HEXTRAN-SMABRE Calculation of the VVER-1000 Transient Benchmark, Main Steam Line Break

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Summary

The VVER-1000 Coolant Transient (V1000CT) benchmark is intended for validation of the coupling of thermal hydraulics codes and three dimensional neutron kinetics core models. VTT participated in the first phase of the benchmark in 2005 using advanced nodal code HEXTRAN for core dynamics and the system code SMABRE for thermal hydraulics model for primary and secondary loop. In 2006-2007, VTT participated in exercises 2 and 3 of the second phase concerning a main steam line break.

Exercise 2 is a coupled 3D neutronics/core thermal hydraulics response evaluation. Only core and reactor pressure vessel are modelled, with thermal hydraulic boundary conditions at the vessel input and output. Exercise 3 is a best-estimate coupled-code full plant simulation of the MSLB transient. In addition to the realistic plant transient, a pessimistic scenario is calculated in which the main coolant pump in the faulted loop fails to trip and the scram worth was assumed reduced.

This paper presents the results from the four calculated cases. Comparison to the results of other benchmark participants has not yet been performed by the benchmark organizers.

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Contents

1 Introduction

The VVER-1000 Coolant Transient (V1000CT) benchmark is intended for validation of the coupling of thermal hydraulics codes and three dimensional neutron kinetics core models. It consists of two phases, the first concerning a switching on of one main coolant pump while the three other pumps were in operation, and the second concerning a postulated main steam line break (MSLB). The cases are partly based on experiments performed on Kozloduy NPP in Bulgaria in 1992.

Phase 1 was calculated at VTT in 2005 [1] using advanced nodal code HEXTRAN for core dynamics and the system code SMABRE for thermal hydraulics model for primary and secondary loop. The parallelly coupled HEXTRAN-SMABRE code has been developed at VTT since the early nineties and it has been in extensive use for analysis of VVER-1000 NPPs. Both codes need their own input models because they can also be used separately. The input models for The Kozloduy NPP in Phase 1 for HEXTRAN and SMABRE were based on VVER-1000 inputs used earlier at VTT.

VTT participated in exercises 2 and 3 of Phase 2. Exercise 2 is a coupled 3D neutronics/core thermal hydraulics response evaluation. Only core and reactor pressure vessel are modeled, with thermal hydraulic boundary conditions at the vessel input and output. Exercise 3 is a best-estimate coupled-code full plant simulation of the MSLB transient. In addition to the realistic plant transient, a pessimistic scenario is calculated in which the main coolant pump in the faulted loop fails to trip and the scram worth was assumed reduced. Both exercises and scenarios were further divided into two cases in which different control rods are assumed stuck. The Kozloduy plant models updated for Phase 1 were used as a basis for the input models in Phase 2.

This paper outlines the input models used in exercise 2 and 3. A total of four cases were calculated, one case per each scenario in both exercises. Calculation results are introduced in Chapter 4 and Figures 4-31.

2 Input models for codes

At VTT, three-dimensional advanced nodal code HEXTRAN [2] is used for core dynamics for hexagonal core geometry and system code SMABRE [3] for primary and secondary loop thermal hydraulics. Input models for Phase 2 are based on the inputs developed for the first phase of the benchmark. The models and changes made on them are described in the following.

In Exercise 2, only core and reactor pressure vessel were modelled and thermal hydraulic boundary conditions were imposed on the vessel inlet and outlet. In exercise 3, the whole plant was modelled. SMABRE plant models for the two exercises differ notably whereas HEXTRAN core models are almost the same. Differences between the realistic and pessimistic scenario are implemented though altered cross-section libraries and choice of stuck control rods in the HEXTRAN input and differences in pump behaviour in the SMABRE model.

2.1 HEXTRAN core model

Three dimensional reactor dynamics code HEXTRAN performs neutronics and thermal hydraulics calculations within the reactor core. Nodal expansion method is used to solve two-group diffusion equations. Neutron kinetics, fuel heat transfer and hydraulic calculations are carried out with implicit time integration. Each fuel assembly is modelled separately with an attached thermal hydraulic channel, individual neutronics and heat transfer calculations. Fuel temperature calculation is performed on an average fuel rod in each assembly.

The HEXTRAN core model used in the first phase of the VVER-1000 Coolant Transient Benchmark is based on an input model created for calculations on Kozloduy NPP related to an EU project [4]. For the V1000CT benchmark the whole core was modelled. Neutron kinetics is calculated in 3D and thermal hydraulics in 1D in parallel channels, although there is an open core geometry in Kozloduy NPP.

The core and fuel geometry is according to benchmark specifications [5]. There are 29 types of fuel arranged in 60 degree symmetry. An option to describe reflector by two-group diffusion equations was added during Phase 1, but the calculations were performed using albedo boundary conditions for radial and axial reflector. The albedo boundary conditions were created earlier for standard VVER-1000 core. For fuel pellets, seven radial mesh point were used and two for cladding.

The model for radial heat generation was improved in 2004, during Phase 1. In the new model [6] heat generation is dependent on location r and burnup Bu according to

$$P(z,r,t,Bu) = P_{ax}(z,t)\frac{1}{N}\cosh\left(\left(\delta_1 + \delta_2\sqrt{Bu}\right)\left(\frac{r}{r_p}\right)^4\right) \quad , \qquad (1)$$

where r_p is radius of fuel pellet, N normalization factor and δ_1 and δ_2 constants. Phase 1 was calculated using the old, volumetrically averaged heat generation model, but variations calculations were made also with the new model.

Some changes were made to the HEXTRAN input in Phase 2 compared to Phase 1. In Phase 1 the numbering of loops was not in accordance with the benchmark specifications. This was corrected by inverting the order of core channels as well as making chances to the SMABRE input. The order of the loops is now same as in the specification but the numbering of fuel assemblies in the input and this paper, shown in Figure 1, still differs from the benchmark specification.

The cross-section libraries provided were more detailed in for Phase 2 than in Phase 1. A complete set of two-group diffusion coefficients and macroscopic cross-sections was provided for every composition tabulated as a function on three variables instead of two. The new variable is moderator temperature. The range of the independent variables was also widened. The added dimension demanded for changes in the XSTAB code, which is used for converting the cross-section libraries into a suitable form for HEXTRAN. These changes are explained in Chapter 3. Cross-sections libraries were developed for 30 axial layers in the core, which required changing the nodalization of the HEXTRAN input model from 20 to 30 axial nodes.

The new, location dependent heat generation model was used. Radial and axial albedo boundary conditions were applied as reflector model, as in Phase 1.

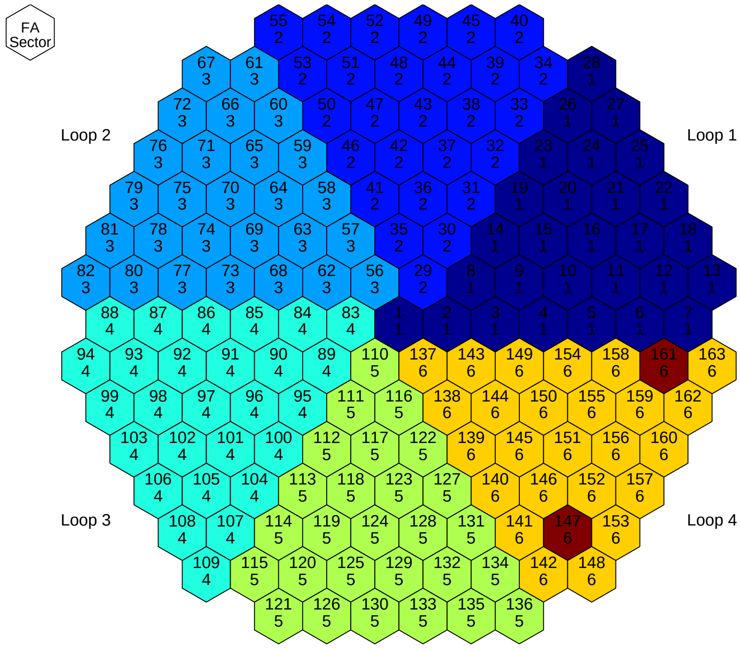

Figure 1. VVER-1000 core channels modelled in HEXTRAN and their division to six SMABRE channels. Numbering of core channels different in this paper compared to the benchmark specification. Stuck control rods are depicted in red.

