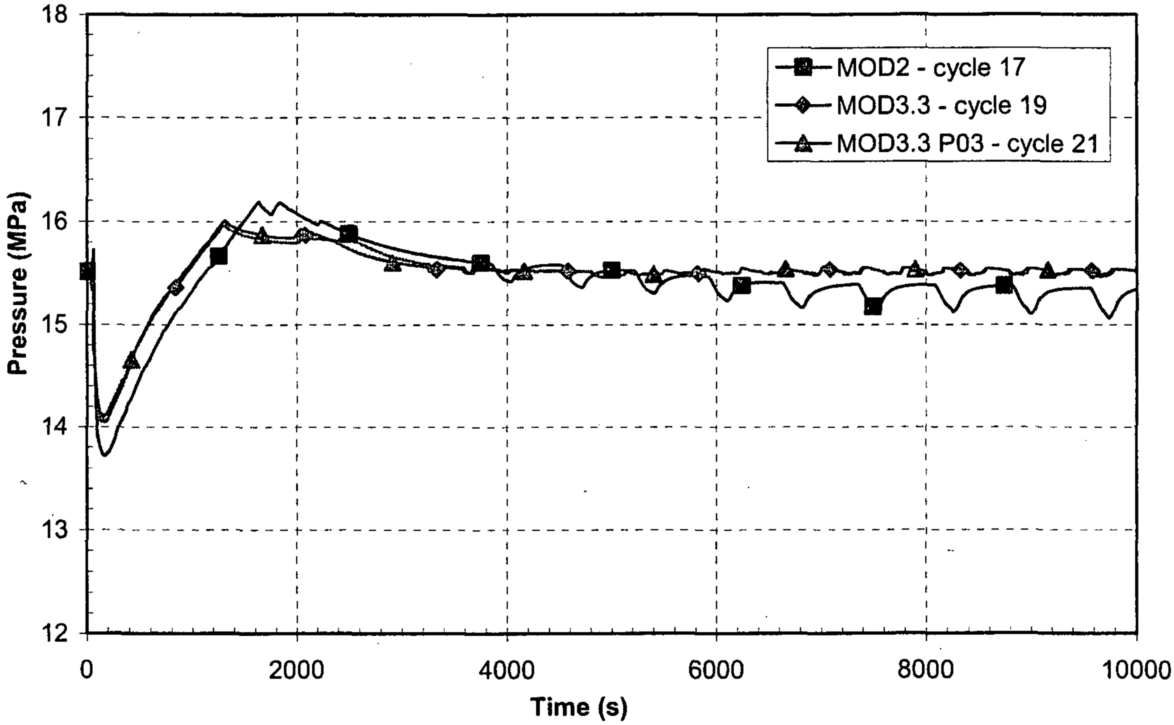


Figure 32 Primary pressure – LOFW with AFW

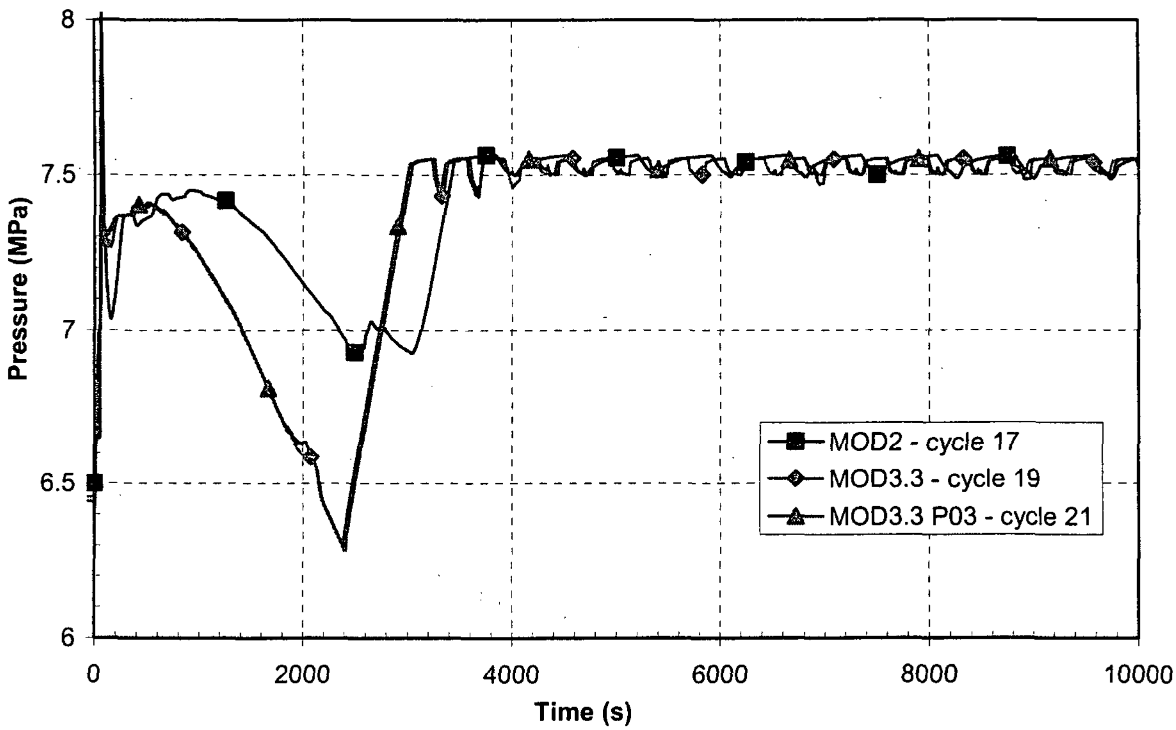


Figure 33 Steam generator no. 1 pressure – LOFW with AFW

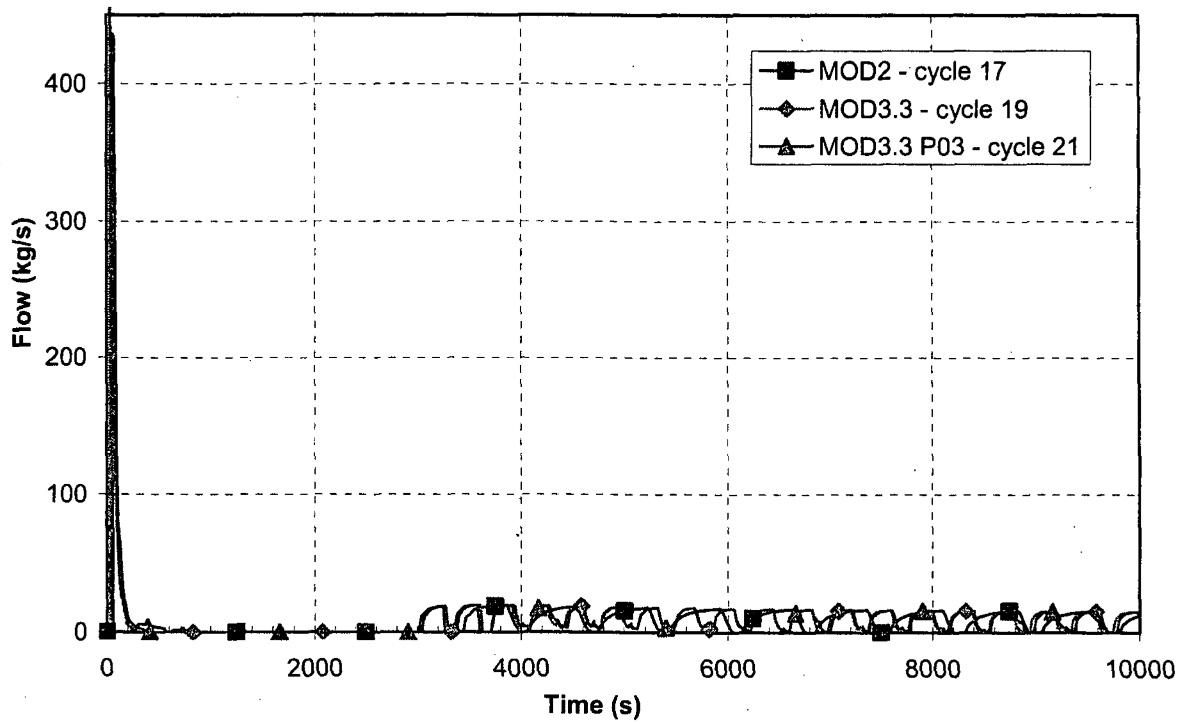


Figure 34 Steam dump flow – LOFW with AFW

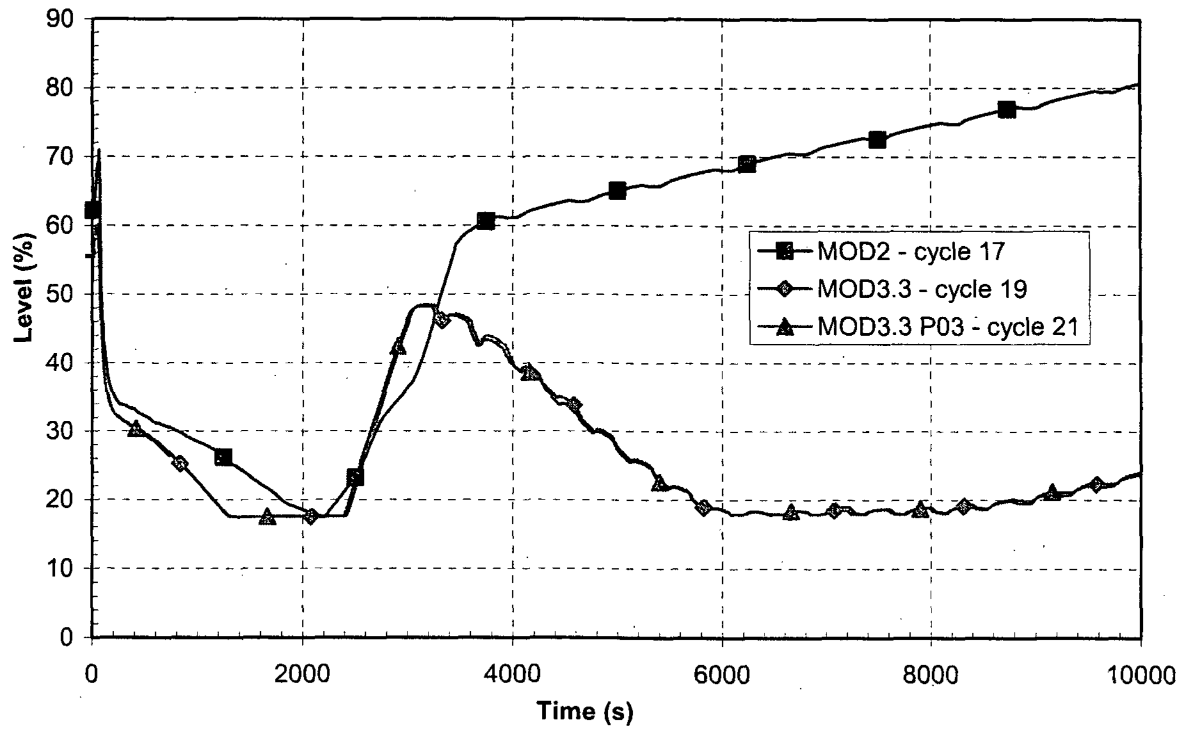


Figure 35 Pressurizer level – LOFW with AFW

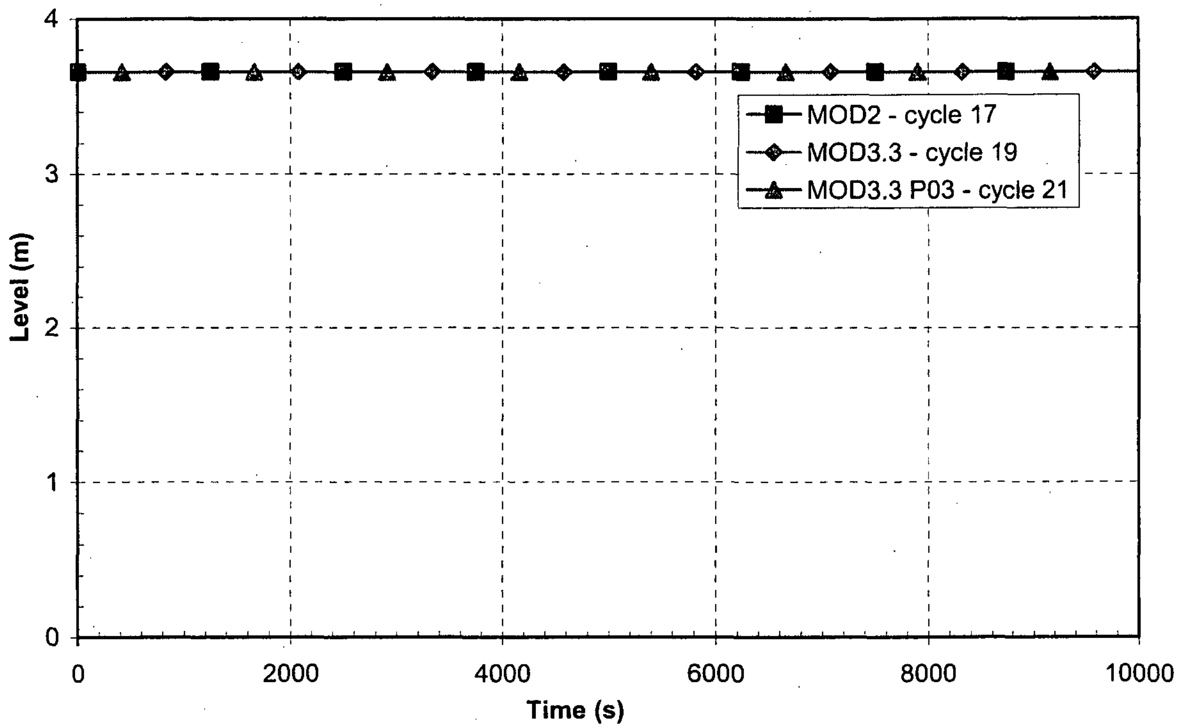


Figure 36 Core collapsed liquid level – LOFW with AFW

5.2.2 Loss of Feedwater without Auxiliary Feedwater Available Results

The results for LOFW with AFW available are shown in Table 3 and Figures 37 through 43. Table 3 shows main sequence of events for the LOFW scenarios, as calculated by RELAP5/MOD3.3 Patch 03 code. The triggering time for each event is given. The loss of feedwater leads to reactor trip after reaching low-low level setpoint in the steam generator (Figure 37), set to 13 % NR span. This consequently caused turbine trip. The primary pressure decreased (Figure 38) due to the reactor trip, while the secondary pressure increased due to the turbine trip (Figure 39).

Almost exactly as in the LOFW scenario with AFW available, negligible amounts of primary coolant was lost in the initial time period. At 618 seconds the SI signal was generated due to low-low steam line pressure (Figure 39), which caused the steam line isolation and disabled the steam dump operation (Figure 40). After the emptying of steam generators the primary temperature and pressure (Figure 38) started to increase. After 1200 seconds the pressurizer is full of liquid (Figure 41). The core uncovering could not be prevented, because the primary pressure became higher than the shutoff head of HPSI and CVCS pumps (Figure 42). Considerably more coolant has been lost to through PRZ PORVs. In fact this loss of primary coolant caused core dryout and overheating. As can be seen from Figure 43 core heat-up started after approximately 3000 seconds. Transient was terminated at 5095 second due to heat structures overheating, which caused a code failure. The results showed that there are negligible differences between RELAP5/MOD3.3 (cycle 19) and RELAP5/MOD3.3 Patch 03 (cycle 21).

