sCO2-4-NPP: Innovative sCO2-Based Heat Removal Technology for an Increased Level of Safety of Nuclear Power Plants

Deliverable 6.3

Representative transients of a European type PWR equipped with sCO2-system monitored and assessed

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1 List of Acronyms

Abbreviation / Acronym	Description / meaning
AC	Alternating current
AKZ	„Anlagen KennZeichnungs-System” (Plant Marking System, a 2 letter code)
ATHLET	Analysis of THermalhydraulics of LEaks and Transients (German reference thermal hydraulic system code, maintained by GRS)
BOC	Begin of Cycle, a burnup state in an equilibrium core
CATHARE	French reference thermal-hydraulic system code
CHX	Compact Heat Exchanger, interface to the steam system
CL n	Cold Leg (with number of loop)
CONTRONIC	Product line of Hartmann&Braun for control purpose
CVŘ	Centrum výzkumu Řež (Czech expert and research company, UJV Group)
DC	Direct current
DG	Diesel Generator
Dymola	Dynamic Modeling Laboratory (Dassault modelling software environment)
EdF	Electricite de France
EPR	European Pressurized Reactor
FMU	Functional mock-up unit
GfS	Gesellschaft für Simulatorschulung
GRS	Gesellschaft für Reaktorsicherheit (German nuclear expert organisation)
HL n	Hot Leg (with number of loop)
I&C	Instrumentation and Control
JSI	Institut “Jožef Stefan” (Slovenian scientific research institute)
KKS	„Kraftwerks-Kennzeichungs-System“ (the German 3 letter code of KWU)
KSG	Kraftwerks-Simulator-Gesellschaft
LOOP	Loss of offsite power
MCP	Main Coolant Pump
Modelica	Modelling libraries for the Dymola environment
MSIV	Main Steam isolating valve
NPP	Nuclear Power Plant
PRZ	Pressurizer

Abbreviation / Acronym	Description / meaning
PWR	Pressurized Water Reactor
RA	Descriptor of the main steam system in the 2-letter code
RELAP	Reactor Excursion and Leak Analysis Program (US reference thermal hydraulic system code)
RL	Descriptor of the feedwater system in the 2-letter code
RPV	Reactor pressure vessel
RZ	Descriptor of the blow down system in the 2-letter code
SBO	Station Black Out
sCO2	Supercritical CO2 (above critical point 30.8 °C, 73.8 bar)
SCRAM	Rapid emergency shutdown of a nuclear reactor
SG	Steam Generator
SGTL	Steam Generator Tube Leak
TAC	Turbine Alternator Compressor
TK	Descriptor of the sCO2-heat removal system in the 2-letter code
UHS	Ultimate Heat Sink, interface to the atmosphere
USTUTT	Universität Stuttgart

2 Executive Summary

The model of a sCO2-based heat removal system has been implemented into a pre-Konvoi-PWR full scope simulator as a comprehensive and detailed system environment. With this enhanced simulator several transients were performed to demonstrate the heat removal capacities of the sCO2 system in different configurations, and to identify and to explore possible operational problems, resulting from details sometimes missed in input decks for qualified nuclear codes, or resulting from possible manual actions of the shift crew.

Into this category fall:

- a permanent steam leakage to the main steam system as steam flowing along the valve stems or turbine valves and turbine bypass valves to the condenser, which will be blocked with a closure of the MSIV
- the lack of an automatic criterium to close the MSIV
- the advantage to be taken from the deliberate closure of the blow-off path (if available) at an early stage, to retain secondary side coolant
- the cross connections in between the blowdown system, exchanging secondary side coolant in between the steam generators according to pressure differences
- the interaction of running sCO2-systems with a depressurisation of a spare SG
- sensitivity of the sCO2-heat removal system to an elevated SG level

Furthermore, the data available to the shift crew had to be assessed, on which decisions may be made for manual interventions. Into this category fall:

- Limited measuring of the SG level
- Limited knowledge about the heat to be removed and the time the system needs to reshuffle the heat removal path after shutting down a subsystem
- Limited knowledge about the saturation or subcooling inside the primary circuit

Finally, quality, stability and usability of the simulator for training purposes were to be assessed. Generally, a typical training sequence of up to 2 hours was performed smoothly. Results from earlier ATHLET calculations about heat removal with 4 subsystems, done within this project, could be reproduced. sCO2-systems could be started, stopped, restarted.

The visualisation tool for the RELAP model of the primary system, the simulator is equipped with, supports presentation and understanding of the processes happening in certain phases of the transients.

Some improvements would be helpful regarding the real time performance and the parameter set needed for a seamless continuation of sCO2 systems run after stops and backtracks.

3 Introduction

During sCO2-4-NPP project, the design of the heat removal system with all its components has been investigated thoroughly with qualified codes as ATHLET and CATHARE, as well as Dymola/Modelica, which is not used for qualified calculations in nuclear industry so far. The main purpose was to model the static and dynamic behaviour and to optimize the technical properties of the crucial components, which are the TAC, the CHX, the UHS. These calculations are focused on the components, setting the boundary conditions, e.g. the interface to the plant, in a simplified manner and scripting the events. Nevertheless, the input decks for these calculations are well established and used by nuclear expert organisations, e.g. the GRS. This work was mainly done in WP2 and WP5.

Regarding the grade of detail, a full scope simulator, well established in the training of licensed shift personal of a nuclear power plant, and assessed several times during construction and training, provides a very comprehensive environment regarding the response of a NPP to the sCO2-loops. So, most simplifications of the input decks will be replaced by the full content of systems modelled to generate the plant behaviour in the desired detail for training of normal operations as well as anomalous and emergency situations. The engineering work for this modelling comprises mostly several man-years from experienced teams.

So, it was the idea for WP6 to bring the results of the project's previous work packages regarding outline and operation of the sCO2 heat removal system into the real time environment of a full scope PWR simulator of a (pre-)Konvoi nuclear power plant, to provide an environment resembling the most comprehensive detailedness available outside a real plant. The grade of details needed to assess such a situation like a station black-out, comprises such things like:

- Availability of component drives from secured power sources (batteries)
- Automatic actions from systems of all safety levels, including controls (not only safety related systems)
- Long term losses to small leakages or draining
- Availability of passive coolant injections, e.g. feedwater tank
- Availability of data, especially measuring range limits and measuring bias.

There are reasons, why a simulator is not a qualified model regarding transient analysis. The demand to real time behaviour enforces some simplification regarding preciseness of the calculations. Nevertheless, the improved quality by increased computing power in the last decades allowed the simulators at KSG/GfS to support several projects at NPP regarding I&C upgrades, even conceptual work for ergonomics of control desks for heat removal systems in safety level 4 as early as in 1999 for NPP Philippsburg 1. The real time feature gives more flexibility to repeat or adapt transients with a direct view to the results at the control room display, even checking some deviations in boundary conditions (e.g. resulting from the assumption of conservative boundary conditions in design calculations vs. best estimate conditions with interfering non-safety related systems or manual interventions in simulator conditions). So, cliff-edge behaviour, where small changes or manual interference can cause a forking in the outcome, may be identified at a simulator more easily. Of course, the next step should always be to take the findings of these simulator experiences to the input deck of a qualified model calculation again.

4 Description of Plant and Simulator

4.1 Description of the reference plant

The reference plant NPP Grohnde, which is represented by the D46 simulator at the Simulator Center in Essen, is a 1300 MWe KWU Type plant, widely referred as “Pre-Konvoi” type. It is nearly similar to the Konvoi reactors Emsland, Isar II and Neckarwestheim II, which were intended as a standardized result of the evolutional progress made from the experience gathered during construction and commissioning of the 1300 MW type. This line begins with Grafenrheinfeld NPP, continuing with Grohnde and Brokdorf. Philippsburg 2 already represented the adaptions in the secondary circuit, e.g. feedwater tank pressure of about 4 bar, instead of formerly 10 bar. From viewpoint of documentation, Philippsburg 2 already uses KKS denomination of components, in contrast to the former AKZ. Two pre-Konvoi units were established abroad, in Angra (Brazil) and Trillo (Spain).

Primary system’s data are quite similar for pre-Konvoi and Konvoi plants: the thermal reactor power is about 3900 MW, with a core mass flow of 20000 kg/s in 4 loops. The average coolant temperature is about 310 °C, with a span from 34 K in between hot leg (~327 °C) and cold leg (~293 °C). The different fuel assembly geometry (18x18 fuel rod lattice for Konvoi, 16x16 for Grohnde) does not influence the problems to be discussed in this work.

The steam generators are of U-tube type, with a secondary pressure of 66 bars (~282 °C). Grafenrheinfeld, Grohnde and Brokdorf used preheater chambers in the steam generators for better subcooling of the cold leg, but the principle was abandoned for Philippsburg 2. After some upgrades at the turbines, Konvoi and pre-Konvoi plants typically provided ~1400 MW electrical power, varying with the cooling water situation of the site. Nominal main steam and feedwater flow was about 2100 kg/s.

The electrical inhouse load is provided by the generator, if in operation, otherwise taken backwards from the main power grid. If the main grid is unavailable, the supply is taken from the auxiliary grid connection (“Reservenetz”), providing the power to maintain the main heat sink, to keep the unit in hot standby, or to deliberately cool down for some repair.

If the offside grid is lost completely (“Loss of Offsite Power (LOOP)”), 4 Diesel Generators (DG) provide the power for the safety related 10 kV buses. The capacity of the DG is not sufficient to power the components necessary for the main heat sink, or to drive the Main Coolant Pumps (MCP) in the primary loop. Therefore, these components are connected to buses separated from the DG-powered buses. Hence, the primary loop flow has to be maintained by natural circulation (initially for about 5 min supported by the flywheels on the MCP), and the heat has to be dumped into the atmosphere as the ultimate heat sink, until the direct cooling by the emergency powered low pressure cooling systems can be used. The feeding of the SG secondary side would be provided by the emergency powered auxiliary feedwater pumps, using the water resources of the feedwater tank for the first couple of hours.

All vital functions of the plant, including light, instrumentation, some air conditioning, are powered from these DG buses and buses transformed to lower voltage. A limited number of functions can be supplied from batteries for a limited time, either with direct current (DC buses, which are supplied normally from emergency powered AC buses via rectifiers), or, via converters from theses DC buses, as alternate current (AC).

A prominent vital function from the 220 V DC powered buses is the operation of the sealing oil pump to prevent escaping of hydrogen from the generator into the turbine building. Another 220 V powered pump provides some lube oil to the turbine coasting down.

Low voltage (24 V) buses are crucial for I&C in the control room.

The secured AC (400 V) is generally used for control drives of "Contronic" product line, most notably the blow-off control valves in Grohnde. So, the control function of these valves is available even in Station Black Out. This will be seen in the beginning of the transients from the partial cool down to 74 bar on secondary side with 100 K/h, after touching the setpoint for the blow-off valves (82 bar). Please note, that this feature is in contrast to other pre-Konvoi and Konvoi plants, where only the safety valves at the SG are supplied with secured power.

For safety assessments, such operational functions are often neglected (or typically assumed not available), because their loss is covered by safety functions in a higher quality.

In case of the loss of the 10 kV DG, e.g. by external impact, 4 bunkered systems with 0.4 kV diesel generators, each of them coupled mechanically with a smaller emergency feedwater pump, would step in, to feed the SG from large bunkered water basins. These functions are essential for the demanded 10 hours autarky of the reactor cooling function in case of external impact. Of course, DC power for instrumentation and control of the bunkered systems has to be provided from DC buses supported by batteries, or fed via rectifiers from the 0.4 kV buses secured by these smaller DG. There are no converters for secured AC from DC in this bunkered part of the plant.

4.1.1 Cross connections

4.1.1.1 Cross connections in RA

The main steam system is cross-connected via the main steam header in the turbine building.

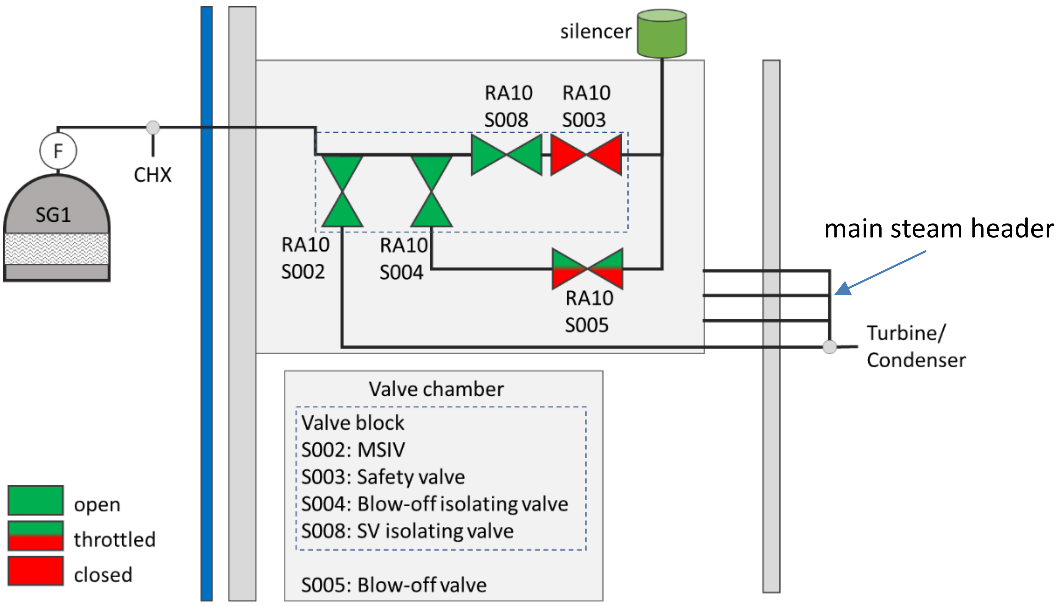

Figure 1: Cross connections and valves in the Main Steam System at the beginning of SBO

At the beginning, without manual intervention, the pressure is limited by the blow-off valves. Each blow off valve controls the pressure from its own SG, but pressure differences can cause backflow from the main steam header in the turbine building at the right hand side. This cross connection can be blocked by closing the MSIV manually, or in case of a rapid pressure drop (indicating a break or large leakage) automatically.

Valves in the valve block are controlled with pilot valves, which need pressurized air and some low voltage power. The blow off valve S005 needs electrical power, but can be isolated by S004.

4.1.1.2 Cross connections in RZ

The connections in blowdown system RZ are depicted in the figure below.

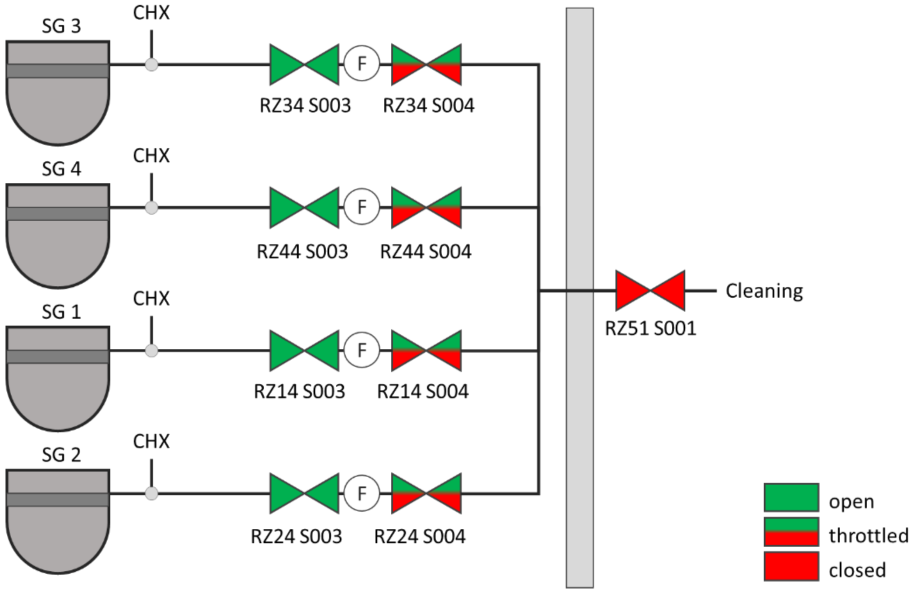

Figure 2: Cross connections on water side of RZ system during SBO

The blowdown path is normally trimmed to drain continuously an estimated amount of water from each steam generator to remove the water with a higher concentration of dirt and salt from the bottom. So, the individual position prior the accident is difficult to predict. Furthermore, the valves are controlled from the bunkered redundancies, which do not have secured 380 V alternating current. Therefore, these valves would have to be operated by makeshift power supply or manually; so far, the conditions in the containment have not deteriorated yet. Generally, these connections should be considered as existing.

4.1.2 Operability of components during SBO

A full scope simulator, with licensed personal trained several times per year over a decade (critically checking scenarios), provides an assessed setup, which drives are available in case of different sets of malfunctions from the buses or DG. In this sense, a well-maintained simulator represents stored knowledge of institutions, authorities, licensees, experts, plant engineers and technicians. So, these dependencies will not have to be checked further here.

Some inputs to simulate actions on components had to be done in a makeshift manner, for convenience handling the instructor station. So, closing of MSIV was done by the malfunction of mispositioning the valve (“Spurious closure”), instead of performing the operation using the instrument-air-powered pilot valves. It was assumed, that the power for the solenoids of the pilot valves was available from the respective batteries, and the pressurized air was available from a local buffer vessel for these purposes.

Some local activities to close valves could be assumed possible, but especially actions at the trim valves in the blowdown system (especially described in case 4) could become complicated, because these valves are located inside the containment. Expecting some deteriorating conditions there, such field operators’ actions should not be credited.

All TK-components were assumed operable, according to the self-powering of the system.

4.1.3 Indicators available in the control room

The control room at a simulator should display all the indicators available for the shift team in the same manner as in real, including measuring errors and response to adverse external conditions, which is in particular important for level metering. For the simulator instructor there are some more indicators available, especially internal parameters as pipe flow or level indicators beyond measured range. So, if suitable, these differences should be taken into account when it comes to the decision making to be expected. Such decisions are the closure of the MSIV or the shut-off of single TK subsystems, to stabilize pressure and temperature. Remarks will be made in the respective sections in the discussion of the transients. Nevertheless, the RELAP viewer of the simulator will be extensively used to follow the evolution of the transients.

4.2 Description of the sCO2-4-NPP heat removal system

4.2.1 Components and control

The model of the heat removal subsystems was described in [1] and [2] before. The interface to the simulator was outlined in [3], and the integration in [4], in the documentation of the project. A good and short overall description can be taken from [5]. From this, a detailed description is not necessary, but the handling of the system in the practical use at the simulator will be described here shortly.

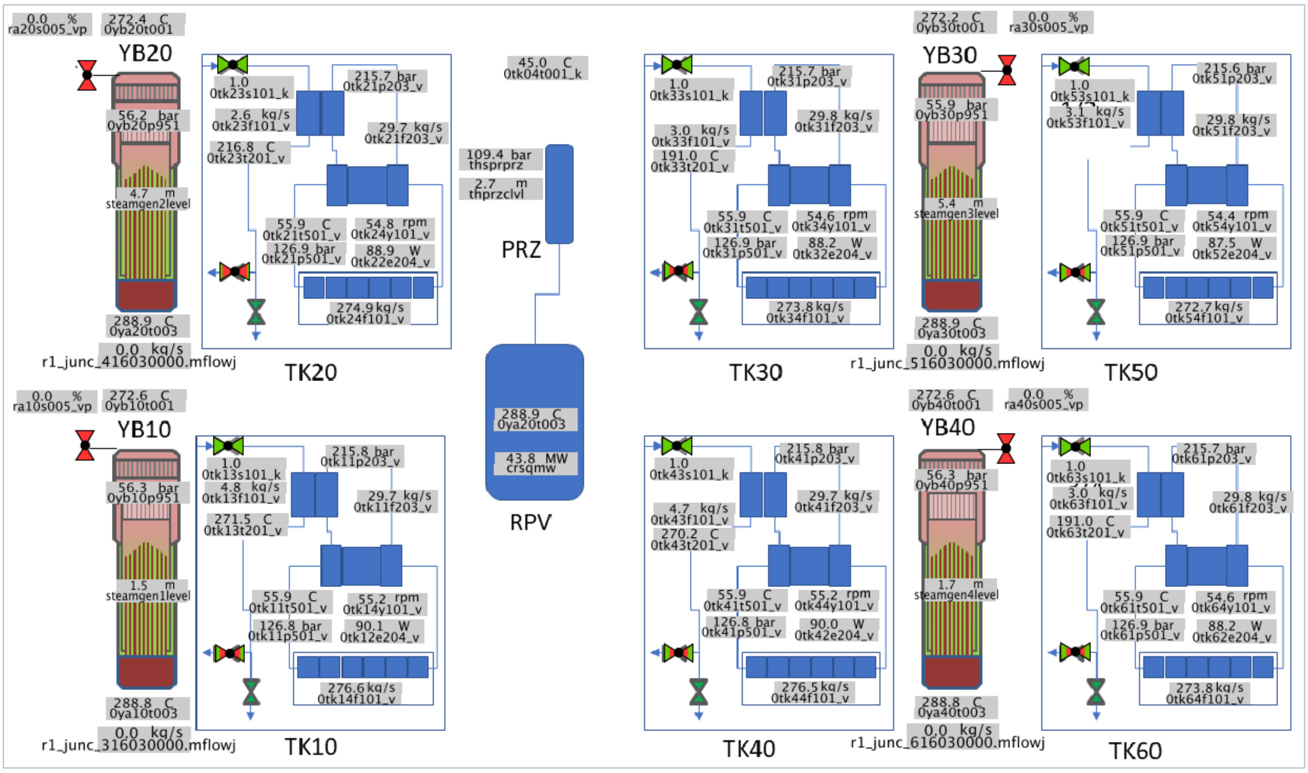

Figure 3: Overview of all TK subsystems with main parameters

The nearly identical 6 subsystems will be here referred to as “TK10” to “TK60”, to fit in the 2 letter code AKZ. TK10, 20, 30 and 40 have a simple order towards the four steam generators SG1 to SG4. TK50 can either be connected to SG1 or SG2, TK60 to SG3 or SG4, but never to both at the same time. This allows a good flexibility regarding symmetry. Cross connections in between steam and condensate path, e.g. taking steam from SG1 but giving back condensate to SG2, are excluded (this is reasonable from physics point of view too, because even slightest pressure differences would hamper the gravity-driven condensate flow). Please note, that in the snaps from the RELAP viewer SG1 is in the lower left corner, and the order of the SG is clockwise. This order was resembled in the systems overview (see Figure 3).

Each subsystem has a nominal heat removal power of 10 MW. To achieve this power, the design parameters should be met, e.g. a speed of 23000 rpm, a compressor inlet temperature of 55 °C (which is controlled by the temperature and air mass flow through the UHS) at a pressure of 127 bar, and a steam inlet temperature of about 290 °C. The CO_2 mass flow is about 30 kg/s.

The temperature behind the CHX is determined by the steam temperature at most, but in second order by the CO_2 temperature at inlet and the condensate temperature achieved at the outlet of the CHX. This condensate temperature would be more supporting from thermal viewpoint, if it were not too cold, but a temperature of about 150 °C was intended to keep the thermal stress limited. For this, the control 0TKx3 C001 (x = number of subsystem) had to operate a valve at the outlet, balancing the condensate flow for proper subcooling during travelling time through the CHX. Some numerical instabilities occurred during this process. Finally, 0TKx3 S201, another valve in the condensate flow path, was trimmed, dampening the oscillations and providing at least some steady subcooling.

The CO_2 temperature at the inlet is determined by the UHS control and gets some boost during compression from about 55 °C to 85 °C. The air mass flow is controlled by the speed of the UHS fans via 0TKx4 C001 (again, x stands for the number of the subsystem).

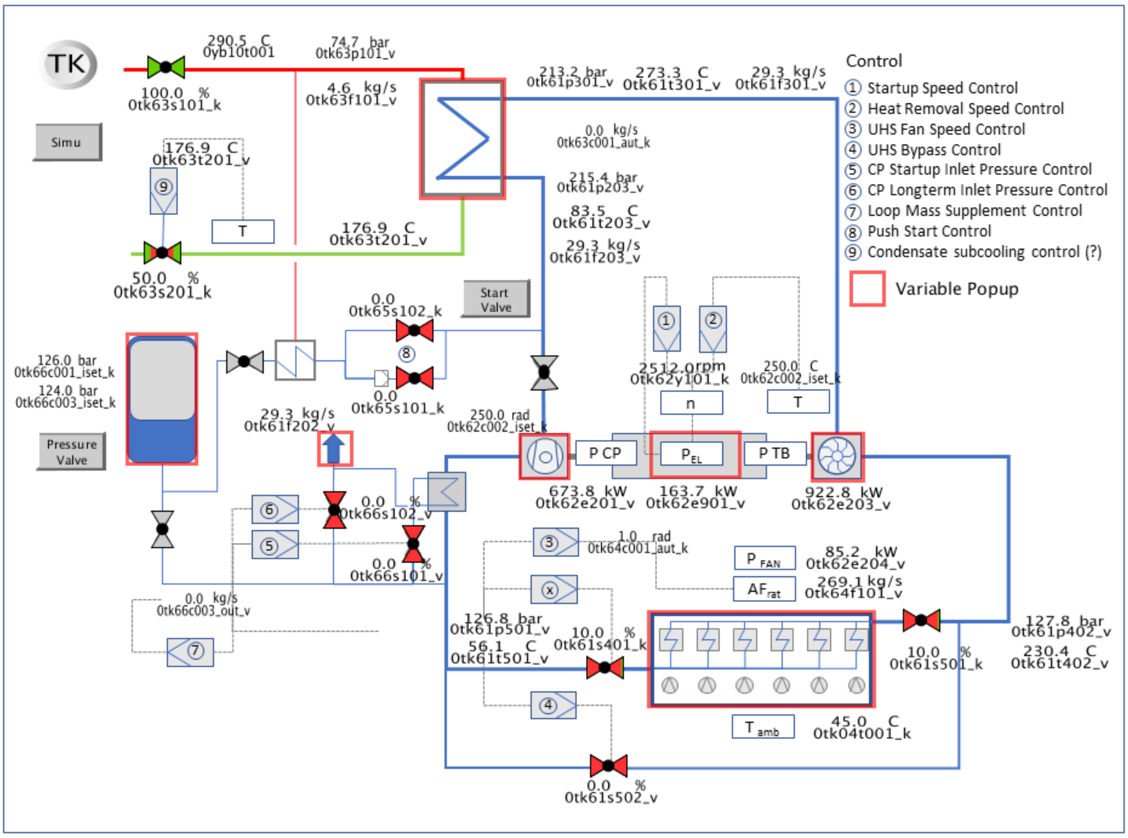

Figure 4: TK60 subsystem after start

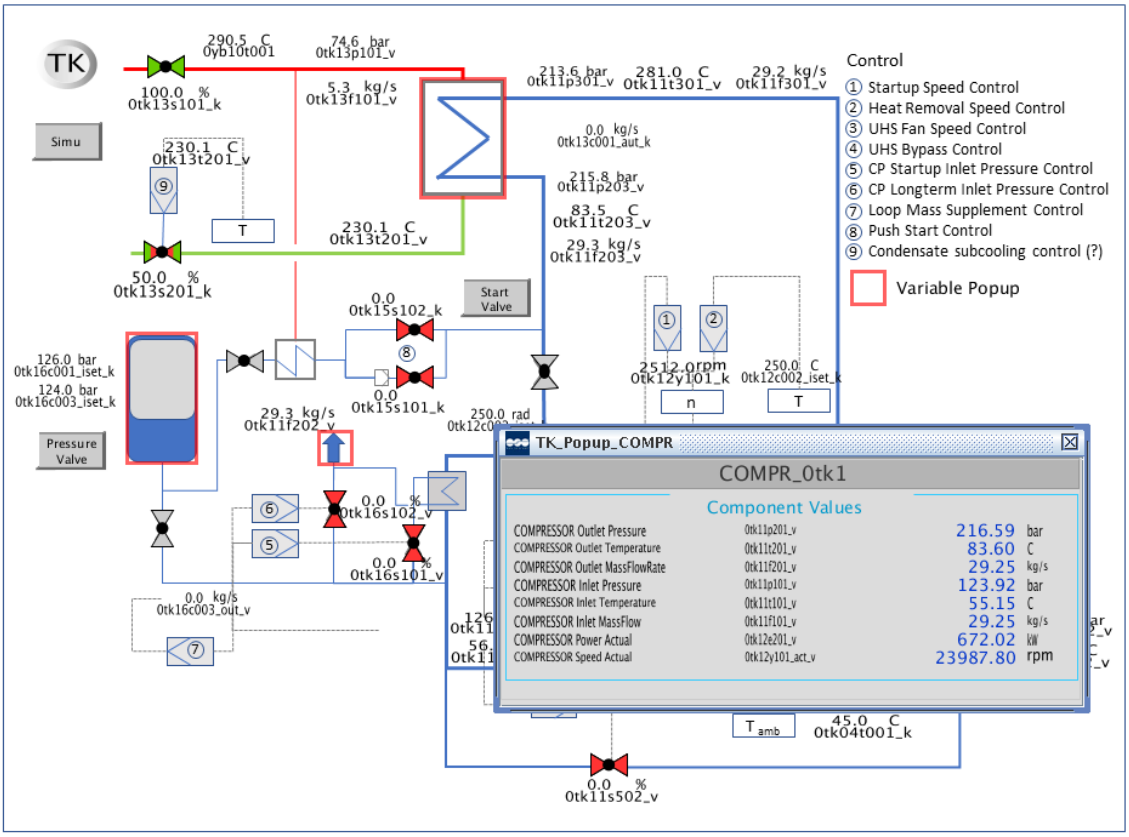

Figure 5: Popup to control Compressor's data

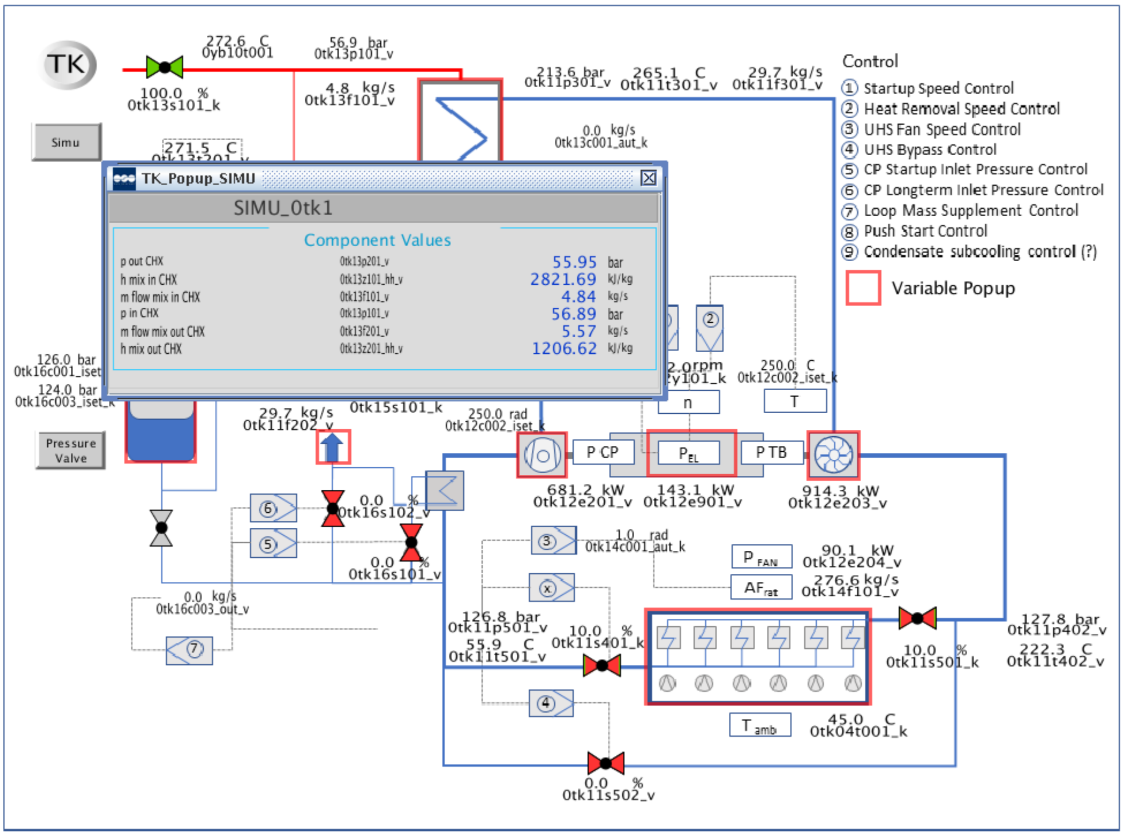

Figure 6: Popup to control thermal hydraulic interface data to simulator

More details about the parameters could be retrieved from pop-ups in the operations picture. Pop-ups are to be detected by the red squares around the components (Figure 5). A special pop-up is about the thermodynamic interface to the simulator (Figure 6), where the thermal power can be retrieved from the mass flow and the enthalpy differences.