2.2 SMABRE plant model

SMABRE plant model for VVER-1000 NPPs is an outcome of several applications concerning for example VVER-91 concept planned for Finland in the beginning of 90’s, VVER-1000 plants in Russia and EU-projects dealing with real transients in Balakovo [7] and Kozloduy [4]. For Phase 1, the pressure vessel model in SMABRE was revised due to the whole core symmetry of needed for HEXTRAN. After re-nodalization, the initial state according to the benchmark specification was achieved by tuning the model with loss coefficients. SMABRE input model in Phase 1 was used as a basis for input model in Phase 2.

In the SMABRE model, all four loops of the primary circuit are modelled separately including the steam generators, reactor coolant pumps, hot and cold legs and the pressurizer connected to hot leg 4 with surge line. For asymmetric behaviour inside the pressure vessel, six parallel channels, sectors, are defined in the pressure vessel below the hot leg elevation. Accordingly, all the volumes in the downcomer, lower plenum, core, and upper plenum are horizontally divided into six volumes. Turbulent mixing model of SMABRE is applied to the horizontal cross flow junctions between volumes in the downcomer and lower plenum. At VTT, the degree of mixing before core in the pressure vessel for VVERs has typically been 20 %.

The core is modelled with ten axial and six parallel nodes, each including heat structures for which heat generation is calculated in HEXTRAN. For using SMABRE without HEXTRAN, the code includes a point kinetics model. Coolant bypass in the core in control rod tubes and reactor baffle is described with one node. Also, one node represents the upper plenum bypass from the core exit to the upper head.

Turbulent mixing of the SMABRE model was tuned in exercise 1 of Phase 2 against measured data from Kozloduy. The data was from a scenario in which the temperature of one loop increases due to closing of a main steam isolation valve in the corresponding steam line. In SMABRE, the mixing coefficients are defined for sectors, not for individual core channels. The mixing coefficients determined in exercise 1 are used in exercises 2 and 3, although mixing behaves differently in the case of one loop cooling instead of heating.

2.2.1 Exercise 2

In exercise 2, only core and pressure vessel were modelled. Therefore, all nodes outside the vessel were removed. The original nodalization of the primary side is shown in Figure 2. Nodes 1-4 in the cold leg and 517-520 in the hot leg were the outermost nodes kept for the SMABRE model in exercise 2. The remaining model for core and vessel consists of 145 nodes and 233 junctions. The wall structures and fuel are modelled with 307 heat slabs.

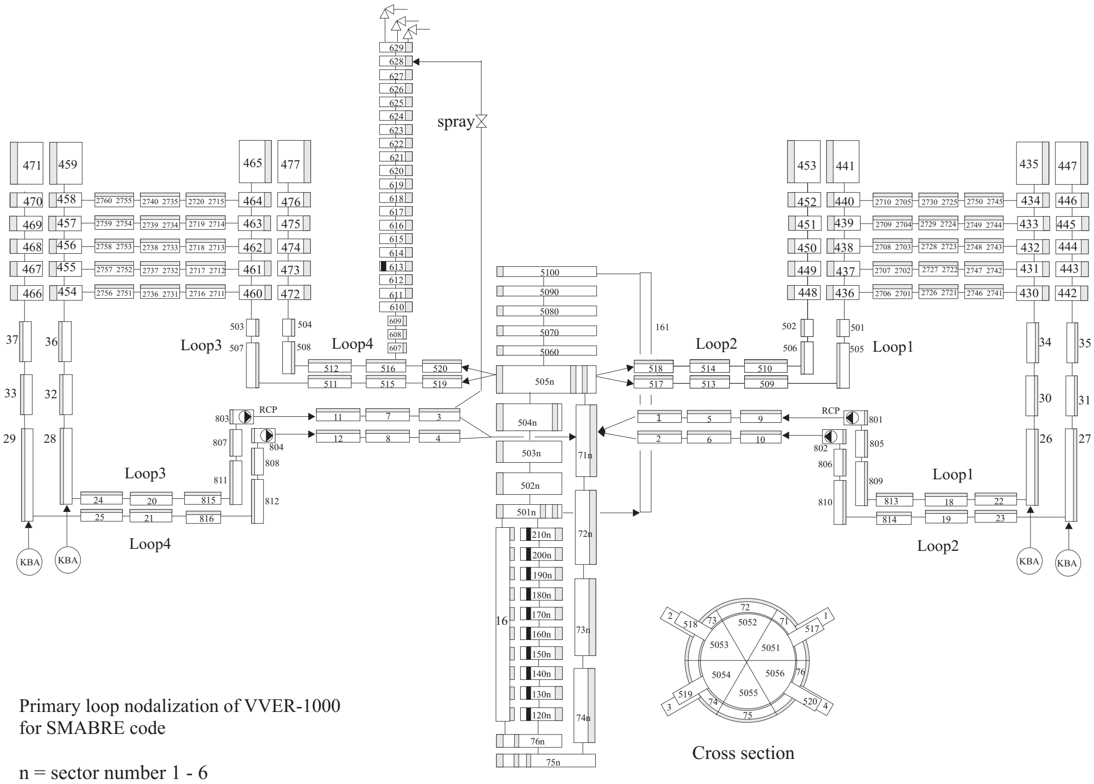

Figure 2. Nodalization of VVER-1000 primary side for SMABRE code.

Boundary conditions for vessel inlet and outlet, calculated with CATHARE code, were given in the benchmark specifications. Coolant mass flow, pressure and temperature as tabulated functions of time were provided for vessel inlet, and coolant pressure and temperature for vessel outlet. Due to the pressure boundary condition for vessel outlet, a new option for giving leak data was added to SMABRE, described in more detail in Chapter 3.

No primary side related operational systems were used in exercise 2.

2.2.2 Exercise 3

Both primary and secondary circuit were modelled in Exercise 3. The primary side nodalization was adopted from Phase 1 as such whereas three nodes (399-410) were added to each loop on the secondary side as well as an extra node (3840) to loop 4 to improve the description of the break location. In general, break flow is modelled with the Moody model, which does not require a very dense nodalization near the break location. The nodalization schemes are shown in Figures 2 and 3. The model consists of a total of 435 nodes, 557 junctions and 612 heat slabs.