Table 3 Main plant signals and sequence of events – LOFW without AFW available

Time: 5095.3 s

SIGNALS	transient timing [s]	TRIP		
Reactor trip signal generation	53	1		
SI signal generation	618	1		
turbine trip	53	1		
steam line 1 isolation	618	1		
steam line 2 isolation	618	1		
MFW 1 isolation	1	1		
MFW 2 isolation	1	1		

EVENTS	transient timing [s]	TRIP		
accumulator no.1 initialization / isolation	0 / 0	0 / 0		
accumulator no.1 first injection	0	0	0.0	[kg]
accumulator no.2 initialization / isolation	0 / 0	0 / 0		
accumulator no.2 first injection	0	0	0.0	[kg]
LPSI pump no.1 initialization	628	1		
LPSI pump no.1 first injection	0	1	2.4023886	[kg]
LPSI pump no.2 injection	628	1		
LPSI pump no.2 first injection	0	1	2.381105	[kg]
HPSI pump no.1 initialization	624	1		
HPSI pump no.1 first injection	624	1	6.4987364	[kg/s]
HPSI pump no.2 initialization	624	1		
HPSI pump no.2 first injection	624	1	6.4987364	[kg/s]
AF MD pump no.1 start	0	0		
AF MD pump no.2 start	0	0		
AF TD pump start	0	0		
RCP 1 trip	1595	1		
RCP 2 trip	1595	1		
charging isolation	618	1		
letdown isolation	798	1		
steam dump - plant trip	53	1		

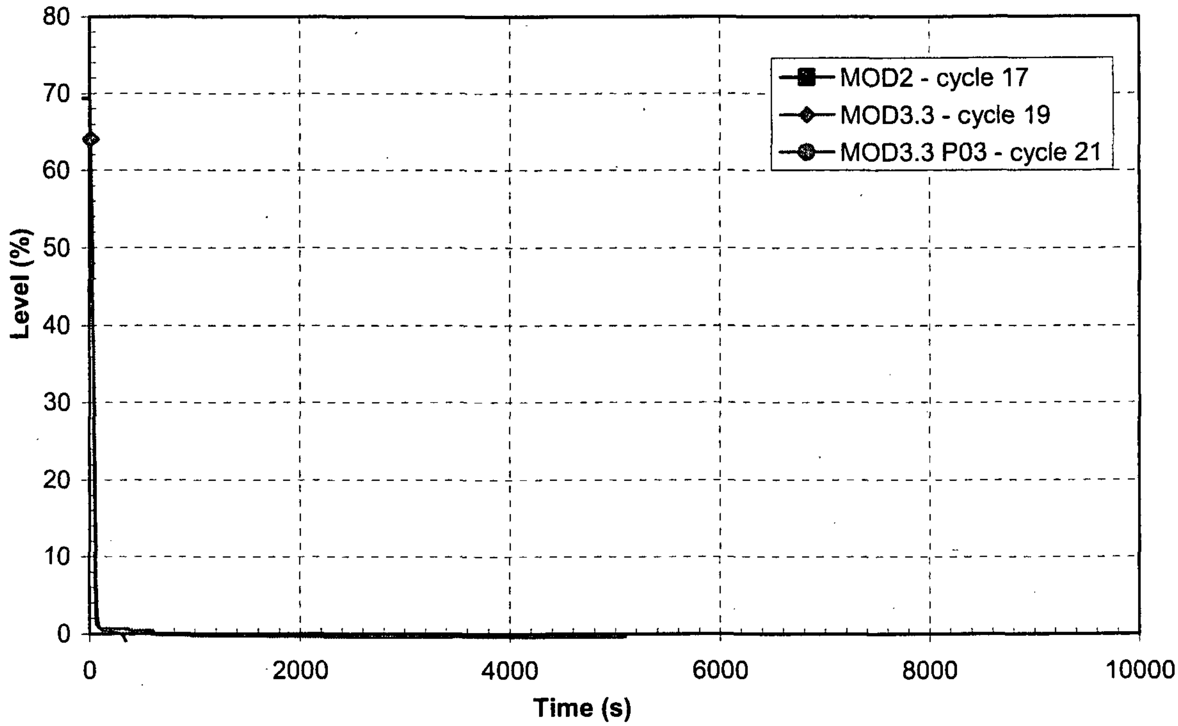


Figure 37 Steam generator no. 1 narrow range level – LOFW without AFW

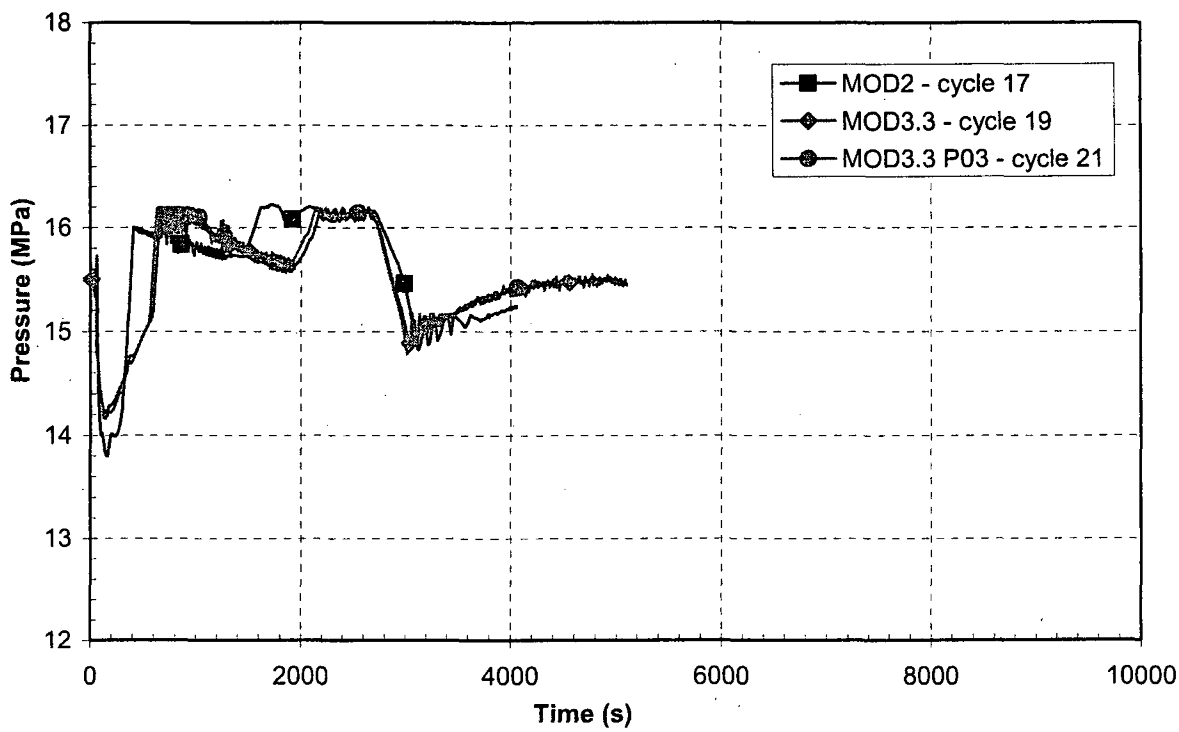


Figure 38 Primary pressure – LOFW without AFW

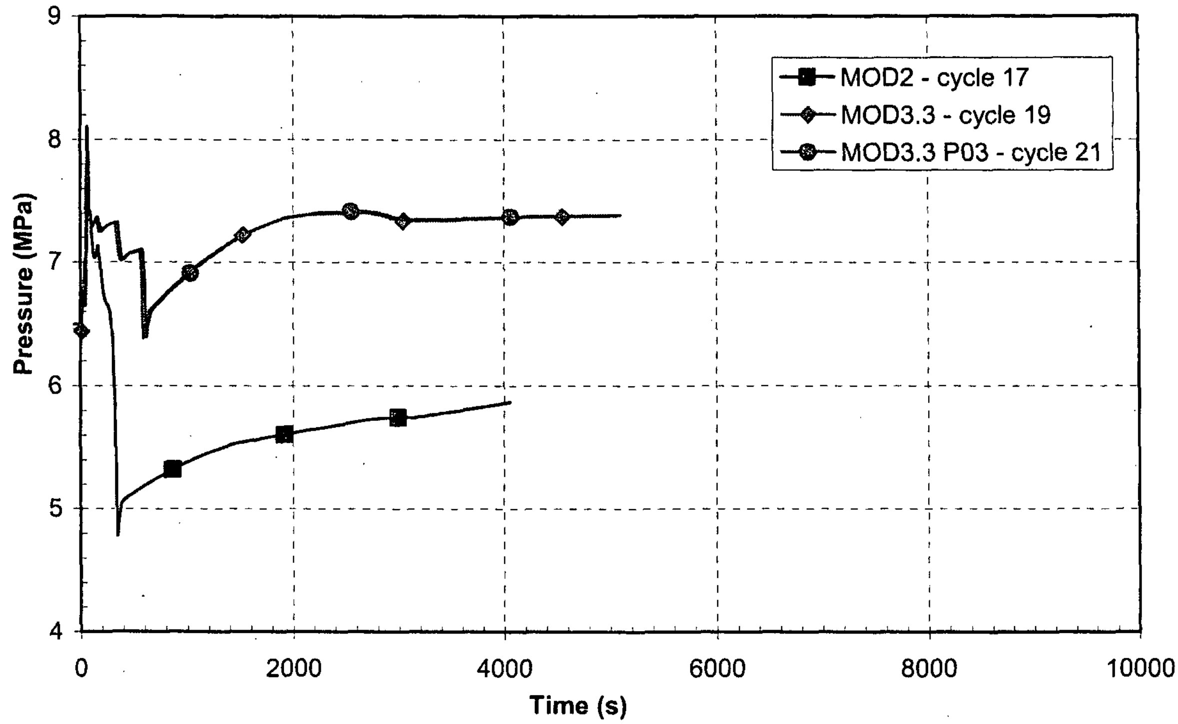


Figure 39 Steam generator no. 1 pressure – LOFW without AFW

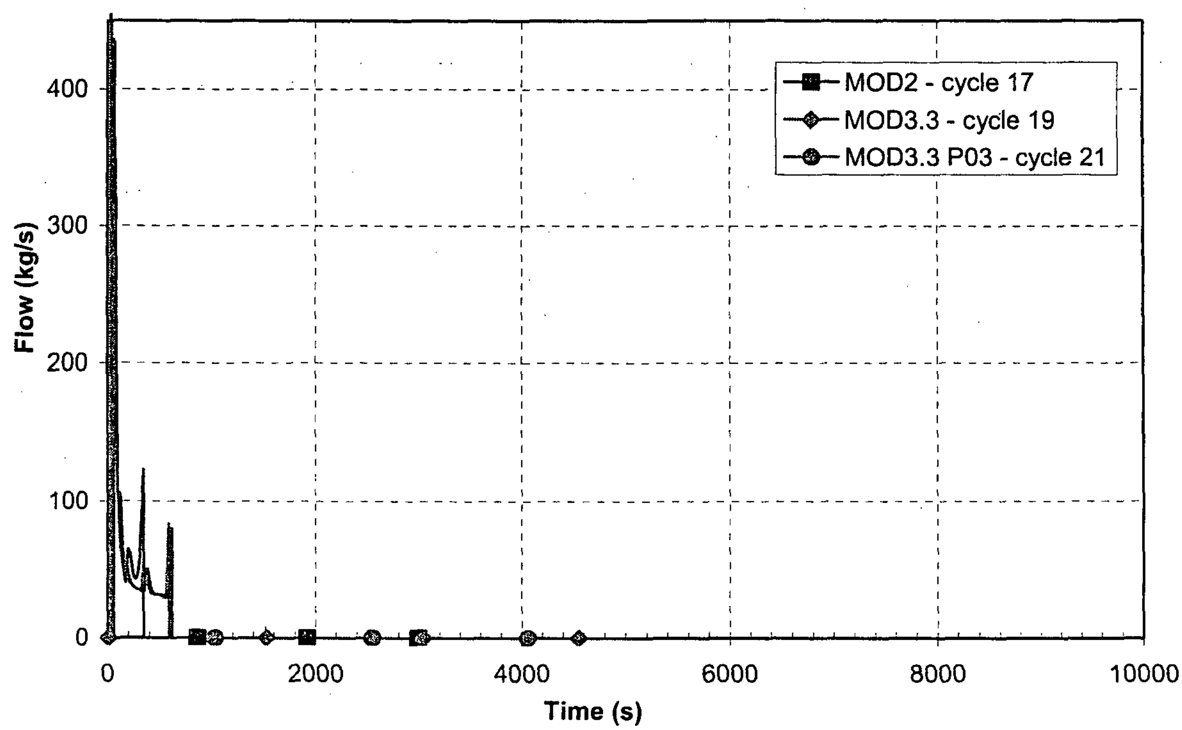


Figure 40 Steam dump flow – LOFW without AFW

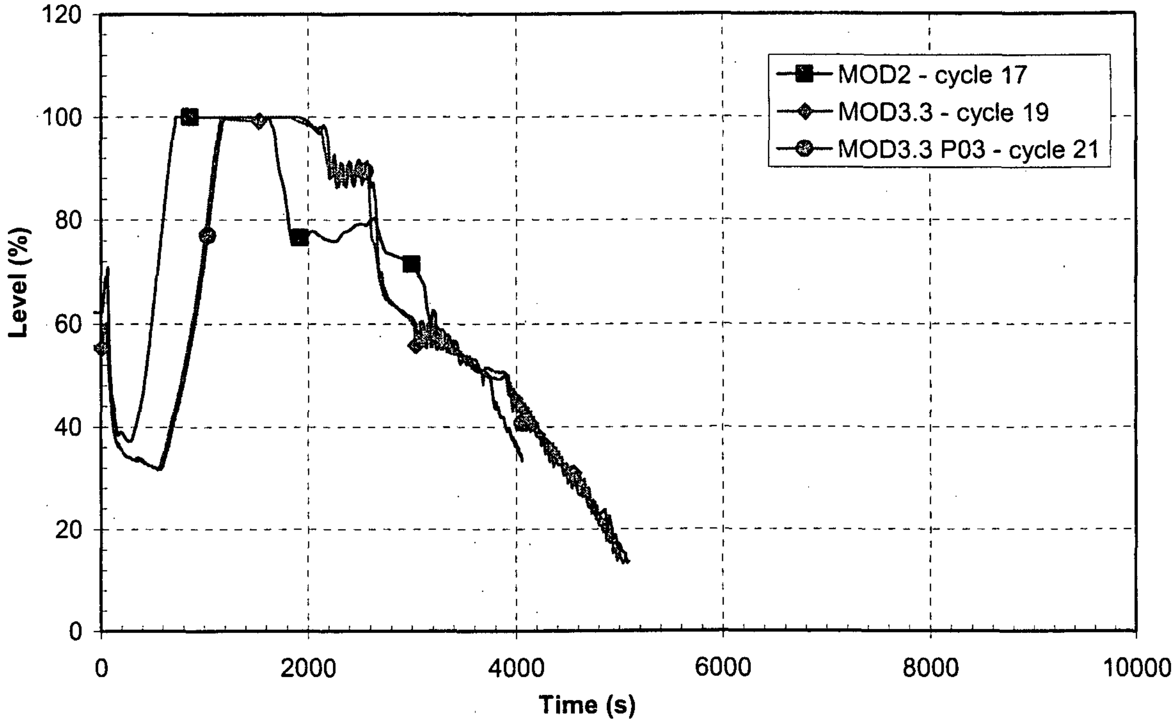


Figure 41 Pressurizer level – LOFW without AFW

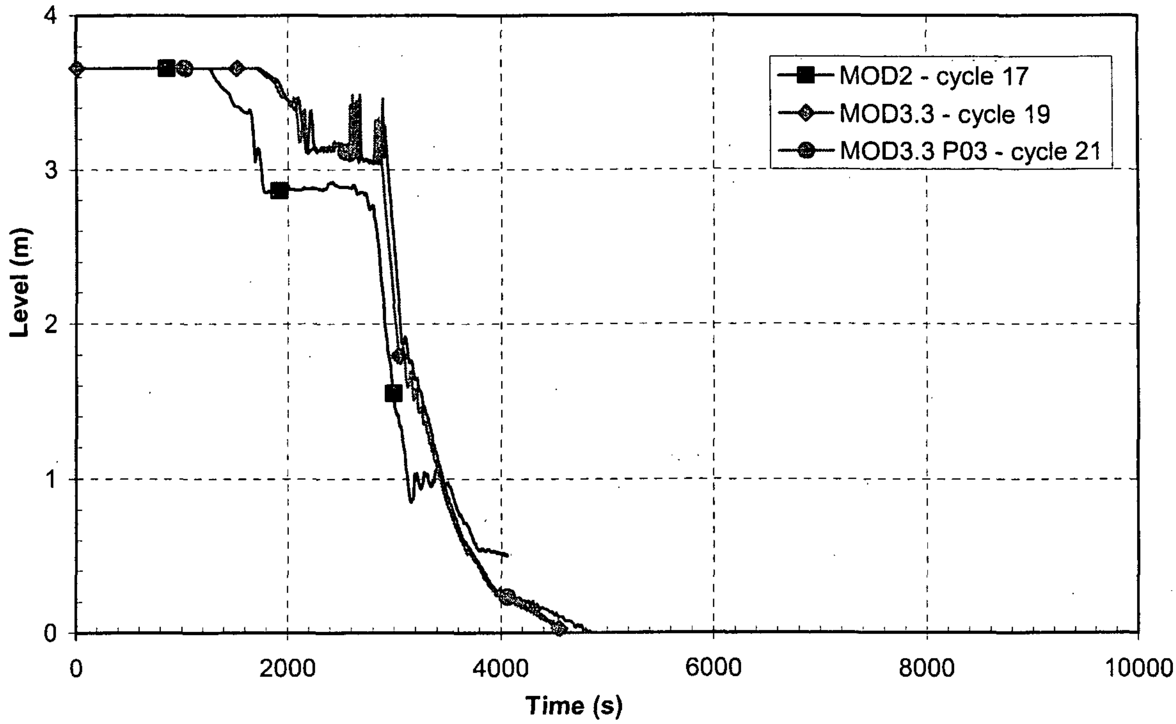


Figure 42 Core collapsed liquid level – LOFW without AFW

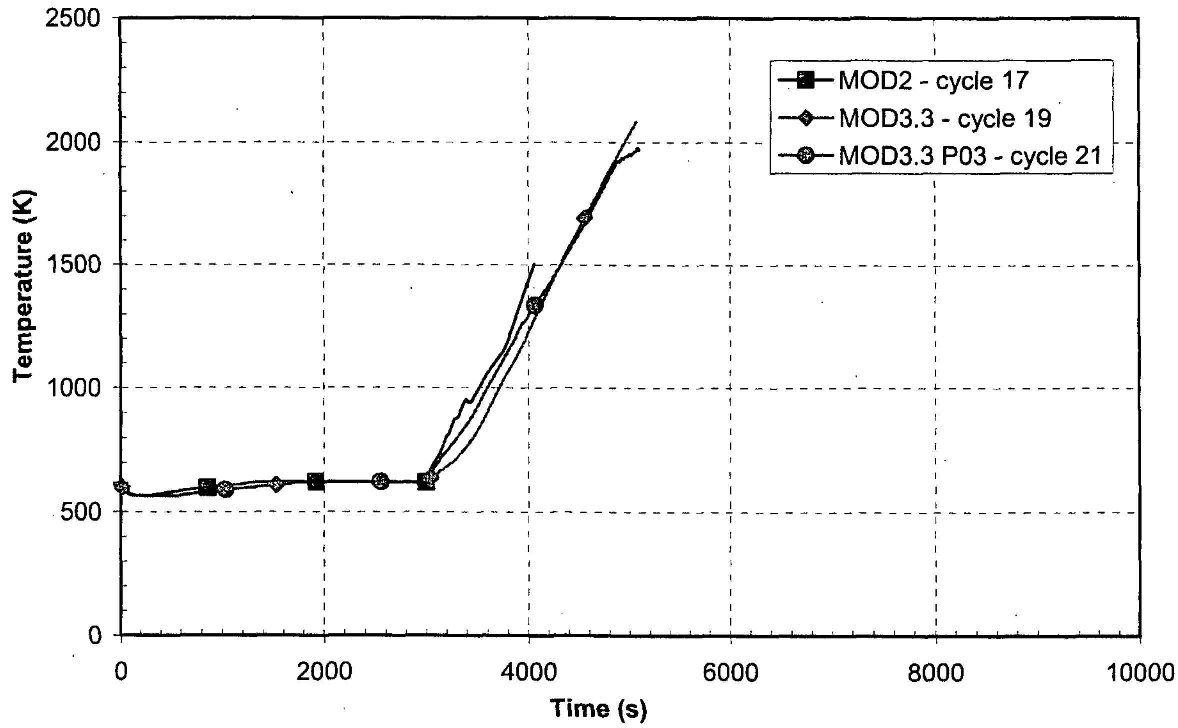


Figure 43 Core cladding outer surface temperature (11 of 12) – LOFW without AFW

5.3 Steam Generator Tube Rupture Results

The results for SGTR are shown in Table 4 and Figures 44 through 50. Table 4 shows main sequence of events for the SGTR accident, as calculated by RELAP5/MOD3.3 Patch 03 code. The triggering time for each event is given. After the initiation of tube rupture, the primary pressure started to decrease (Figure 44). Pressurizer heaters were turned on trying to rebuild the primary pressure. Pressurizer pressure and level (Figure 45) continued to decrease. Rapid pressure decrease was followed by reactor trip (at 334 second in RELAP5/MOD3.3 Patch 03 calculation) and SG isolation according to emergency operating procedures (on 5% difference in SG liquid levels). The reactor trip caused decreasing of the primary temperature, while the primary pressure continued to decrease because of the rupture. The safety injection signal setpoint was actuated (at 342 second in RELAP5/MOD3.3 Patch 03 calculation) on low pressure setpoint 12.27 MPa. The HPSI pumps started to pump with 5 seconds delay after the SI signal generation. After the actuation of HPSI pumps the pressurizer level started increasing. Since the operator did not turn off the safety injection, the pressurizer level continued to increase till the end of the transient (Figure 45). The primary liquid remained subcooled throughout the entire transient. Since enough subcooling was maintained, there was no need for the operator to trip RCPs as per emergency operating procedures.