4.2.2 Start-up and operation

The start-up and stop of the TK subsystems was performed with simulator specific scripts (the so called “APP”-files), prepared by KSG and CVŘ. The main technological steps were:

- Start of the TAC with secured power, to fill, circulate and preheat the CO_2. Limited throttled opening of the steam line valve. Power balance is negative. At start of this phase, the UHS air temperature was defined to 45 °C of model reasons.
- Filling of the system and push the turbine to power from the CO_2-tanks. Electrical Power balance becomes positive. Complete opening of the steam valve.
- Close the push start valves, opening the condensate valve.

After this, the control of the air mass flow at the UHS was set in automatic mode (this was not scripted, so it was done manually), so the temperature at the UHS outlet was controlled at 55 °C. Same was tried for the condensate temperature control, but revealed unstable, from the changing backpressure due to the lowering SG water level. So, some adjustments were done with TKx3 S201 in a fixed position, to maintain some subcooling.

4.2.3 Shutdown and restart at the simulator

The shutdown of a subsystem was again performed with a prepared script, where the connection in between the so called FMU (for explanation see [4]) was simply shut off, with the TK subsystem remaining virtually in some kind of readiness state. A restart was done performing the start script again (or in case of a switch of the SG for TK50 or TK60 the specific script for the parallel connection).

5 Transients

5.1 SBO Boundary condition

5.1.1 Initial Condition and Scenario

The initial condition was set at 100 % rated thermal power of about 3900 MW. Considering burnup, a Begin of Cycle (BOC) state in equilibrium (with fuel elements history of typically up to 5 cycles back) was used. So, the decay heat starts with about 260 MW at shutdown.

The SBO was implemented by a combination of malfunctions, started with a prepared script at the same time with a trigger. See Table 1.

Table 1: SBO script

Malfunction	Comment
Malfunction "Emergency Power"	Predefined combination (AT00A), Loss of Grid and no inhouse operation. Loss of main heat sink and MCP. SCRAM.
Malfunction of all 10 kV DG	4 predefined malfunctions (GY10A...GY40A), so the 10 kV emergency buses are not supplied, not any auxiliary feedwater pump available
Malfunction of all 0.4kV DG	4 standard malfunctions (block of start valves 5GY53...8GY83 S020), so the bunkered emergency 0.4 kV buses are not supplied, not any emergency feedwater pump available

The SCRAM results immediately from the loss of rotational speed of more than 1 MCP. There is no signal for closing of the MSIV – this would be done in case of a secondary side leak, causing a rapid pressure drop in the SG. Nevertheless, as shown later, the closure of MSIV is needed to avoid long term losses to the gland seal packages along the stems of the large turbine and bypass valves.

From the loss of power, the main heat sink will be isolated, from loss of hydraulic fluid pressure, so the blow off valves have to dump the steam into the air. This starts, when the secondary side pressure has increased to 82 bar, stimulating a partial blow-off to 74 bar. This feature is available only if the blow-off valves are operable from secured AC power, which is the case for the reference plant. Otherwise, the pressure would reach 87 bar, the setpoint for the safety valves, to be limited there in an intermittent opening with a hysteresis of about 5 bar.

A "snapshot" was saved as a new initial condition, when pressure had been stabilised at 74 bar after about 5 min, to serve as the uniform initial condition set for all transients with TK system operation. From viewpoint of operation, manual interference in such a scenario should start only after getting an overview to make sound decisions, so this delay in time would be the minimum to be expected.

5.2 Overview about the Transients

The scenarios were chosen to highlight some questions about operational details, typical for the framework of a simulator for training, as well as for verification of procedures of the simulated plant.

Table 2: Test scenarios

Case number	Order of subsystems to SG	Boundary conditions
Reference: run without TK, depressurisation	No TK in action	SBO from initial condition until overheat of the core, no TK started
Case 1: 6 subsystems with closed MSIV	SG1: TK10 SG2: TK20, TK50 SG3: TK30, TK60 SG4: TK40	Systems started about 10 min after blackout. MSIV closed when pressure is below 70 bar and power expected to be below capacity (blow-off valves already closed). TK50 and TK60 shut down, when power is at about 40 MW Further: 0TKx3 S201 throttled, to stabilize condensate temperature
Case 2: 6 subsystems delayed	SG1: TK10 SG2: TK20, TK50 SG3: TK30, TK60 SG4: TK40	Systems' start delayed, about 30 min after SBO. RA remains open. TK50 and TK60 shut down, when power is at about 40 MW. Followed until stabilizing temperatures with 4 subsystems.
Case 3: 4 subsystems with failure concept	SG1: - SG2: TK50 SG3: TK30, TK60 SG4: TK40	N+2-test. TK20 in repair, backed by TK50. TK10 fails at start. Start within 10 min after SBO. RA remains open, to force long term steam cooling and to demonstrate losses to the Main Steam system.
Case 3a: 4 subsystems symmetrically (reference to ATHLET)	SG1: TK10 SG2: TK20 SG3: TK30 SG4: TK40	Closed MSIV soon after SBO. 4 systems started about 10 min after SBO Further: 0TKx3 S201 throttled, to stabilize condensate temperature
Case 4: 6 subsystems with closed Blow-off path	SG1: TK10 SG2: TK20, TK50 SG3: TK30, TK60 SG4: TK40	Systems started immediately, Main steam closure valves remain open to below 80 bar, but main steam blowout control valves' path blocked. Resembles normal Konvoi. Further: 0TKx3 S201 throttled, to stabilize condensate temperature RZ connections manually closed (RZ14/24/34/44 S003) shortly before closing main steam (after 1 hour). After 2 hours stop TK60.
Case 5: 5 subsystems	SG1: - SG2: TK20, TK50 SG3: TK30, TK60 SG4: TK40	Systems started immediately, blow-off isolating valves closed after start, main steam isolating valves kept open until power dropped below capacity of 5 subsystems (pressure below 80 bar), RZ connections kept open Further: fixed trim for condensate valves, air flow control in automatic mode.

Case number	Order of subsystems to SG	Boundary conditions
Case 5a: Case 5 continued with depressurisation	SG1: - SG2: TK20, TK50 SG3: TK30, TK60 SG4: TK40	Depressurisation of a dried out SG1, to refill from feedwater tank.

5.3 Reference: SBO with depressurisation

The transient was done to demonstrate the grace time available in case of SBO, before the heat-up of the core sets in. A transient with heat-up until overheating was simulated and delivered already for D2.2 at an earlier stage of the project, the temperature evolution in the core until start of overheating is depicted in Figure 7.

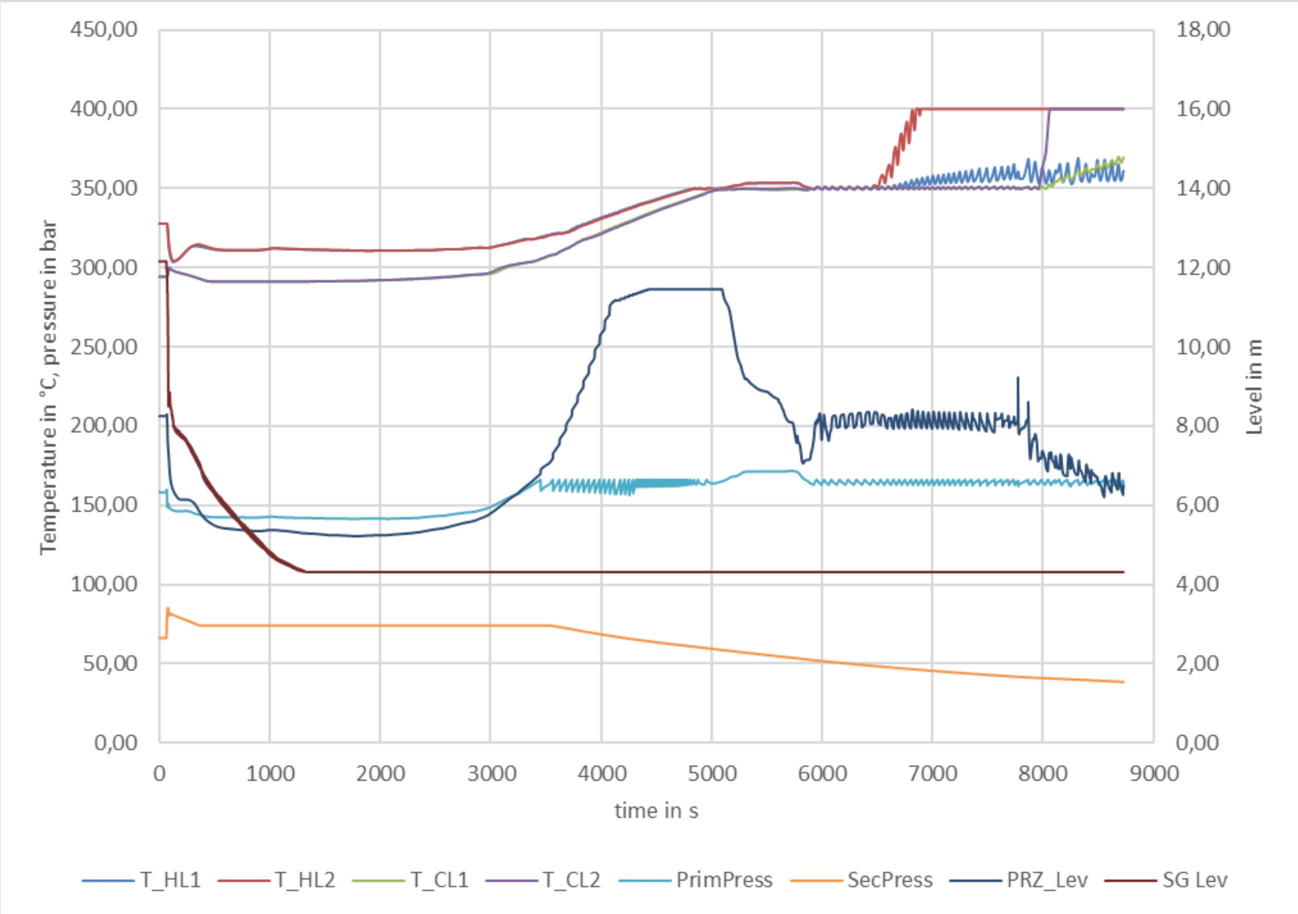

Figure 7: SBO reference run for D2.2 until overheating of the core

From this the heat-up is to be seen beginning at less than 1 hour after SBO occurred, with primary coolant spilled out from pressurizer into the pressurizer relief tank after about 1 hour. Emptying of the primary circuit leads to boil-off of the core, where uncovering and escalation of heat-up can be derived from HL2-temperature (the path of the steam towards the pressurizer), steeply increasing after 6500 s. The understanding of the thermal hydraulic effects determining the path of these parameters is necessary to follow the transients with TK systems below.

Beside this, a new transient run was started to:

a) Confirm that the basic conditions at D46 simulator for the SBO regarding the initial condition and the models did not change since end of March 2020,
b) Get some more depictable states from the RELAP viewer, regarding the phases of the transient,
c) Demonstrate a classic accident management measure, the depressurisation of the secondary side (done with limited resources, so only one SG was depressurized in the first step), to highlight the capability of the simulator to demonstrate such complex scenarios, supported from the RELAP viewer as visualisation tool.

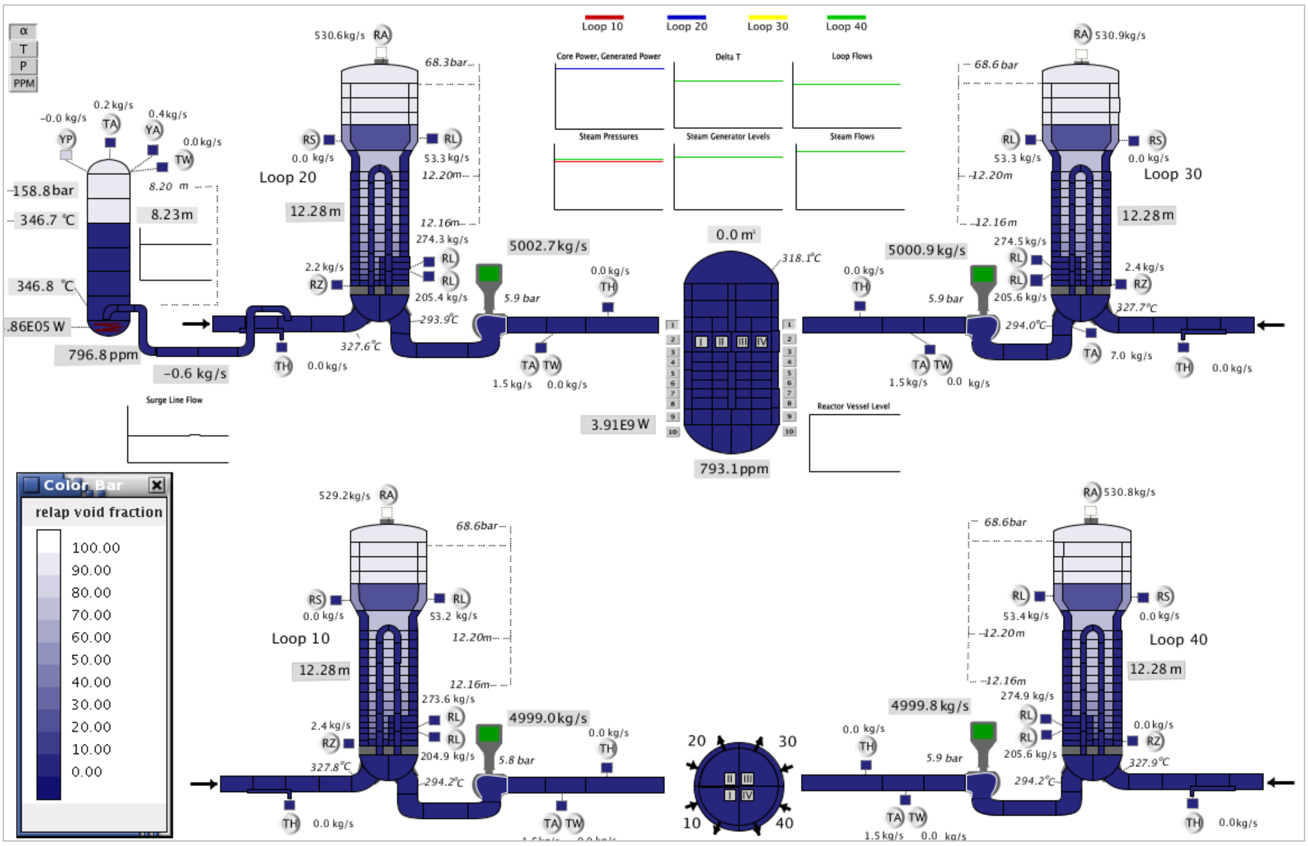

Figure 8: RELAP view of the initial conditions before SBO

The RELAP view of the initial condition (Figure 8) shows a reactor power of 3910 MW and the typical mass flow of about 5000 kg/s in each loop, with running main coolant pumps. The shade of blue depicts the volume content of steam in each node. From this there can be taken, that the most of the inner part of the steam generators is filled with void of typically 80 %, whereas the downcomer is filled with water subcooled from feedwater. The special existence of the preheater chambers can be derived from the split of the feedwater flow to the bottom near the cold leg side of the SG-outlet, to support the subcooling of the cold leg. Nevertheless, a temperature of 294 °C is given for the CL. A smaller part of the feedwater is given into the ring around the separators, so the water in the downcomer becomes subcooled. Please note, that the level metering measures the column in the downcomer. The level metering stops at the lower end at about 4.2 m (as to be seen in Figure 7), mainly because an orifice below to restrict and stabilize the liquid flow would influence the pressure difference to the top. Fortunately for the analysis, the RELAP viewer gives an effective water level from the internal balance.

The downcomer is separated from the riser around the U-tubes by a shroud. The volume of the water below the measured level is mostly given as 70 m³ per SG, but there will be about 40-45 t of water (including the steam area) in each SG.

If the heat transfer from primary side has ceases after scram, the void inside the shroud will collapse and water is shifted from the downcomer inwards. The feedwater flow will stop immediately. The extensive blow off to remove the residual heat as well as the cool down to stabilize the secondary pressure at 74 bar (gauged, therefore 75 bar total pressure indicated in the viewer) causes a drop in the water level down to about 7 m within 5 minutes.

The residual power comprises more than the decay heat: it is the fission power on the way to become subcritical, the heat stored into the fuel for temperature profile to perform the heat conduction through the oxidic fuel and last, but not least, the decay heat, beginning with around 6 % of the nominal power.

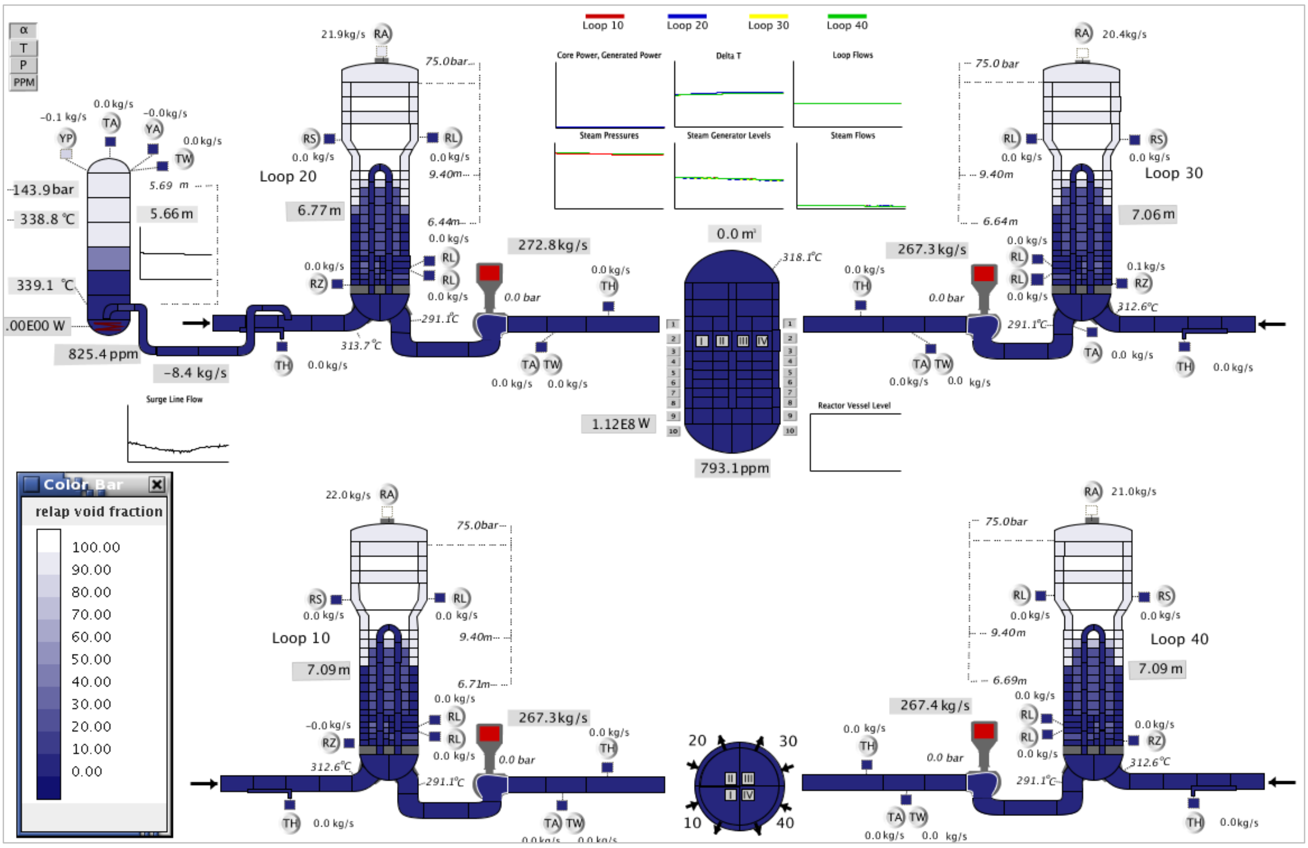

Figure 9: Conditions for the uniform initial state for the transients, 5 min after SBO

This state, depicted above in Figure 9, was taken as the initial condition for the following transients.

With a decay heat of still above 100 MW (10 min after scram it is typically still 2.2 % to 2.4 % of the nominal power, depending from the uncertainties included), the water will be boiled off steadily, in the depicted case via the blow-off valves. A diagram for the decay heat for the simulator is attached in A.1.1.

After less than 1 hour, the SG will fall dry. In Figure 7, the increase of the coolant temperatures can be seen setting in already before, because of the reduction of wetted heat transfer area at the outer side of the U-tubes. Being not able to follow the liquid water level below 4 m in the control room, this temperature increase gives the shift crew the information that the SG is drying out now. The situation with dried SG is depicted in Figure 10.

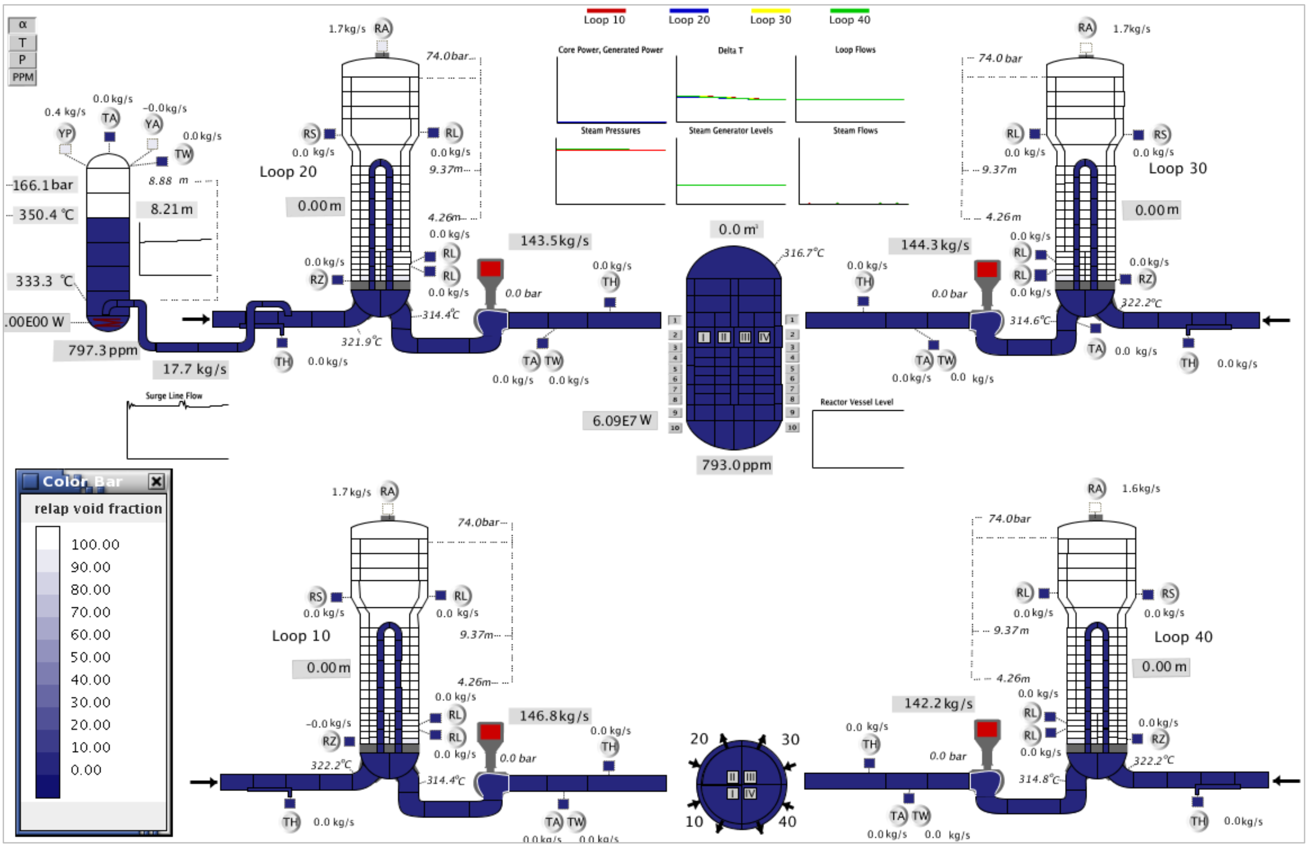

Figure 10: SG dried out, primary heat up and blow-off with PRZ relief valve

Another sign for the heat-up can be seen here: the heated liquid in the primary system will expand, hence the pressurizer has to take over the surplus. Initially the level has shrunken from contraction after scram, decreasing the coolant pressure down to about 140 bar (please refer to Figure 9). Now, the level will increase, compressing and therefore overheating the steam cushion on top of the pressurizer. At 167 bar the pressure extents the setpoint of the pressurizer relief valve, which blows the overheated steam off into the pressurizer relief tank. These blow off events are comparably short, because the water phase below the steam cushion is still subcooled, so no boiling will support the steam cushion against the depressurisation. The heat of the reactor is still buffered by the latent heat of the still subcooled liquid in the loops, steadily increasing temperature. Please note, that the heat capacity reaches values of above 8 kJ/(kg K) at around 340 °C.

These short releases of volume flow will continue even after the steam volume is released, and liquid water with a certain subcooling (it had reached the pressurizer at an earlier moment of the heat-up) has to be spilled out. For this, the pressure will show still the saw-tooth shape, but with higher frequency, as to be seen in Figure 7 before 5000 s.

The situation escalates with the reactor outlet reaching boiling temperature. Now the spill out intensifies, because the volume increase is dominated by boiling. This situation is depicted in Figure 11. Liquid and two-phase mixture is pushed into the pressurizer, which keeps the pressure at setpoint of the relief valve. In Figure 7, this can be noted after 5000 s, where the HL-temperature goes horizontal, and the pressure is stabilizing at an elevated level, whereas the liquid mass level in the pressurizer decreases from boiling off.