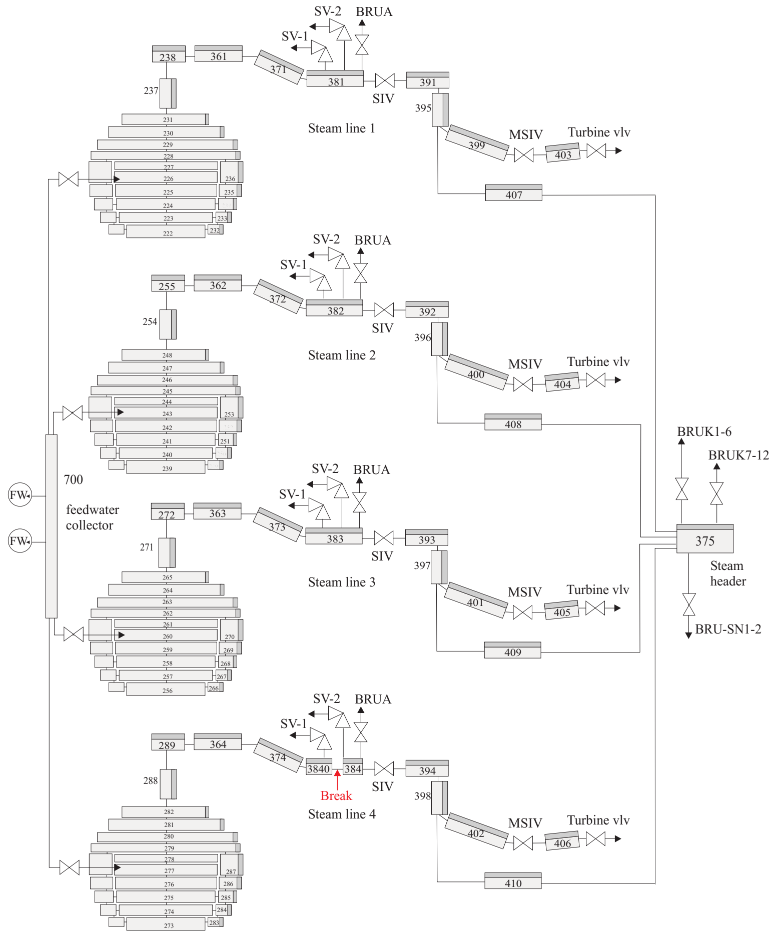

Figure 3. Nodalization of VVER-1000 secondary side for SMABRE code.

On the secondary side, the liquid volume below the nominal water level and also the steam dome are divided vertically to five nodes in order to describe better the phase separation. The surrounding water outside the steam generator tube volume is modelled as a separate downcomer. Each steam line is modelled separately and the steam header with a single node. The horizontal heat transfer tubes are modelled with five levels. This model enables an internal circulation in the primary side in some special transients and further, concerning also the nominal state, an internal circulation below the water level in the secondary side. The calculated water level in the steam generator is collapsed level in the downcomer area simulating the pressure difference measured outside the heat transfer tube volume.

Most of the primary side related operational systems are modelled but their operation is prevented during the transient. Only pressurizer heaters and high pressure injection systems (HPISs) are in operation. On the secondary side, feed water boundary conditions to SGs are used. No SG level control is modelled. Bypass to house consumption header (BRU-SN) and bypass to condenser (BRU-K) are modelled as specified in the benchmark.

In SMABRE, pump characteristic is given with homologous curves in eight sections. These describe the pump and turbine operation with forward and reverse rotation defining flow rate and pressure increase in pump operational points. In Phase 1, the homologous curves were modified in order to gain the wanted pressure differences and mass flows in the pump start-up. In Phase 2, the original curves were used instead of the ones defined for Phase 1.

3 Code changes

Due to new features in the benchmark specifications, some chances were made on the codes that were used. XSTAB is a small utility code used for converting cross-section libraries from the benchmark format into a form suitable for HEXTRAN. Its dimensioning needed to be altered to fit the dimensions of the given cross-section libraries. In SMABRE, a new way to give time dependent leak data was added to enable the use of the thermal hydraulic boundary conditions in their original form. Both changes are described in more detail in the following.

3.1 SMABRE

In the benchmark specifications only a pressure boundary condition was given for vessel outlet in exercise 2. In SMABRE input, time dependent leak parameters require information for both pressure on the other side of the leak as well as total friction coefficient or leak flow rate. A new option was added in which only the pressure following the leak needs to be given as a tabulated function of time. This option is used when the node index of the node preceding the leak is negative. In this case the pressure of the preceding node is directly set equal to the external pressure.

3.2 XSTAB

In the benchmark specifications cross-section libraries are given in a format in which the material compositions are handled one at the time, giving separate tables for the diffusion coefficients and cross-sections in which the cross-section data is provided at different possible core states defined by the independent variables. On the other hand, the format that HEXTRAN uses also handles material compositions one at the time, but it requires the different cross-sections one after the other for a certain core state, not as separate tables in which the core state alters. Hence a program is needed for converting the array of the cross-section data.

The original XSTAB-code (xstab2.f) for Phase 1 reads the cross-section libraries and rewrites them in the wanted format. In Phase 1, the independent variables that defined the state of the core were fuel temperature and density of moderator. Five values of fuel temperature were defined and four values of moderator density. There were 283 material compositions.

A new independent variable, moderator temperature, was added in Phase 2. The order of the variables in the specifications was fuel temperature, moderator temperature, moderator density, whereas in HEXTRAN the order is fuel temperature, moderator density, moderator temperature. The need to change the order of the variables added some complexity to the code (xstab_oma5.f). Fuel temperature, moderator temperature and moderator density were defined in 5, 5 and 6 points, respectively, and 843 material compositions were given in accordance with 29 different fuel assembly types and 30 axial layers.

4 Main steam line break transient

The MSLB transient is calculated in four cases: two scenarios with vessel inlet and outlet boundary conditions and the same two scenarios modeling the whole plant. The first scenario in both exercises is close to the current licensing practice while the second is a pessimistic scenario with unfavourable assumptions. In the benchmark, six steady states at hot zero power are also defined for comparison of scram and stuck rod worths, as well as cases in which the scenarios are calculated with different stuck control rods. Only one case in each scenario for both exercises is described in this paper.

The transient is initiated by a main steam line (MSL) break between the steam generator and steam isolation valve in MSL-4. Due to decreasing pressure on the secondary side large asymmetric cooling of the core and large primary coolant flow variations are characteristic for the event. The break is followed by scram during which one control rod assembly is stuck and remains withdrawn from the core. The stuck rod assembly is assumed to be located close to the maximum overcooling in sector 6, #161 in scenario 1 and #147 in scenario 2, according to the numbering in Figure 1. Due to the overcooling, possible recriticality and return to power after the scram are major concerns.

In Scenario 1, the main coolant pump (MCP) of the faulted loop trips to reduce the overcooling. In the pessimistic scenario it is assumed that the pump fails to trip on signal and all pumps remain in operation. In scenario 2, the return to power is enabled also by reducing the scram rod worth by adjusted cross sections.

4.1 Initial state

At the initial state, the reactor is assumed to be at the end of cycle (EOC) at nominal power level with 0.3 boron acid concentration and equilibrium Xe and Sm concentrations. Control rod groups 1-9 are fully withdrawn from the core and control rod group 10 is 80 % withdrawn. The steam generator water inventory is about the possible maximum at hot full power conditions. The main parameters of the initial steady state from the benchmark specification and calculated for Exercise 3 scenario 1 are shown in Table 1. For the other cases, the calculated initial states were very similar.

Steady state calculation with SMABRE is started 52 s and HEXTRAN-SMABRE calculation 2 s before the break opening. In all figures, the time 0 seconds is fixed at the beginning of the transient.

4.2 Vessel calculation with given boundary conditions, Exercise 2

In Exercise 2, the MSLB transient was calculated only in the core and pressure vessel with thermal hydraulic boundary conditions on vessel inlet and outlet. Scram commenced at 0.36 s of the transient and control rod drop time during scram was 4.0 s.

Table 1. Measured and calculated initial state in Exercise 3 scenario 1.