The core stayed totally submerged throughout the entire transient. This kind of transient cannot cause core depletion whenever at least one HPSI pump is available. Due to rupture flow from the primary side (Figure 46) the secondary pressures in both steam generators (intact and ruptured) initially started to increase. The steam generator no. 1 pressure stabilized below

7.8 MPa (Figure 47), while the steam generator no. 2 pressure oscillated below 8 MPa (Figure 48) and was regulated by opening and closing of SG no. 2 PORV valve. Instantaneous decrease of the steam generator no. 1 and 2 mixture level (Figure 49 and Figure 50) at the beginning of the transient was caused by collapsing of vapor bubbles due to loss of heat source just after the reactor trip. After that the operator maintained the narrow range liquid level between 68 and 72% in the intact steam generator no. 1. Steam generator no. 2 level increased later due to rupture flow from the primary side (steam generator no. 2 is isolated) and due to secondary pressure increase, caused by turbine trip. Instantaneous closure of steamline flow at the beginning of the transient following the turbine trip caused that the steam dump drew a small amount of steam to the condenser. After the steam generator isolation the oscillations of the steamline no. 2 mass flow were caused by opening/closing of the SG no. 2 PORV.

Table 4 Main plant signals and sequence of events – SGTR

Time: 10000.0 s

SIGNALS	transient timing [s]	TRIP
Reactor trip signal generation	334	1
SI signal generation	342	1
turbine trip	334	1
steam line 1 isolation	472	1
steam line 2 isolation	472	1
MFW 1 isolation	342	1
MFW 2 isolation	342	1

EVENTS	transient timing [s]	TRIP	
accumulator no.1 initialization / isolation	0 / 0	0 / 0	
accumulator no.1 first injection	0	0	0.0 [kg]
accumulator no.2 initialization / isolation	0 / 0	0 / 0	
accumulator no.2 first injection	0	0	0.0 [kg]
LPSI pump no.1 initialization	352	1	
LPSI pump no.1 first injection	0	1	2.5712736 [kg]
LPSI pump no.2 injection	352	1	
LPSI pump no.2 first injection	0	1	2.6257865 [kg]
HPSI pump no.1 initialization	348	1	
HPSI pump no.1 first injection	348	1	17.404655 [kg/s]
HPSI pump no.2 initialization	348	1	
HPSI pump no.2 first injection	348	1	17.597588 [kg/s]
AF MD pump no.1 start	368	1	
AF MD pump no.2 start	368	0	
AF TD pump start	0	0	
RCP 1 trip	0	0	
RCP 2 trip	0	0	
charging isolation	342	1	
letdown isolation	218	1	
steam dump - plant trip	334	1	

There were some differences between RELAP5/MOD3.3 and RELAP5/MOD3.3 Patch 03 calculations. The reason is that MD AFW pump should be isolated after main steam isolation valve (MSIV) closure, which occurred at 466 s, but this does not happen in the case of RELAP5/MOD3.3. The isolation in RELAP5 was modeled with 'motor valve'. In

RELAP5/MOD3.3 Patch 03 the motor valves work correctly. It should be noted that at ATWS the reason of differences was also motor valve. Namely, the discharge flow rates for pressurizer PORV between RELAP5/MOD3.3 and RELAP5/MOD3.3 Patch 03 were different. Finally, the RELAP5/MOD2 calculations are in a reasonable agreement with the RELAP5/MOD3.3 Patch 03 trend in spite of the differences in initial and boundary conditions, break flow model and the core cycle.