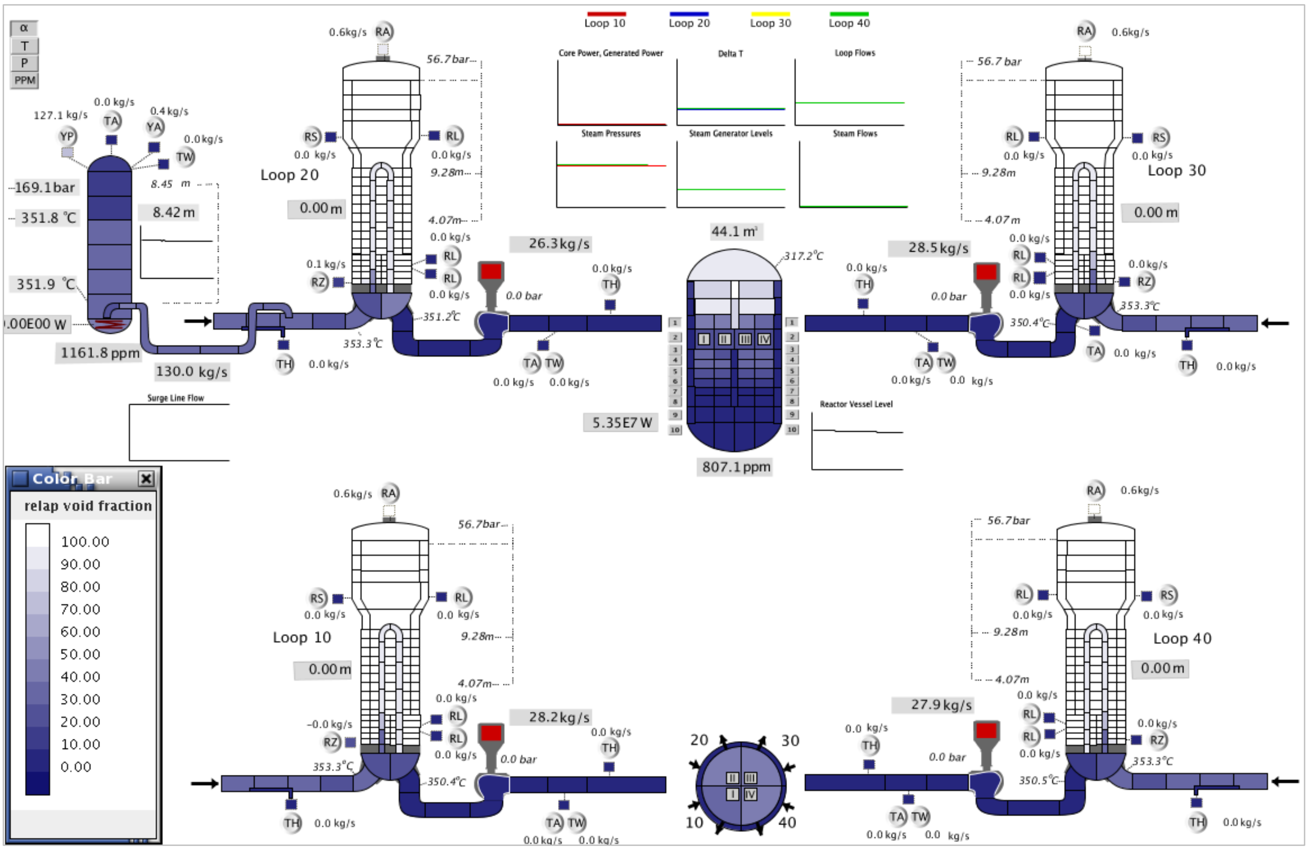

Figure 11: Dual phase flow and heat removal via PRZ into containment

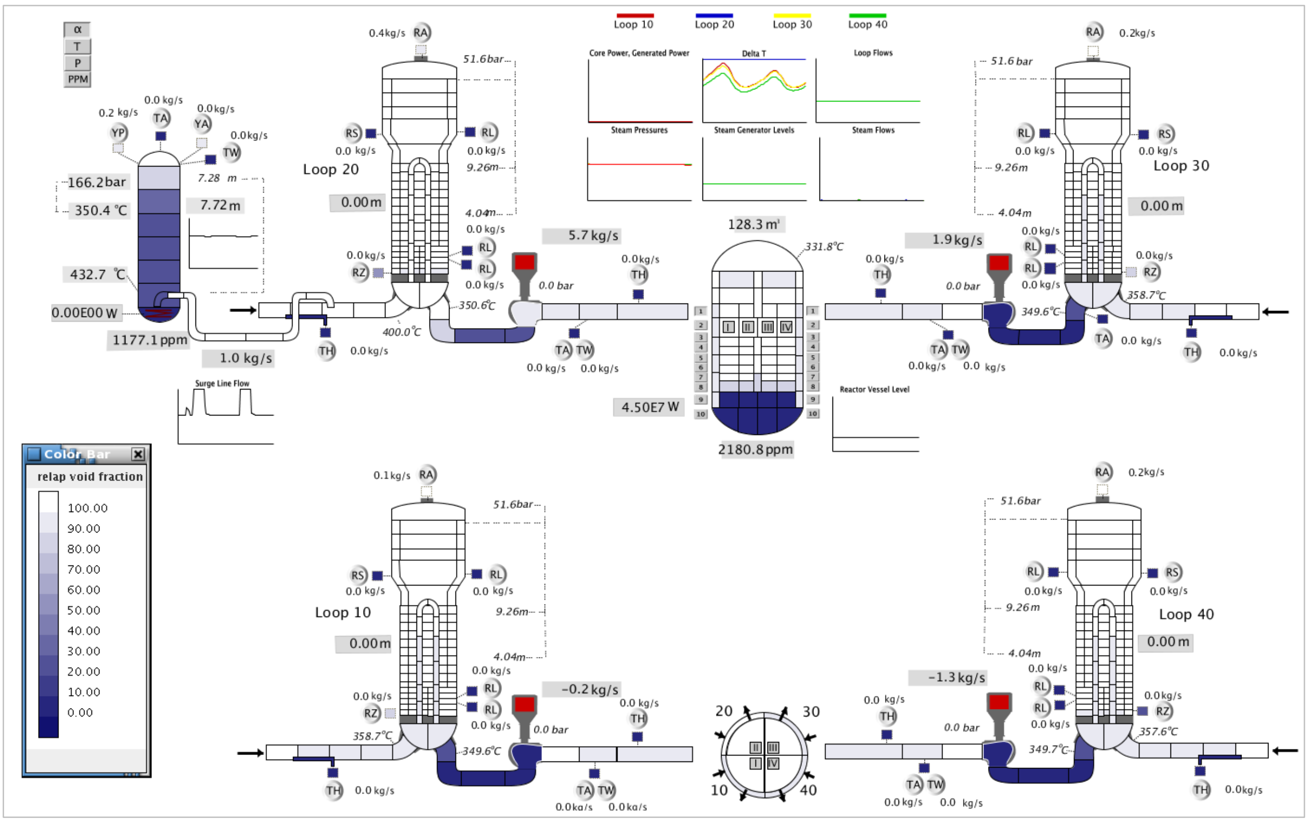

Figure 12: Core uncovered and overheated after less than 2 hours

Now at latest, the pressurizer relief tank relief disk will burst open, and the coolant will spill into the containment, triggering loss-of-coolant signals. In some Accident Management procedures this is referred as a moment to initiate a secondary side depressurisation, to get a passive injection from the feedwater system still standing at about 20 bar from the high pressure preheaters (about 220 °C), or from the feedwater tank with about 10 bar. If this is not available, the lower pressure may allow to feed the depressurised SG with a mobile pump.

If the heat removal to the secondary side cannot be re-established, the reactor will boil off and overheat. This can be followed after about 6000 s in Figure 7, and a representative state is depicted in Figure 12, taken from another run, but in principle presenting the well-knownTMI-2-accident situation: the core is empty, some liquid is still located in the pump bows, but the pressurizer still displays a filled state.

After about 2.5 hours, the run in Figure 7 was stopped, when the cladding temperatures exceeded 1200 °C, because the simulator was not designed for a degraded core.

5.3.1 Depressurisation

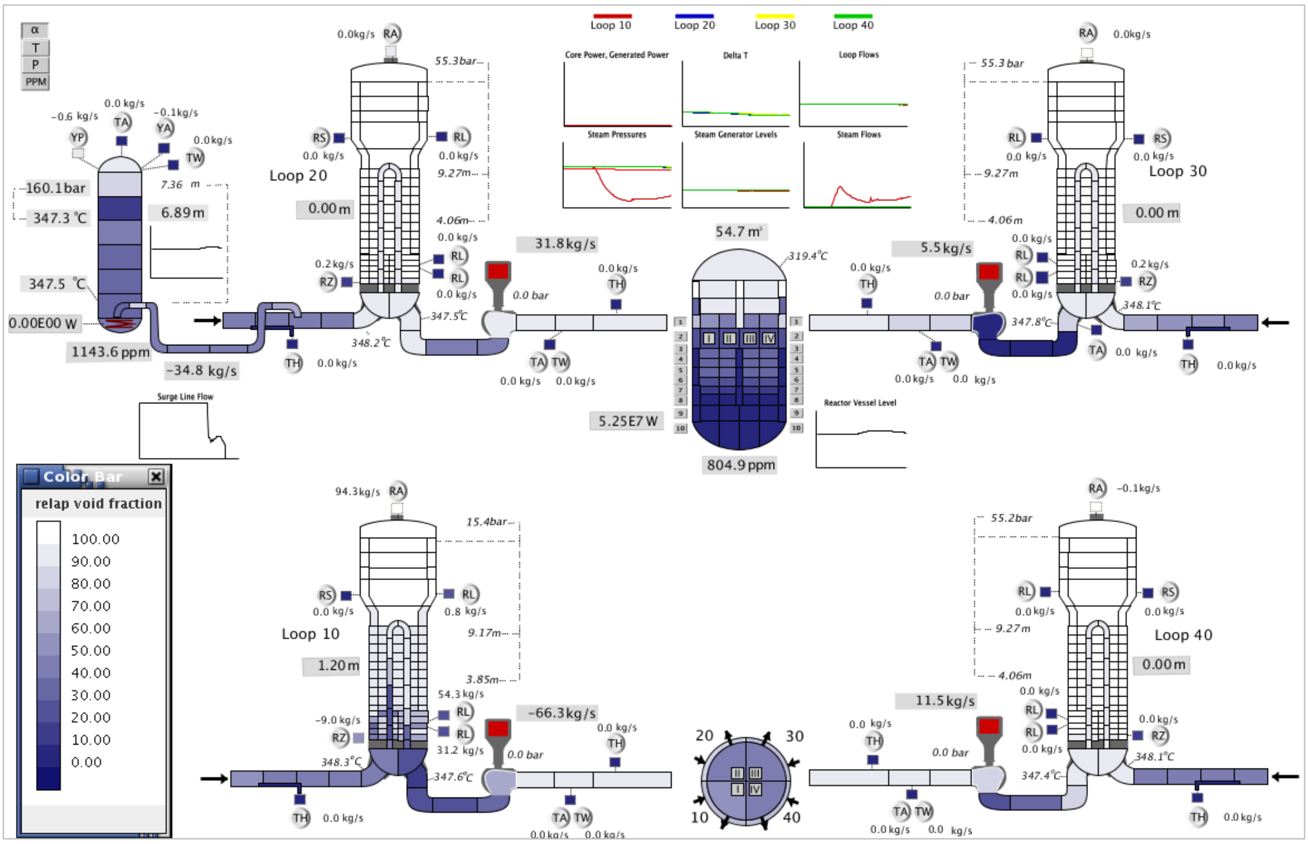

Figure 13: Depressurisation of SG1 during two phase flow in primary circuit, influx of feedwater begins

Establishing a blow-off path for the steam of at least one SG, one would get a rapid drop in pressure, because no supporting water mass has to be boiled off, to cool down along the saturation line. This was done here after about 6000 s, after establishing of two-phase conditions on primary side, about 15 min after the situation which is depicted in Figure 11. The timeline can be followed in Figure 18.

The water in Figure 13, marked with the AKZ “RL” already spills in from the pipes behind the preheaters, quickly flashing at the overheated surface of the U-tubes. On the other side, in primary system, the steam of the two-phase mixture condenses, which brings the pressure down below setpoint of the relief valve, and causes a backflow of liquid from the pressurizer into the loop 2. The fill up of the secondary side is limited by the steam volume produced from the re-established wetting of the U-tubes, so the increase of volume hampers the influx of feedwater. But there is no need to speed-up, because boiling cools the still water-covered core. The temperature for the HL and CL fluid decreases according to the saturation, as can be followed in Figure 18, after 6000 s.

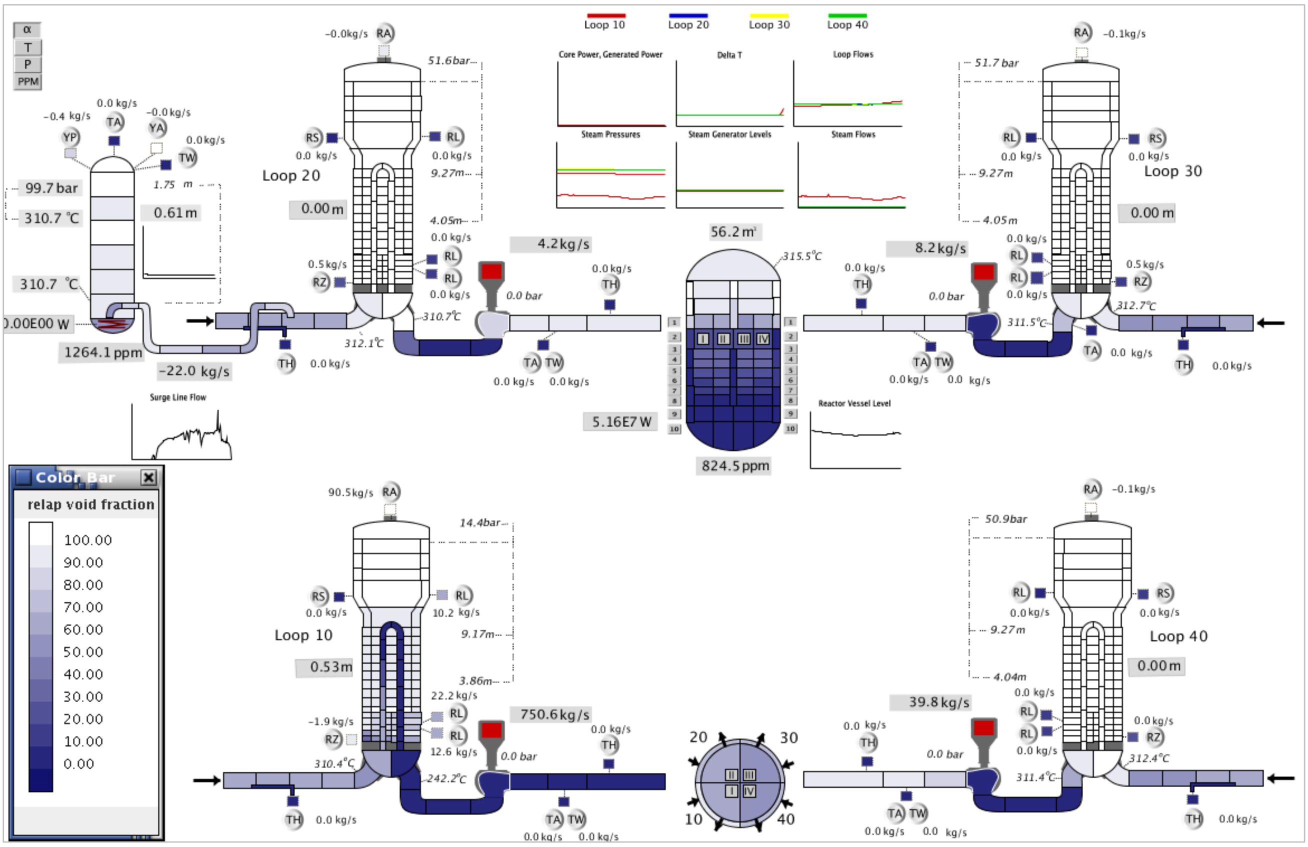

Figure 14: Pressure drop by condensing in the cooled SG1

Continuously removing heat over the depressurised SG, the pressurizer will be stripped of the liquid, whereas the pressure goes down in parallel. Here, the pressure drop in the coolant circuit causes the pressurizer to press out the liquid over the surge line, an effect regularly demonstrated at the Glass Model.

So, this liquid partially could refill the reactor, but merely is collecting as condensate in the pump bows, or, as to be seen in Figure 14, to fill the cold leg of the depressurised SG's loop.

Notably the SG secondary side is still not filling, but the cooling is sufficient to reduce the pressure in the primary circuit further, finally below 25 bar, the injection set point of the accumulators.

The injection is not only needed to fill up the liquid lost to the containment, but is much more important to bring in the boron necessary to keep the primary system subcritical after cooling down. The first injection is caught in Figure 15, filling up the loops, which become subcooled widely.

Some increase in boron concentration can be noted, too.

As a consequence of this fill-up, the two-phase flow to SG1 is blocked, and single-phase natural circulation is hampered by some steam, still to be condensed in the U-tubes. Checking the temperatures in the upper part of the SG internally revealed a stable overheating there, so the condensation will need a fill-up of the secondary side before.

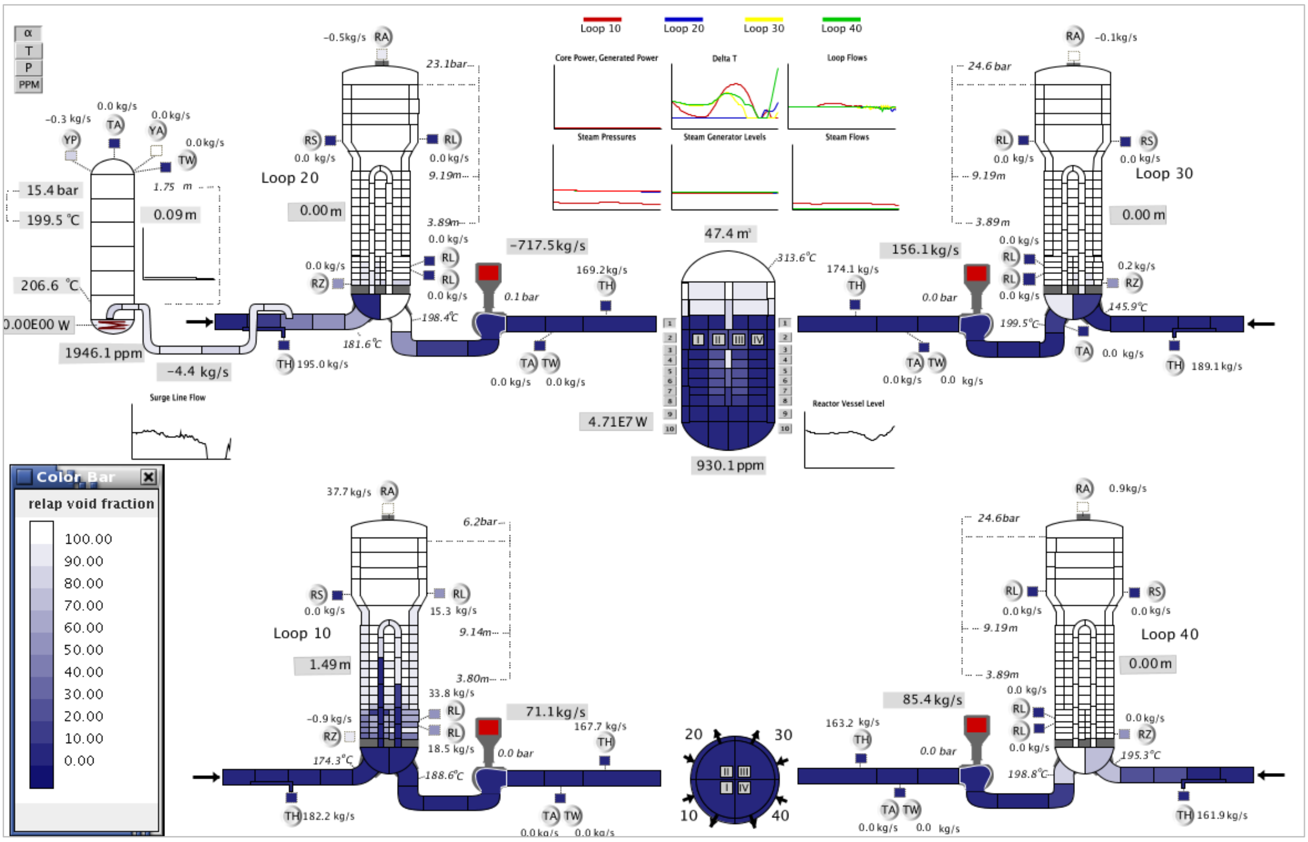

Figure 15: Injection pressure of accumulators passed, refilling and boronizing primary system

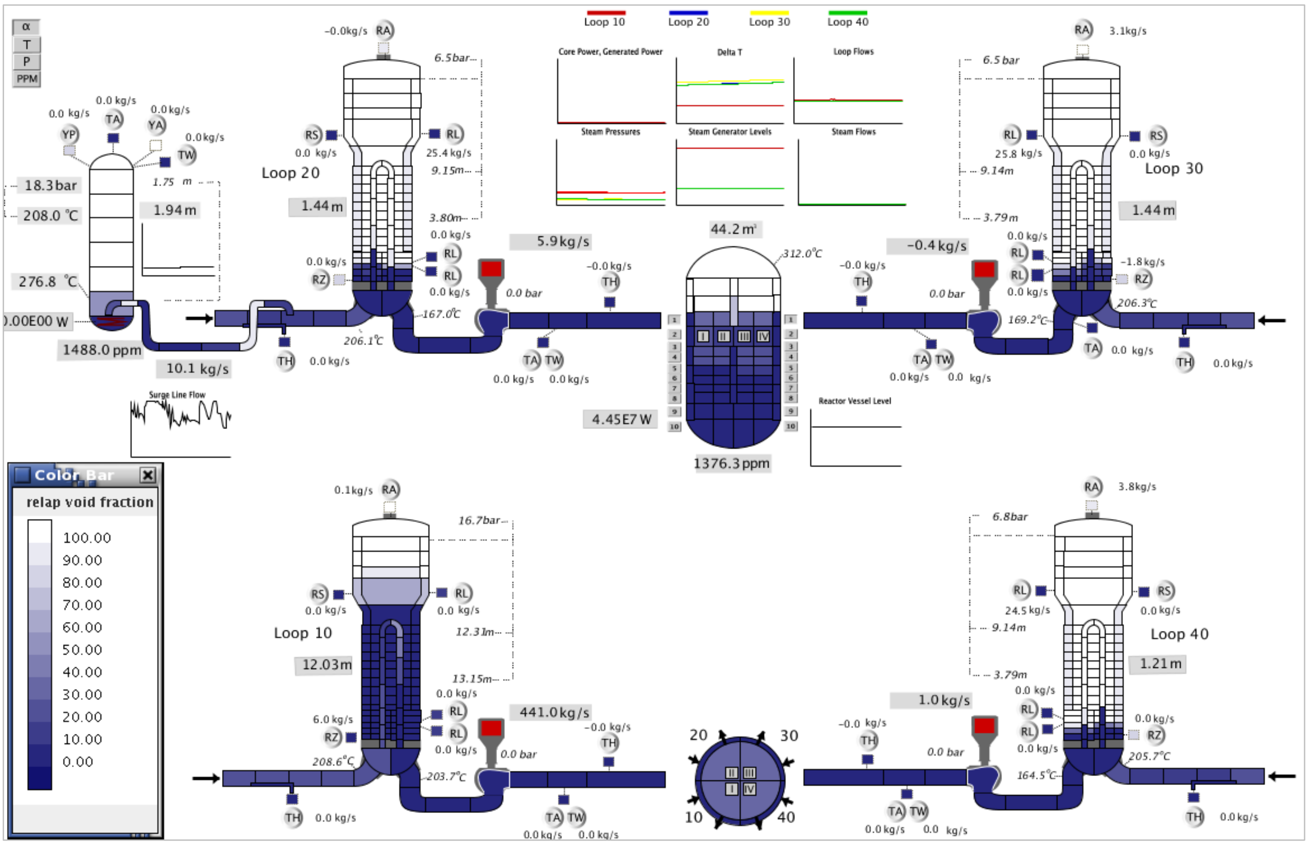

Figure 16: SG1 closed, SG2-4 depressurizing by 100 K/h blow-off

As a consequence, the pressure increases again in the primary circuit, the reactor vessel head (saturation pressure from steam temperature) and the pressurizer (compression by filling) compete to each other to determine the pressure.

The lesser heat transfer to the secondary side allows a further depressurisation, so finally the pressure of the feedwater tank is reached. The fill up of the SG had to be stopped by closing the steam path, to avoid a spilling of the coolant over the blow-off path. This is depicted in Figure 16. Please note the condensation inside the U-tubes and the onset of dual phase natural circulation in loop 10.

In parallel, the loss of coolant triggers had activated the 100 K/h cooldown for the other SG, so they took over the water from the feedwater tank. As a consequence of the initial blow-off, SG1 did not take part in this process, but remained isolated.

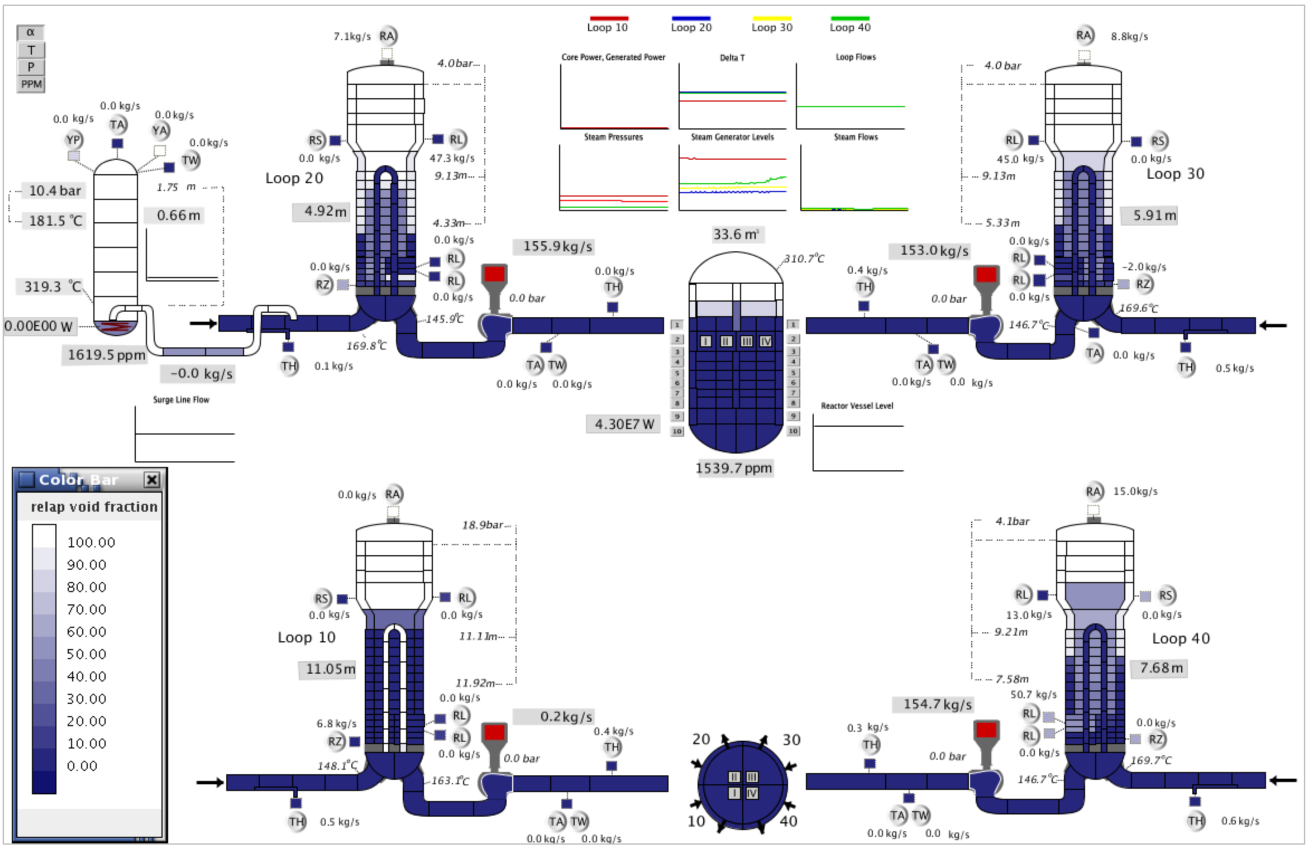

Figure 17: State before heat up, when feedwater tank is empty

The final snapshot in Figure 17 depicts the situation, when the feedwater tank had become completely empty at the end of the timeline in Figure 18. The cooldown of the three other SG had initiated another depressurisation of the primary circuit by condensation inside the U-tubes. In these loops the natural circulation has been re-established already. Only SG1, with a warmer secondary temperature and pressure (compared to the primary pressure), has lost the natural circulation by completely boiling off the fluid in the U-tubes.

The vessel head bubble is unaffected by the natural circulation, so it remains overheated. This can be derived both from the metal surface temperature and by the strict white colour, representing 100% steam.

The pressurizer is empty. The injection from the accumulators has stopped nearly. The boron concentration in the reactor would be sufficient for further cooldown, but now there is the need for another water source on secondary side. Without such an injection, the water on secondary side would boil off again within some hours (there is still 43 MW decay heat, so currently 30 kg/s are blown off to reduce the pressure and temperature further), restoring the heat-up.

These were only the first 3 hours of such a scenario, whose timeline can be followed in Figure 18. For the long run, a more sustainable solution would be needed. This is where the TK system comes in.