Parameter	Plant data	HEXTRAN-SMABRE
Core power, MW	3010	3015.6
Lower plenum pressure, MPa	15.842	15.843
Pressure above core, MPa	15.7	15.65
Cold leg 1 temperature, K	560.85	562.32
Cold leg 2 temperature, K	560.85	562.35
Cold leg 3 temperature, K	560.85	562.33
Cold leg 4 temperature, K	560.85	562.65
Hot leg 1 temperature, K	591.55	592.39
Hot leg 2 temperature, K	591.55	592.43
Hot leg 3 temperature, K	591.55	592.42
Hot leg 4 temperature, K	591.55	592.58
Coolant heat up over the core, K	30.6	30.04
Loop 1 volumetric flow rate, m3/h	21596	21596
Loop 2 volumetric flow rate, m3/h	21188	21596
Loop 3 volumetric flow rate, m3/h	20911	21596
Loop 4 volumetric flow rate, m3/h	21709	21598
Average loop flow m3/h	21351	21597
Reactor mass flow rate kg/s	17824	17807
Bypass through CR guide channels, %	2.2	2.9
Core flow rate, kg/s	17289	17267
Bypass through the core periphery, %	0.7	-
RVP bypass, %	0.1	0.1
Total bypass, % / kg/s	3.0 / 535	3.0 / 540
Reactor pressure drop, MPa	0.406	0.417
Pressurizer level, m	8.7	8.7
SG outlet pressure, MPa	6.27	6.28
SG steam outlet temperature, C	278.5	278.62
Feedwater flow, kg/s	409	401
Feedwater temperature, C	220	220
SG level, m	2.4	2.4

In scenario 1, vessel inlet temperature drops in all loops (Figure 12). The minimum on inlet temperature in loop 1 is reached at 166 s. Mass flow rate (Figure 20) in loop 4 decreases and is reversed at 19 s. Therefore, the outlet temperature of the faulted loop 4 drops rapidly. The scram decreases power (Figure 4) quickly to zero and there is no recriticality after scram (Figure 8).

In scenario 2, vessel inlet temperature (Figure 13) in loop 4 drops dramatically in the beginning of the transient, while mass flow rate (Figure 21) in the loop increases. This causes overcooling of the core and power increases (Figure 5). Recriticality (Figure 9) is reached temporarily at 49 s.

4.3 Full plant simulation, Exercise 3

In Exercise 3, scram signal is caused by low secondary pressure in SMABRE and the scram starts with 0.3 s delay after the signal. Feed water to the steam generators was given as boundary condition. For the intact SGs, the feed water decreases to zero in a linear fashion in 100 seconds. The dependency is more complicated for SG-4 and different for both scenarios.

In scenario 1, the reactor trips at 2.75 s. Vessel inlet temperature (Figure 14) of loop 4 starts to drop sharply and MCP-4 trips at 5.2 s to reduce the overcooling. Mass flow rate (Figure 22) in loop 4 is reversed at 34 s. The scram decreases power (Figure 6) to zero. The amount of liquid in the break flow (Figure 30) is very small. Total integrated break flow is about 75 500 kg. Collapsed levels of SG-4 (Figures 24 and 26) lower to zero at about 400 s. The sequence of events in scenario 1 is shown in Table 2.

In scenario 2, scram occurs at 2.77 s of the transient. MCP-4 fails to trip, which contributes to the cooling of loop 4 (Figures 15 and 19). Mass flow rate (Figure 23) in loop 4 increases rapidly. The collapsed levels of SG-4 downcomer and riser (Figures 25 and 27) fall to zero at about 150 s, which stops the power exchange in loop 4 (Figure 29). Lack of water inventory in the loop also stops the break flow (Figure 31), leading to total integrated break flow of about 65 000 kg. Sequence of events in scenario 2 is shown in Table 3.

Table 2. Sequence of events in Exercise 3 scenario 1.

TIME (s)	EVENT	CAUSE
-52.0	Steady state calculation with SMABRE	
-2.00	Calculation with HEXTRAN-SMABRE	
0.00	Double ended break opens	
1.87	Pressurizer heater groups 1 and 2 on	Pressurizer pressure < 15.579 MPa
2.45	SCRAM signal, SIV-4 closure in 57s	Secondary side pressure < 4.9 MPa
2.75	Reactor trip; control rod speed 88.75 cm/s	0.3 s delay after SCRAM signal
3.55	Pressurizer heater groups 3 and 4 on	Pressurizer pressure < 15.378 MPa
5.20	MCP-4 trips	Secondary side pressure < 4.4 MPa
5.20	Bypass to house consumption header (BRU-SN) starts to open	MCP-4 trip and MSH pressure > 5.5 MPa
12.60	Turbine valve 4 closed	
12.65	Turbine valves 1, 2 and 3 closed	
56.25	BRU-SN opened	
61.35	Pressurizer heaters 1, 2, 3 and 4 off	Pressurizer level < 4.2 m
69.55	BRU-SN valves starts to close	MSH pressure < 5.297 MPa
119.45	BRU-SN valves closed	
600.0	Calculation ends	

Table 3. Sequence of events in Exercise 3 scenario 2.

TIME	EVENT	CAUSE
-52.0	Steady state calculation with SMABRE	
-2.00	Calculation with HEXTRAN-SMABRE	
0.00	Double ended break opens	
1.87	Pressurizer heater groups 1 and 2 on	Pressurizer pressure < 15.579 MPa
2.47	SCRAM signal, SIV-4 closure in 58s	Secondary side pressure < 4.9 MPa
2.77	Reactor trip; control rod speed 88.75 cm/s	0.3 s delay after SCRAM signal
3.62	Pressurizer heater groups 3 and 4 on	Pressurizer pressure < 15.378 MPa
12.55	Bypass to house consumption header (BRU-SN) starts to open	MCP-4 trip and MSH pressure > 5.5 MPa
12.65	Turbine valve 4 closed	
12.70	Turbine valves 1 and 3 closed	
12.75	Turbine valve 2 closed	
39.95	Pressurizer heaters 1, 2, 3 and 4 off	Pressurizer level < 4.2 m
69.55	BRU-SN valves starts to close	MSH pressure < 5.297 MPa
500.0	Calculation ends	

5 Conclusions

Exercises 2 and 3 of VVER-1000 Coolant Transient Benchmark were calculated at VTT using HEXTRAN-SMABRE. The transient was a main steam break in Kozloduy NPP. In exercise 2 only pressure vessel was modeled using given boundary conditions for vessel inlet and outlet. In exercise 3 the whole plant was modeled. In both exercises a realistic and a pessimistic scenario were calculated.

The results are shown in Figures 4-31. Comparison to the results of other benchmark participants has not yet been performed by the benchmark organizers.

The temperature of loop 4 in scenario 2 remains higher in exercise 3 than in exercise 2. This leads to lower power raise after scram in exercise 3 and no recriticality while in exercise 2 positive reactivity is temporarily reached. The smaller drop in inlet temperature in loop 4 is possibly due to differences in steam generator modeling. The feed water boundary conditions given in the specification may not be applicable for the SG model in SMABRE. The very low amount of liquid in break flow is also due to the steam generator modeling and it could cause differences in results if other participants have larger liquid break flows.

In the future, exercise 3 could be recalculated using varying feed water boundary conditions to examine whether results more consistent with exercise 2 could be reached and to study the differences in steam generator modeling between SMABRE and CATHARE. More insight to the results will be achieved when the comparisons to other participants' results are published in the near future.