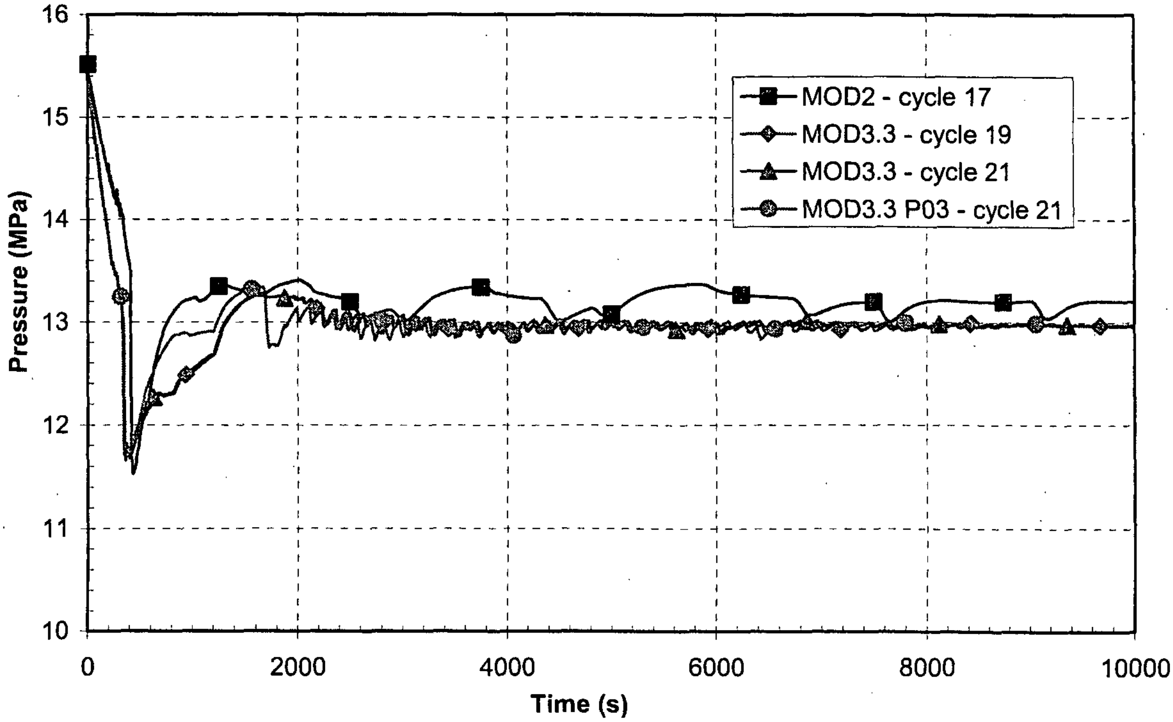


Figure 44 Primary pressure – SGTR

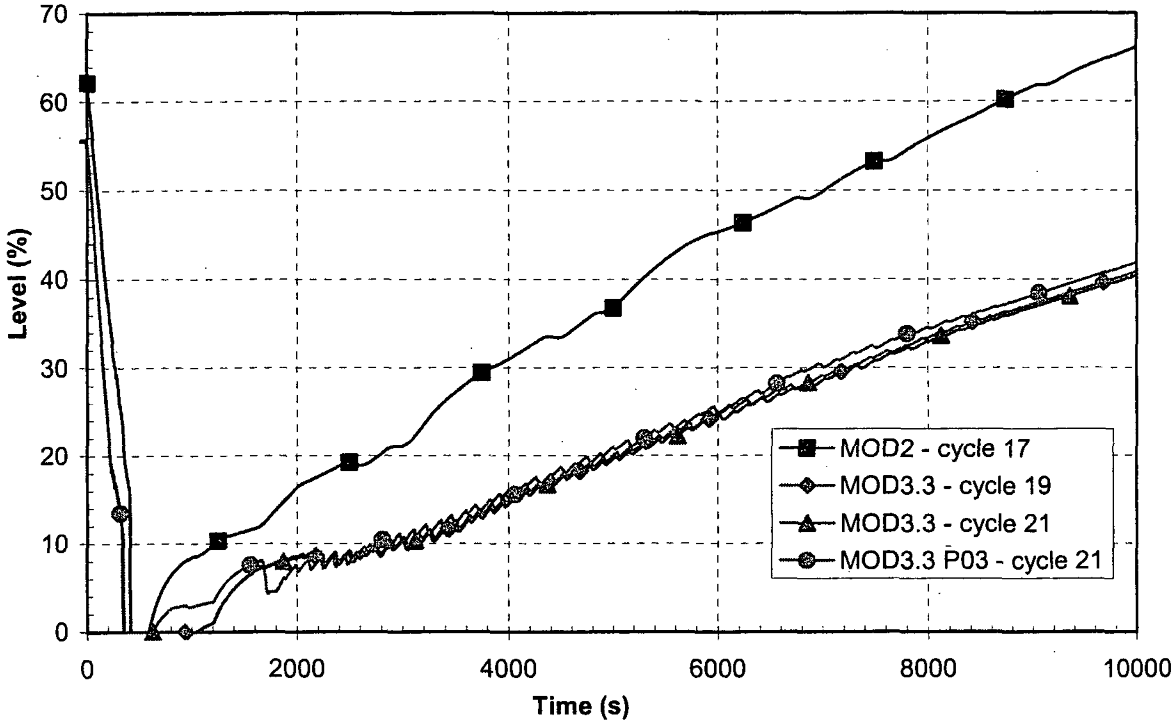


Figure 45 Pressurizer level – SGTR

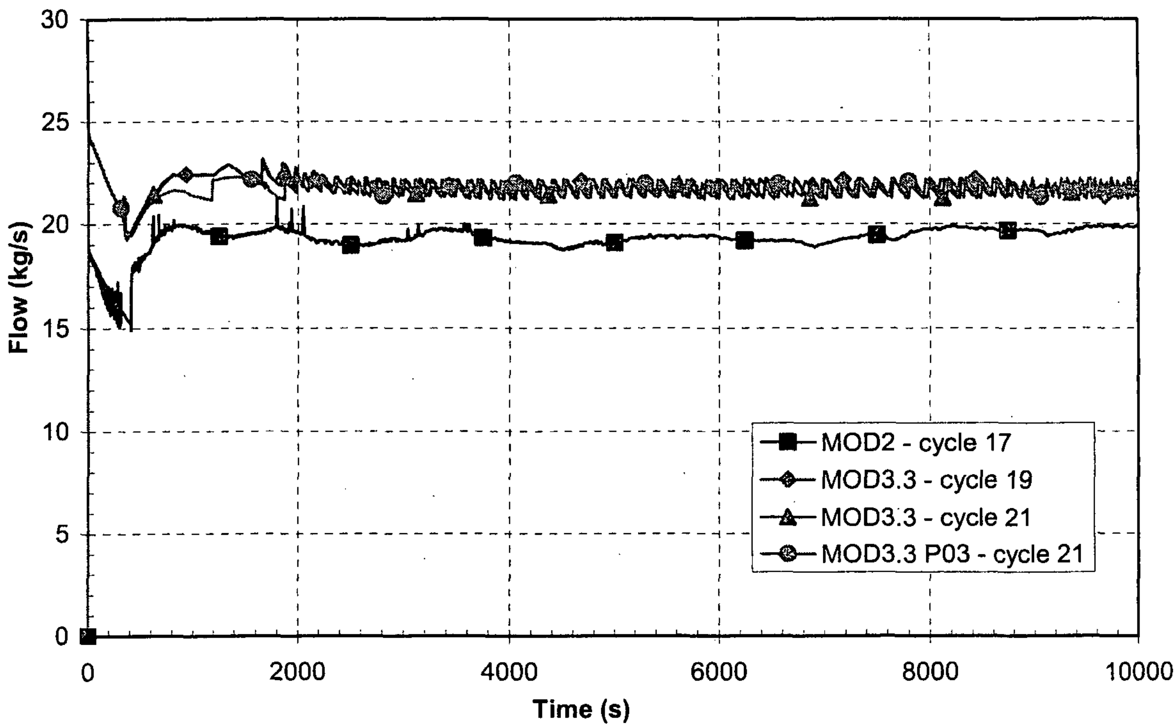


Figure 46 Rupture flow – SGTR

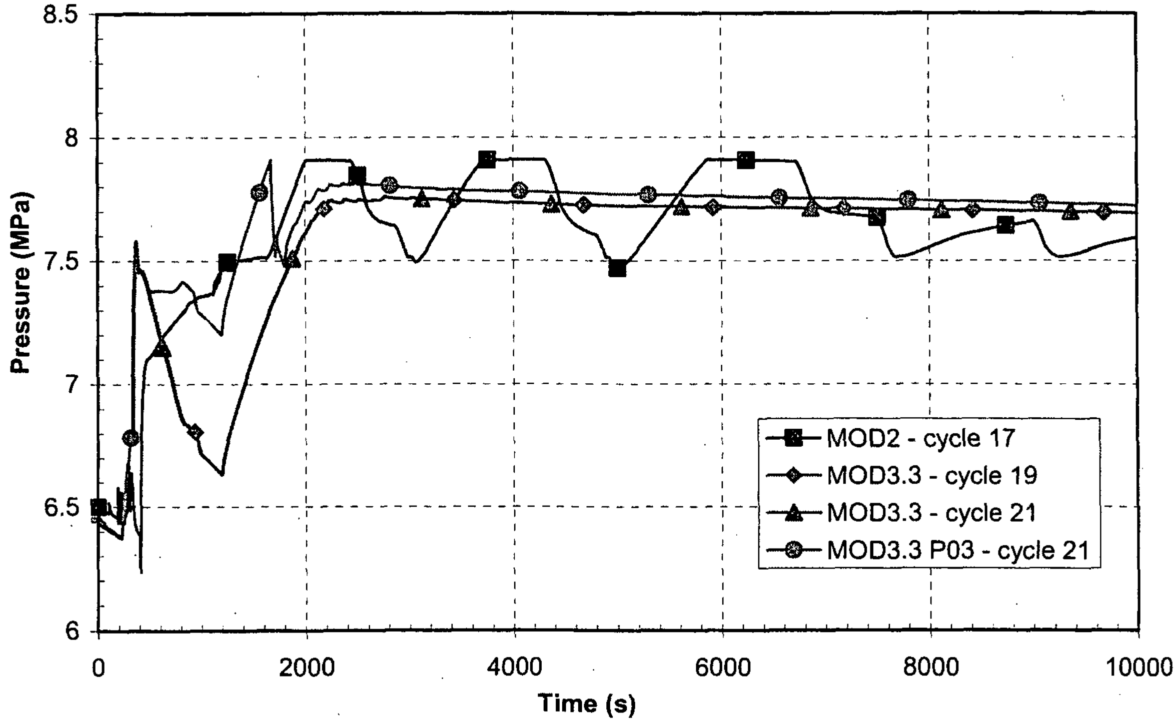


Figure 47 Steam generator no. 1 pressure – SGTR

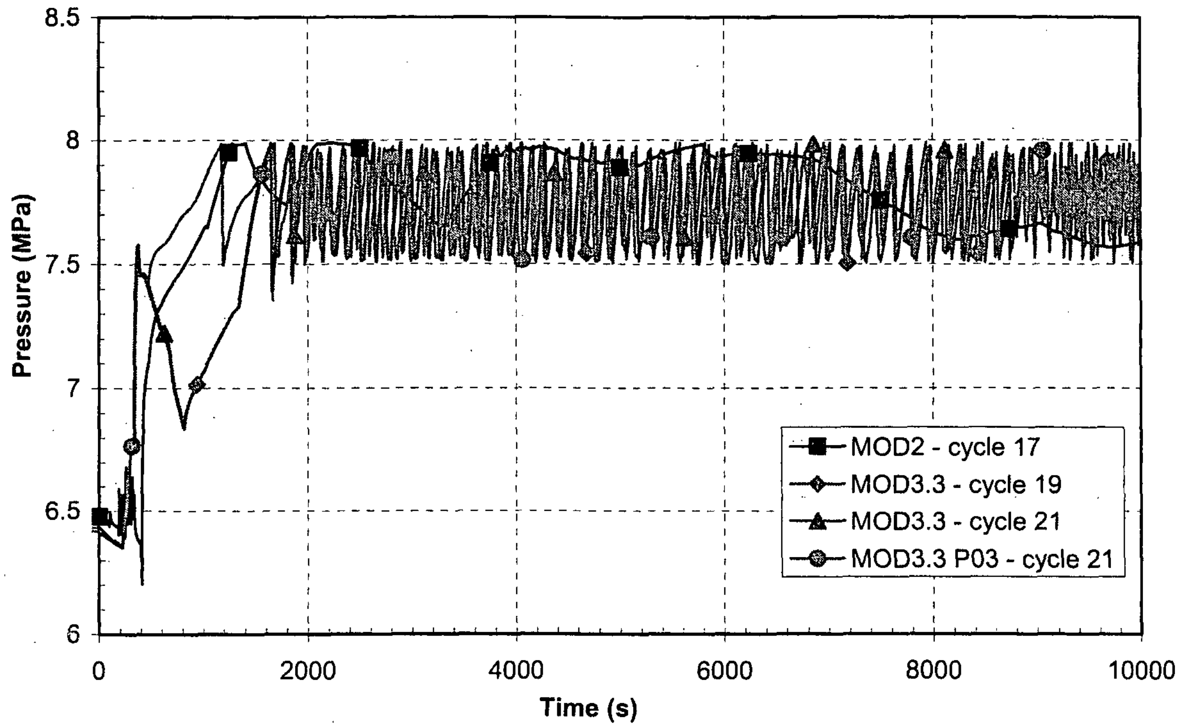


Figure 48 Steam generator no. 2 pressure – SGTR

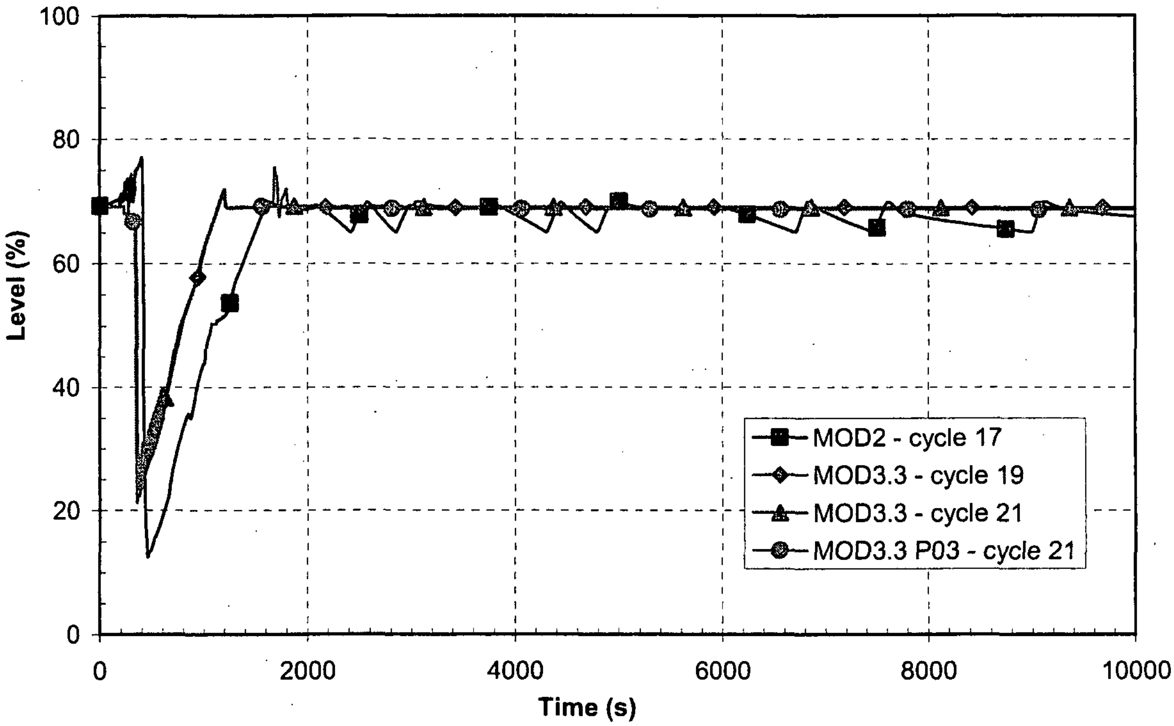


Figure 49 Steam generator no. 1 level – SGTR

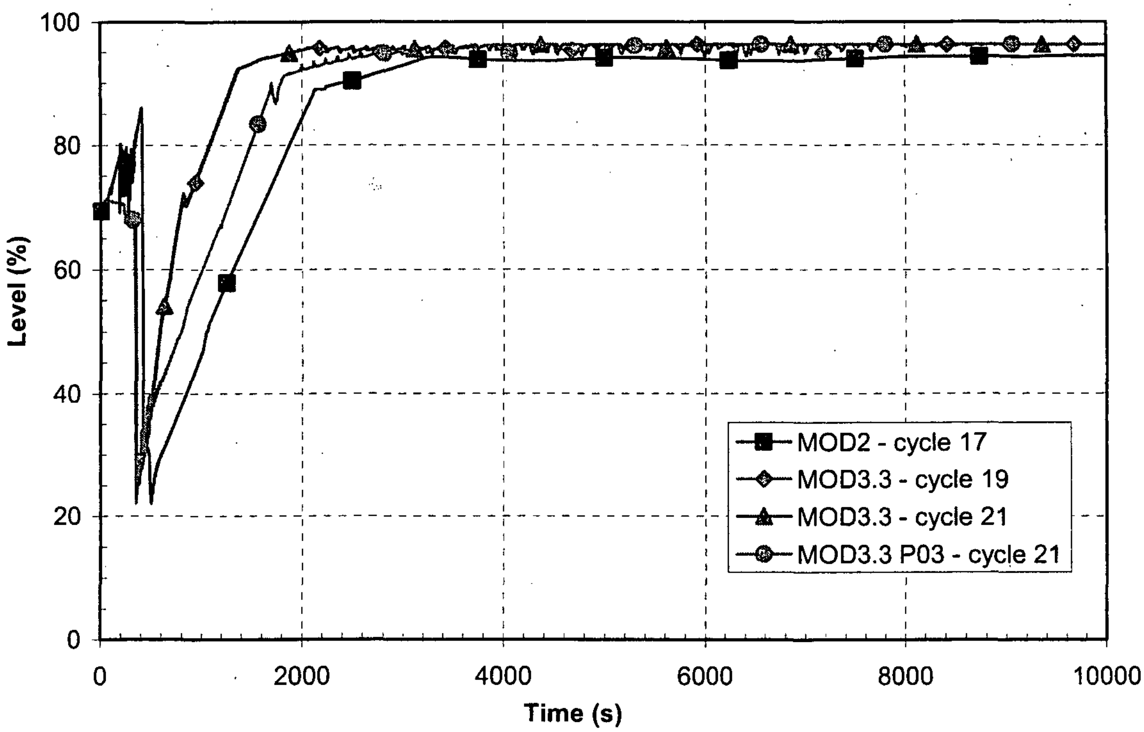


Figure 50 Steam generator no. 2 level – SGTR

5.4 Small Break Loss-of-Coolant Accident Results

5.4.1 5.08 cm Break Size Small Break Loss-of-Coolant Accident Results

The results for 5.08 cm break size SBLOCA are shown in Table 5 and Figures 51 through 57. Table 5 shows main sequence of events for the 5.08 cm break size SBLOCA, as calculated by RELAP5/MOD3.3 Patch 03 code. The triggering time for each event is given. The break opens at 0 second. The HPSI pump actuation is delayed 5 seconds on SI signal. The LPSI pumps started but injection setpoint has not been reached during transient. The AFW pump start is delayed 25 seconds on SI signal and the injection is terminated when steam generator level is recovered.

Table 5 Main plant signals and sequence of events – 5.08 cm break size SBLOCA

Time: 10000.0 s

SIGNALS	transient timing [s]	TRIP	
Reactor trip signal generation	22	1	
SI signal generation	30	1	
turbine trip	22	1	
steam line 1 isolation	0	0	
steam line 2 isolation	0	0	
MFW 1 isolation	30	1	
MFW 2 isolation	30	1	
EVENTS	**transient timing [s]**	**TRIP**	
accumulator no.1 initialization / isolation	2320/ 0	1 / 0	
accumulator no.1 first injection	2320	1	33847.31 [kg]
accumulator no.2 initialization / isolation	2320/ 0	1 / 0	
accumulator no.2 first injection	2320	1	33957.89 [kg]
LPSI pump no.1 initialization	40	1	
LPSI pump no.1 first injection	0	1	2.5949624 [kg]
LPSI pump no.2 injection	40	1	
LPSI pump no.2 first injection	0	1	2.6337874 [kg]
HPSI pump no.1 initialization	35	1	
HPSI pump no.1 first injection	35	1	37.820465 [kg/s]
HPSI pump no.2 initialization	35	1	
HPSI pump no.2 first injection	35	1	38.236958 [kg/s]
AF MD pump no.1 start	55	1	
AF MD pump no.2 start	55	1	
AF TD pump start	0	0	
RCP 1 trip	126	1	
RCP 2 trip	126	1	
charging isolation	30	1	
letdown isolation	27	1	
steam dump - plant trip	22	1	

The reactor coolant system inventory mass and heat is removed through the break during SBLOCA. Therefore the primary pressure (Figure 51) and cold leg temperature (Figure 52) dropped, primary inventory decreased (Figure 53), and the core uncovered (Figure 54). The integrated break flow mass is shown in Figure 55. The closure of the turbine valves and core heat transferred to the steam generators resulted in an initial steam pressure increase (Figure 56), which resulted in a decrease of calculated steam generator water level (Figure 57).