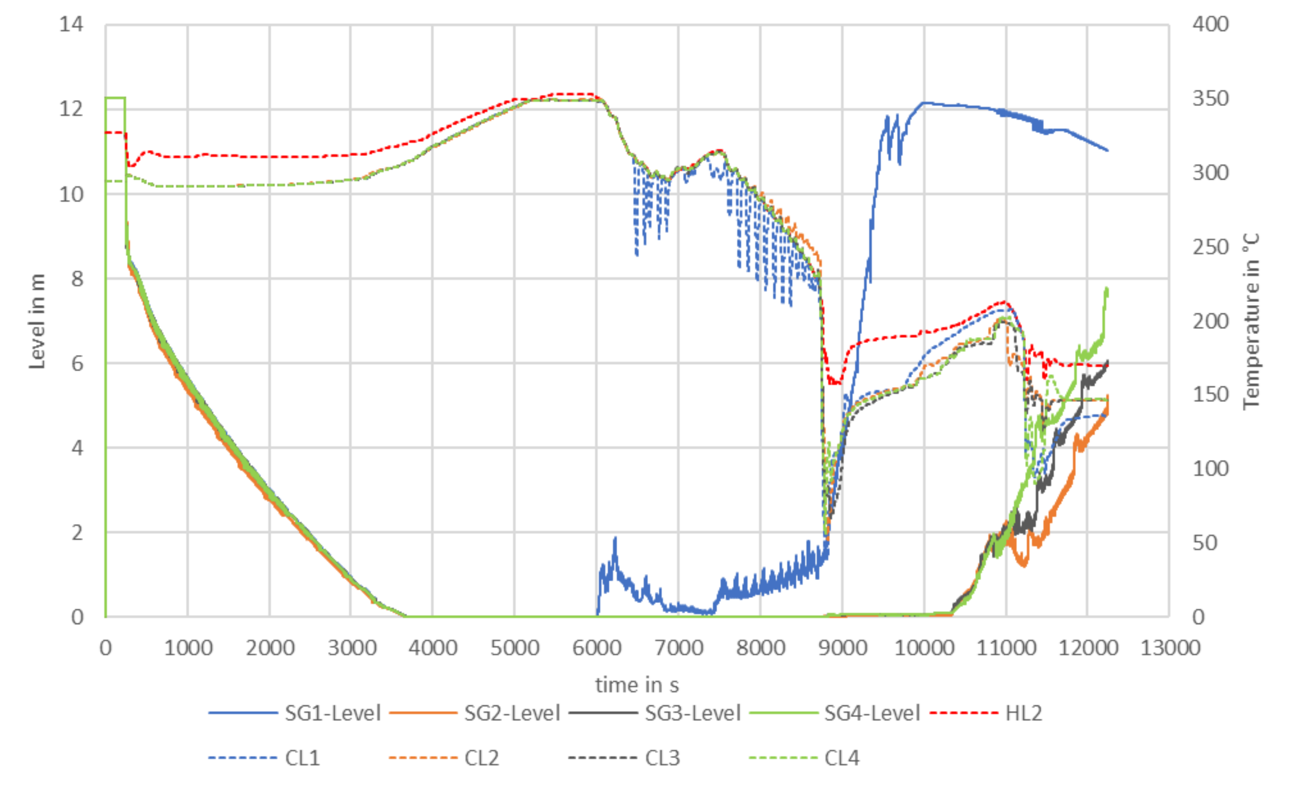

Figure 18: Timeline of SBO for the figures before

5.4 Case 1: Run with 6 TK subsystems

5.4.1 Description of the conditions

The first transient was to demonstrate the best conditions, when all 6 TK subsystems could be started about 5 to 10 min after SBO, from the initial condition mentioned above, when the blow-off valves had stabilized secondary pressure at 74 bar, removing the residual heat after Scram. SG2 and SG3 were connected to the TK systems TK50 and TK60.

The MSIV were open at the beginning, allowing a slow pumping up of the feedwater tank, but were later closed, as soon as the power balance from decay heat to the TK subsystems was reached, to stop the unavoidable slow loss of steam to the turbine valve shafts and drains in the main steam system.

5.4.2 Evolution of the transient

Soon after start up, a different tendency of SG level could be observed (Figure 19). Communicating to the primary side uniformly via the saturation temperature of ~290 °C (74 bar), the SG with two TK subsystems secured a bigger share of condensate from the main steam, uniformly available for all SG by backflow from the main steam header. So, the higher steam consumption of SG 2 and SG3 was levelled out.

Once the blow-off valves had been closed, the pressure dropped below 74 bars. Because a significant amount of heat was assumed to be removed by the leakages in the main steam system, in order to avoid a re-opening of blow-off valves, the closure of the main steam valves was delayed until the pressure had dropped below 70 bars. The immediate increase of pressure in the SG1 and SG4 at about 4000 s, reveals, that this precaution was necessary.

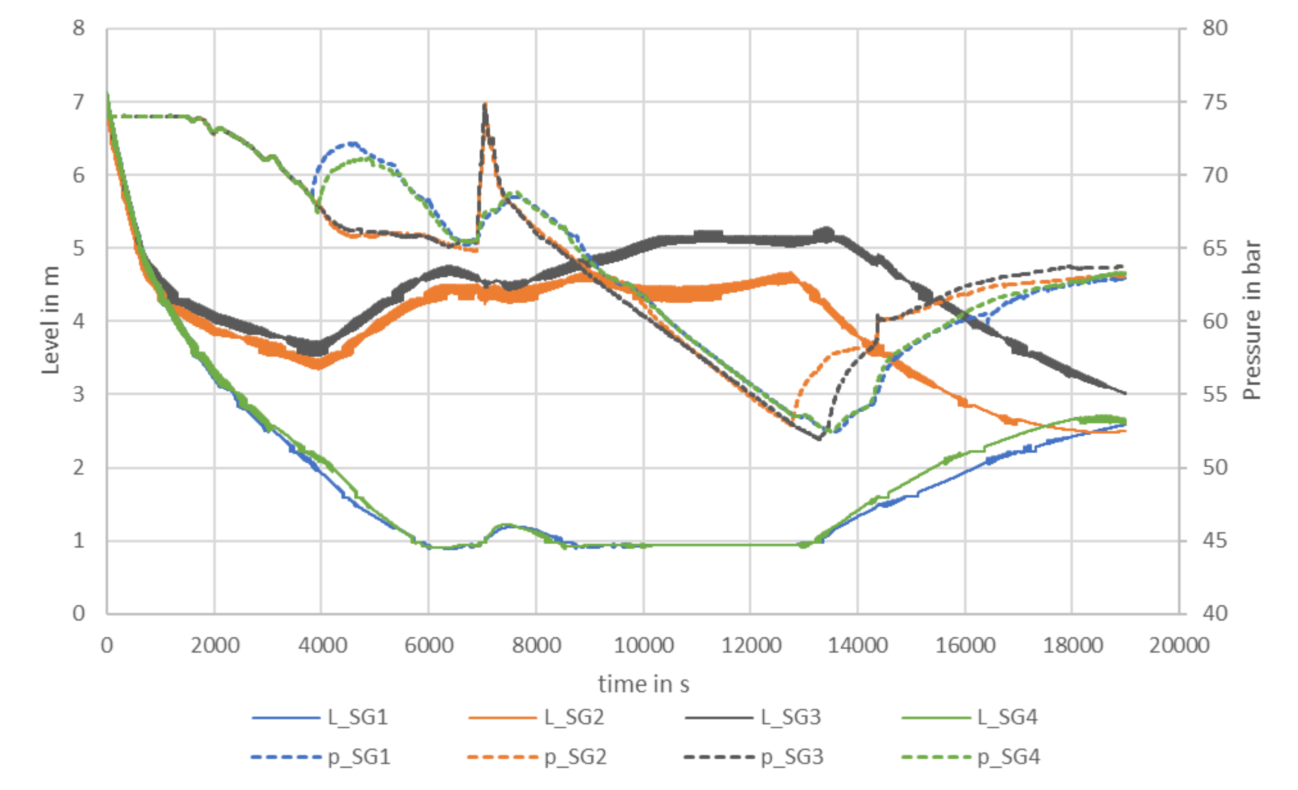

Figure 19: Case 1, SG level and pressure

From Figure 20 can be seen, that at this moment the decay heat was well below the heat removal capacity of 6 TK subsystems. But in case of closed MSIV, the share of heat removal from the primary circuit will be settled individually for each SG: with the same hot leg temperature, the filling grade and the temperature on secondary side decides about the portioning of heat transfer.

So, different numbers of heat removal system result in different:

- pressures (lowest for the double cooled SGs),
- levels (lowest for the single cooled SG), and;
- natural circulation mass flow (lower for the single cooled).

This can be derived from the snapshot in Figure 21.

Changing conditions like the MSIV position will cause a reshuffling of heat removal intensity, by SG level or temperature and pressure. The precondition for the level balance (reducing heat transfer area from lost wetting) is a cross connection for the water, which is given via the RZ system. If closed or tightly throttled, the balance had to be reached only from the temperature span, resulting in a higher pressure for less cooled SG.

The difference in natural circulation results from a lower subcooling of the water in the U-tubes, such reducing the driving water density column in the SG. This column is beside the water column in the RPV the other driving force for natural circulation, and it is normally the longer one of both, but with partial filling of SG this advantage gets lost.

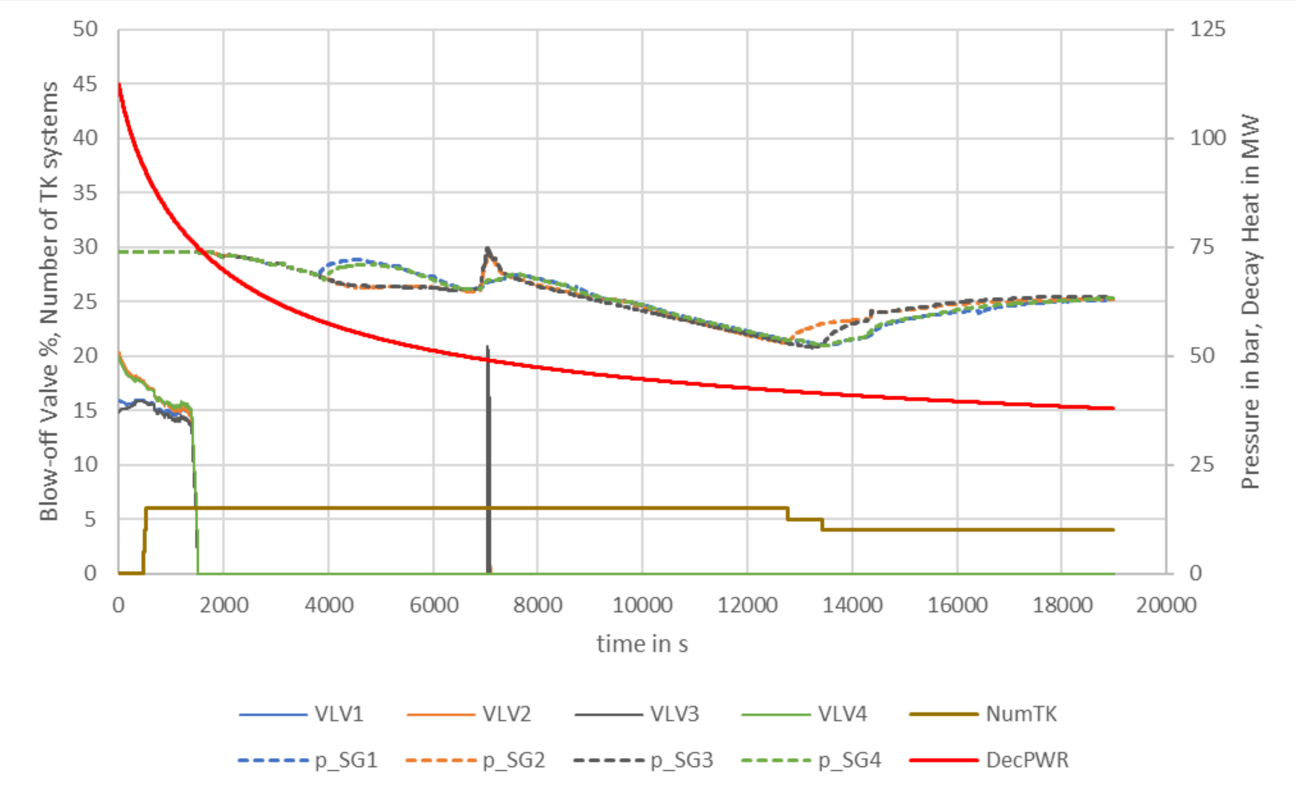

Figure 20: Case 1, blow-off valves and number of TK systems vs. SG pressure

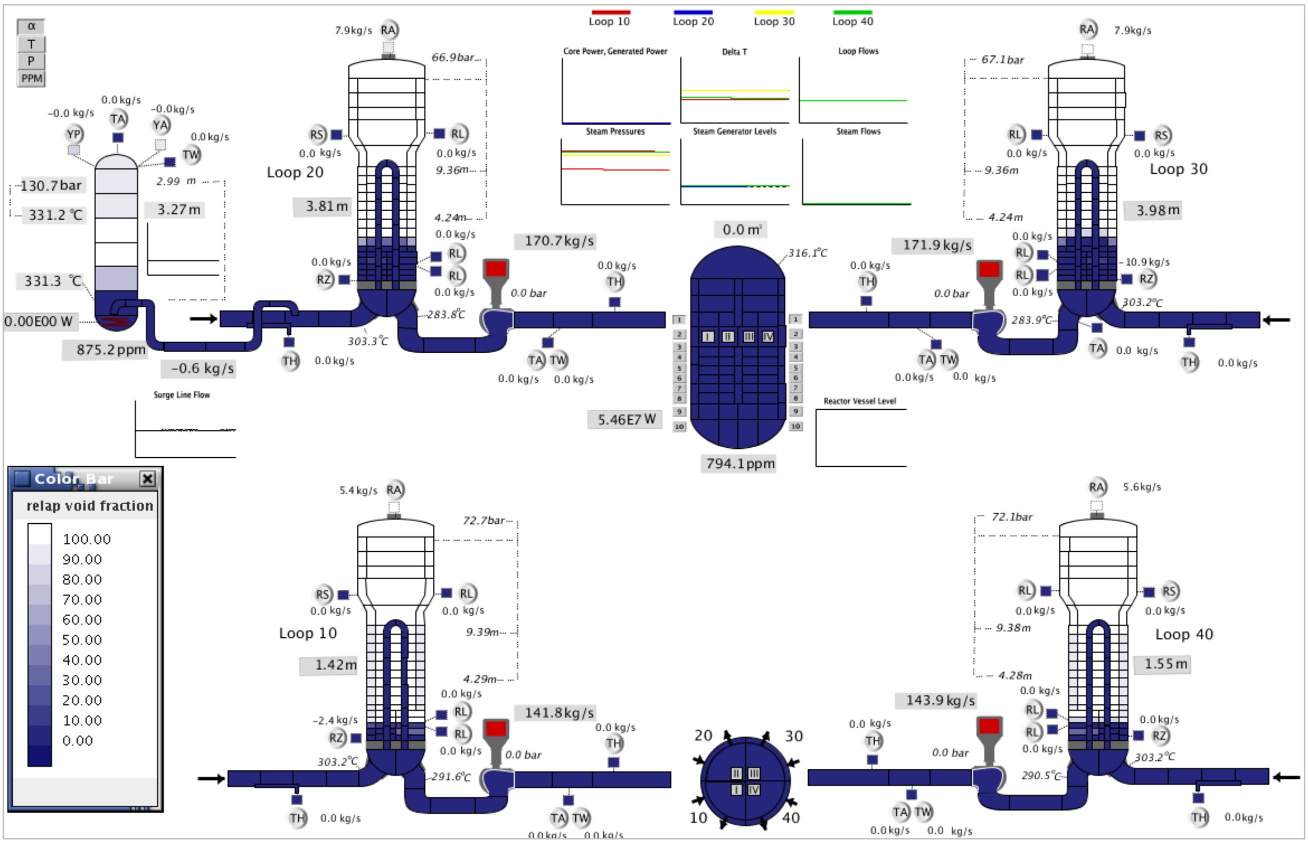

Figure 21: Cooldown with 6 TK subsystems, power and level distribution

Figure 21 catches the moment, when the pressure in SG1 and SG4 is peaking (at about 4500 s), with already adapted natural circulation, different temperature span and still diverging levels in the SG. The water transfer in between the SG is driven by the pressure difference mainly.

With level heavily reduced in SG1 and SG4 by the cross transfer, the power balance led nearly to equilibrium in pressure (Figure 19, Figure 20). The peak at 7200 s for the position of blow-off valves and the pressure spike at this time step are of artificial nature and were caused by the connection to the FMU server. Formally, the FMU were still connected, but had to be restarted to re-establish their heat removal performance.

The subsequent cooldown resulted in a pressure decrease of the primary circuit, when the pressurizer was emptied by the shrinking coolant inventory. Dual phase mixture came into contact with subcooled liquid from the HL2.

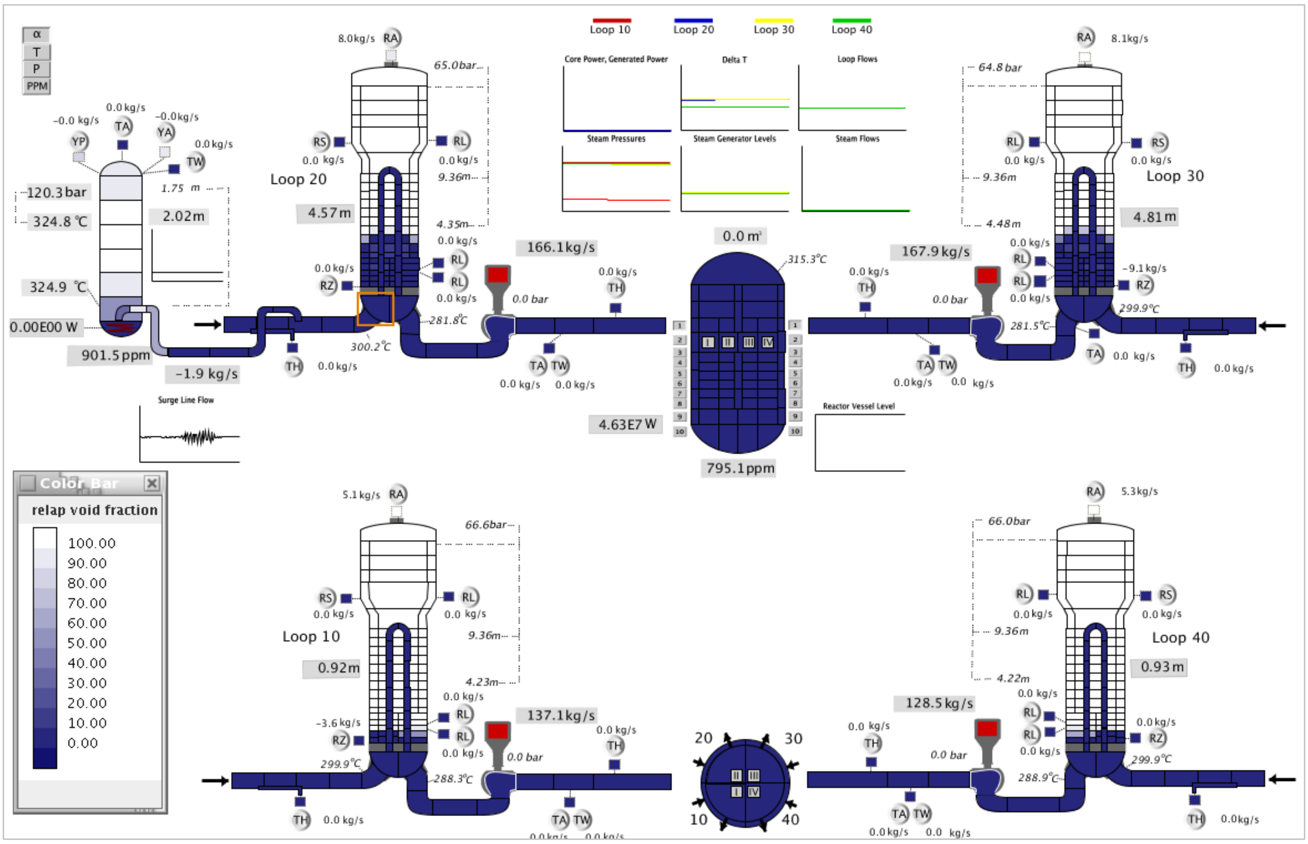

Figure 22: Pressure drop from condensation in surge line

The exchange of medium in the surge line can be seen in the small embedded diagram "surge line flow" on the middle of Figure 22 on the left side. This effect limits the shrinking of the coolant, because condensation of the steam from pressurizer would be accompanied by a further drop of pressure, and the result must be sooner or later the loss of subcooling and the occurrence of void in the primary circuit.

This boil off occurs first in the reactor vessel head, from the enclosure of trapped hot water, which cannot be purged with natural circulation (a well-known sequence from the reactor glass model, resembling such a vessel head bubble event from Biblis NPP in the early 80th of the last century). Figure 23 catches the moment, when saturation had been reached in the vessel head, beginning to form steam.

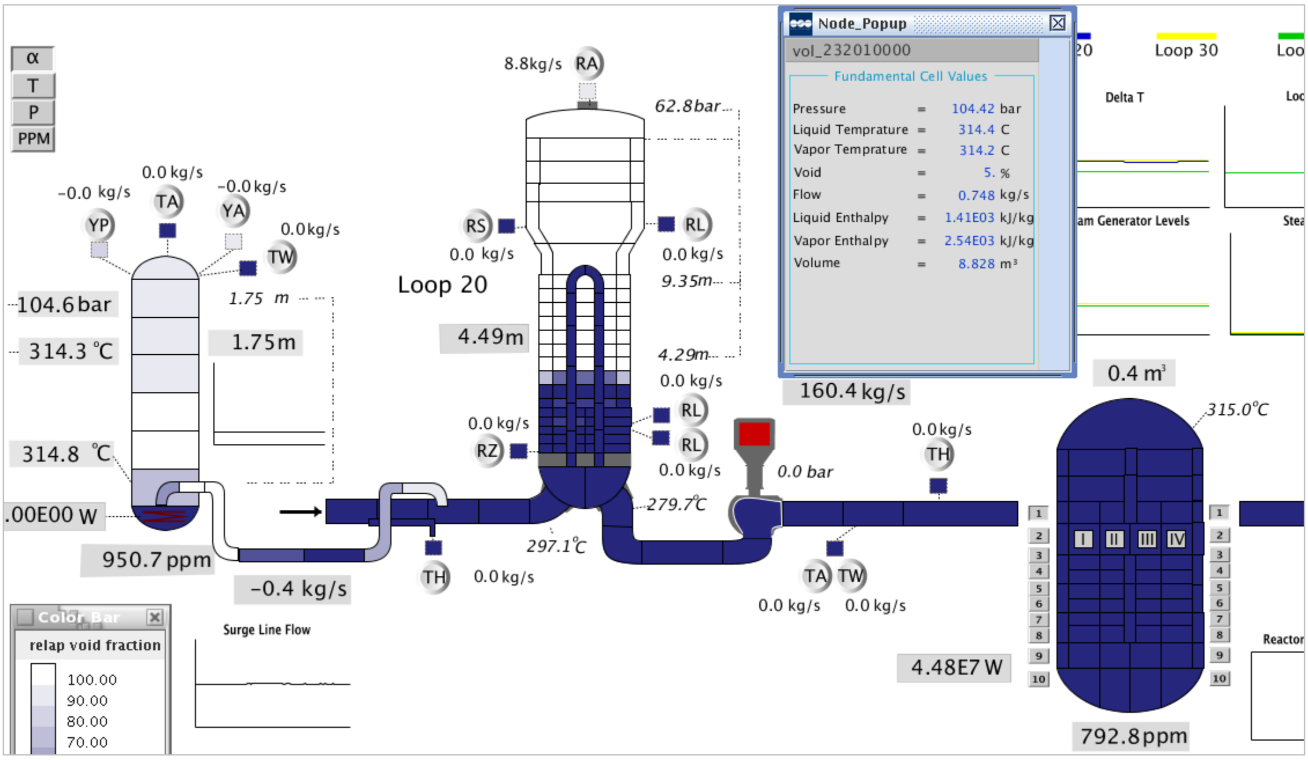

Figure 23: Forming RPV head bubble

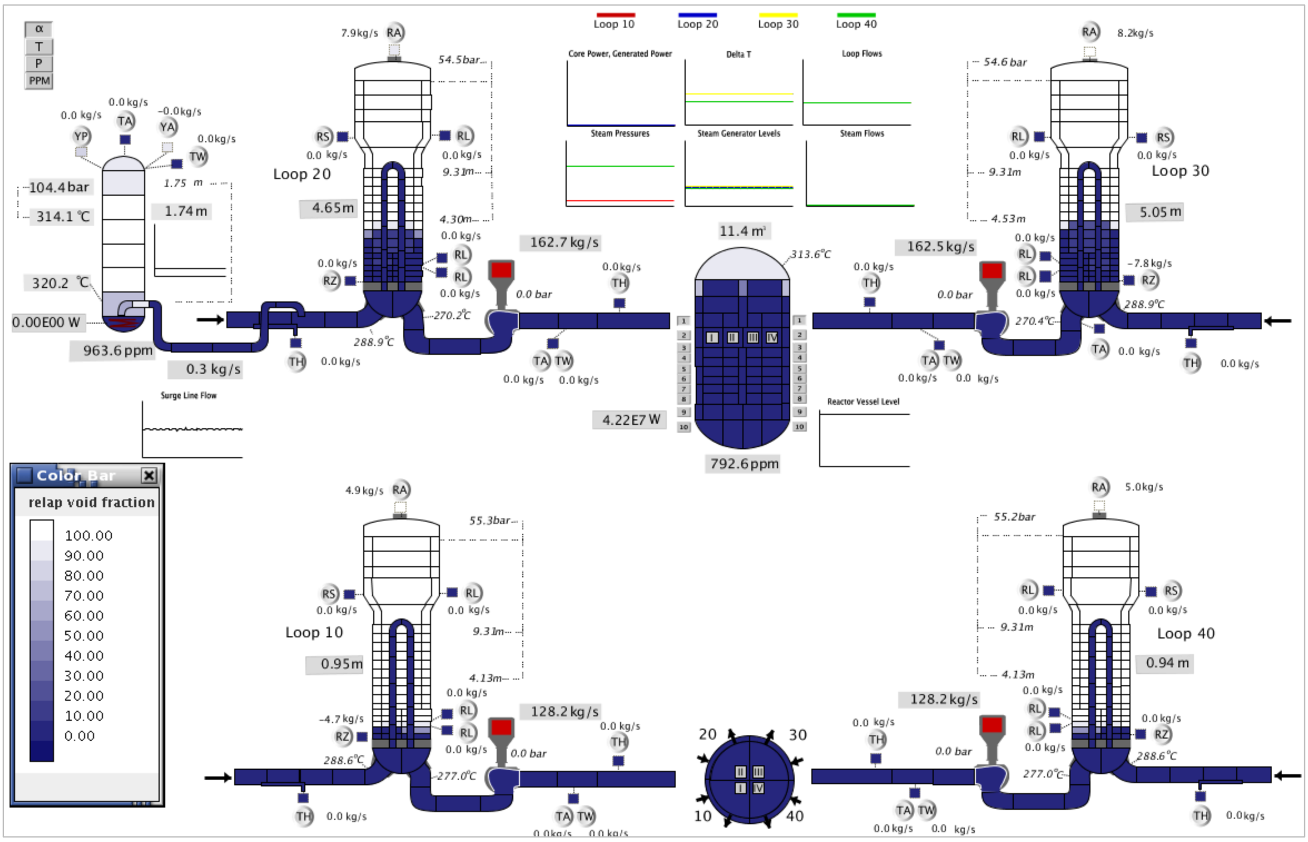

Figure 24: Stable pressure with RPV vessel head bubble

In Figure 24, the situation has stabilized, because the subcooled water, which had been pressed towards the pressurizer, clogged the surge line. Condensation at the surface of this water inside the pressurizer is limited, because direct contact in between steam cushion and subcooled water, which would result in condensation, is blocked by an isolating saturated water surface, maintained by the steam from above.

In a comparable manner, the contact of the cooled HL-water to the steam in the vessel head bubble is prevented by a significant saturated water layer on top in the upper structures of the RPV, balancing any shrinking of the coolant with evaporation, thus slowly increasing the size of the steam bubble.

To reverse or at least to stabilize the situation, the cooldown was attempted to stop by shutdown of TK50 and TK60 at 14400 s (see Figure 19, Figure 20). After restart of TK10 to TK40, the conditions for the heat transfer had to become symmetrical, so pressure, level, flow tended to equalize.

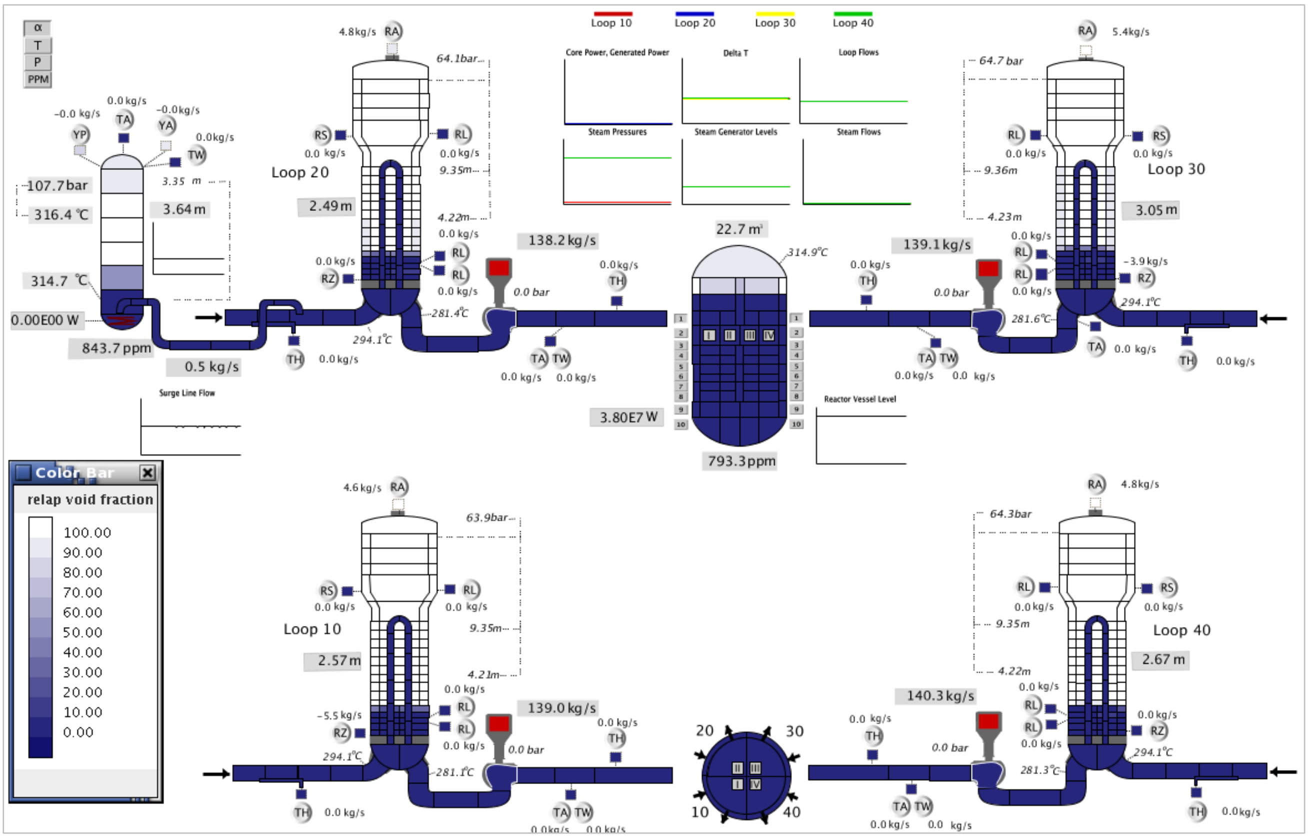

Figure 25: Levelling of SG coolant after shutdown of TK50 and TK60

Figure 25 presents the final state at the end of the transient, with TK10 to TK40 operating.