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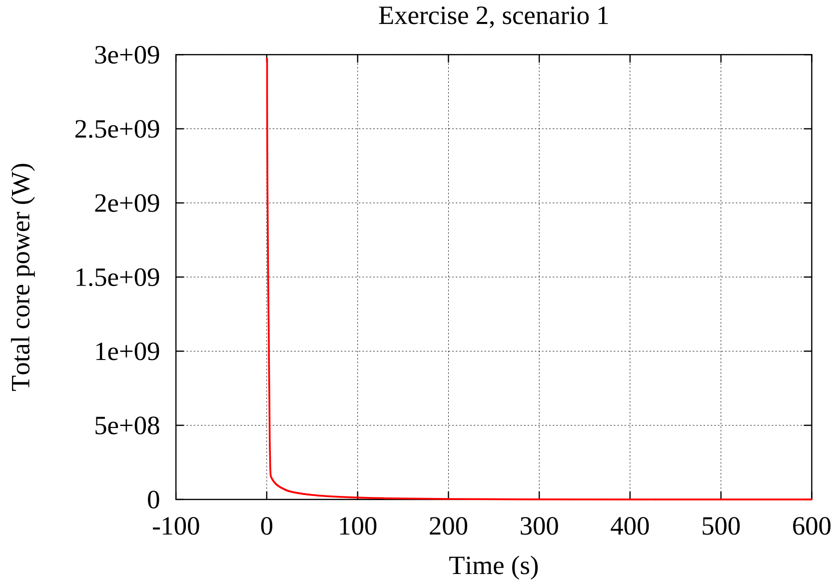

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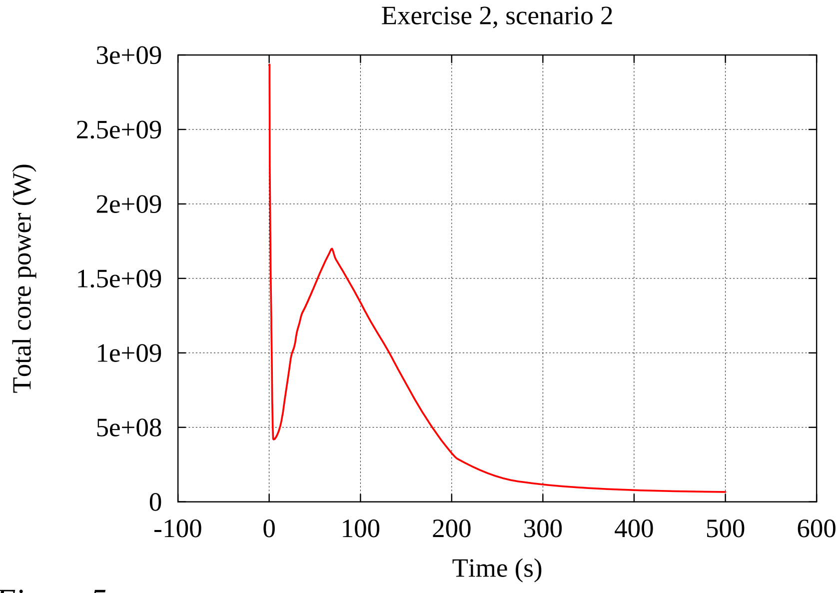

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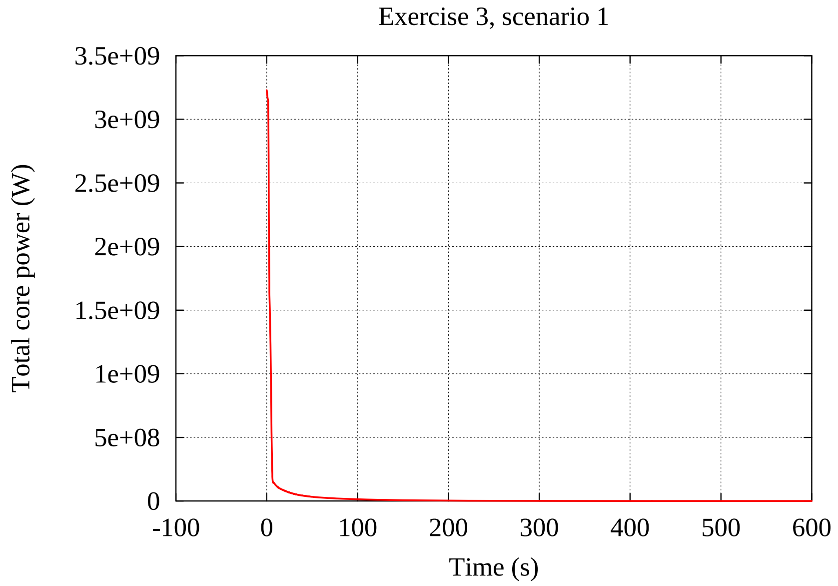

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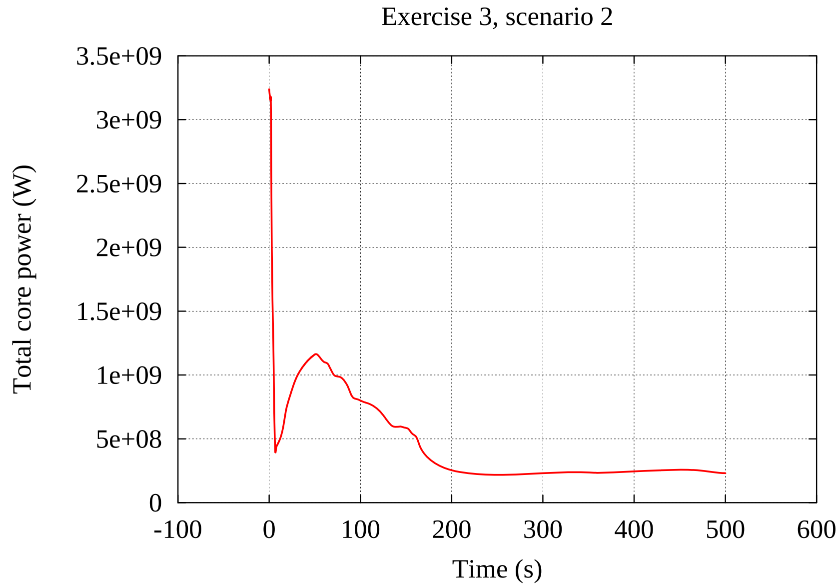

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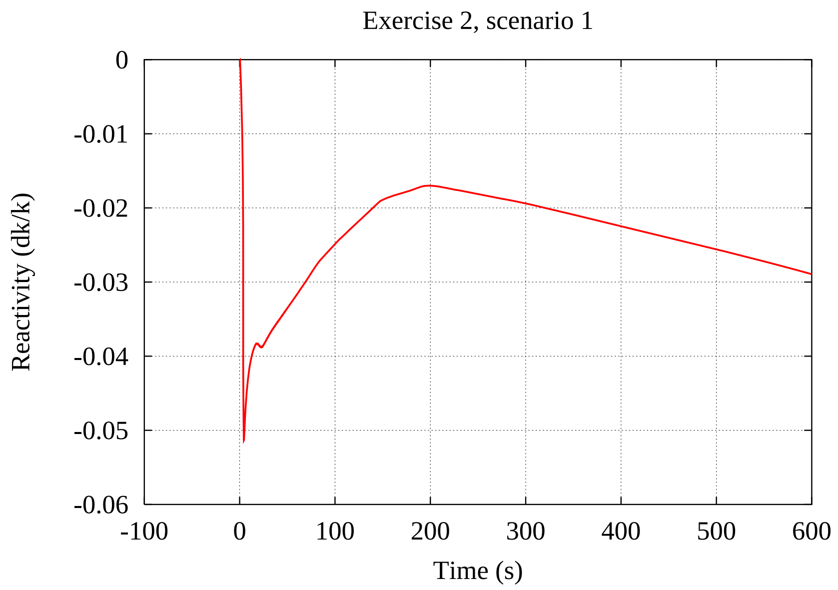