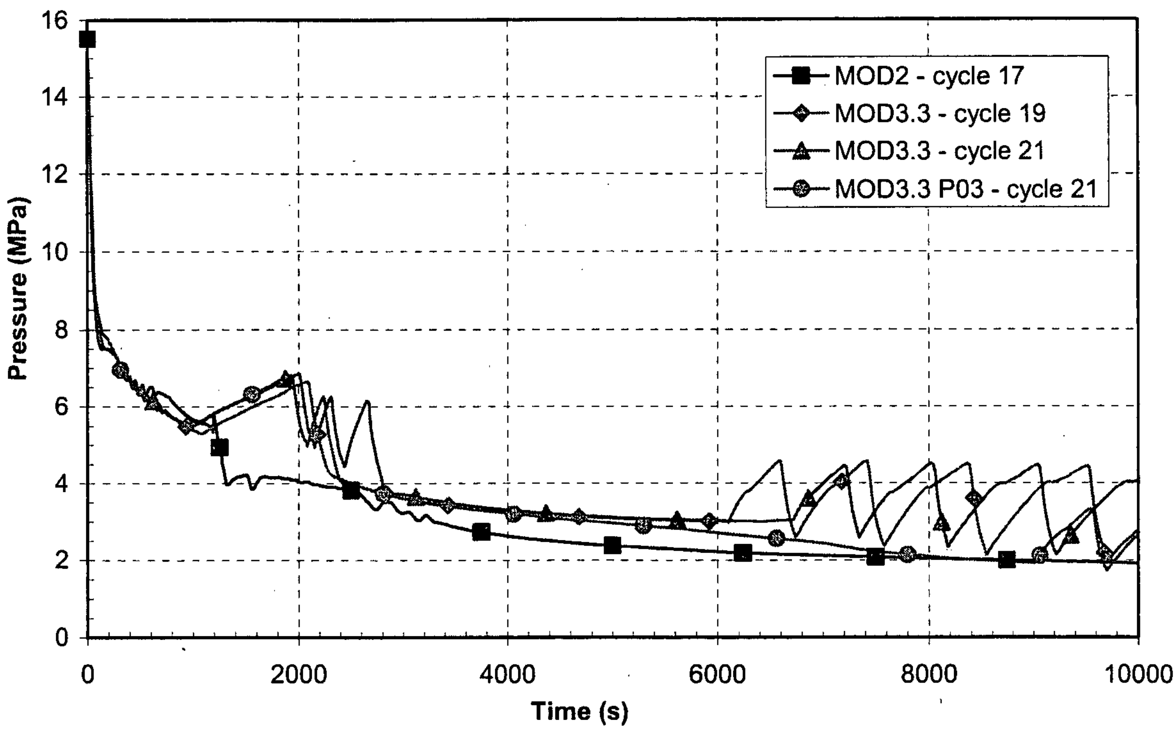


Figure 51 Primary pressure – 5.08 cm break size SBLOCA

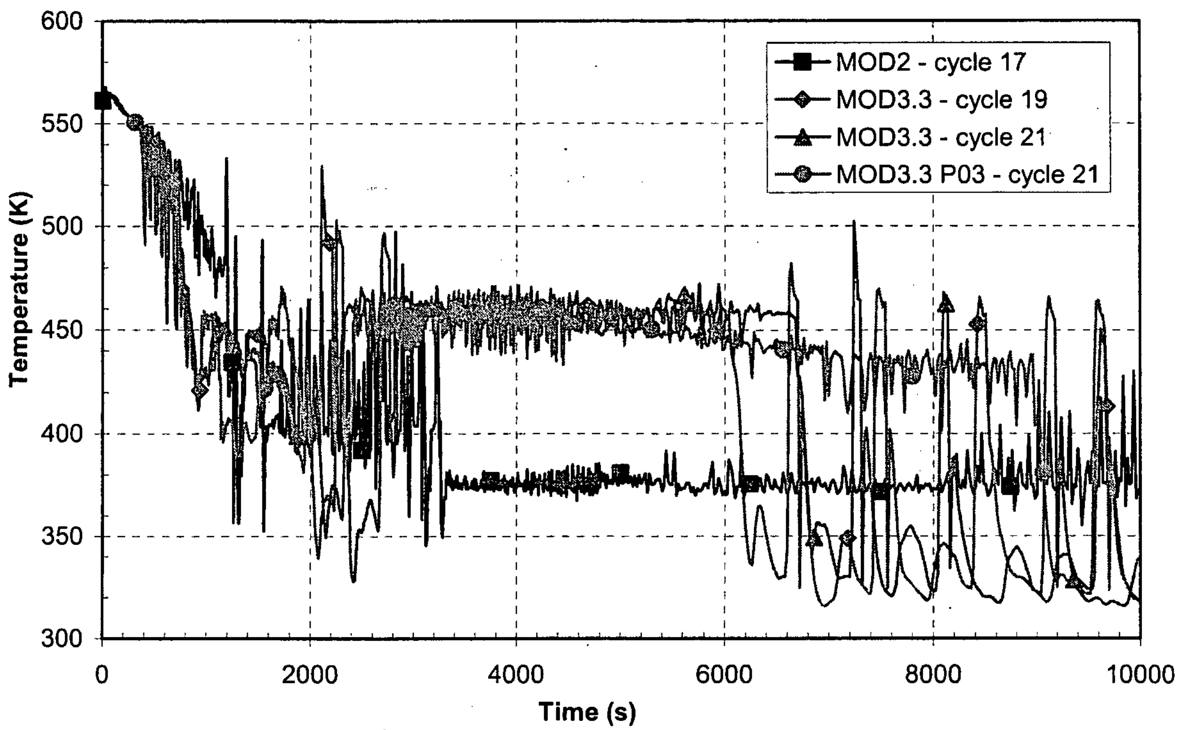


Figure 52 Cold leg no. 1 temperature – 5.08 cm break size SBLOCA

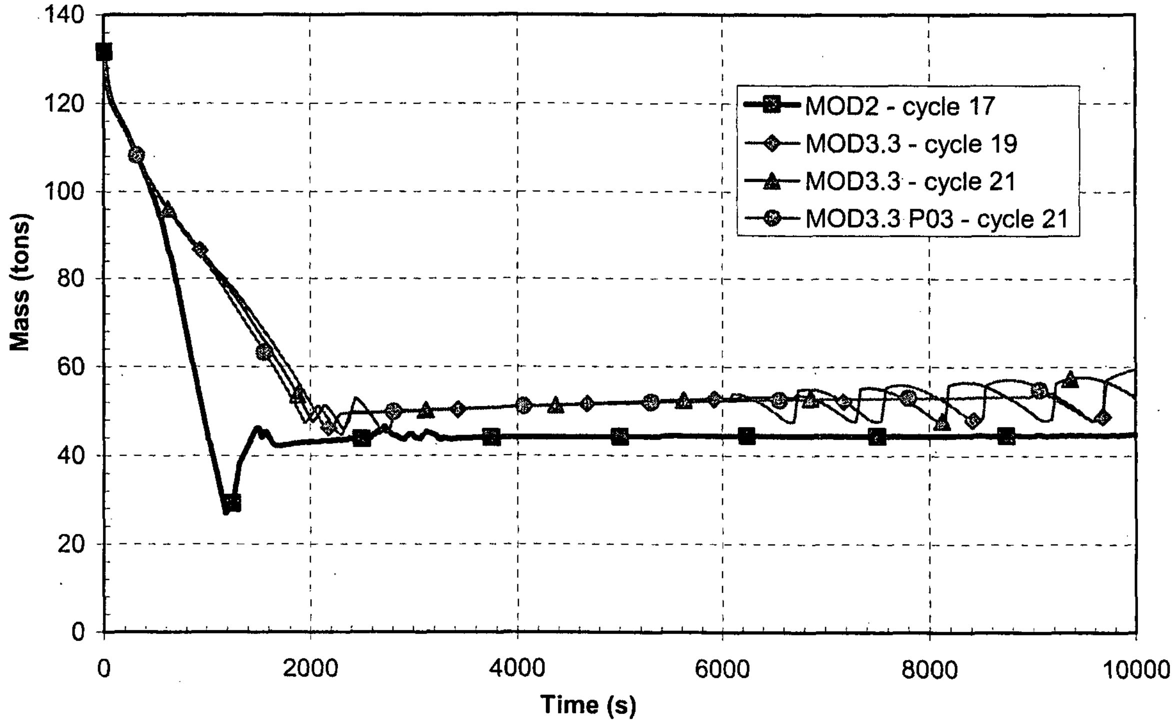


Figure 53 Reactor coolant system mass – 5.08 cm break size SBLOCA

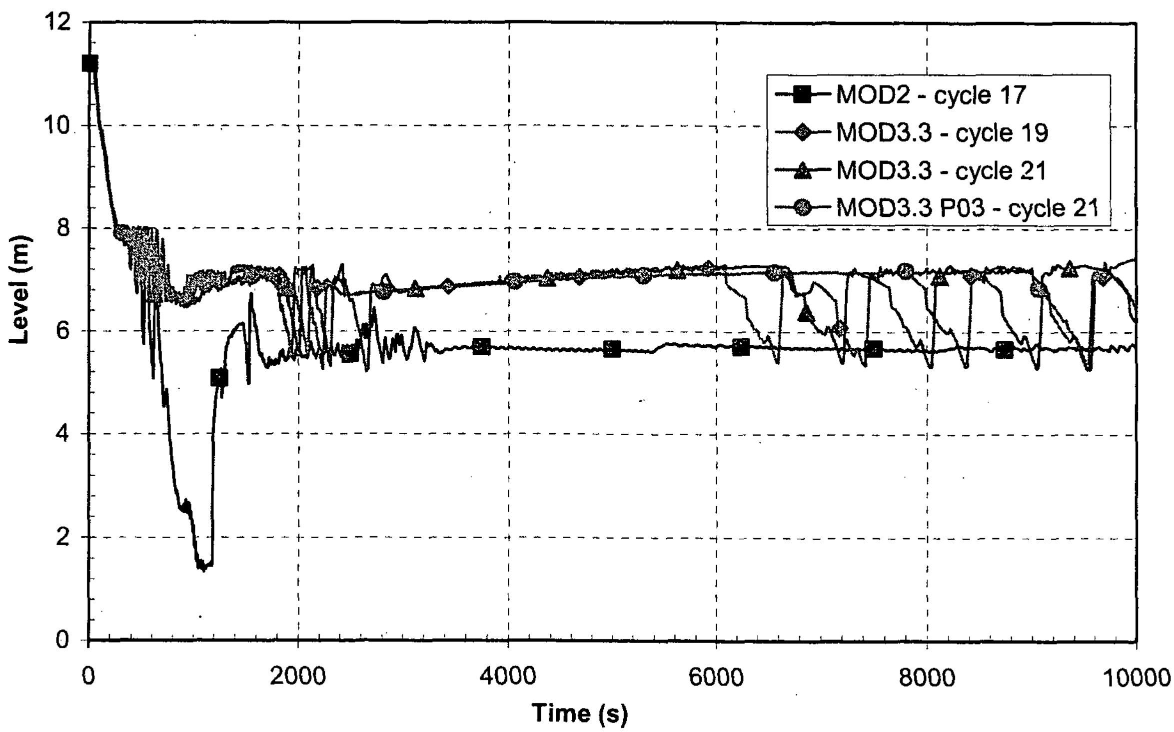


Figure 54 Reactor vessel collapsed liquid level – 5.08 cm break size SBLOCA

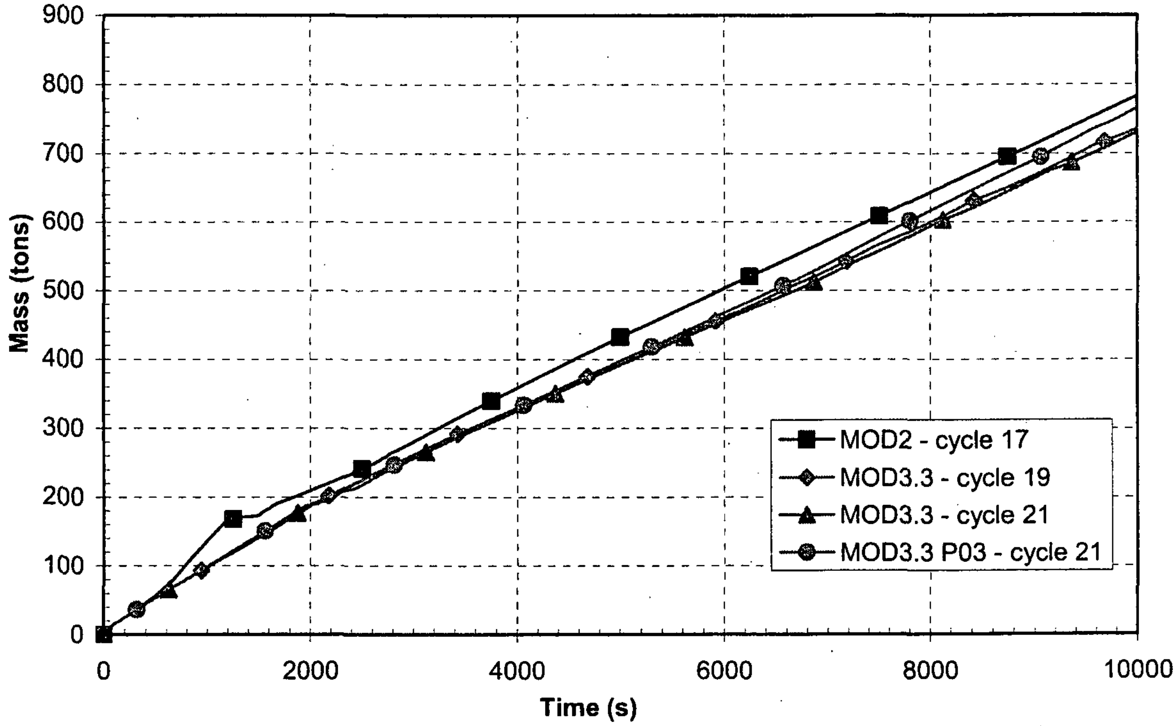


Figure 55 Integrated break flow – 5.08 cm break size SBLOCA

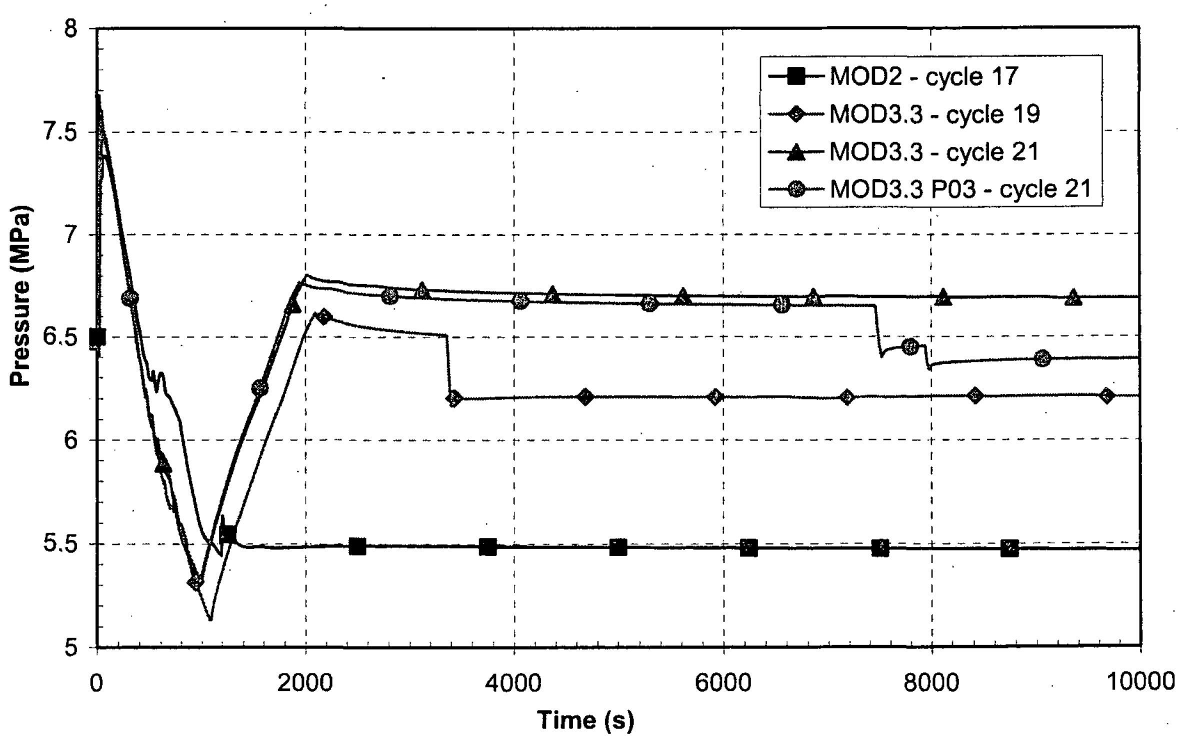


Figure 56 Steam generator no. 1 pressure – 5.08 cm break size SBLOCA

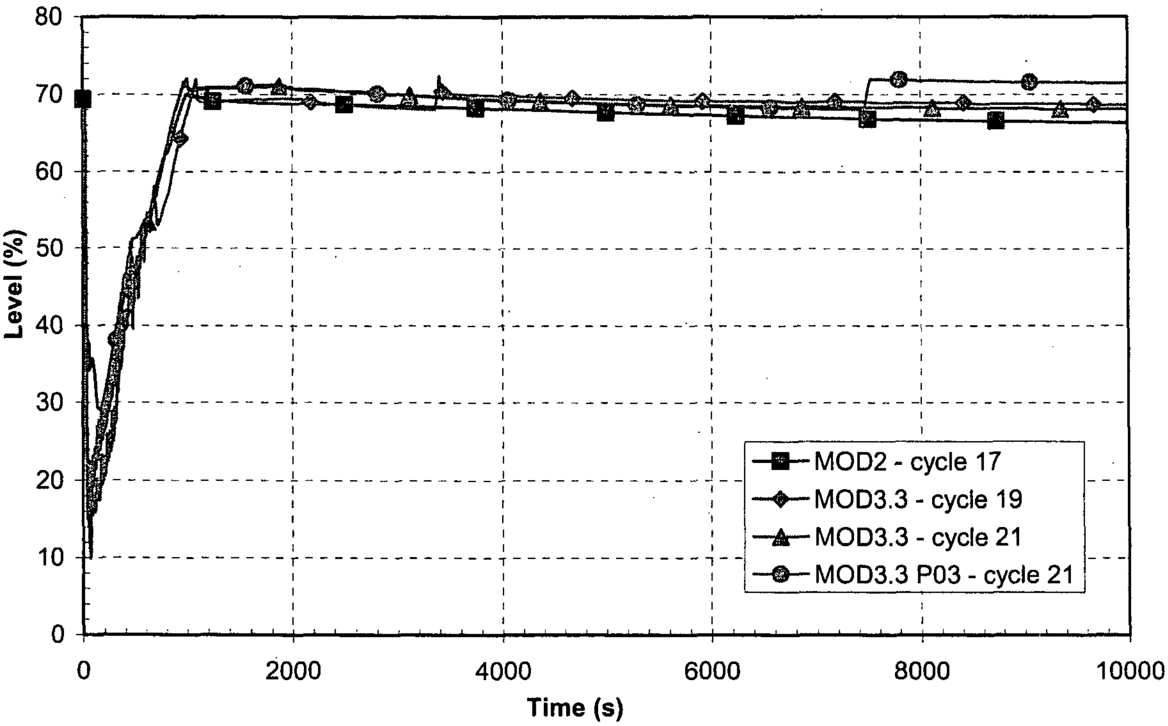


Figure 57 Steam generator no. 1 level – 5.08 cm break size SBLOCA

5.4.2 20.32 cm Break Size Small Break Loss-of-Coolant Accident Results

The results for 20.32 cm break size SBLOCA are shown in Table 6 and Figures 58 through 64. Table 6 shows main sequence of events for the 20.32 cm break size SBLOCA, as calculated by RELAP5/MOD3.3 Patch 03 computer code. The triggering time for each event is given. Due to the assumption of simultaneous break size and station blackout all signals listed in Table 6 were generated after break occurrence. The break opens at 0 second. Reactor trip, SI signal, turbine trip, steam line isolation, main feedwater isolation and reactor coolant pump trip were generated after 0 second (in Table 6 is shown at 1 s, as data are plotted in one second interval and trip times were obtained via Python, see Section 4.2). The HPSI pump actuation is delayed 5 seconds on SI signal and 10 seconds are additionally needed for diesel generator start. The LPSI pumps started with 10 seconds delay plus 10 seconds for diesel generator start but injection setpoint has not been reached during transient. The AFW pump start is delayed 25 seconds on SI signal plus 10 seconds for diesel generator start and the injection is terminated when the steam generator level is recovered. The accumulator discharged their inventory in about 3 minutes. Soon after accumulator isolation the LPSI no. 1 pump started to inject. From Table 6 also the total mass injected after 10000 seconds for accumulators and LPSI no. 1 pump can be seen.

The calculated plant response during SBLOCA largely depends on the break size. As larger is the break size, as faster is the primary system pressure drop (Figure 58), more quickly the reactor coolant system inventory is lost (Figure 59), the core uncovers earlier and sharper

(Figure 60) and the core is heated up earlier due to emptying refueling water storage tank (Figure 61). At the larger break also more coolant is discharged through the break (Figure 62). Steam pressure and level for steam generator no. 1 are shown in Figure 63 and Figure 64, respectively. The closure of the turbine valves and core heat transferred to the steam generators resulted in an initial steam pressure increase. Later the steam generator no. 1 pressure dropped as a result of cooling through the primary side break. The steam generator no. 1 refilled due to AFW no. 1 pump operation.

Table 6 Main plant signals and sequence of events – 20.32 cm break size SBLOCA

Time: 10000.0 s

SIGNALS	transient timing [s]	TRIP	
Reactor trip signal generation	1	1	
SI signal generation	1	1	
turbine trip	1	1	
steam line 1 isolation	1	1	
steam line 2 isolation	1	1	
MFW 1 isolation	1	1	
MFW 2 isolation	1	1	

EVENTS	transient timing [s]	TRIP	
accumulator no.1 initialization / isolation	98 / 276	0 / 1	
accumulator no.1 first injection	99	1	35504.93 [kg]
accumulator no.2 initialization / isolation	98 / 274	0 / 1	
accumulator no.2 first injection	99	1	35505.023 [kg]
LPSI pump no.1 initialization	21	1	
LPSI pump no.1 first injection	368	1	901577.75 [kg]
LPSI pump no.2 injection	0	0	
LPSI pump no.2 first injection	0	0	0.0 [kg]
HPSI pump no.1 initialization	16	1	
HPSI pump no.1 first injection	16	1	-3.560202E-11 [kg/s]
HPSI pump no.2 initialization	0	0	
HPSI pump no.2 first injection	0	0	0.0 [kg/s]
AF MD pump no.1 start	36	1	
AF MD pump no.2 start	0	0	
AF TD pump start	0	0	
RCP 1 trip	1	1	
RCP 2 trip	1	1	
charging isolation	1	1	
letdown isolation	1	1	
steam dump - plant trip	1	1	