5.5 Case 2: Delayed start of TK

The delayed start of the TK subsystems was motivated as manual action, presuming some time to analyse, to decide, to order and to perform the actions. This time span is sometimes linked to the “30 min” criterion of full automatic covering or intrinsic grace time of events, but it would not be strictly applicable in this case, because it is demanded for safety analysis in the framework of design basis accidents, not to such events as SBO.

Furthermore, the MSIV were not closed, to highlight the loss of coolant to the main steam system and to the condenser via the valve shafts of the turbine and bypass valves.

After shutdown of TK50 and TK60, a situation comparable to Case 1 was reached, but with much less water left on the secondary side of the SG, which can be seen in Figure 26. Again, the vessel head bubble was formed, stabilizing the pressure in the primary system along the slow cooldown.

Obviously, the very low level in the SG did not prevent the cooldown, once the balance of power had been reached, a result already got by Hofer [5] in his calculations with a reduced number of TK systems.

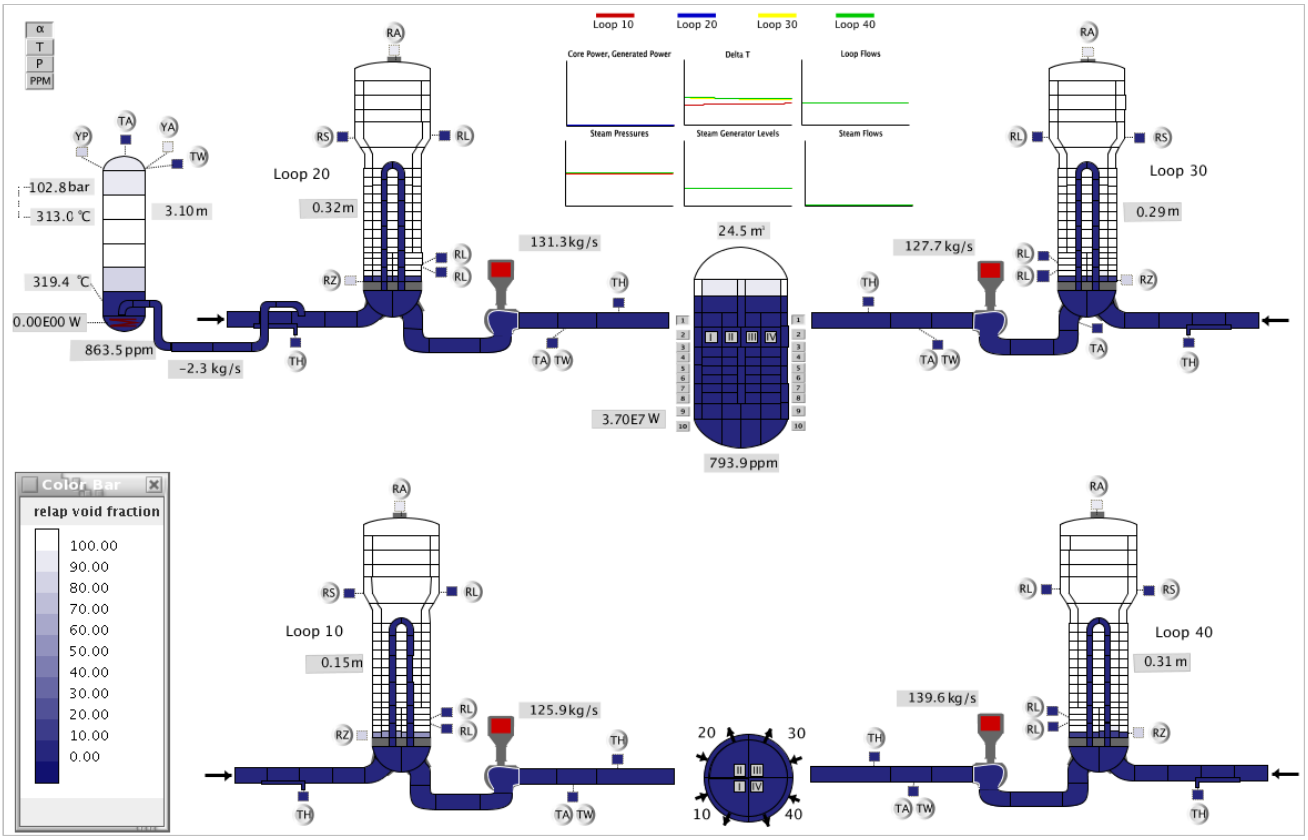

Figure 26: Final state after delayed start of 6 TK systems, with vessel head bubble

So, this result highlights the necessity of an early start of the TK system as well as the closure of the MSIV to avoid long term drain of coolant to the condenser.

5.6 Case 3: Four TK subsystems in failure concept

5.6.1 Failure concept

This case demonstrates a typical failure concept for safety related systems, where a “N+2”-approach is common. This means, that 1 subsystem is out for maintenance or repair (e.g. after a failed test), and another system fails at start for another reason.

So, in the storyboard of this case, system TK20 had revealed some problems during a test, so it was secured and unavailable. System TK50 took over its role at SG2. In order to achieve extreme unfavourable conditions, the loss of TK10 is assumed resulting in a definite loss of symmetry of heat removal.

TK30, TK40, TK50 and TK60 were started within 10 min after SBO, air flow control was set in automatic mode. Some adjustments were made to control the condensate backflow temperature, but finally any backflow had to be accepted for stability reasons. The option to keep some more coolant available by simply closing the

MSIV was used in case 3a. The connections via RZ were kept open, so some water was dripping back to the bottom of the SG1 there, even with no TK subsystem running at this SG.

5.6.2 Evolution of the Transient

There are 3 different responses to be seen in Figure 27.

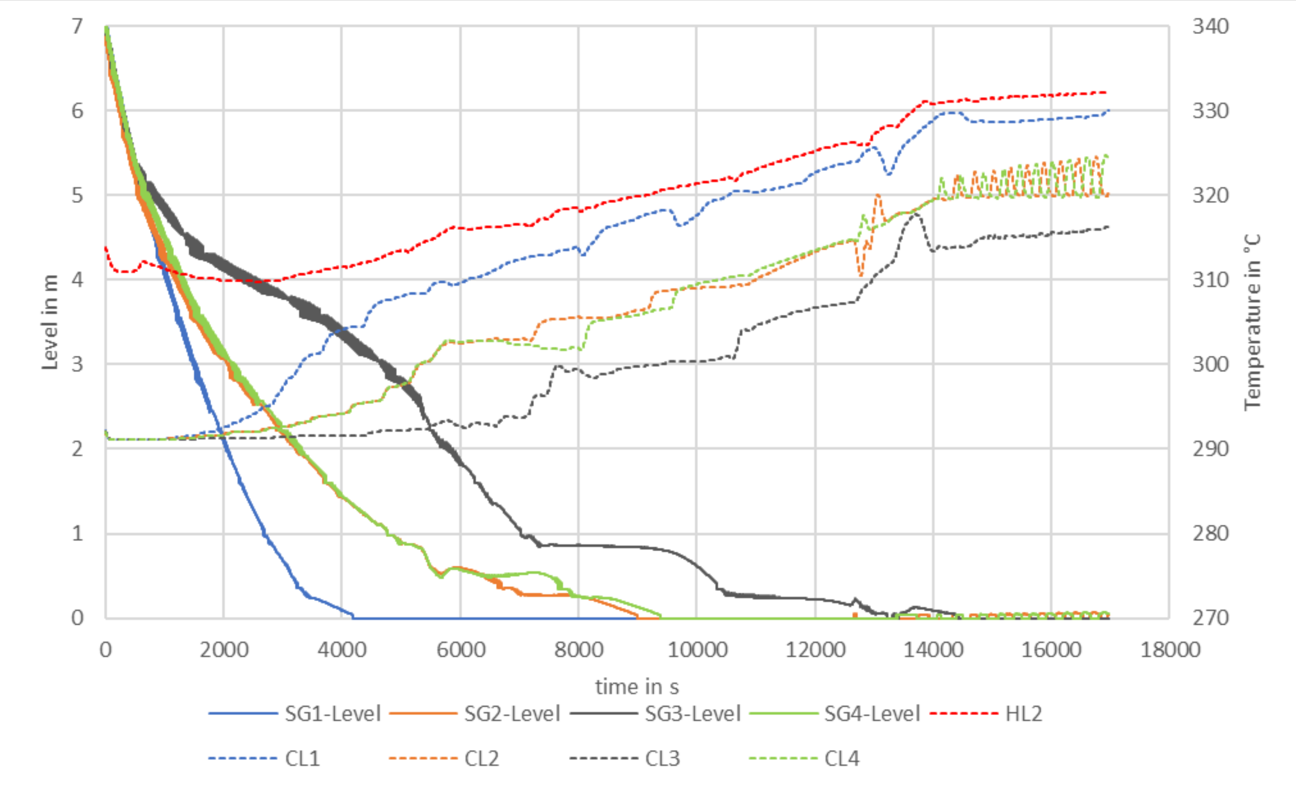

Figure 27: SG level and coolant temperatures in Case 3

The dry-out of SG1 causes an increase of CL1-temperature against the HL-temperature. Please note that generally only the hot leg temperature from loop 2 (HL2) is depicted, representing all other HL temperatures for reasons of symmetry, if natural circulation is not hampered (therefore the exception in Figure 7).

The dry-out is accelerated by the connection over the main steam system, where the SG3 drags steam towards the CHX of TK30 and TK60, even slightly reducing the need for the blow-off valve. With the pressure reduced or equalized to the other SG, the condensate remains in SG3, which depicts a slowed loss of level.

The proper cooling via SG3 results in the CL3 temperature being the lowest among the CL temperatures.

SG2 and SG4 are not as affected as SG1, but after about 2 hours they suffer some coolant drag towards SG3. The permanent subcooling of the CL2 and CL4 temperatures indicate, that at least the condensate produced in the CHX provides some heat removal from the bottom of the SG and by steam flow along the U-tubes, even if the internal level indicates a total dry out. The mismatch in between heat production and heat removal causes a steady heat-up of the primary circuit, until the decay heat has dropped below 40 MW.

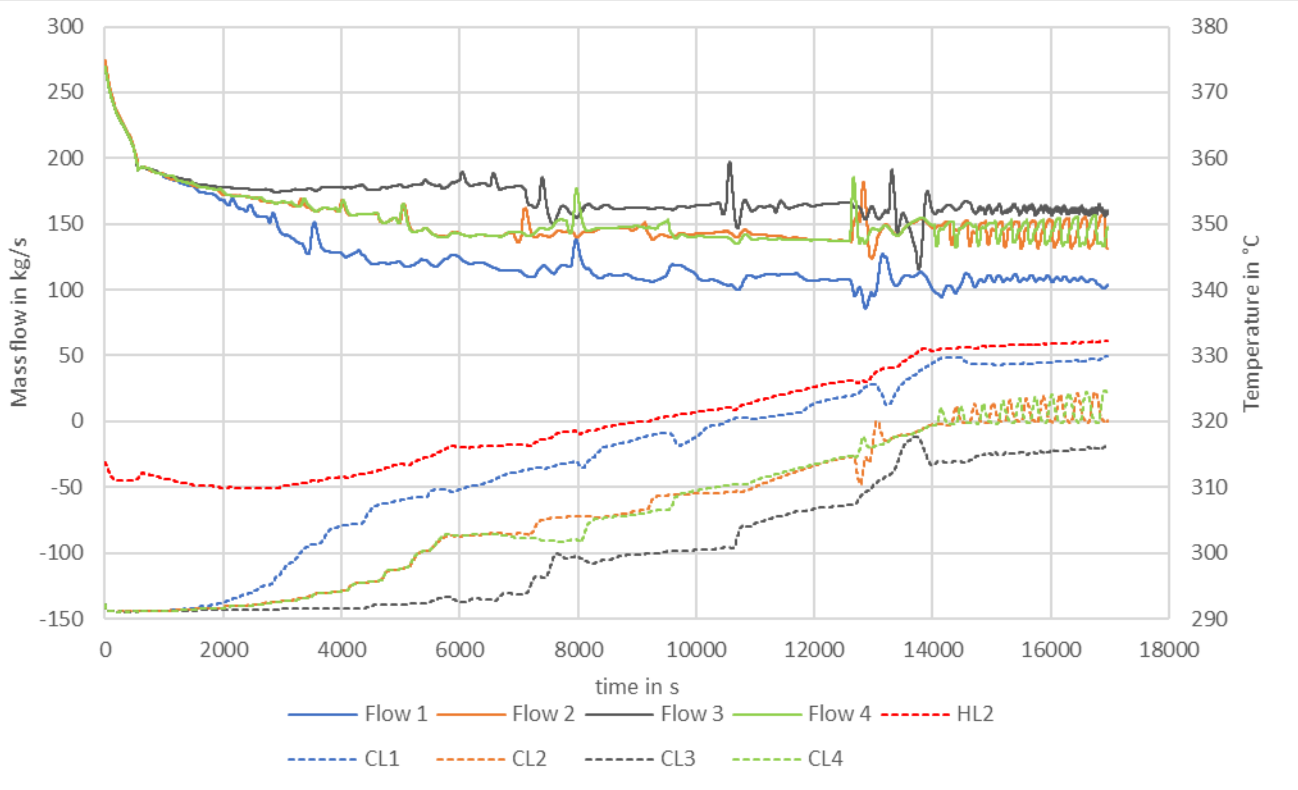

Figure 28: Natural circulation vs. coolant temperatures in Case 3

With some asymmetric configuration, the natural circulation has to be evaluated. The graphs in Figure 28 reveal that natural circulation is stable in all loops, with different intensity. As expected, the most dominant flow occurs in the best cooled loop, the least flowing in the first loop, which is only slightly cooled. For all loops, the water columns in the reactor provide a stable basic flow, even in a totally uncooled and isolated SG. This flow can be hampered by rapid subcooling of concurrent loops, which will be demonstrated in case 5.

For a simulator instructor it is necessary to discuss some potentially misleading interpretations of indications in the main control room. Many of the parameters to be depicted here are not directly displayed or made available in other form for the shift crew. The closure of the blow-off valves must not be interpreted as a sign for the balance of heat production and heat removal. Rather the surplus heat is removed to the seal leakages along the stem of the turbine valves and other technologically necessary or unavoidable steam pathways. Another factor is the deteriorating heat transfer from primary to secondary side. The vanishing fluid coverage of the U-tube enforces an enlarged temperature span, which is evolving to both sides – lower pressure and temperature on secondary side, increasing temperature at primary side. By the heat-up of the primary side, latent heat is kept back in the primary system, thus not transferred to the secondary side (Figure 29).

The permanent leakage to the high pressure gland steam package side of the valves has not vanished at the end of the transient run. Rather there could be assumed an equivalence of the leak flow vs. the expansion of the steam volume in the main steam system, which occurred permanently after closing of the blow-off valves. The regain of pressure (Figure 30) at ~12500 s was caused by an attempt to activate the automatic condensate temperature control 0TKx3 C001, which had to struggle against a really long water column dragging at the outlet of the CHX. The response of the control to the changing level in the SG is a problem yet to be solved.

The final seconds of the transient run reveal an exchange of liquid in between the SG, where the available liquid (only some cm at the bottom) boosts the heat transfer temporarily.

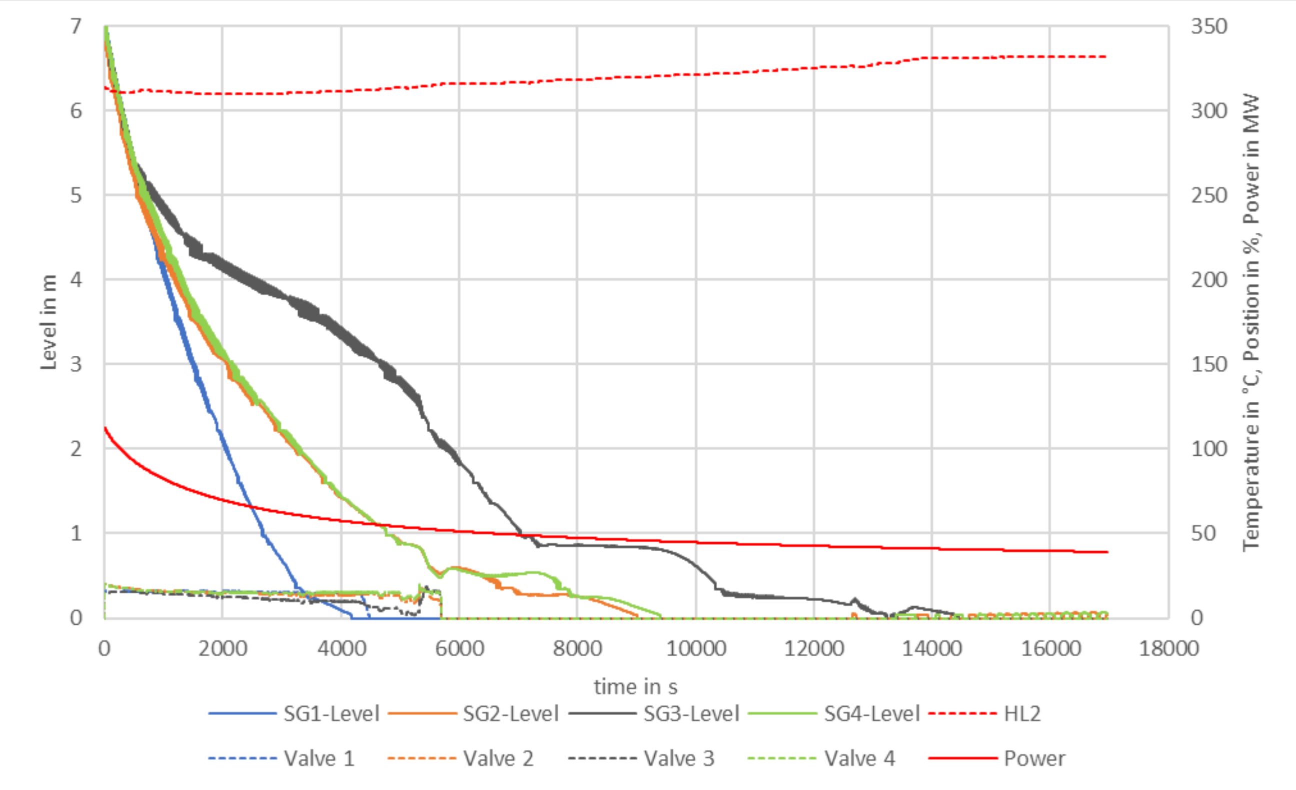

Figure 29: Power balance with blow out and heat up in Case 3

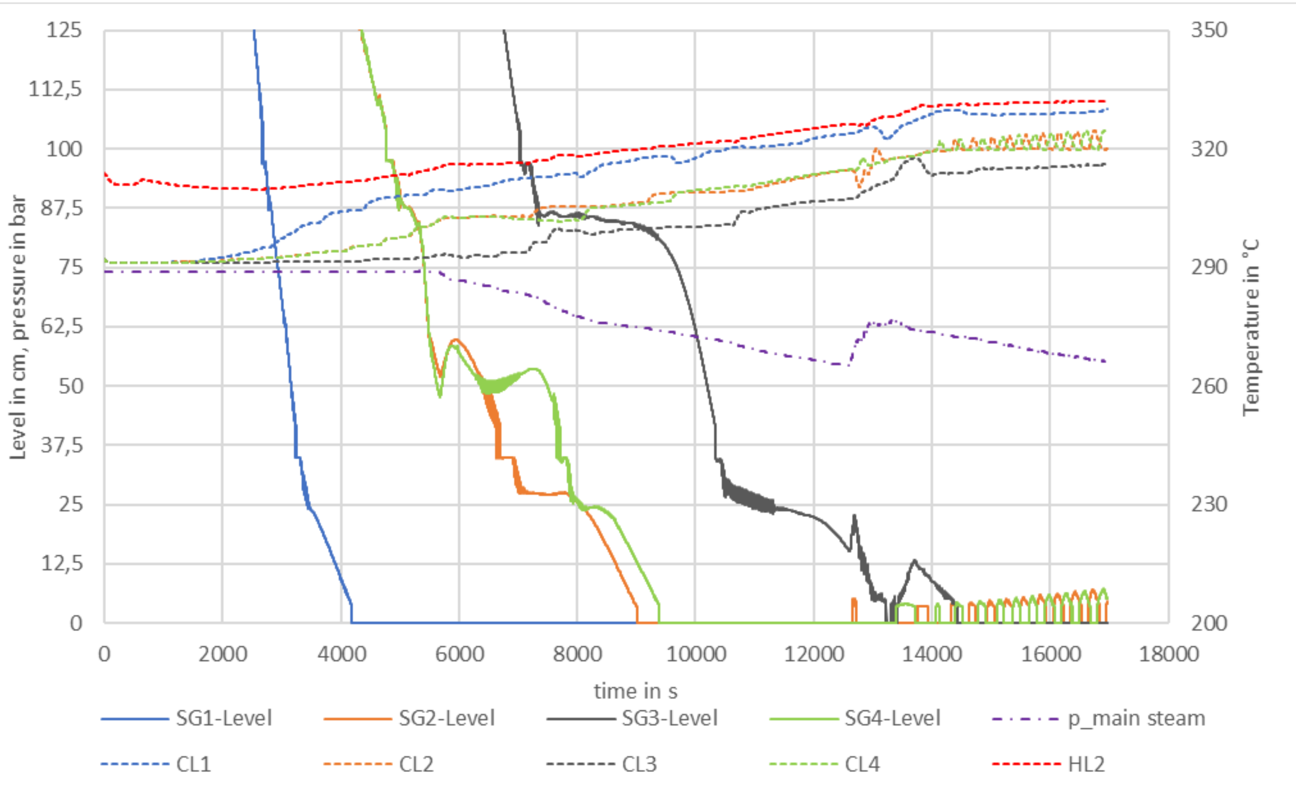

Figure 30: Heat transfer in the nearly dry SG in Case 3

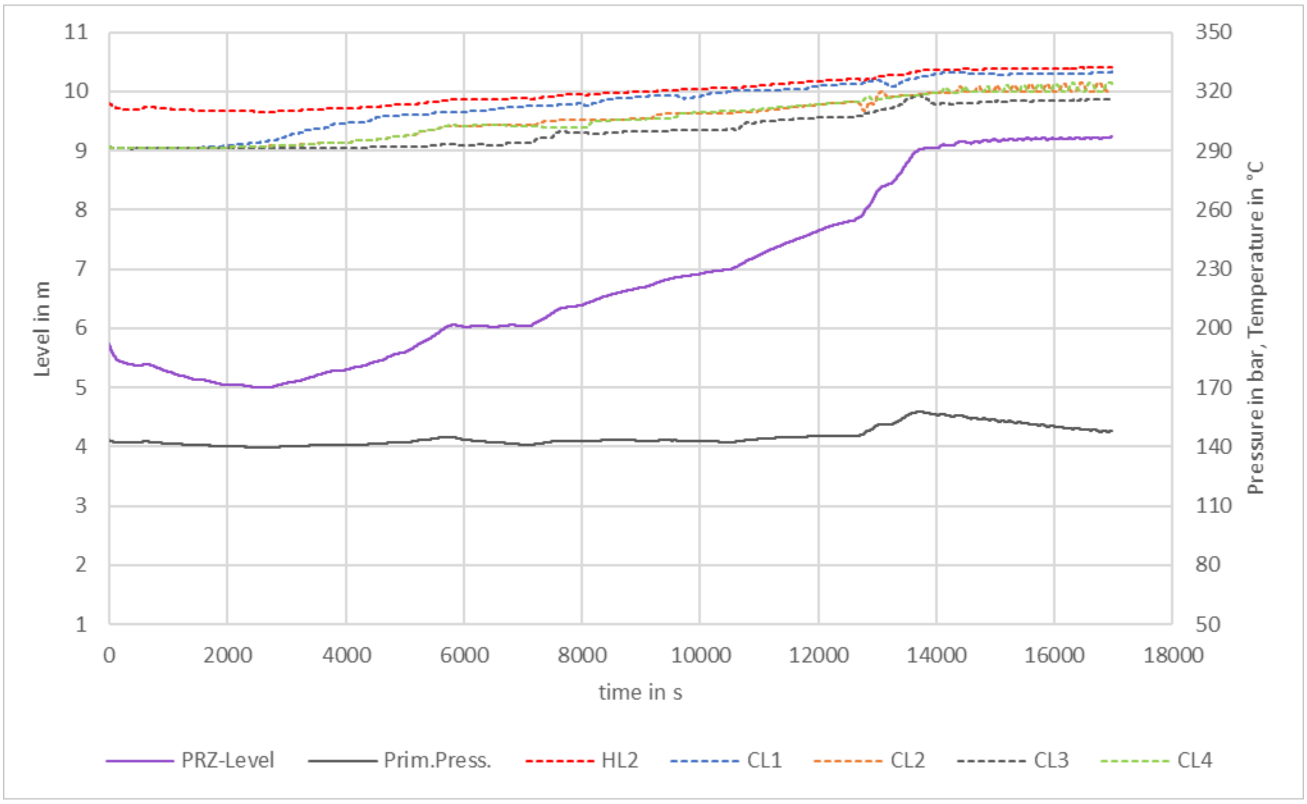

Figure 31: Pressurizer level and primary pressure in Case 3

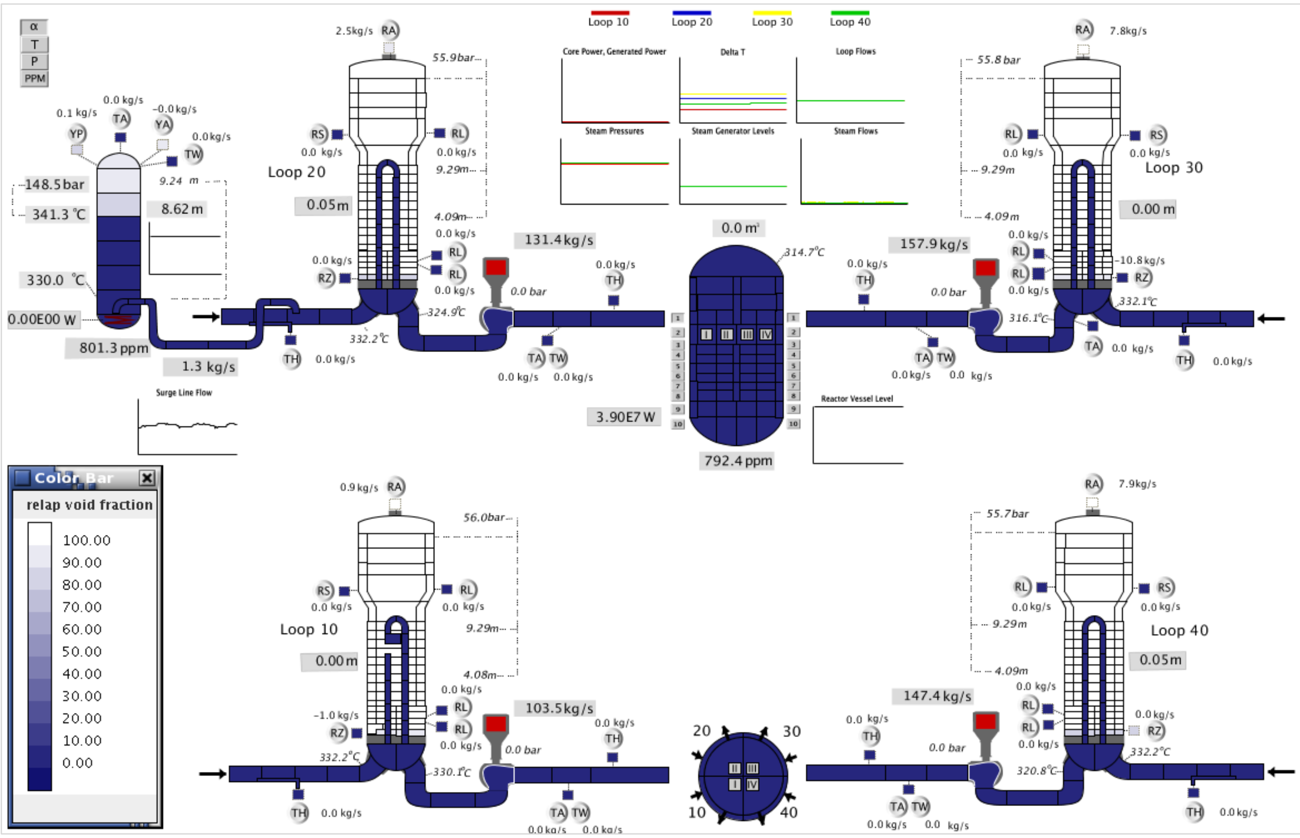

Figure 32: Final state of Case 3

Finally, the heat-up can be followed by the pressurizer data (Figure 31). The increasing level compresses the steam bubble on top. With a lack of spray, the compression leads to an increased coolant pressure, keeping the primary circuit subcooled, unless a relief valve would open, or the metal of the pressurizer will cool down over the surface or by contact to the subcooled liquid coming back from the surge line. This happens at the end of the transient, where the level is stable or still slightly increasing, but the pressure goes down.