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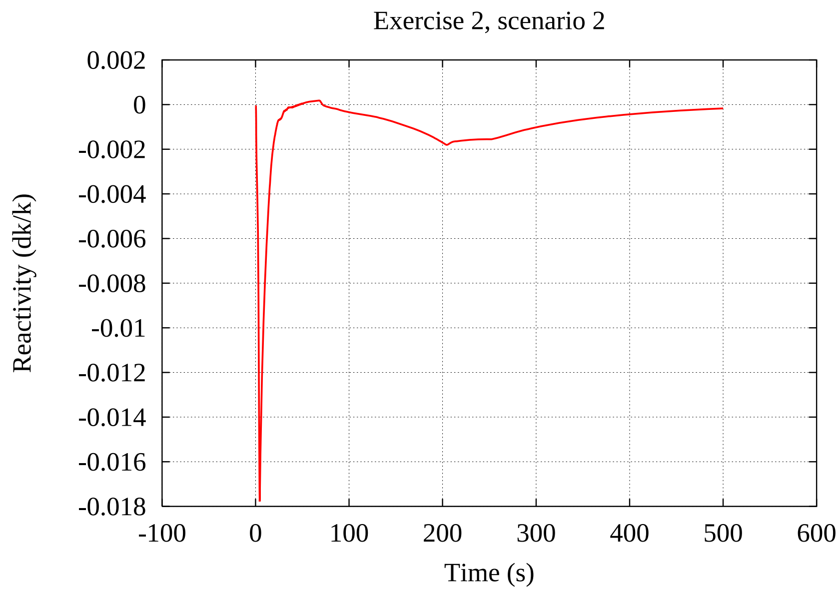

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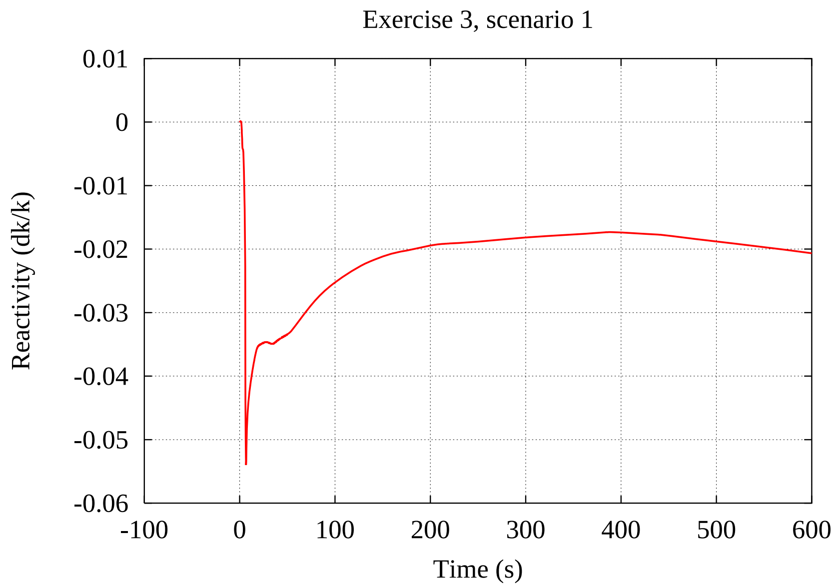
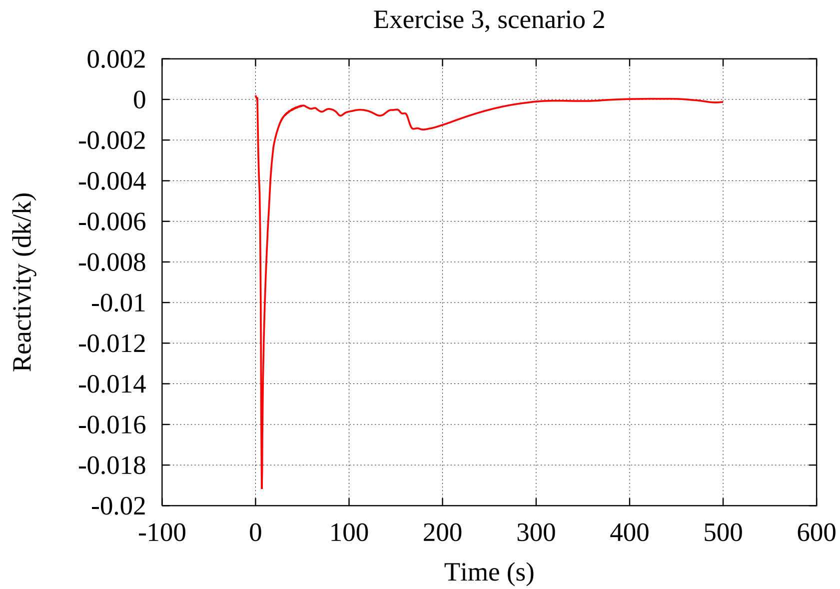


Figure 10.



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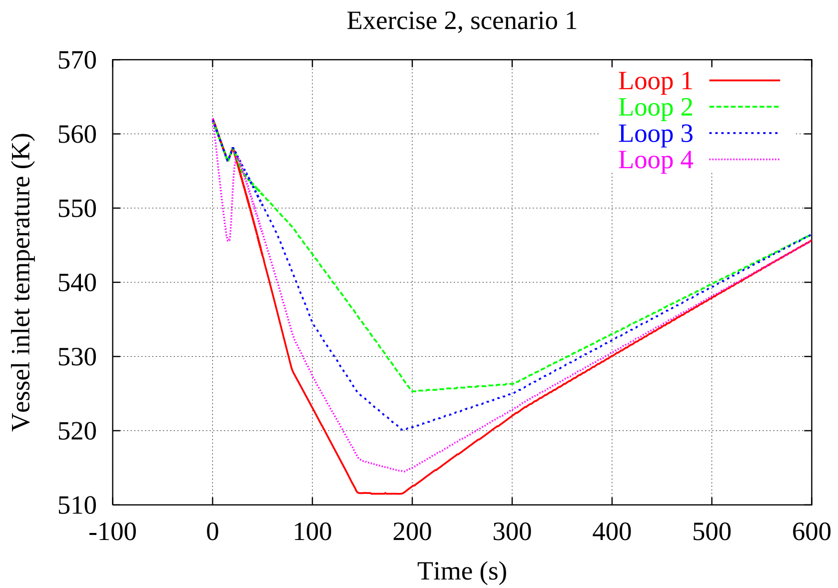

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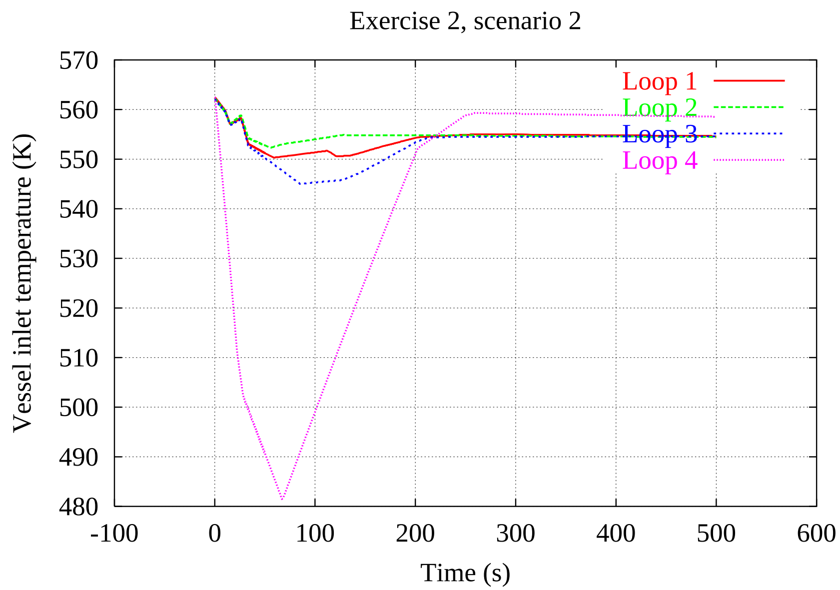