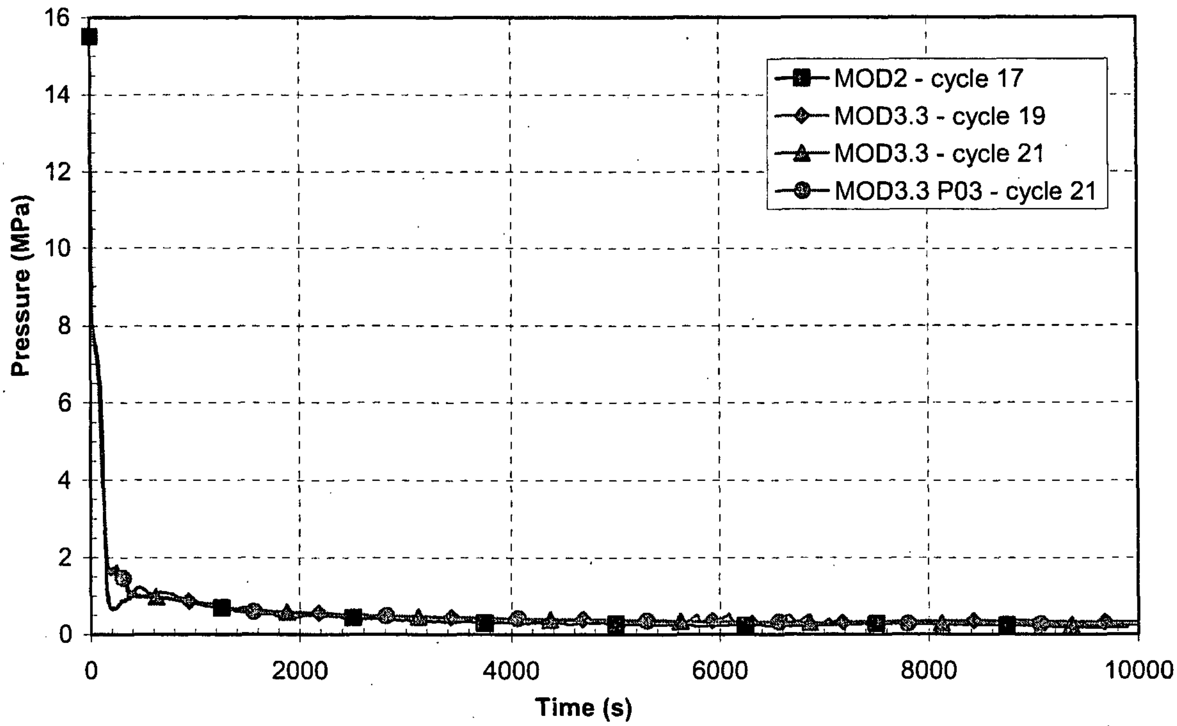


Figure 58 Primary pressure – 20.32 cm break size SBLOCA

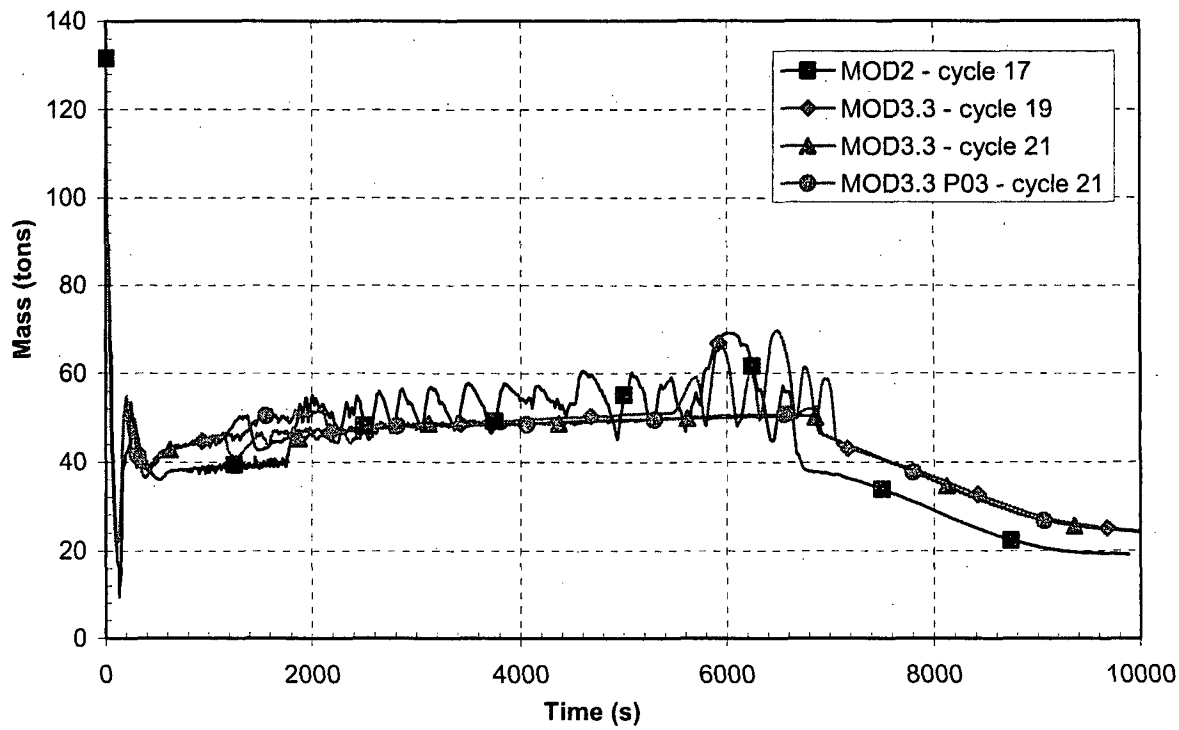


Figure 59 Reactor coolant system mass – 20.32 cm break size SBLOCA

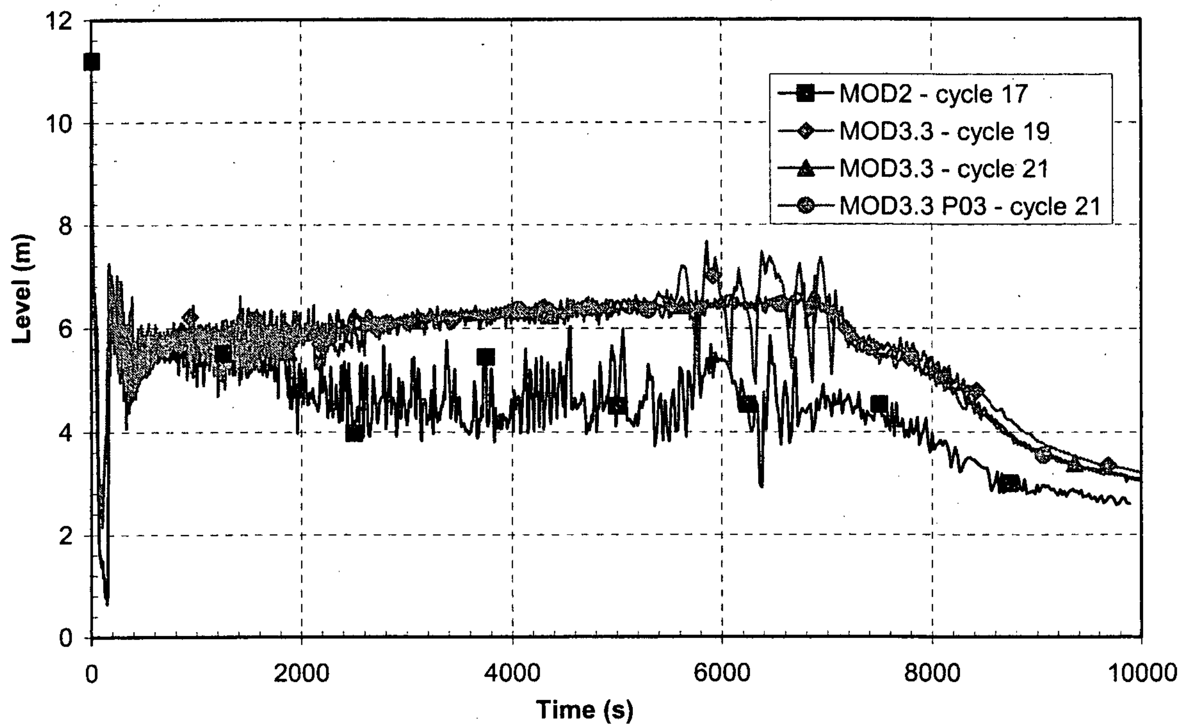


Figure 60 Reactor vessel collapsed liquid level – 20.32 cm break size SBLOCA

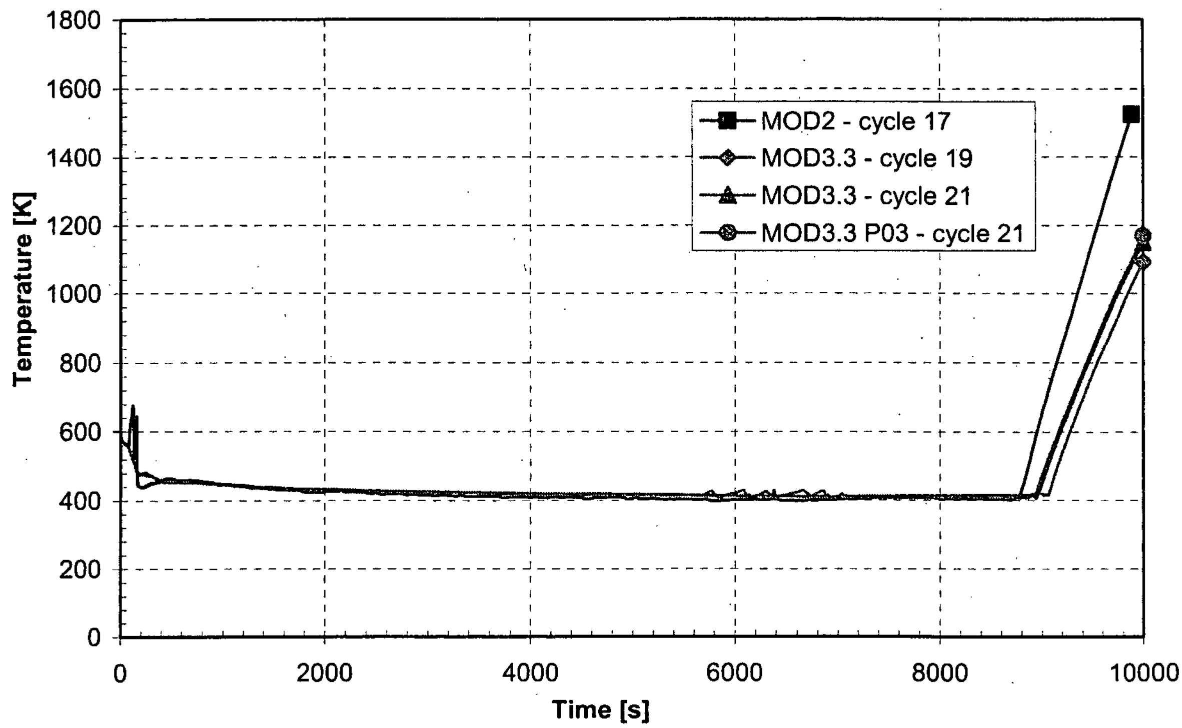


Figure 61 Core cladding outer surface temperature (8/12) – 20.32 cm break size SBLOCA

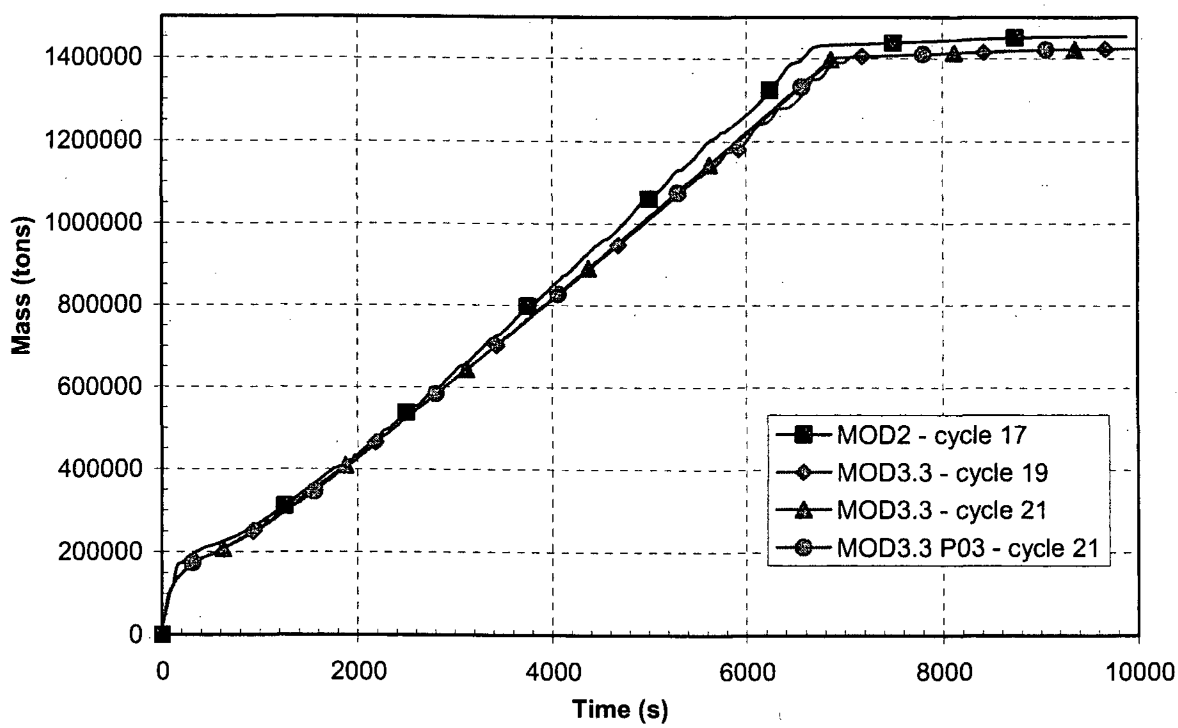


Figure 62 Integrated break flow – 20.32 cm break size SBLOCA

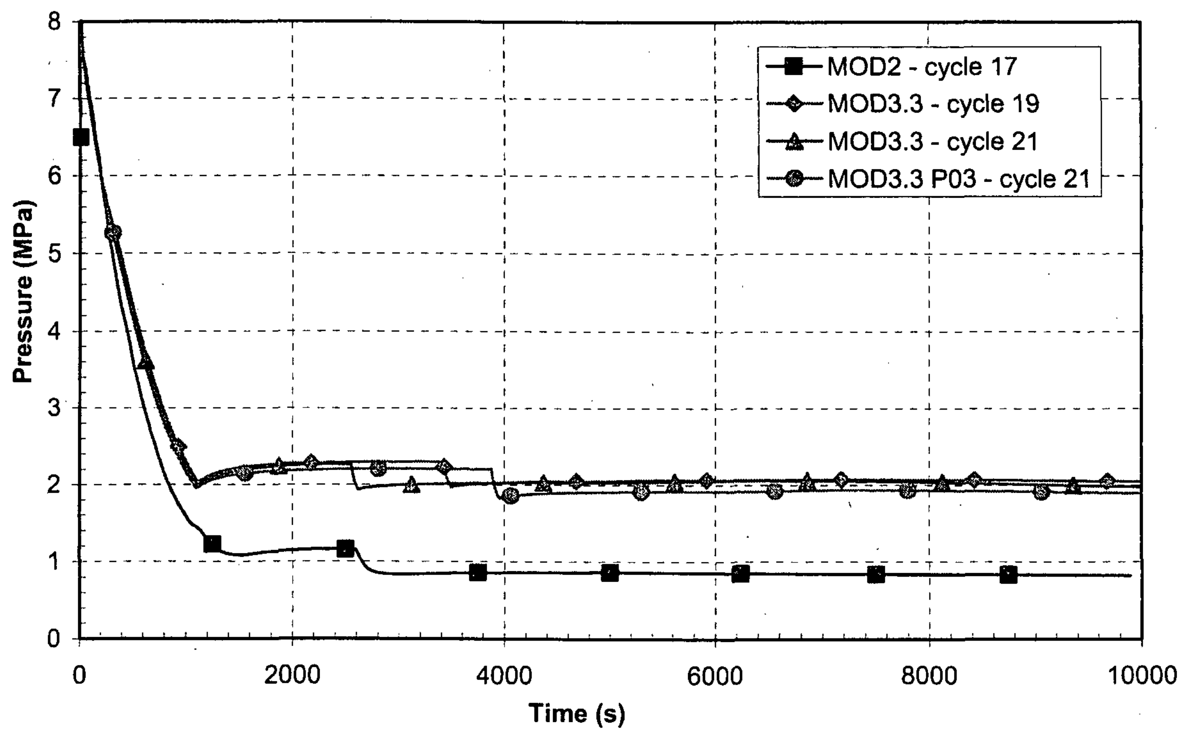


Figure 63 Steam generator no. 1 pressure – 20.32 cm break size SBLOCA

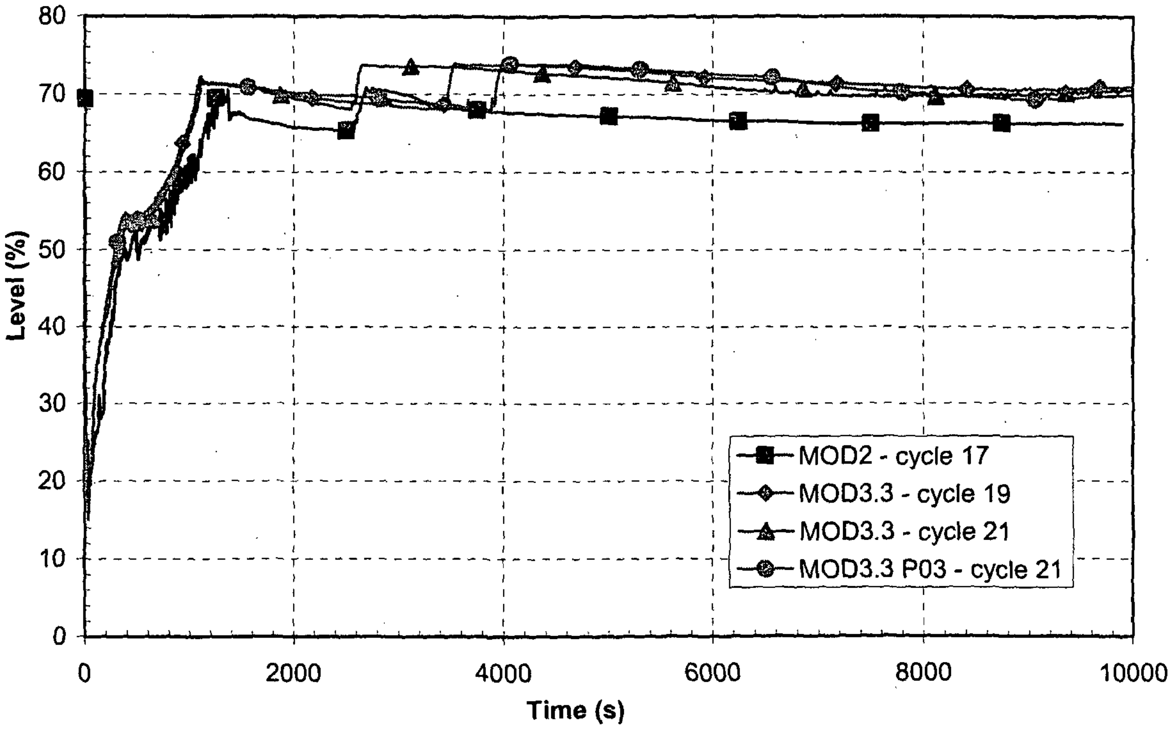


Figure 64 Steam generator no. 1 level – 20.32 cm break size SBLOCA

6. EXAMPLES OF ANIMATIONS

6.1 Steam Generator Tube Rupture Accident Animation

The first example of using Krško NPP animation model is SGTR accident animation. The animations are shown in Figures 65 through 70. Table 4 from Section 5.3 already shows the times and status of several trip signals and plant components during SGTR. It can be seen that the reactor was tripped in 334 second and SI signal was generated in 342 s, causing also MFW isolation. On SI signal HPSI, LPSI and MD AFW pumps were started in appropriate SI sequence. Main steamline was manually isolated in 472 second as part of procedure for the faulted steam generator no. 2 isolation. Figure 65 further shows on which input signals the reactor trip and SI signal were generated. These were low pressurizer for reactor trip and low-low pressurizer signal for SI signal.