The temperature conditions at the end of the transient run, with a subcooled water bottom in the pressurizer, are depicted in Figure 32.

5.7 Case 3a: Four TK subsystems running symmetrically

5.7.1 Description

This case is cited widely in the project as the reference situation, with the minimal configuration necessary for long term stable cooling. Its role bases on calculations of Hofer [5] with ATHLET. Hofer stated, that with 4 subsystems, each of them connected to a steam generator, overheating of the core would be prevented, even if only a small amount of liquid water is still available within the secondary side of the steam generators. With this case 3a, it was intended to reproduce these results with the setting at the D46 simulator.

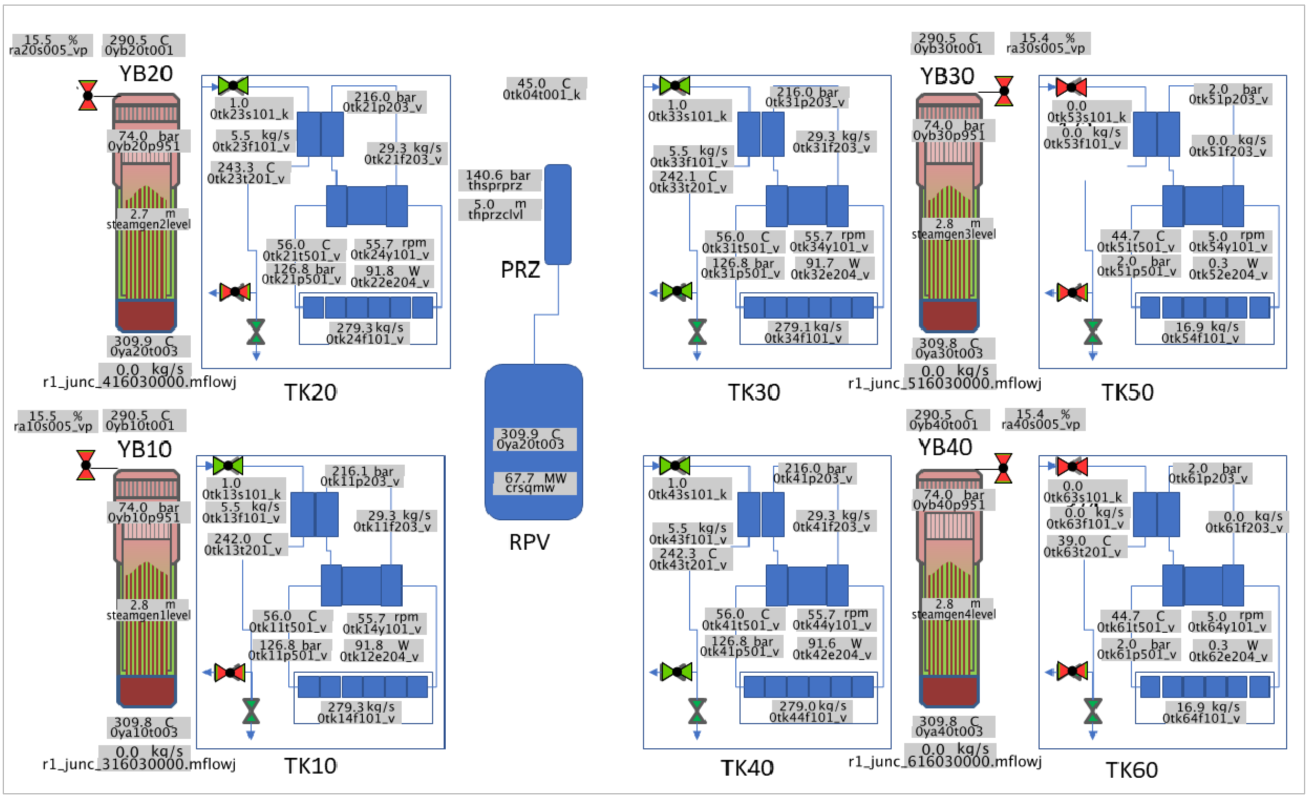

Figure 33: Configuration after start-up in case 3a

Most important adaption was the closure of the MSIV at the beginning of the transient, so after closure of the blow-off valves there will be only a very limited amount of coolant loss to the drains of the main steam lines, which would be further limited with the expected overheating of the steam towards the TK subsystems.

The air flow control was set to automatic mode, as soon as the systems had reached a steady state. After this, the condensate backflow valves were trimmed to 20 %, to provide a stable subcooling along the changing water level in the SG (the sensitivity is demonstrated in case 5 at the restart against a filled SG).

No further corrections were implemented. The transient was followed until the closure of the main steam blow off valves and the stabilisation of coolant temperatures signalised the break-even in heat production and heat removal.

5.7.2 Evolution of the transient

The steam generator level quickly dropped below the measured range. Generally, a visible heat-up set in, when the secondary side level dropped below 2 m, to be seen in pressurizer level increase (about this effect in general e.g. refer to Figure 27 in connection to Figure 31, after 2000 s).

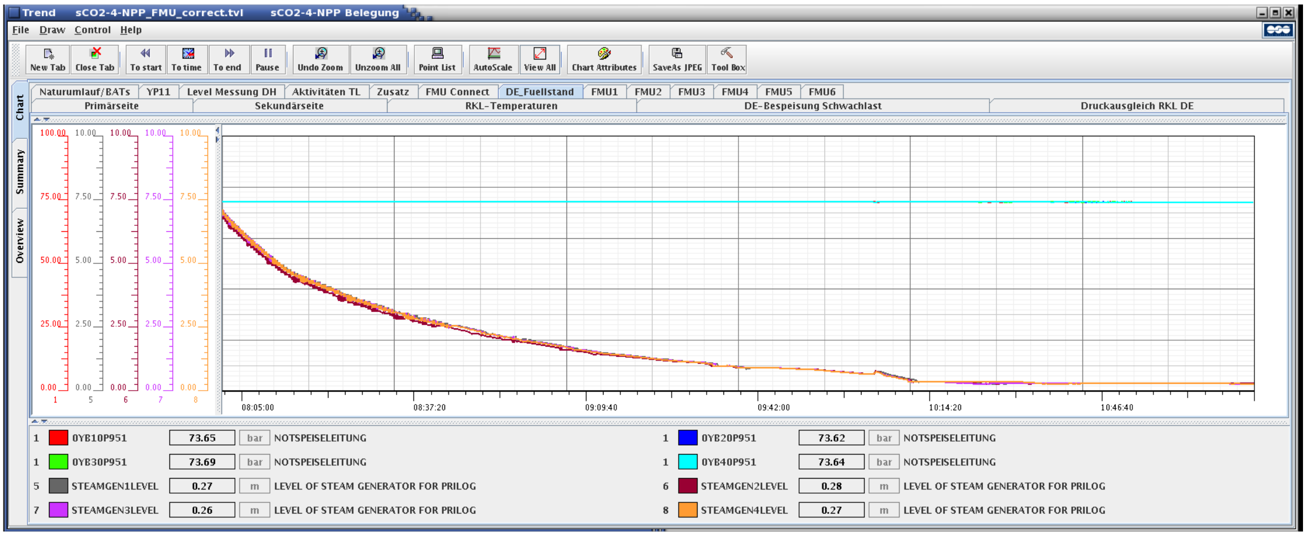

Figure 34: Trend plot at simulator: SG level going down symmetrically

The level in all SG ran down symmetrically, and finally stabilized above 25 cm. The blow off valves closed after about 2 ½ hours, before power balance had been reached, so heat up occurred in the primary circuit from a slight surplus of decay heat vs. heat removal.

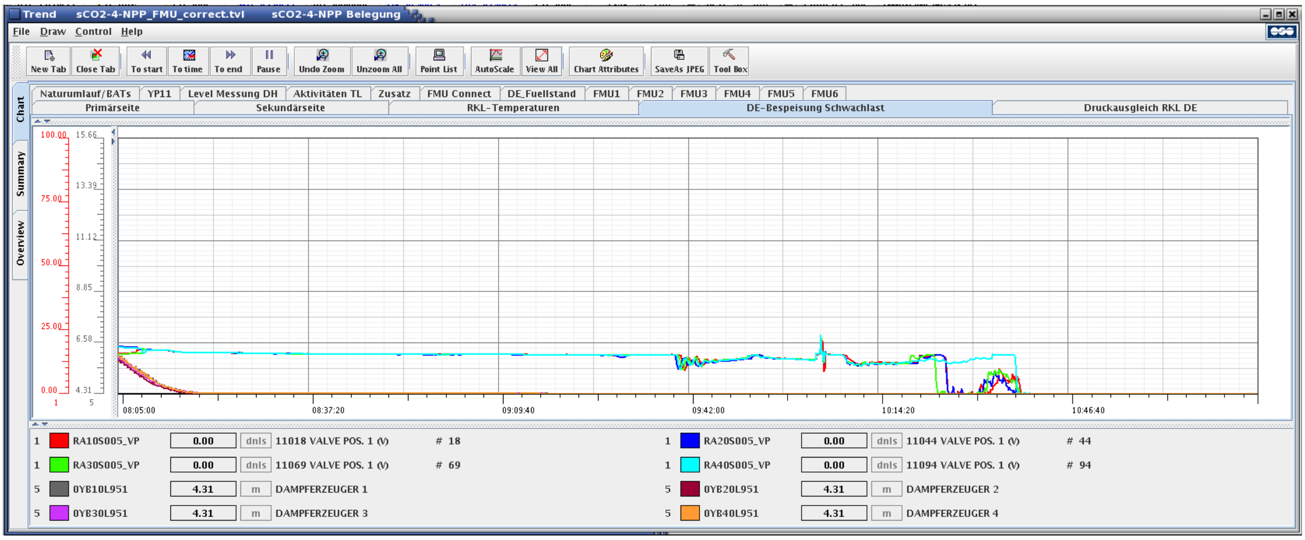

Figure 35: Trend plot at simulator: Closure of Blow-off valves after 2 1/2 h

Figure 34 and Figure 35 were taken as screenshots from the instructor station to present the trend plots as a tool here.

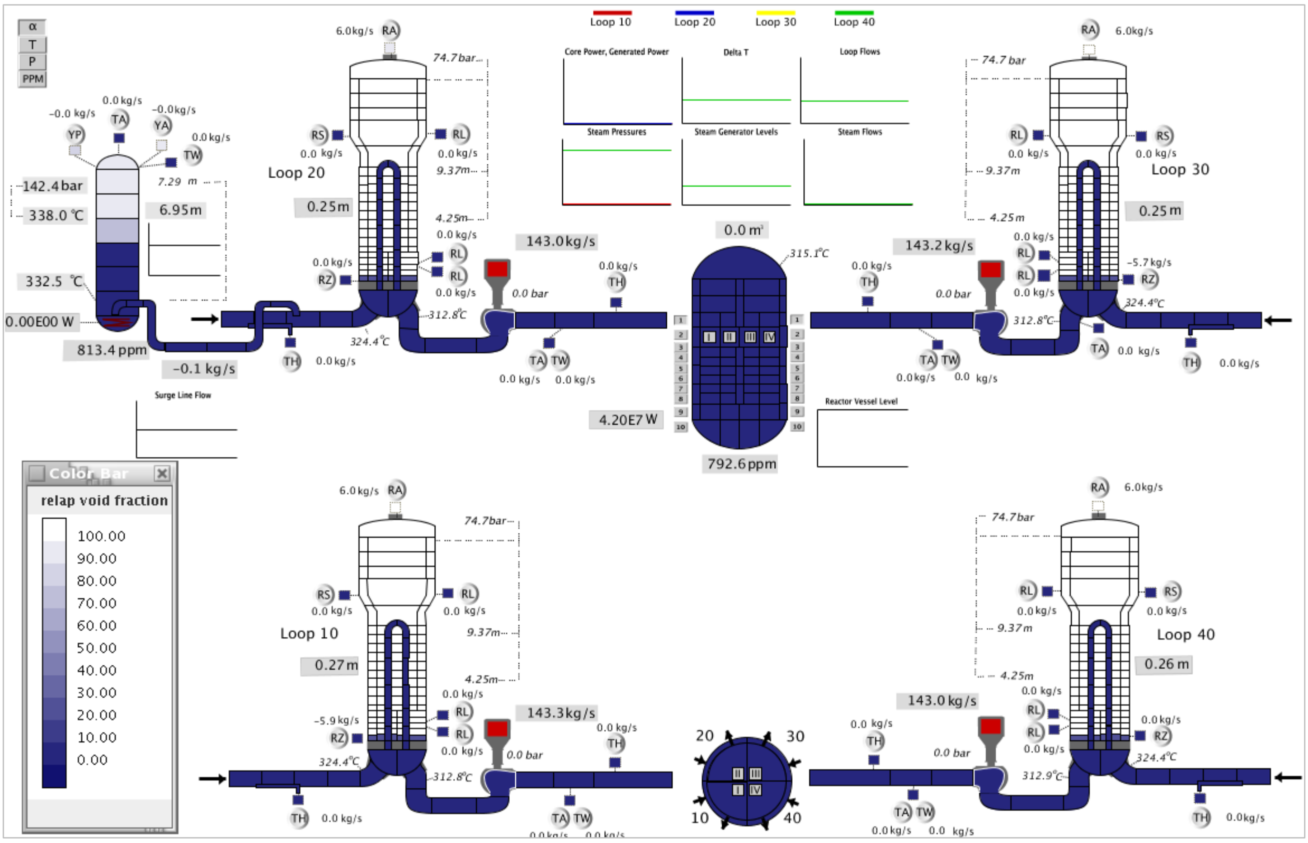

Figure 36: Near perfect symmetry at the end of the transient run

Figure 36 depicts the final state of the run, with power balance reached, but no cooldown performed yet. Heat removal was working even with a boiling layer on secondary side at SG bottom of about 25 cm.

5.8 Case 4: Closing Main Steam Blow-off Path

5.8.1 Description of the Problem

The motivation comes from 2 different facts:

- First, not all Konvoi/pre-Konvoi-NPP are equipped with a battery buffering for the main steam blow off control valves. Most of them rely in such a case on the safety valves, which open at about 87 bar and close with a certain hysteresis.
- Second, the blowout path can be blocked deliberately for several reasons, e.g. when a blowout control valve is malfunctioning. The block feature is necessary to avoid a cooling transient for the primary circuit in such a case.

It is obvious, that storing heat in the water on secondary side would preserve coolant for long term operation of TK, but it was not clear, how TK could cope with the rapidly changing steam pressure and condensate side backpressure. Of course, a real time training simulator cannot give a reliable answer to such a question, if compared to a qualified code. But from viewpoint of training, the stability of the models has to be evaluated, too.

Best strategy of all would be, in the case of having a choice, to store as much coolant as possible, without actuating the safety valve.

5.8.2 Evolution of the transient

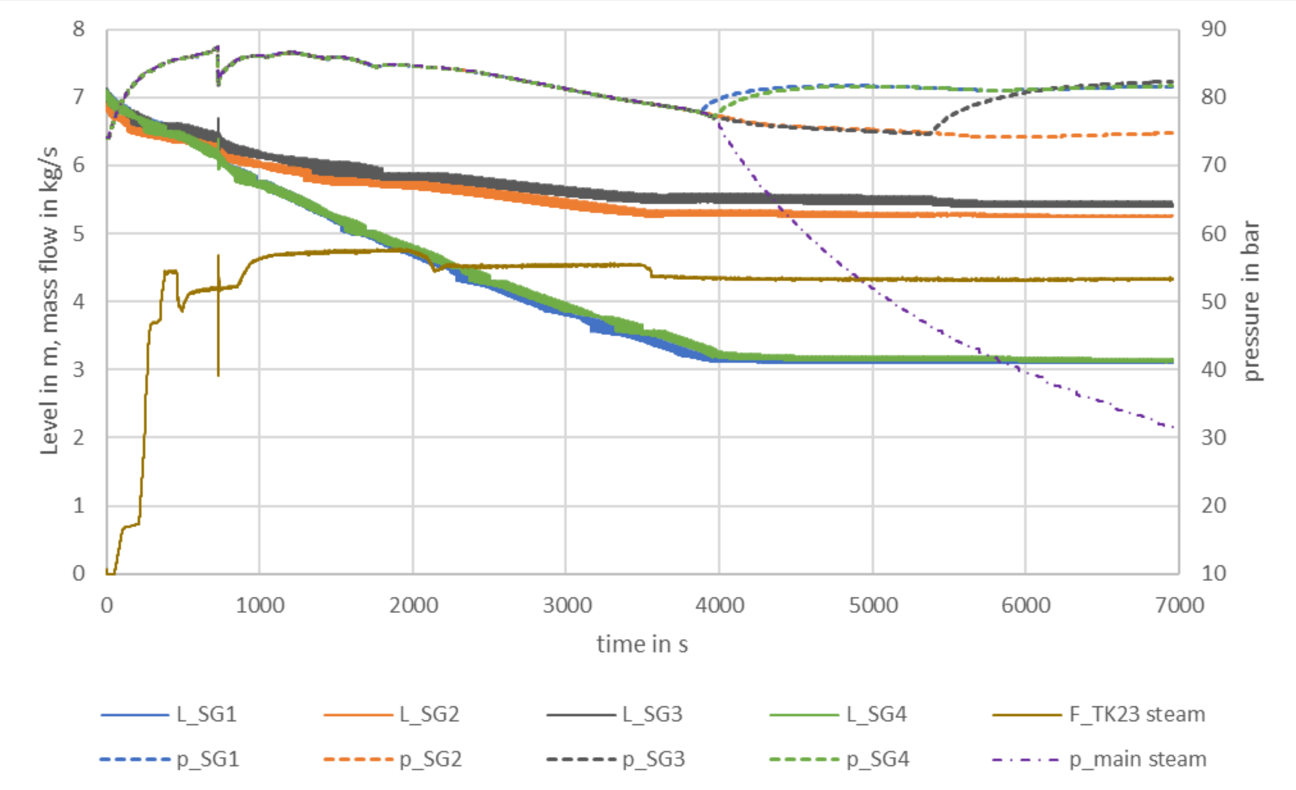

Figure 37: Case 4- SG level and pressure, TK steam mass flow

Figure 37 depicts some key parameters to follow the history of the transient. First, closing the blow-off path with the respective isolating valves, the pressure in all SG ramped up. The uniform increase was due to the still available connection over the steam header in the turbine building.

At the same time, all the TK systems (6) were started, which can be followed by the steam flow toward the CHX for TK20 (TK23 is the water/steam side of the system). Within less than 15 minutes the setpoint of 87 bar for the safety valves was reached. The sudden pressure drop caused a short breakdown of the flow to 3 kg/s, but this did not stop the TK systems. The power surplus dropped shortly, but remained positive. Anyway, such short interceptions could be bridged with the help of the batteries, used for the start-up and excitation of the TAC before.

In the aftermath, the already known split of the level occurred, which relies on the connection over the steam header. After 4000 s, this connection was cut off closing the MSIV. The pressure curves split immediately. To verify the role of the blowdown (RZ) system's cross connections, the respecting valves were closed from the instructor station, regardless the conditions in the field (there was at least not a steamy or activated atmosphere in the containment). After this, the level of the different SG was kept quite constant, regardless the pressure difference. This pressure difference results from the balance of heat removal to the different SG conditions. Without the tool of reducing the wetted surface, only the secondary side temperature (hence the pressure) will balance the heat transfer according to the cooling capabilities. In second order, the flow through the lesser cooled loops will slow down adequately. This situation is depicted in Figure 38.

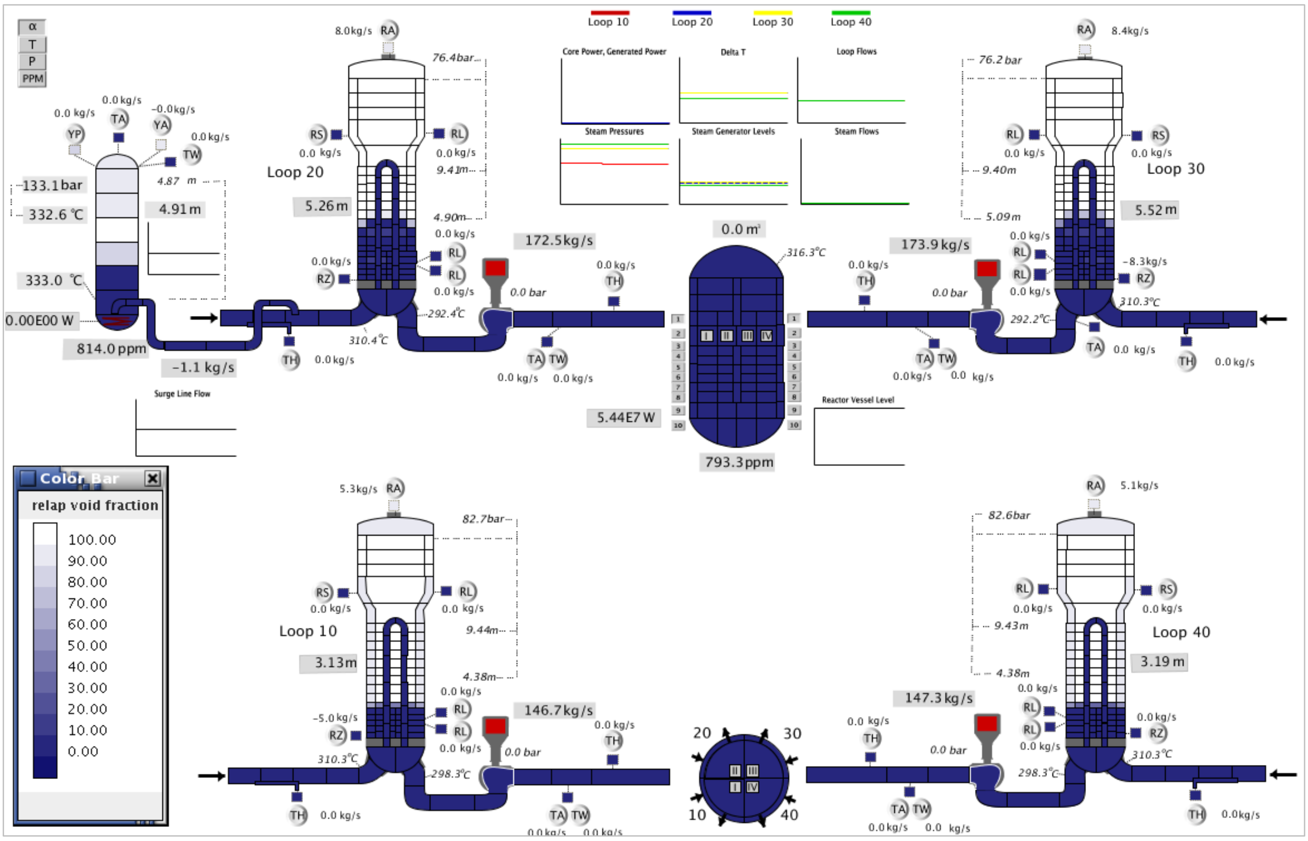

Figure 38: Case 4 (closed blow-off path), after closure of MSIV, 6 systems running

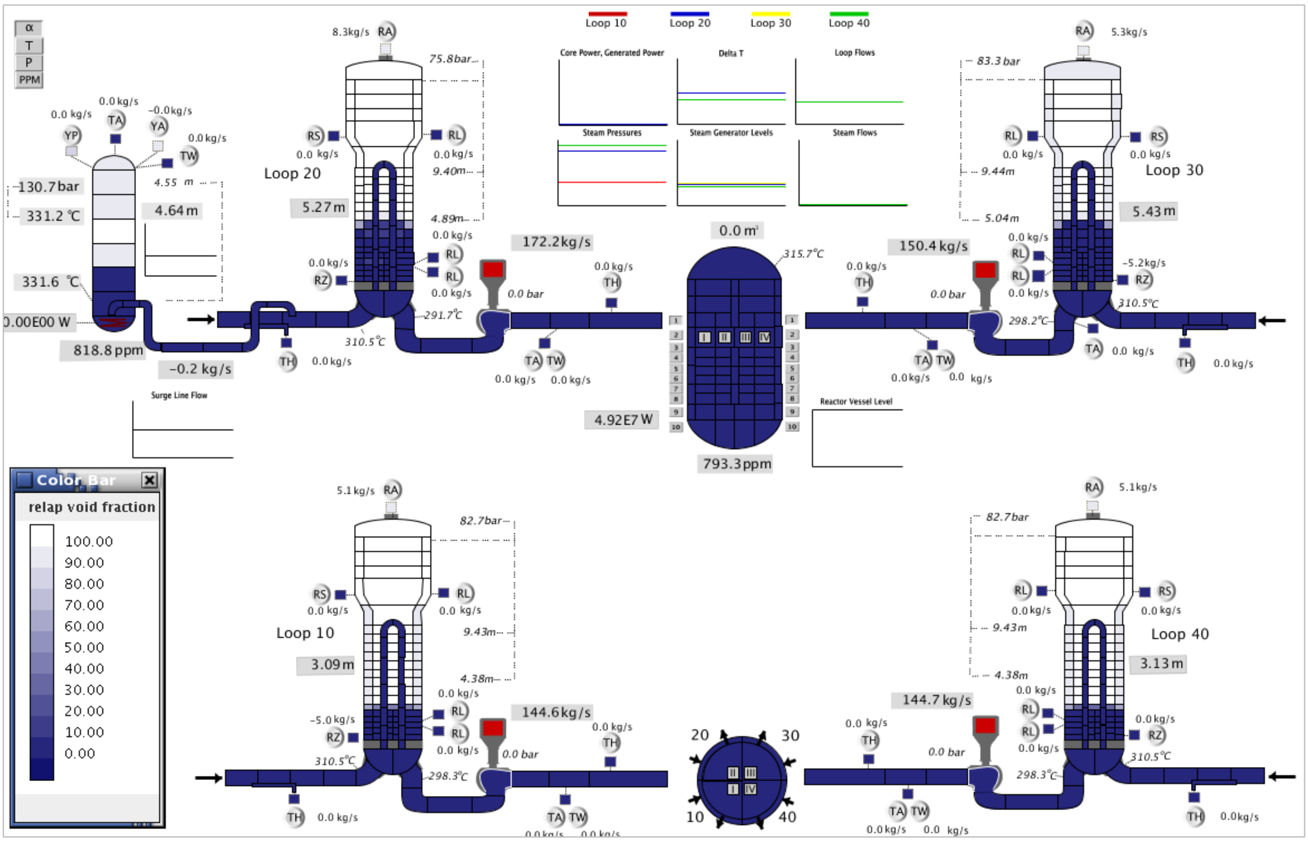

Figure 39: Shift of power and pressure after shutdown of TK60

This mechanism was repeated after shutting down TK60, once a sufficient reduction of decay heat had been reached. For the better filling in SG3, the pressure (or temperature) to balance the heat had to get even about 0.6 °C (0.6 bar) higher than in SG1 or SG4 (Figure 39). To provide a smooth operation of the TK systems, such operations should be done after having analysed previously the margins to the safety valve's setpoint before.

Generally, the closure of the blow-off path left all the SG with more coolant content than in case 1, so this operation procedure should be investigated further.

5.9 Case 5: 5 systems running with closed blow-off isolating valves

5.9.1 Description

With the positive effect from case 4, regarding the content of secondary side coolant, this gain was used to stretch the limits, with only 3 SG remaining in operation, from failure of TK10 at SG1, rendering SG1 left behind in the cooldown process. A nearly complete loss of secondary coolant in SG1 was expected (it is ongoing in Figure 40).