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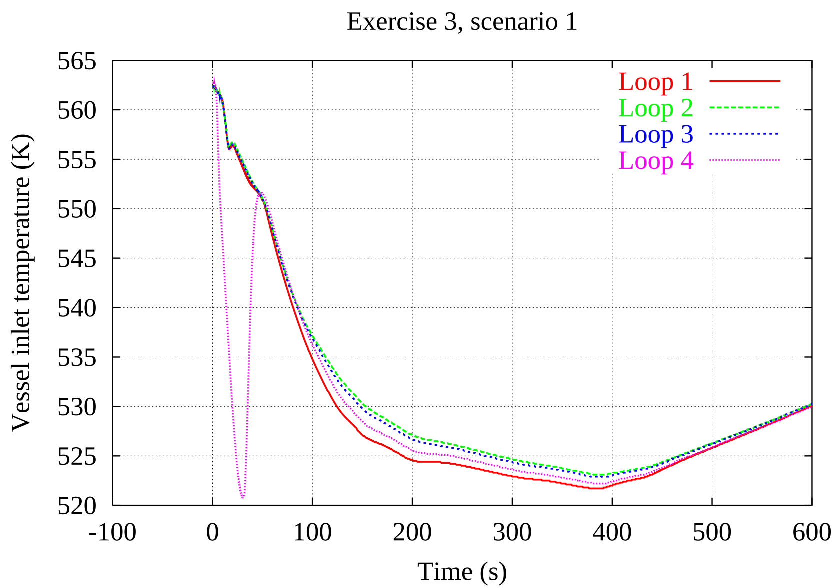

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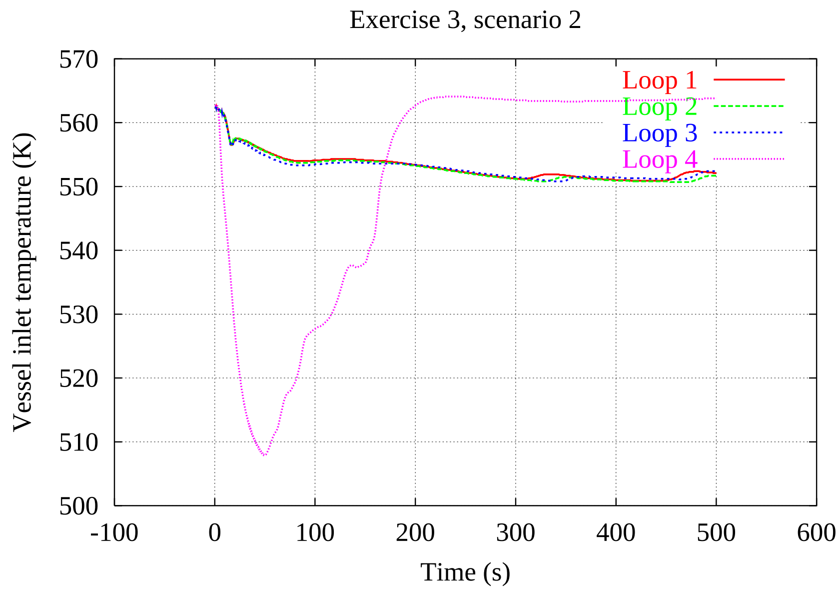

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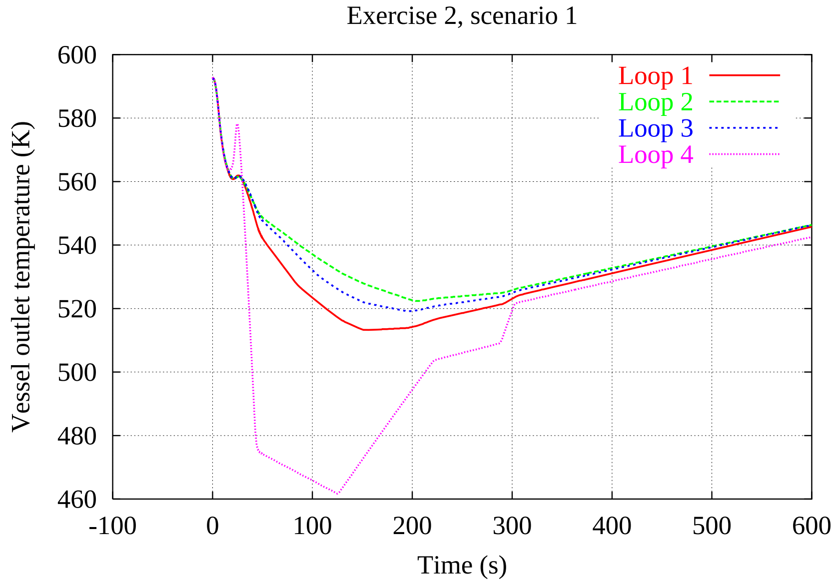

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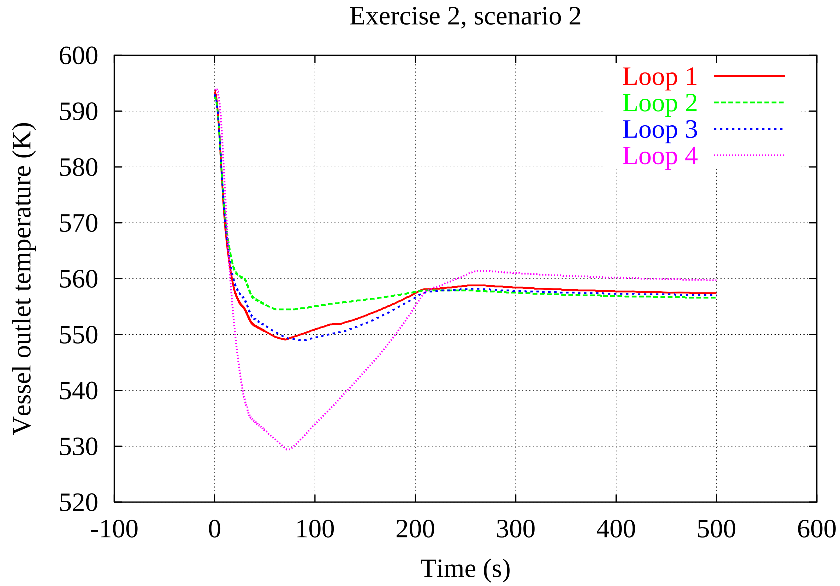

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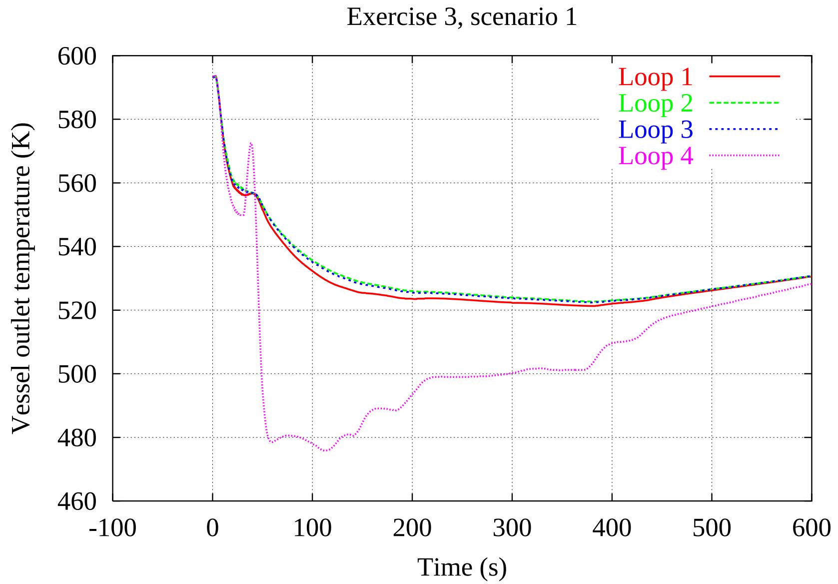