Reactor trip status 1.0 at 334 [s] Time: 10000.0s

Reactor trip signals	setpoint	trip	transient timing [s]	with assumed delay [s]
[illegible]	12.994 [MPa]	1	334	2
high pressurizer pressure	16.511 [MPa]	0	0	2
high pressurizer level	92.0 [%]	0	0	3
low SG 1 level	13.0 [%]	0	0	4
low SG 2 level	13.0 [%]	0	0	5
low loop 1 flow	5.71 m3/s	0	0	1
low loop 2 flow	5.71 m3/s	0	0	1
overtemperature dT loop 1	29.4 K	1	340	1
overtemperature dT loop 2	29.4 K	1	340	1
overpower dT loop 1	39.7 K	0	0	1
overpower dT loop 2	39.7 K	0	0	1
manual		0	0	0
SI signal		1	342	0
turbine trip		1	334	0

SI signal status 1.0 at 342 [s]

Safety injection signals	setpoint	trip	transient timing [s]	with assumed delay [s]
[illegible]	12.27 [MPa]	1	342	0
high containment pressure	0.129 [MPa]	0	0	0
low - low steam line 1 pressure	4.928 [MPa]	0	0	0
low - low steam line 2 pressure	0.0 [MPa]	1	1880	0
manual		0	0	0

Figure 65 SNAP animation mask for reactor trip and SI signal – SGTR

The Krško NPP general animation mask is shown in Figure 66 is shown at time 365 seconds. The color map for void fractions shows regions with water (blue) and steam (white). The status of pumps and valves is shown by color, green indicating open valve and running pump, and red the opposite. On right side of Figure 66 is color map for core temperatures. From Figure 66 it can be seen that the levels in the pressurizer and the steam generator dropped. Figure 67 shows the steam generator no. 1 which was intact during SGTR event. It can be seen that at time 365 second the U-tubes are partly uncovered. Again information about important parameters is given like cold leg flow and temperature, steam flow, feedwater and auxiliary feedwater flow and temperature, steam generator mass and power. On the left side are shown void fractions and on the right side the flow regimes. Steam generator level data are shown in Figure 68 for main steam system. Information is given also on steam flows and status of SG steam and relief valves including mass discharged. It can be seen that most mass was discharged through faulted SG PORV due to the high pressure following the steam generator tube rupture. Figure 69 shows the AFW system, status of pumps and valves, and the injected mass in each steam generator. Finally, Figure 70 shows the status of ECCS. It can be seen that due to broken tube the HPSI pumps are still injecting. We can also see that for LPSI the injected mass (integrated flow) the value is negative. The reason is that in the RELAP5 input model the check valve is not modeled causing some recirculation flow in the ECCS piping. This deficiency of the RELAP5 input model was discovered during building animation model. For each of the data value shown on the mask the trend can be directly plotted from the SNAP.

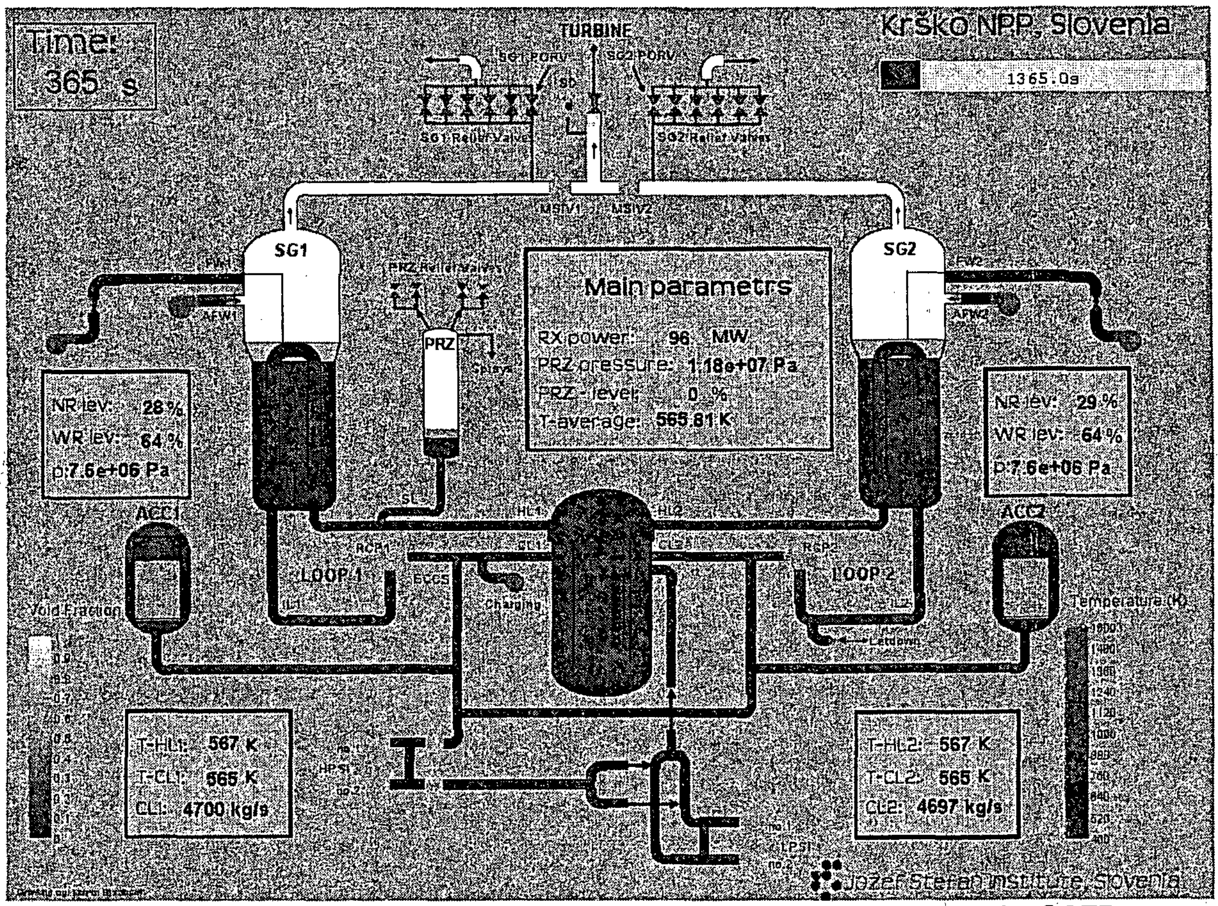


Figure 66 SNAP animation mask of Krško NPP plant at 365 second – SGTR

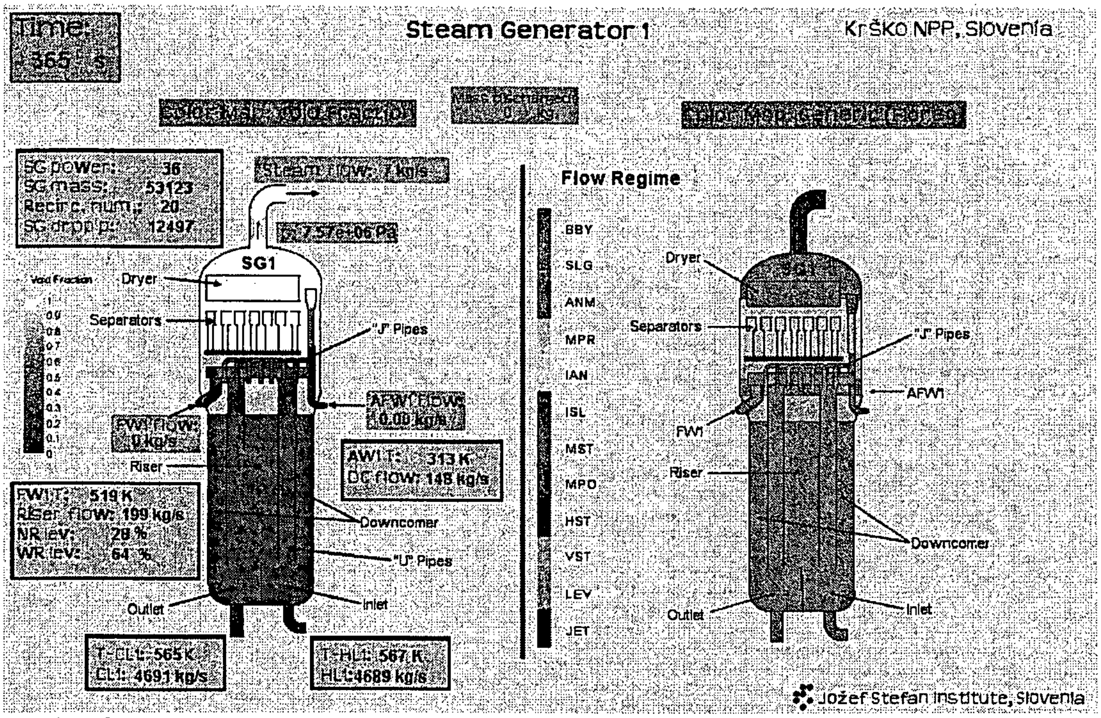
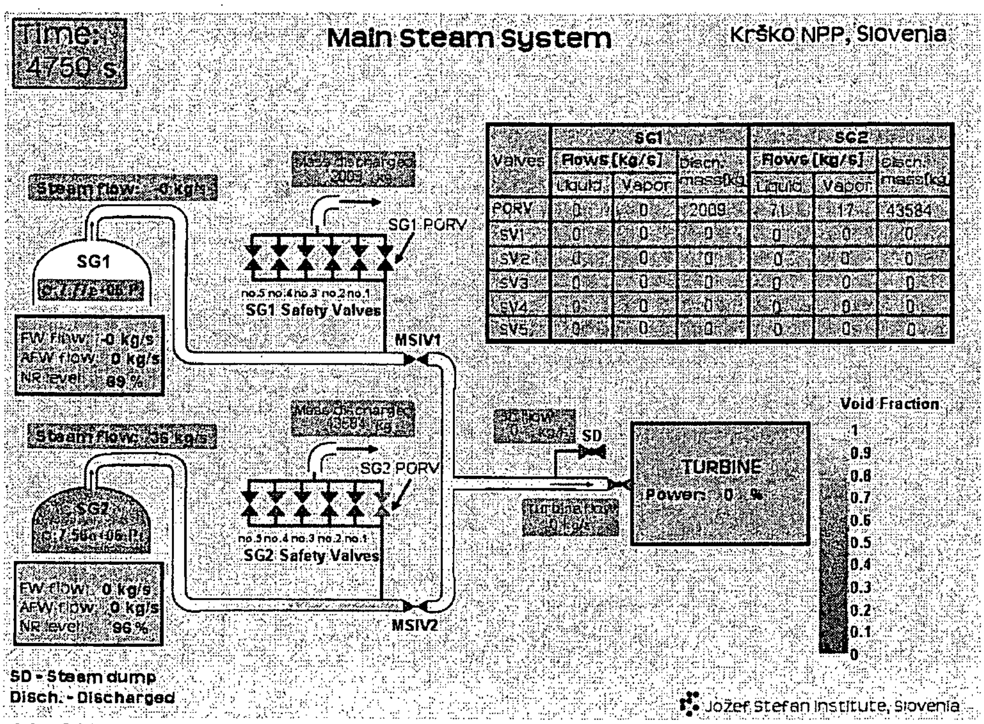


Figure 67 SNAP animation mask for SG1 at 365 second showing void fractions (left) and flow regimes (right) – SGTR



Valves	SG1 Flows [kg/s] Liquid	SG1 Flows [kg/s] Vapor	SG1 Disch. mass[kg]	SG2 Flows [kg/s] Liquid	SG2 Flows [kg/s] Vapor	SG2 Disch. mass[kg]
PORV	0	0	2009	7.1	17	43584
SV1	0	0	0	0	0	0
SV2	0	0	0	0	0	0
SV3	0	0	0	0	0	0
SV4	0	0	0	0	0	0
SV5	0	0	0	0	0	0

Figure 68 SNAP animation mask for main steam system at 4750 second showing SG2 PORV discharging – SGTR

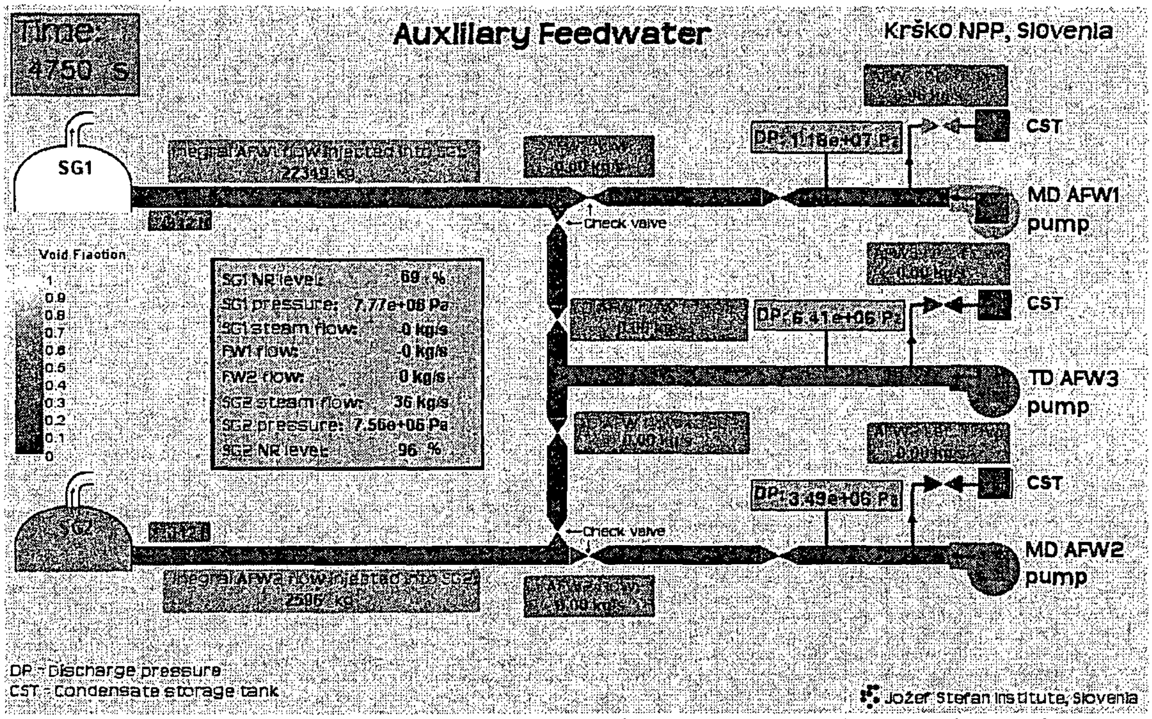


Figure 69 SNAP animation mask for auxiliary feedwater at 4750 second showing AFW system not injecting – SGTR

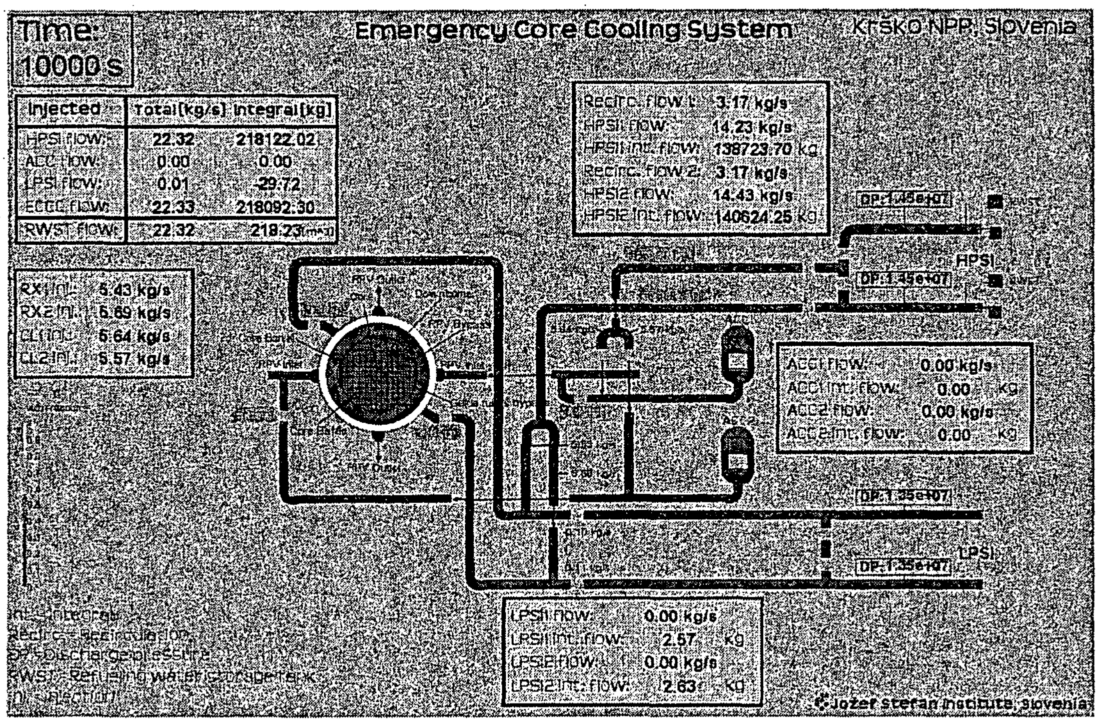


Figure 70 SNAP animation mask for emergency core cooling system at the end of calculation showing HPSI pumps injecting – SGTR

6.2 Small Break Loss-of-Coolant Accident Phenomena Animation

As second example of using Krško NPP animation model, the 20.32 cm break size SBLOCA phenomena are shown in Figures 71 through 74.