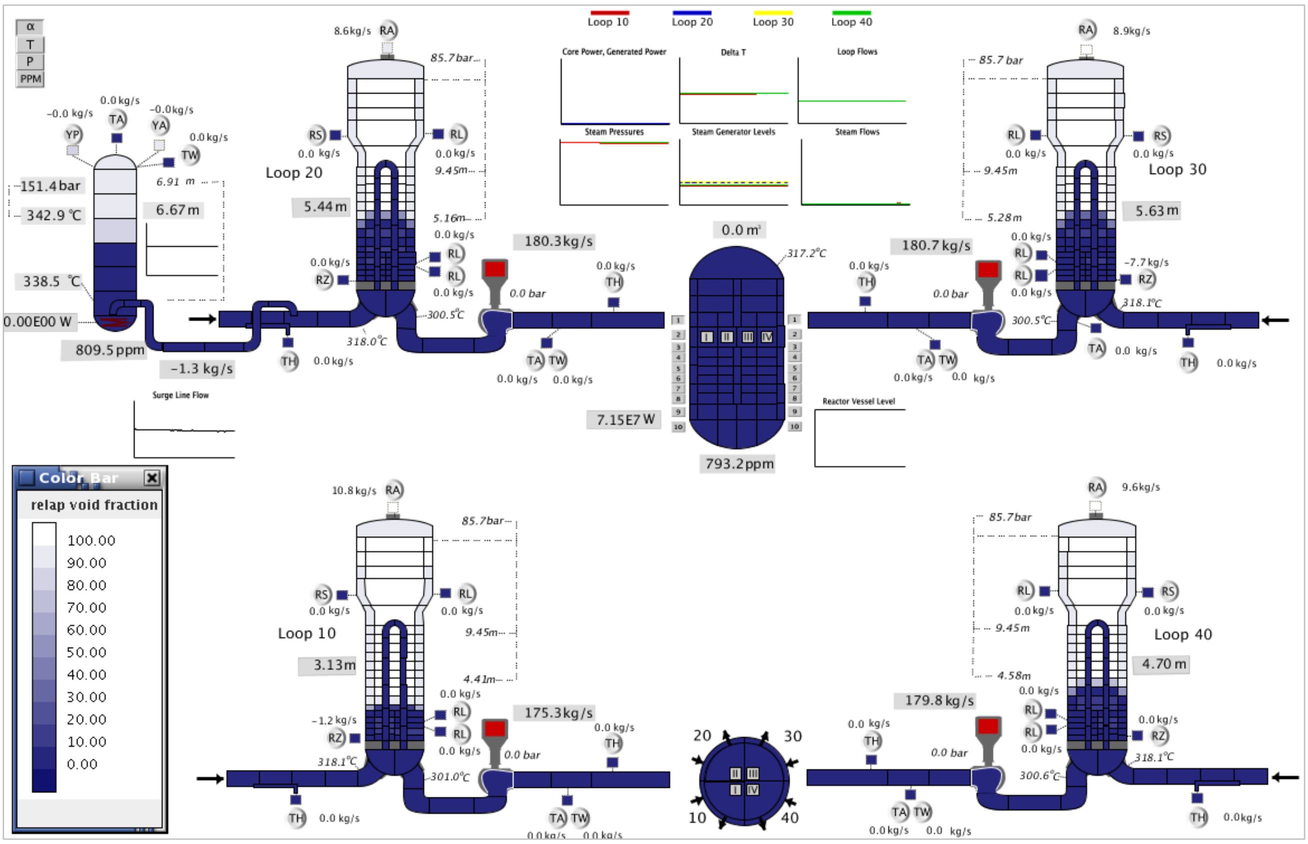

Figure 40: Boil-off of uncooled SG1

The focus was set on behaviour of coolant flow through the loop 1. It was expected that the coolant flow would be preserved low, but steady, so boron concentration in between the loops would remain uniformly, considering later attempts to inject boron with makeshift power supply to boron pumps.

As known from case 4, the power distribution to the SG according to their heat removal capacity can be trimmed by the secondary side level to obtain a quite uniform secondary side pressure, even with closed MSIV from the reason to stop loss of coolant towards the components and pipes in the secondary circuit. Therefore, the MSIV were closed manually, when the heat removal capacity of the running TK subsystems roughly matched the expected decay heat, with a certain threshold towards the setpoint of the SG safety valves of ~87 bar. To balance the secondary coolant level, the connections inside the blowdown system RZ were kept untouched, hence open in a throttled position.

5.9.2 Level forking

In this case 5, the set-point of 87 bar was avoided fully, because the blow-off path was closed a little bit later than in case 4. As expected, the level of the uncooled SG1 dropped steadily to zero (Figure 41), whereas the level in SG4, cooled from single subsystem TK40, was running in between SG1 and the doubly supplied SG2 and SG3 levels. SG1 coolant was pressed out completely via RZ, after the MSIV were closed shortly after 5000 s, and the pressure increased in SG1 instantly.

In the aftermath, heat transfer into SG4 had to be balanced by decreasing the coolant cover of the U-tubes, to get into a new steady state. It became obvious from individual pressure evolution in the separated SG that this shifting needs time, which means all measures should be carried out with a certain respectful distance to critical parameters, here the pressure set-point of the SG safety valves.

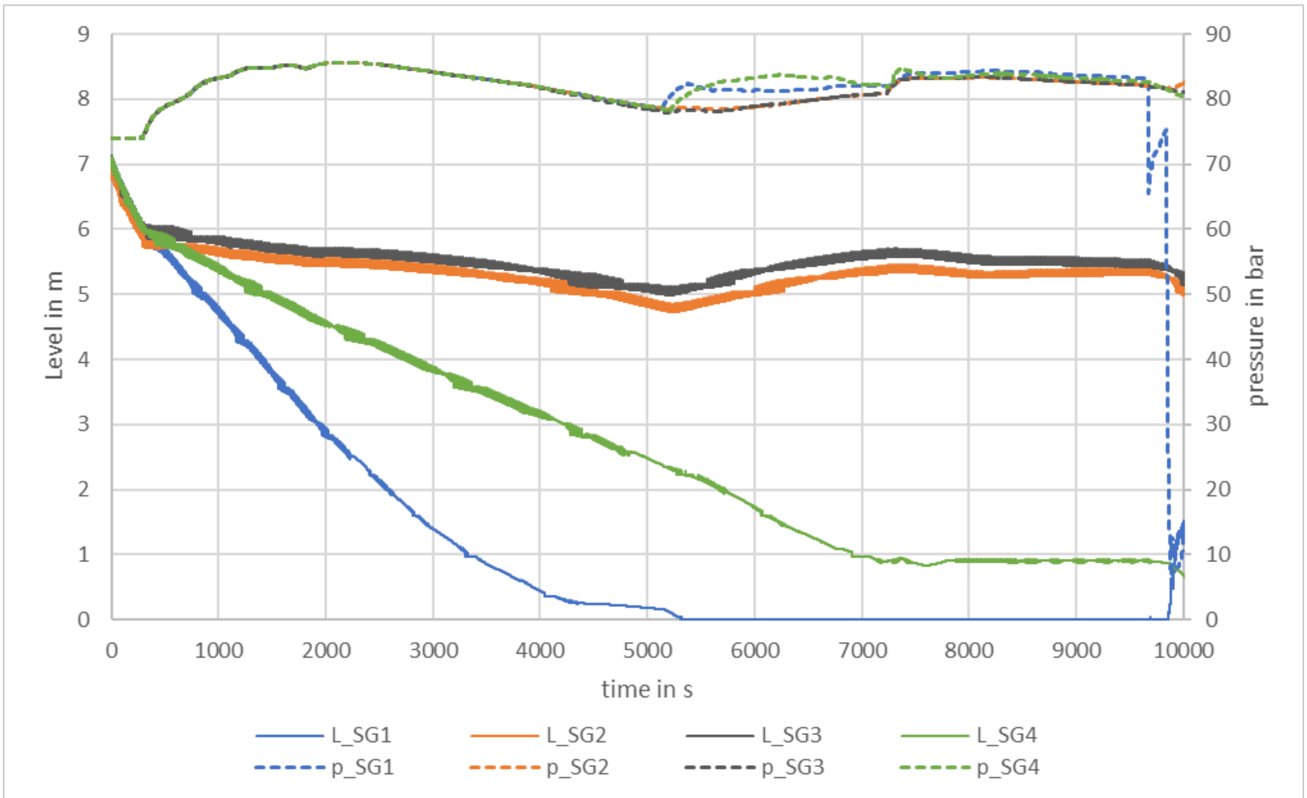

Figure 41: Level splitting according to the different cooling capacity for the SG and MSIV state

This situation can be followed in the snapshot of the RELAP viewer too (Figure 42). The snapshot was taken at about 7200 s. The expected steady state was reached about 15 min later, with SG4 level at about 0.9 m.

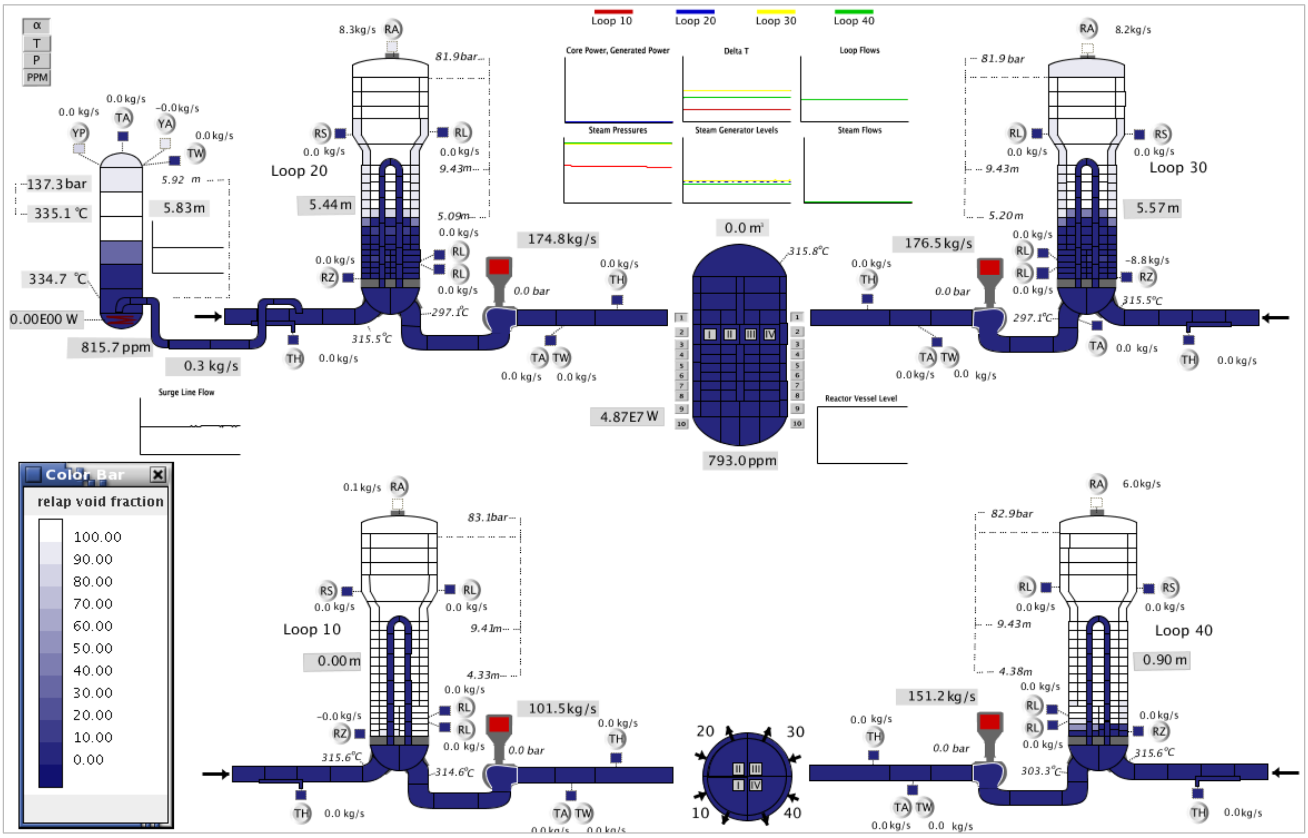

Figure 42: RELAP snapshot of primary system near the end of redistribution over RZ with closed MSIV

SG1 is uncooled, so the inlet and outlet temperatures are nearly the same. The pressure has stabilized at about 83 bar, the highest of all SG. So, there is no backflow from RZ (blowdown system), and the heat is only transferred to the steam inside, which has become overheated (it was checked exemplarily for the separator node to be at 313.7 °C). Natural circulation is only driven from the reactor side, so flow is reduced significantly, but running steadily.

SG4 is not in a steady state yet, further reducing level. Given the reduced temperature span and mass flow, the power transfer has already decreased. But there is still 1 bar pressure difference to SG2 and SG3, so the draining will continue for some minutes.

Because the power removal into SG2 and SG3 is hardly depending from level in this situation, the redistribution, taking power away from SG4, has to be accompanied by a slight increase of primary coolant temperature. The enhanced temperature difference in between inlet and outlet of SG2 and SG3 respectively, drives the natural circulation, so this temperature difference will be less than twice the difference at SG4 (if one would simply take the power ratio as the determining factor for the temperature difference).

5.9.3 Some remarks about closed blow-off path, MSIV and cross connections

It seems to improve the coolant situation on secondary side, if the blow-off is stopped, to store the heat in the fluid, instead attempting to keep a controlled pressure at 74 bar. From that the missing feature of battery buffering for blow-off control valves in most Konvoi and pre-Konvoi plants is an unintended advantage. Nevertheless, a first blow-off calms the situation for the start of TK subsystems considerably.

The smooth increase of temperature with a lack of partial blow-off provides a better performance of the sCO2-loops regarding power yield.

From viewpoint of smooth operation, as long as break even in power is not yet reached, it is useful to keep the main steam lines open. Some of the steam will be used to pressurise the feedwater tank, which could be supported manually, in preparation of a secondary side depressurisation. If the power balance is expected to be fulfilled, and some distance to the set-point of safety valve actuation is reached, the MSIV can be closed. The connection to balance power and pressure is maintained via the blowdown system trim valves. The operability of the trim valves during this situation should be checked for comparable configurations in power plant designated for installing such a heat removal system. As far as known about the EPR, such cross connections are planned to be handled to exchange water from an isolated SG into another during SGTL situations.

5.10 Case 5a: Deliberate secondary side depressurisation

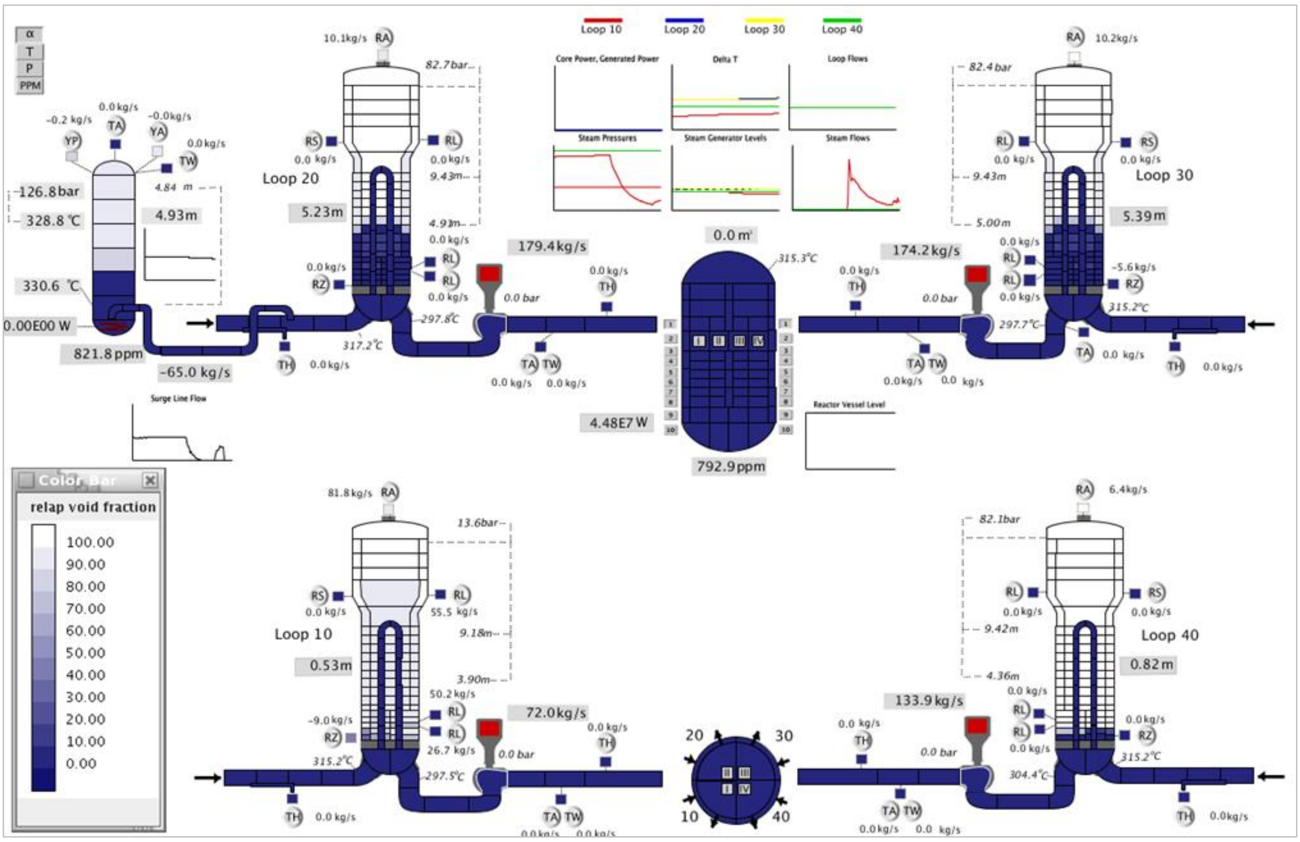

Figure 43: Begin of feedwater injection by boiling preheaters

Finally, it was intended to perform a complex scenario, typical for simulator training. With a quite useless SG1 now, a secondary side depressurisation was attempted, to bring back some coolant from the pumped up feedwater tank into the SG1. Away from the real procedure, the depressurisation was simply realised (from instructor station's point of view) by clearing the way through a safety valve 0RA10 S003. To be clear, this is merely to demonstrate the principle of passively getting some coolant back from the feedwater system. Furthermore, it was intended to demonstrate the perils of a good intention at the wrong time. No plant parameters at this situation would indicate the need for such a depressurisation, especially because there had been no possibility to inject some boron into the primary system. For this, a two-phase state in primary system would be needed to depressurise the primary system from condensing at the U-tubes of the heavily cooled

SG. From this, the primary system pressure would be lowered below the injection pressure of the accumulators at 25 bar, as demonstrated in the reference case at the beginning.

The depressurisation of secondary side went quickly down due to injection of the feedwater, at first providing mixture from the preheaters, beginning shortly below 20 bar pressure.

From drop of level in other SG it became clear, that the blowdown line of SG1 had to be closed, so 5RZ14 S003 was operated manually. Again, it has to be taken with some caution, because the operability of this component would not be guaranteed in such a situation and had to be provided by emergency procedure measures. If not available, the depressurisation hat to be avoided definitely for dragging the coolant from the other SG.

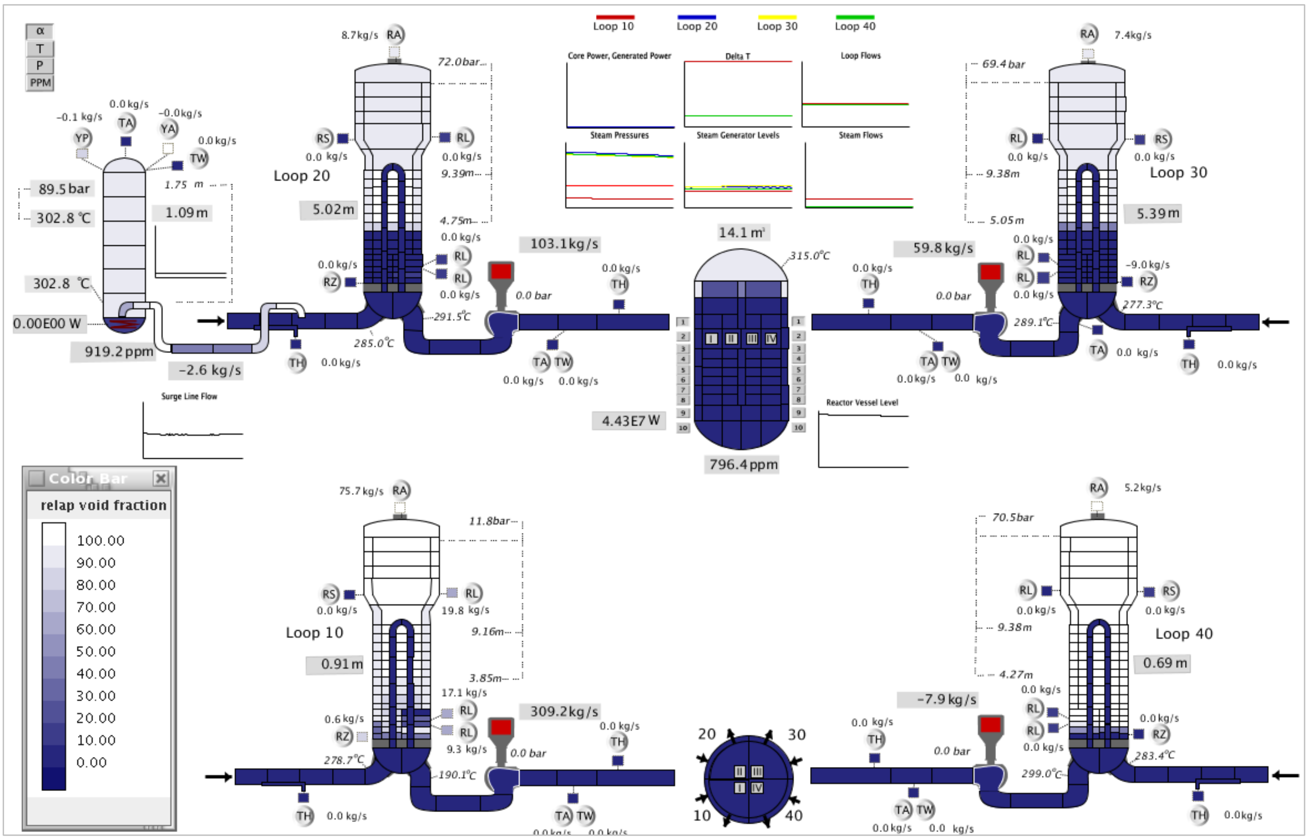

Figure 44: Stagnation of natural circulation in Loop 4, also beginning in Loop 3

Cooldown of primary circuit from Loop 1 lead to a reduction in natural circulation in all other loops. When the water came from the hot leg into the SG with a lower temperature than behind the SG, the rising column became heavier than the sinking one. This reduced the mass flow further and finally led to stagnation, first to be seen in stagnation in Loop 4. This is a well-known effect from PWR operators training (and can be demonstrated at the glass model).

The forced shrinking of the coolant in the primary circuit lead to a pressure drop, once the steam of the emptied pressurizer got into contact with the liquid in the HL2 (Figure 44). As a consequence, a steam bubble formed beneath the RPV head. Another boil-off occurred in the stagnating U-tubes of SG4 (Figure 45).

To bring the water from feedwater tank forward, the pressure in the boiling feedwater system inside the preheaters had to drop well below 10 bar. After this, the steam cushion on top of the feedwater tank pressed the saturated water forward, filling up SG1 quite rapidly.

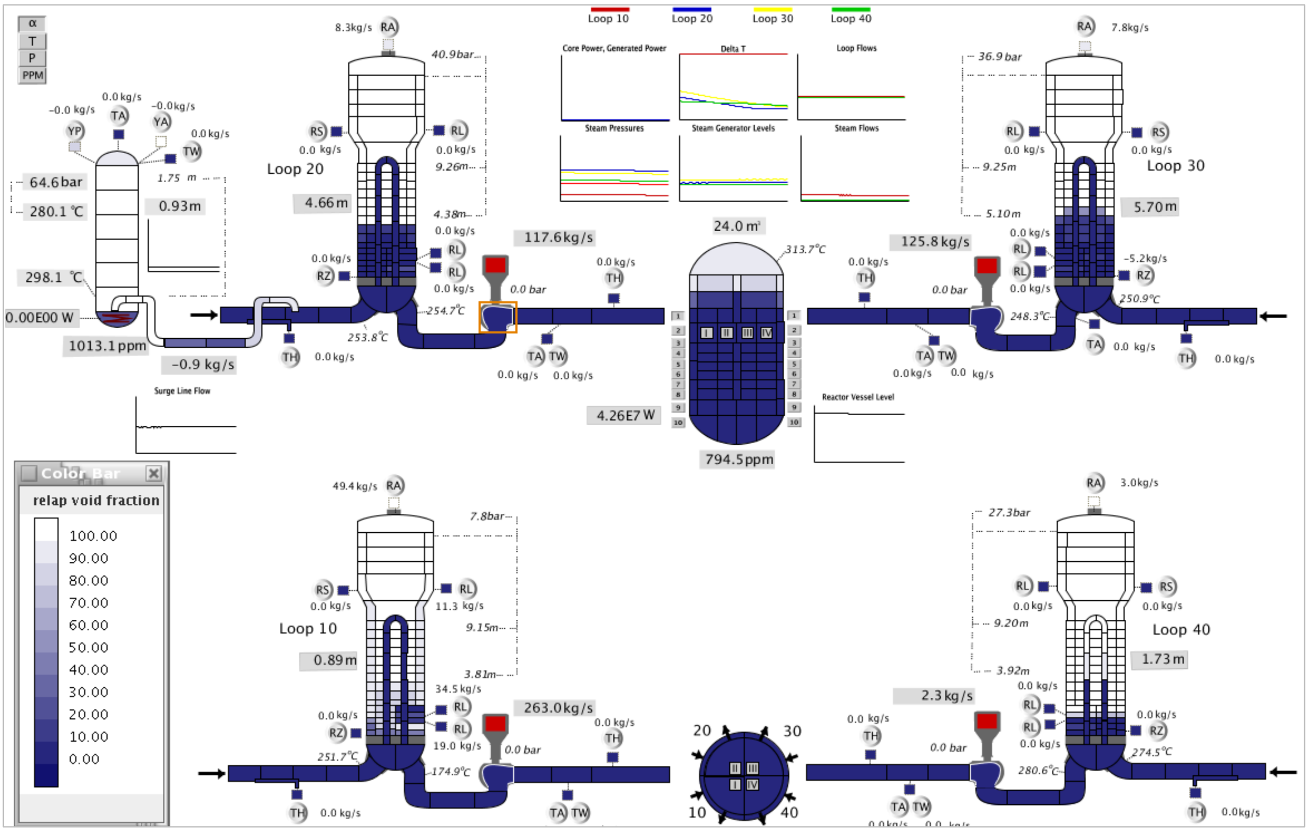

Figure 45: Boil off in U-tubes of SG4, TK40 inoperable from pressure drop

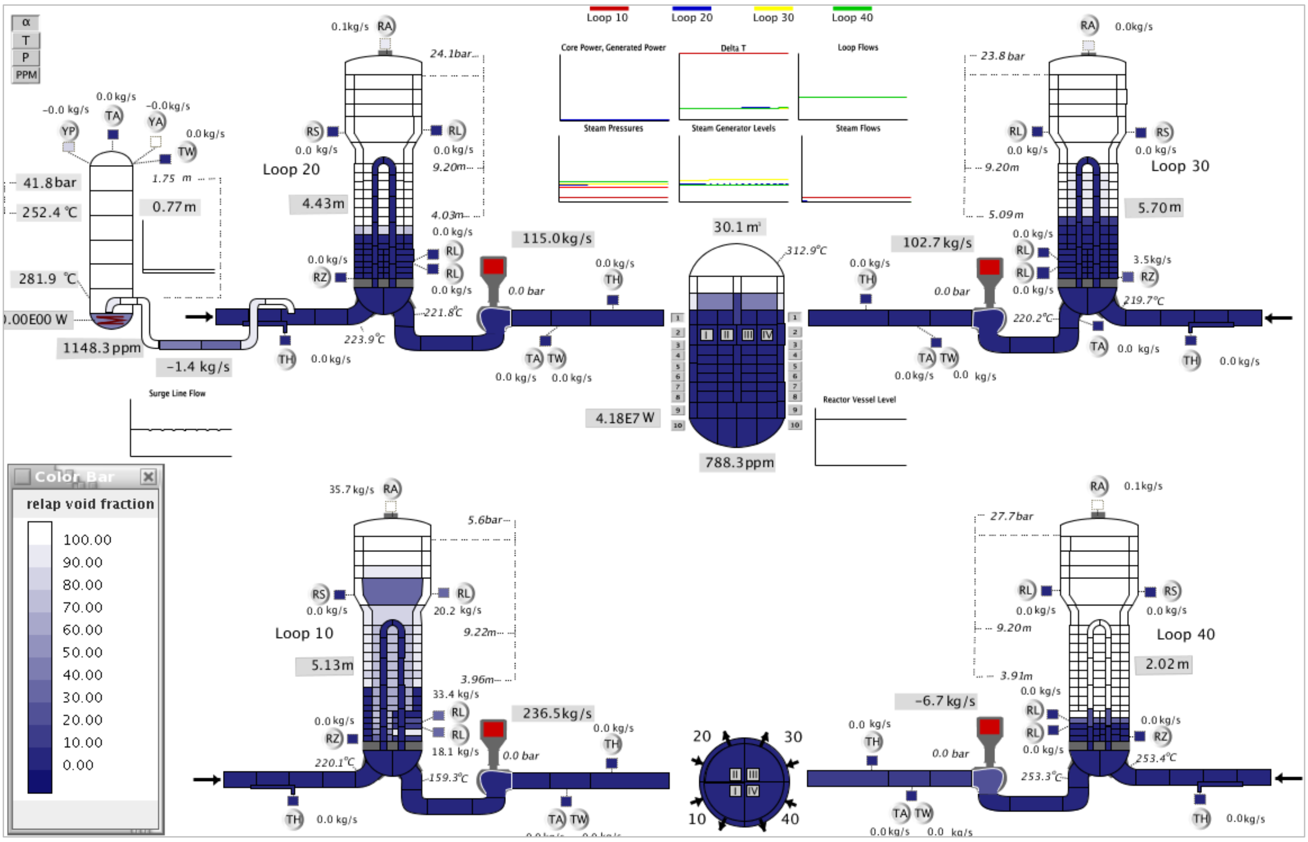

Figure 46: All TK subsystems stopped

Cooldown forced rapid pressure decrease in the SG with operating TK subsystems. At about 25 bar steam inlet pressure, power balance became negative for the TK subsystems. Subsequently, TK systems with negative power balance were stopped deliberately (Figure 46). First subsystem to be shut down was TK40, which had drained the pressure in SG4 into superheating, because of the lack of heat transfer from primary side, after breakdown of natural circulation in loop 4.

With SG1 filled up to 12 m, but feedwater tank was still half filled, it was tried to fill SG4 with the same method. Depressurisation was performed, 8RZ44S003 had to be closed.

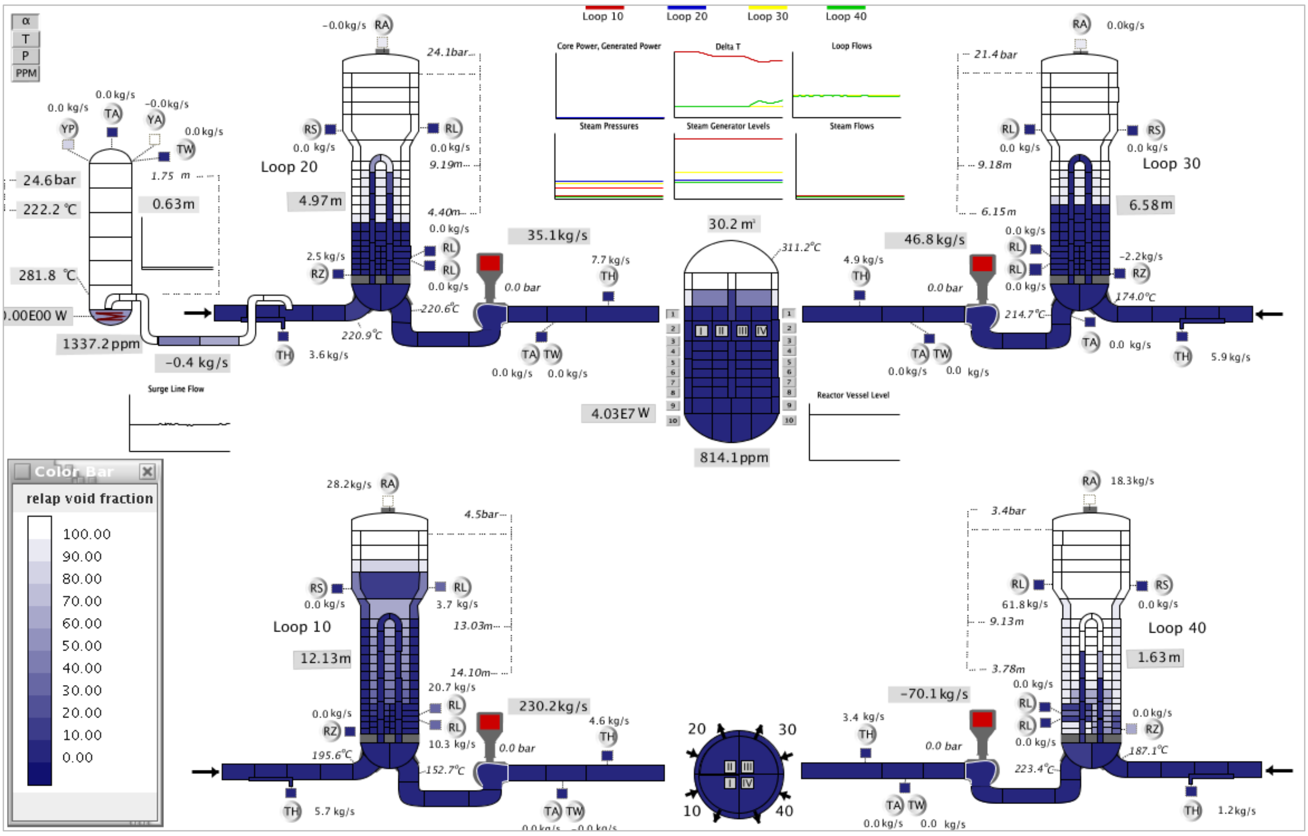

Figure 47: Depressurisation in SG4, Injection of accumulators below 25 bar

On primary side, the cooldown caused a pressure drop below 25 bar (Figure 47). The RPV head bubble had expanded until contact with the cooled water, so it could not compensate further shrinking of the coolant. At contact from surge line mixture with subcooled HL2-water, the pressure went down. Below 25 bars, some injection from accumulators occurred, but Boron concentration could not be improved significantly.

In SG2 now U-tubes boiled off, so natural circulation stopped in this loop and was reduced to condensation.

Secondary side depressurisation was stopped, when the feedwater tank was emptied. After this, a long period of heat-up occurred (Figure 48), dominated by SG1 and SG4, whereas heat transfer to SG2 and SG3 had come to a standstill, due to the breakdown of natural circulation. For all SG, natural circulation recovered finally, alongside the heat-up of the primary system.

So, with a pressure of more than 60 bar reached on secondary side, a restart of TK subsystems was performed. First, TK40 was started, but the elevated level in SG4 hampered the condensate flow, even with completely opened condensate valve (Figure 51). To check this, TK30 was restarted and performed well (Figure 50, Figure 52). To confirm this, TK20 was restarted successfully, again with a lowered level in SG. For transfer, the RZ connection from SG4 was reopened. With further pressure increase and level decrease, TK40 came slowly back into positive power balance.

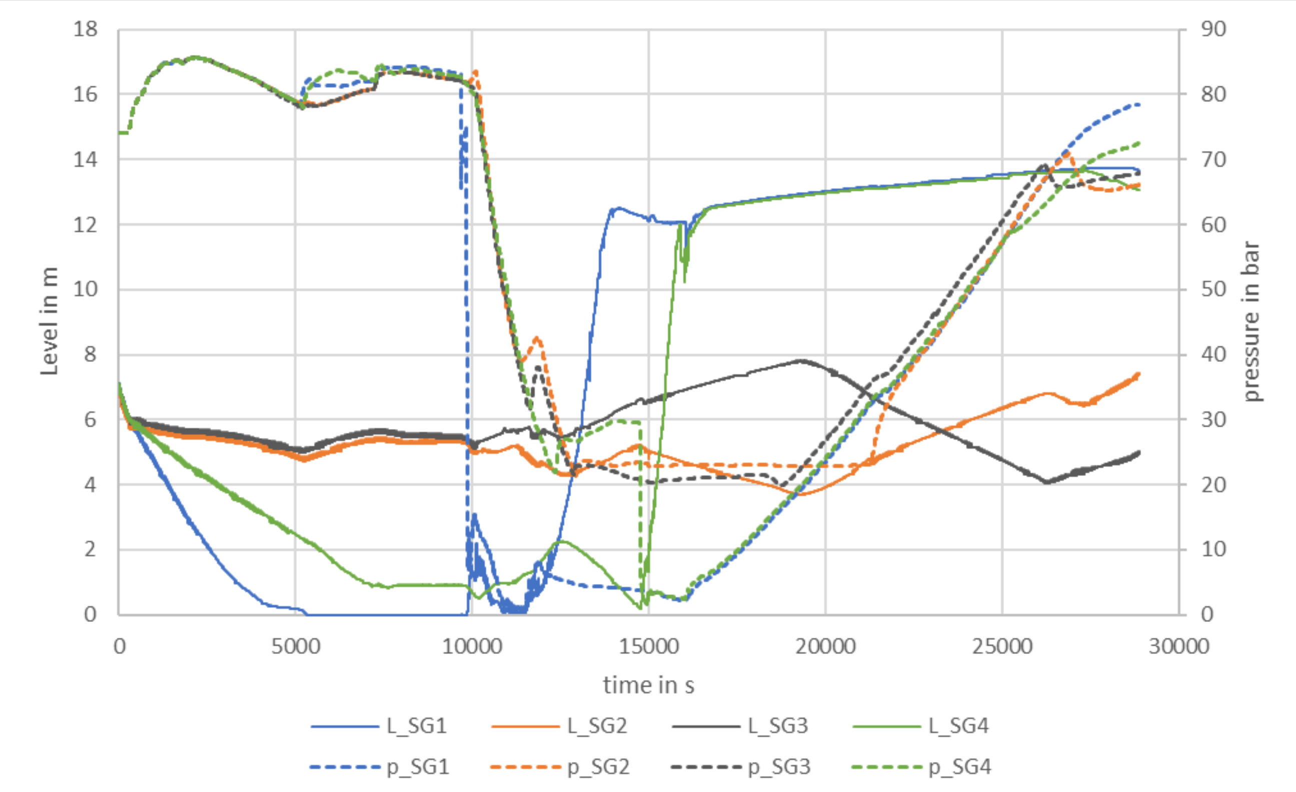

Figure 48: Timeline with depressurisation of SG1 and SG4, heat up and TK restart

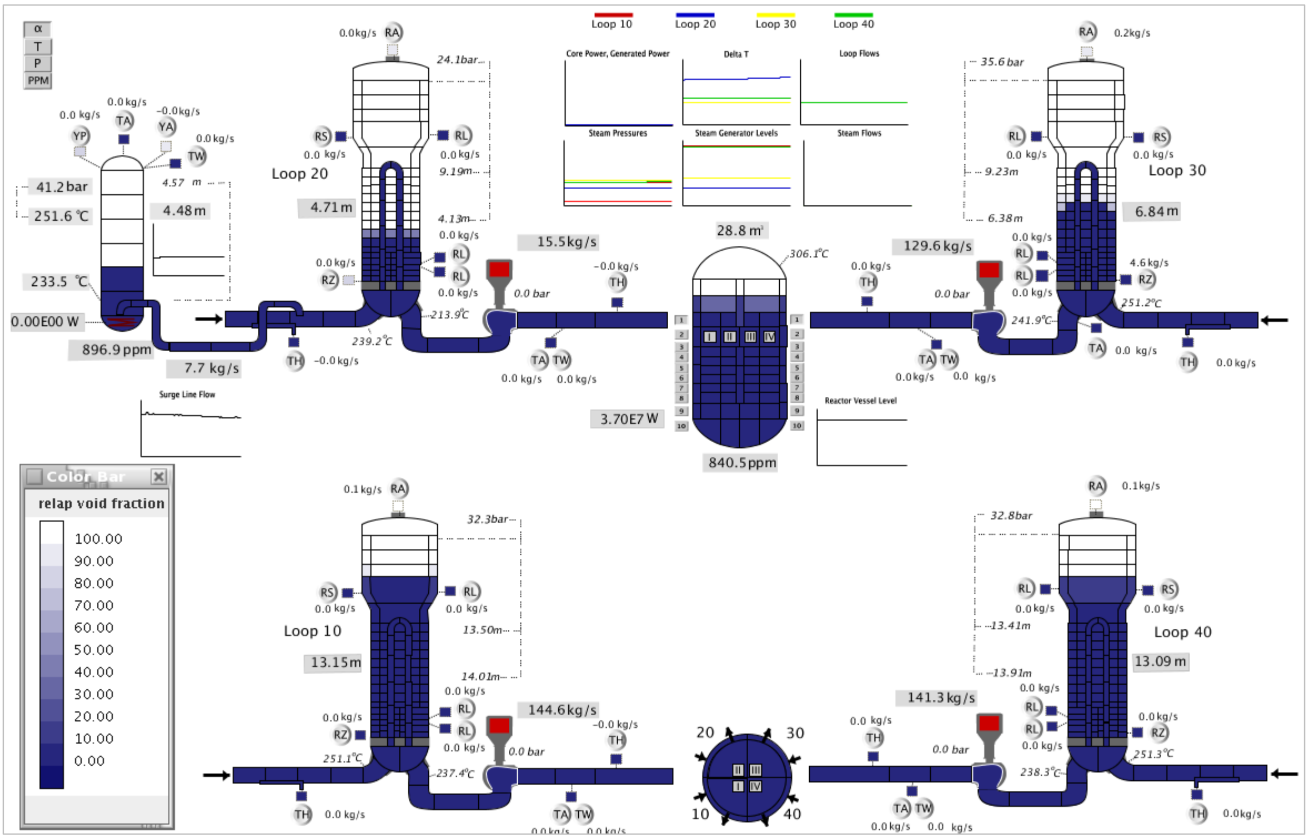

Figure 49: Recovery of natural circulation during heat-up (here: SG2)

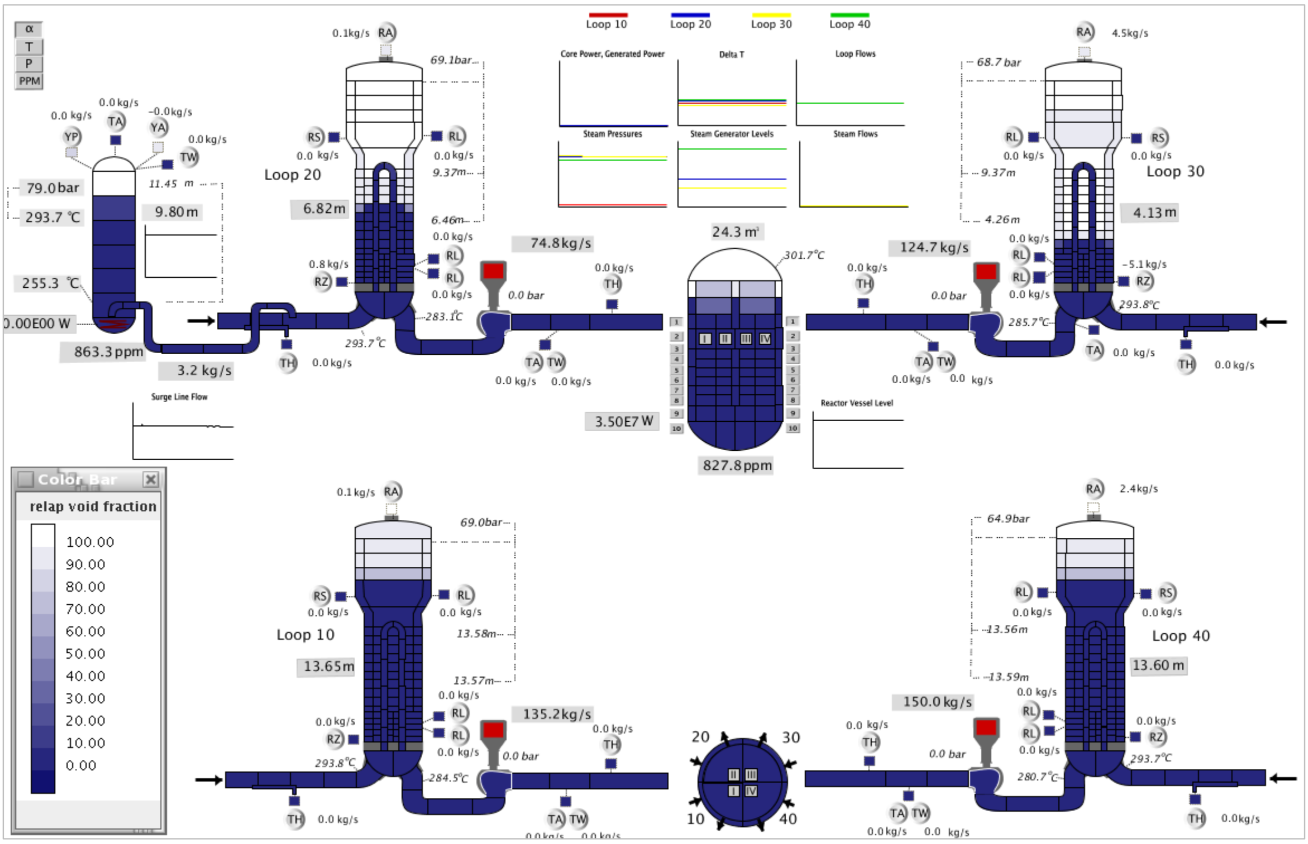

Figure 50: Performance of TK30 and TK40 with filled SG, to be seen from the steam flow (RA)

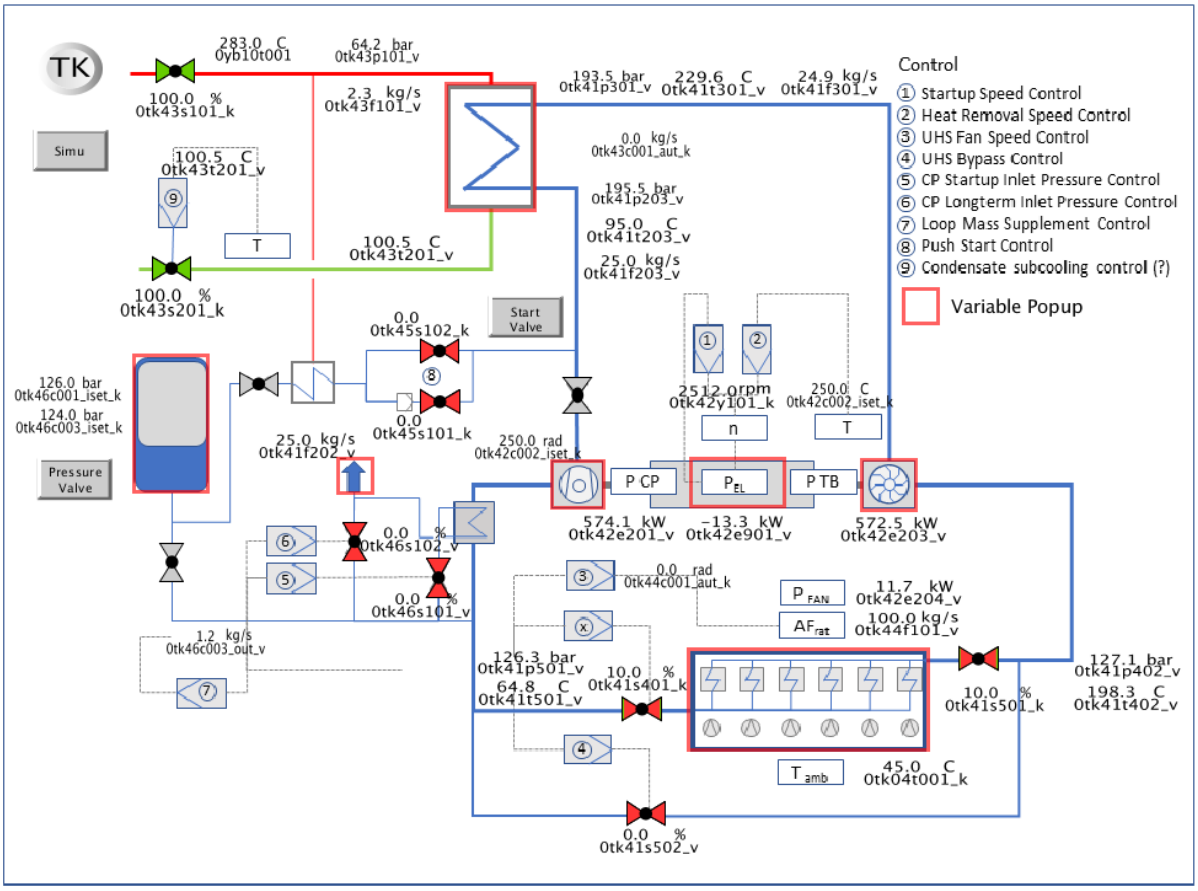

Figure 51: TK40 with blocked condensate path, visible from subcooling

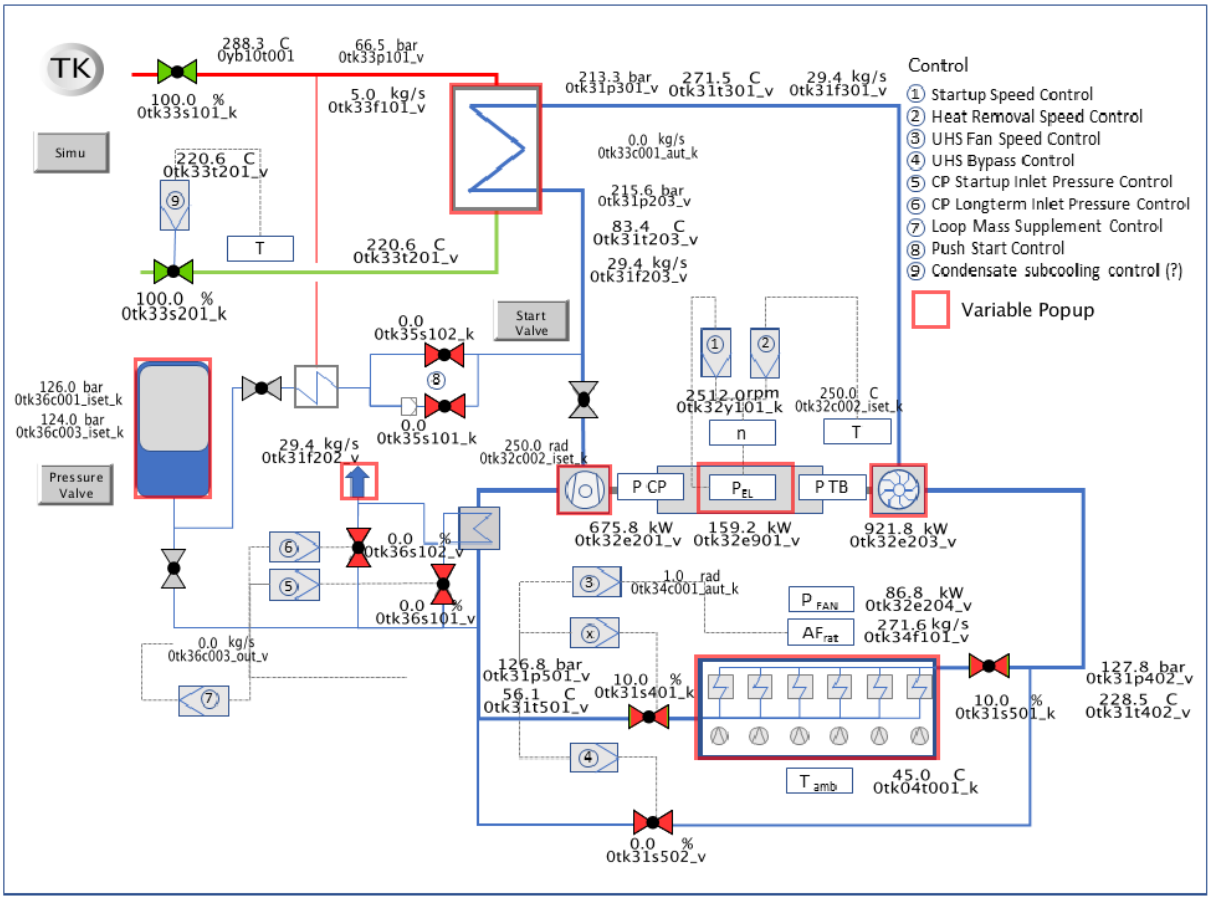

Figure 52: Performance of TK30 after restart, condensate valve TK33 S201 untrimmed yet

6 Conclusion

Performance of the simulated TK system as well as the implementation into the D46 simulator allowed to run several transients, to highlight operational issues for the use of the sCO2 heat removal system in case of a SBO. Start-up, stop, and restart of the TK subsystems at various SG were performed. Some improvements would be helpful for communication stability and real-time performance.

A total number of six sCO2 power cycles have virtually been attached to the secondary side: One of them to each of the four steam generators, the other two such that they can be connected to one pair of steam generators each, but never to both steam generators at the same time. This arrangement enables to analyse different heat removal strategies, e.g. symmetric and non-symmetric operation of the cycles and the feedback of this arrangement on the primary loop of the PWR.

In all cases demonstrated, core uncover was avoided, i.e. a flexible, robust operation of the power cycles could have been demonstrated.

The simulator confirmed former results from Hofer [5] that for a Konvoi-type PWR four power cycles will successfully remove the decay heat. This underlines the good state of primary side models (RELAP) at the simulator. So, the simulator can be assumed to be fit for further analysis with improved models of sCO2 heat removal systems, and for other conditions than SBO.

The simulator confirmed several thermal hydraulic effects, like RPV head steam bubble, ceased natural circulation and the boil off of U-tubes, primary depressurisation by cooling from secondary side, which were depicted in the RELAP viewer and are well known from the glass model trainings.

The transient runs highlighted the importance of some cross connections (in RZ here) and permanent losses (via RA here) to be included into the input decks of the qualified codes. However, there is some uncertainty about the conditions in these systems at the beginning of an event, so these conditions would have to be further studied and possibly defined for each individual NPP in consideration.

Regarding the influence of manual actions, some observations could be made during the transients, which will have to be addressed in further studies:

- The level in the SG developed not uniformly, but according to the number of heat removal systems. Generally, for shut off, the symmetry of the heat removal chains should be maintained, as long as no other strategies are followed, which would possibly need a dry SG.
- There was no automatic criterion to close the MSIV. Thus, a permanent loss of some kg per second occurred. The amount may be based on assumptions, but the MSIV have to be closed in time, and there have to be solutions to substitute such losses very early. Therefore, further cross connections of power produced by TK, to small pumps, feeding the SG, should be investigated.
- Having expanded the grace time for several hours, the interaction with other accident management measures has to be taken into account. Case 5a revealed, that the depressurisation and passive feeding of one SG could force the running TK systems (and their electric power generation) out of business for several hours, waiting for the heat-up of the primary and secondary system. It further highlighted the importance of level in the SG to the performance of the condensate backflow line. Again, the cross connections and their operability during such a transient (far from being a safety related system!) have to be taken into account thoroughly.
- The sensitivity of TK to act against a normal or slightly elevated level has to be considered for testing of the operational readiness. The response of the CHX is crucial, modelling details have to be

considered thoroughly. The TK modelling has yet to be extended to temperatures below critical point, yet the external air temperature was still to be fixed to 45°C for stability reasons.

Beyond such technical issues, performing a complex scenario at the simulator in real time will contribute to gain detailed knowledge about the operation of this new sCO2 power cycle and its interaction with a nuclear power plant. In addition, training of reactor personnel right from an early stage of sCO2-power cycle design, will give valuable feedback from the operator and trainer's point of view performing simulations under normal and accident-like conditions.

7 References

[1] Deliverable 5.4, “Thermodynamic performance of the heat recovery system integrated into the plant”, O. FRÝBORT, D. KŘÍŽ, T. MELICHAR, P. VLČEK, V. HAKL, L. VYSKOČIL, M. HOFER

[2] Deliverable 5.6, “Fast running version of the sCO2 heat removal system for implementation in control logic of PWR simulator”, O. FRÝBORT, D. KŘÍŽ, T. MELICHAR, P. VLČEK, V. HAKL

[3] Deliverable 6.1 “Specification for interface” P. LASCH

[4] Deliverable 6.2: “sCO2 System integrated in PWR-simulator”, P. LASCH

[5] Poster for the FISA 2022: An Innovative Supercritical Carbon Dioxide Cycle for Decay Heat Removal in Existing and Future Nuclear Power Plants” M. HOFER, F. HECKER, M. BUCK, J. STARFLINGER, A. CAGNAC

Appendix A Data

A.1 Simulator Data

A.1.1 Decay Heat curve

The following curve depicts the power from radioactive decay at the simulator. The time starts with the scram at the original initial condition, the power of the initial condition used for the transients sets in at about 330 s with 113 MW. The right hand side stops at about 30 000 s.

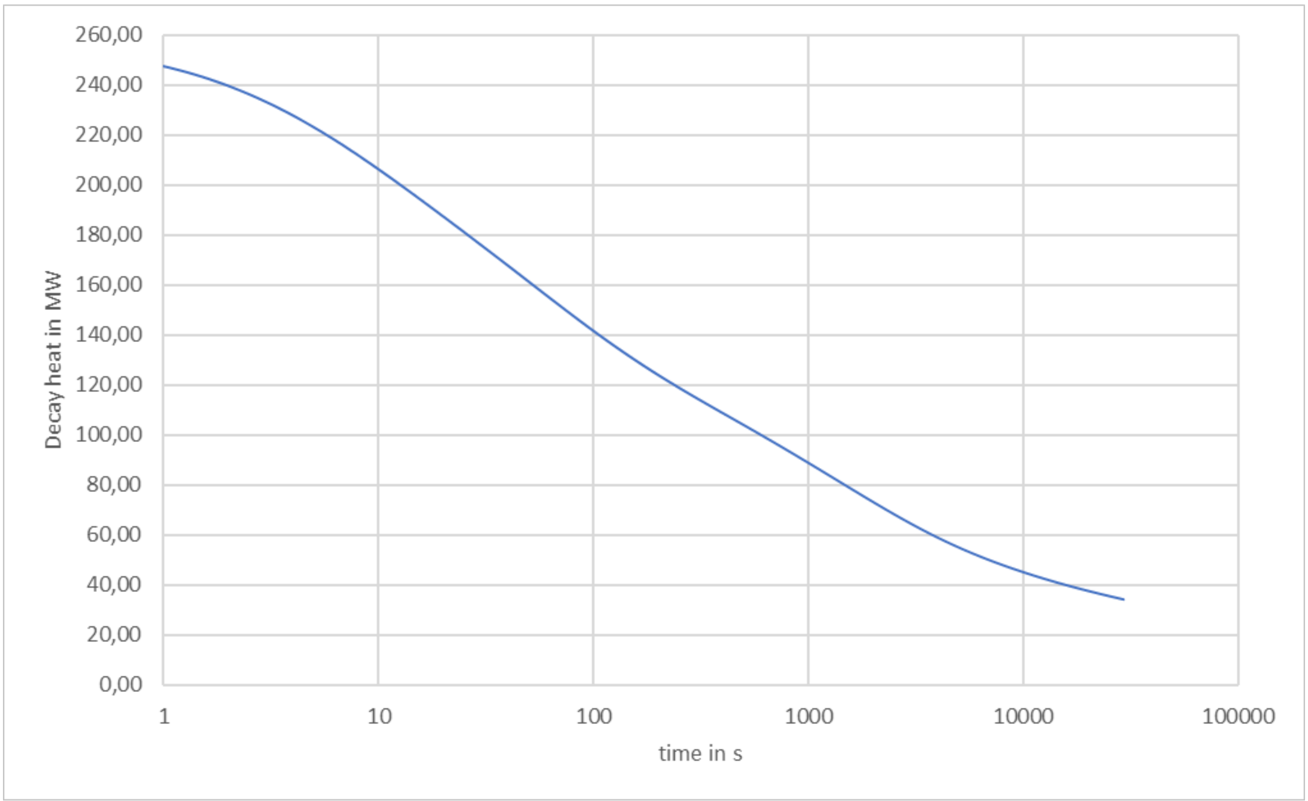

Figure 53: Decay heat during the transients in MW