Figures 71 and 72 show the SBLOCA depressurization phenomenon. From Figure 71 it can be seen how the pressurizer empties, the boiling in the upper core, and the voids in the upper plenum and hot leg. In Figure 72 can be seen saturated conditions in the hottest regions of primary system.

SBLOCA core uncovery process driven by inventory loss is shown in Figures 73 and 74. Figure 73 shows that the core is boiling dry, while Figure 74 shows superheated steam in the core, the upper plenum, and the hot leg.

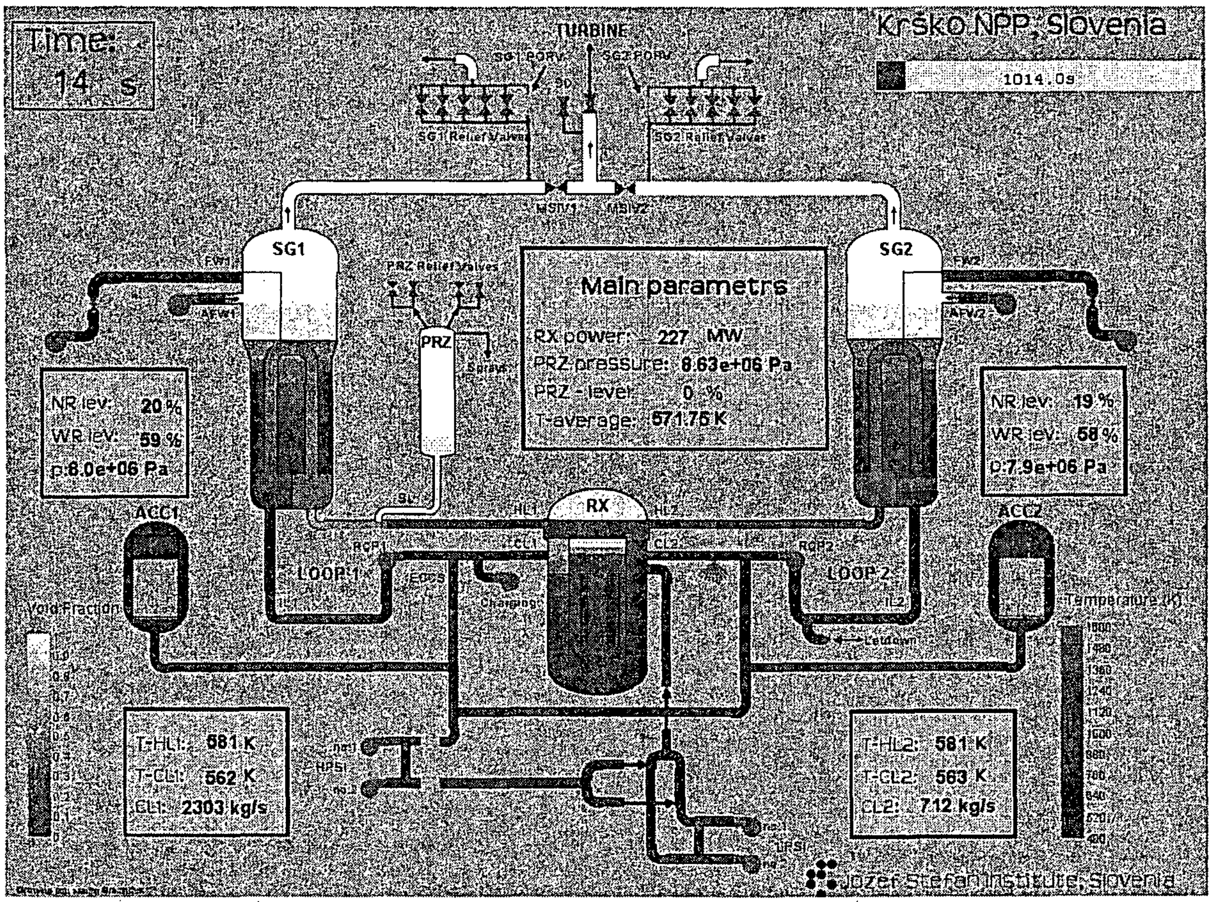


Figure 71 SNAP animation mask for plant, showing void conditions – 20.32 cm break size SBLOCA

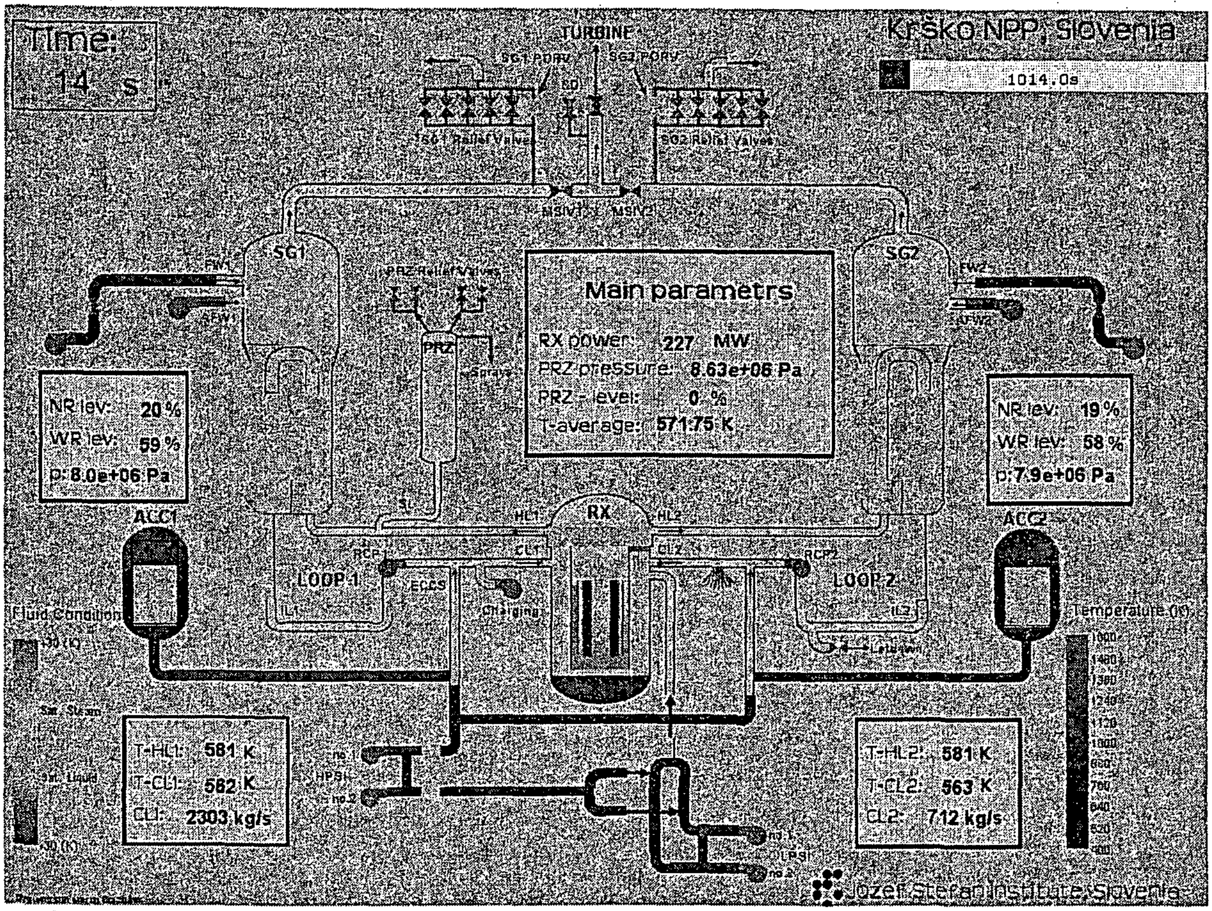


Figure 72 SNAP animation mask for plant, showing fluid conditions – 20.32 cm break size SBLOCA

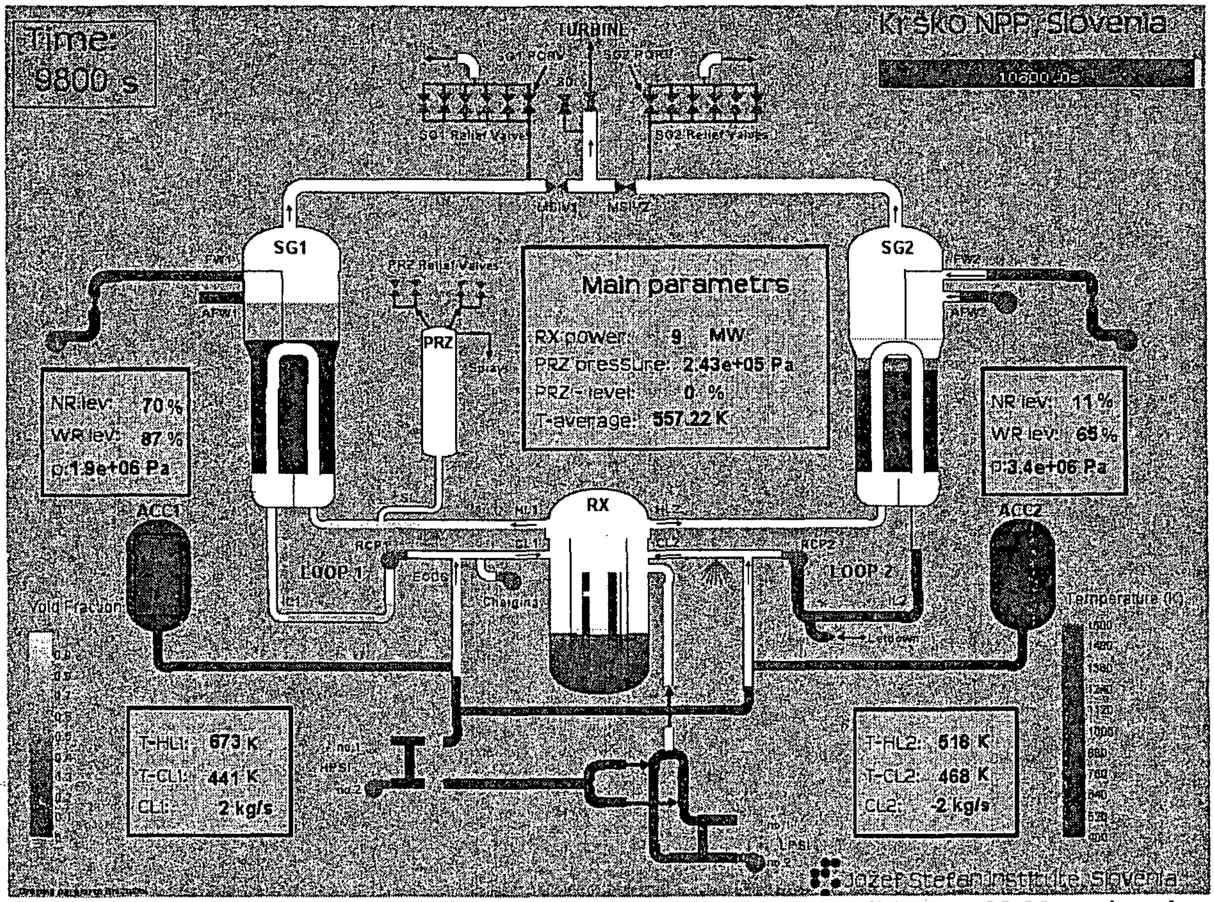


Figure 73 SNAP animation mask for plant, showing fluid conditions – 20.32 cm break size SBLOCA

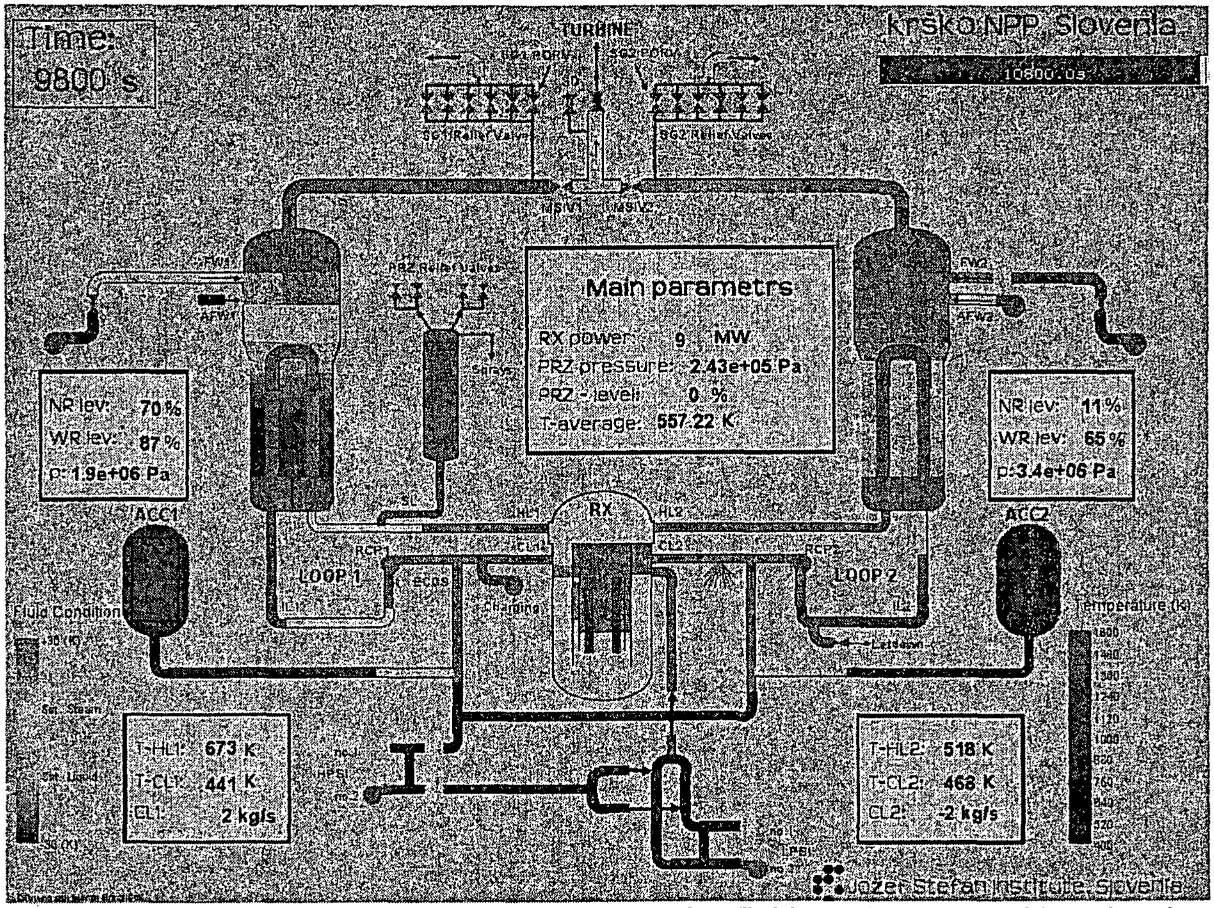


Figure 74 SNAP animation mask for plant, showing fluid conditions – 20.32 cm break size SBLOCA

7. CONCLUSIONS

The calculations of design basis accidents used for Krško full scope simulator validation were performed with the latest RELAP5/MOD3.3 Patch03 computer code to provide source data for animation model of Krško NPP. The calculations were also compared to calculations performed with previous RELAP5 code versions. For each calculation the scenario is described and important results are discussed. For animations the SNAP was used. Animation masks were created for the plant, the reactor vessel, the pressurizer with pressurizer relief tank, the main steam system, the steam generators, the main feedwater system, the emergency core cooling system and the auxiliary feedwater system. Besides, the signals and time sequence of events masks were added for better understanding of the transient progression. Finally, all important control system masks were developed. Two examples on the use of animations masks were shown, for SGTR accident and for investigating SBLOCA phenomena. The developed animation model of Krško nuclear power plant showed several benefits like better understanding of the calculated physical phenomena and processes, user friendly tool for understanding the nodalization and the detail of plant modeling, better presentation of the results due to visualization and movies, a convenient tool to train new users of thermal-hydraulic code etc. All these contribute to higher quality of safety analysis. Besides it can also be concluded that such modern tool may increase the interest of people to work with system codes comparable to the interest for computational fluid dynamics codes.

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10. SUPPLEMENTARY NOTES
A. Calvo, NRC Project Manager

11. ABSTRACT *(200 words or less)*
This report presents the developed animation model for Krško nuclear power plant (NPP). For animations the Symbolic Nuclear Analysis Package (SNAP) was used. Krško NPP, which is a two-loop pressurized water reactor, Westinghouse type, before modernization in 2000 obtained plant specific full scope simulator. In the present study reference design basis calculations for Krško full scope simulator validation were analyzed with the latest RELAP5/MOD3.3 Patch 03 code to get the source data needed for development of animation model. In total six scenarios were analyzed: two scenarios of the Small Break Loss-of-Coolant Accident (LOCA), two scenarios of the Loss of Main Feedwater (LOFW), scenario of the Anticipated Transient Without Scram (ATWS), and scenario of the Steam Generator Tube Rupture (SGTR). Animation masks were created for the primary and the secondary system, important plant systems, the plant signals and the control systems. The use of SNAP for animation of Krško nuclear power plant analyses showed several benefits, especially better understanding of the calculated physical phenomena and processes. It can also be concluded that the use of such support tools to system codes significantly contributes to better quality of safety analysis.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*	13. AVAILABILITY STATEMENT
SNAP Thermalhydraulic code calculations RELAP5/MOD3.3 Krško NPP base input model Krško NPP Reactor Trip Westinghouse 2-loop PWR plant New steam generators (SGs) Jožef Stefan Institute Republic of Slovenia Nuclear steam system	unlimited 14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified 15. NUMBER OF PAGES 16. PRICE

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