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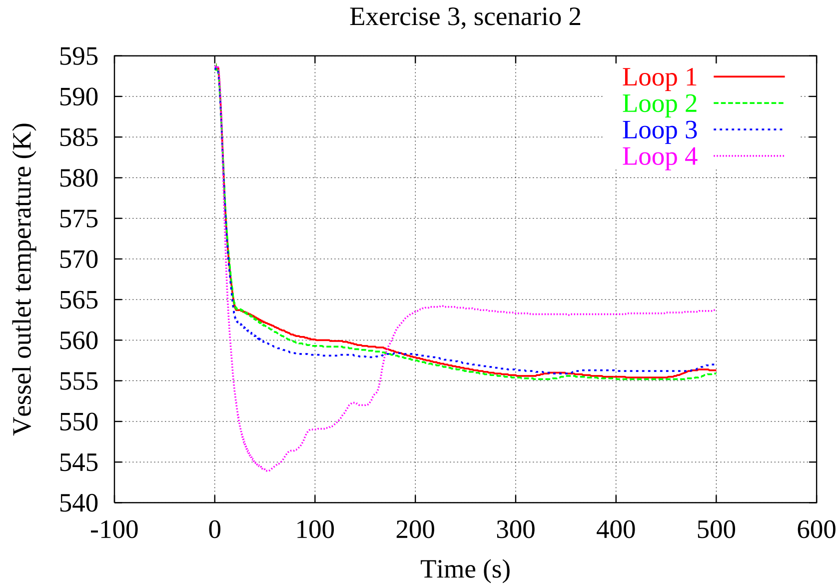

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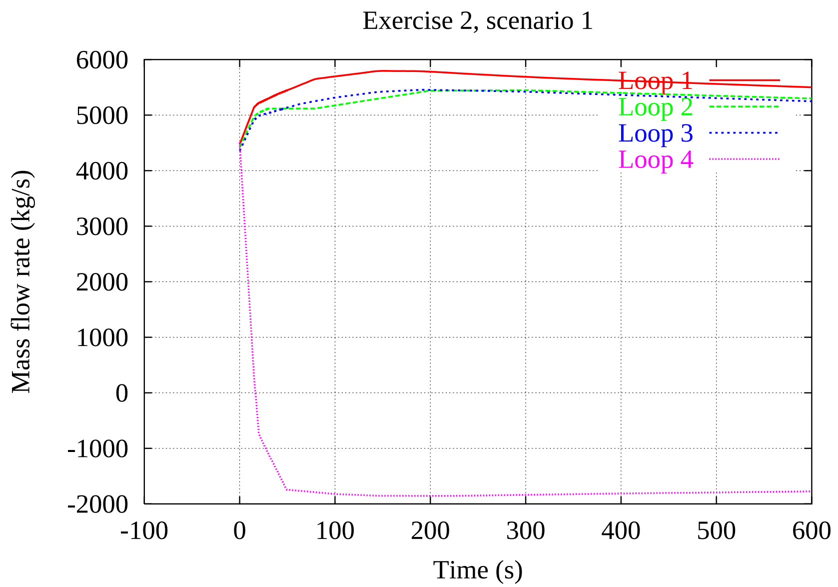

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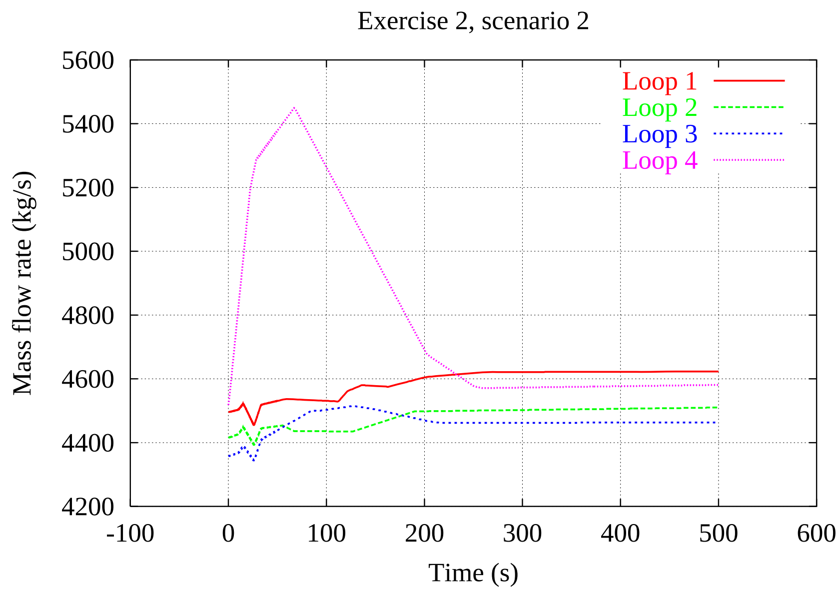

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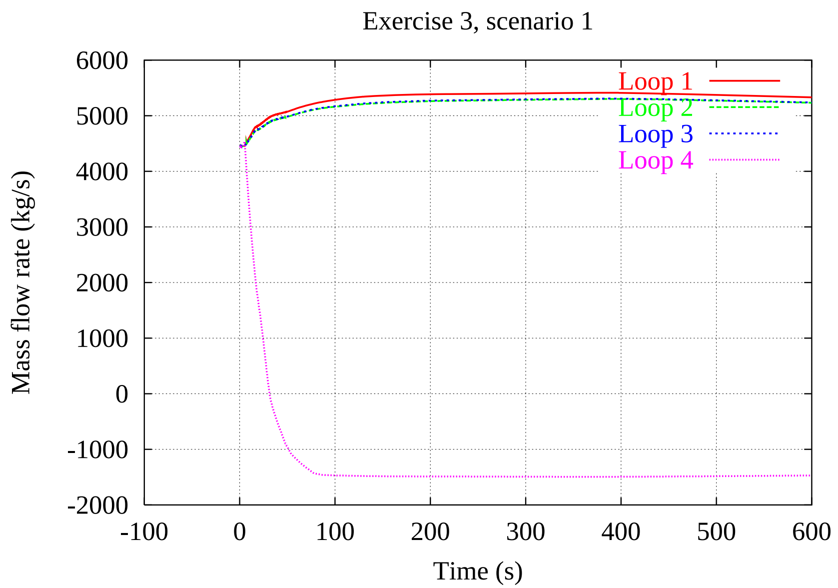

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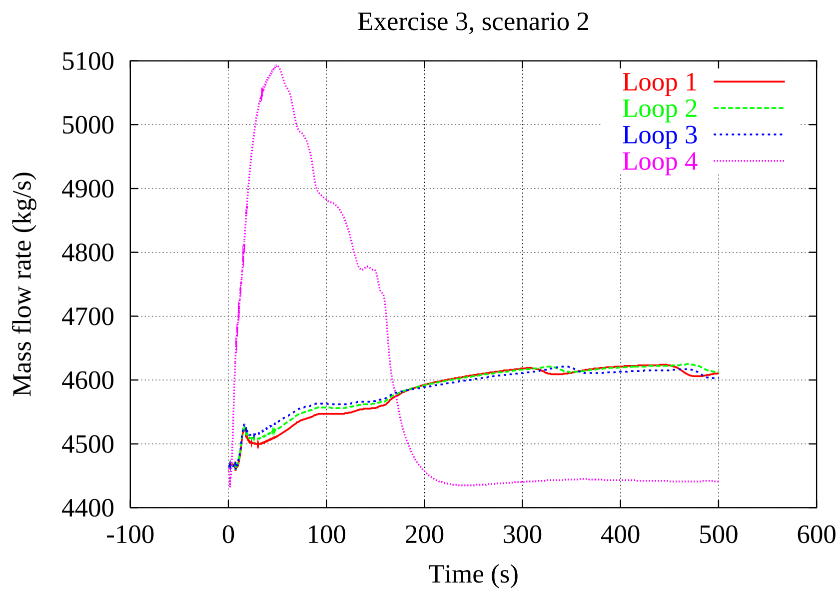

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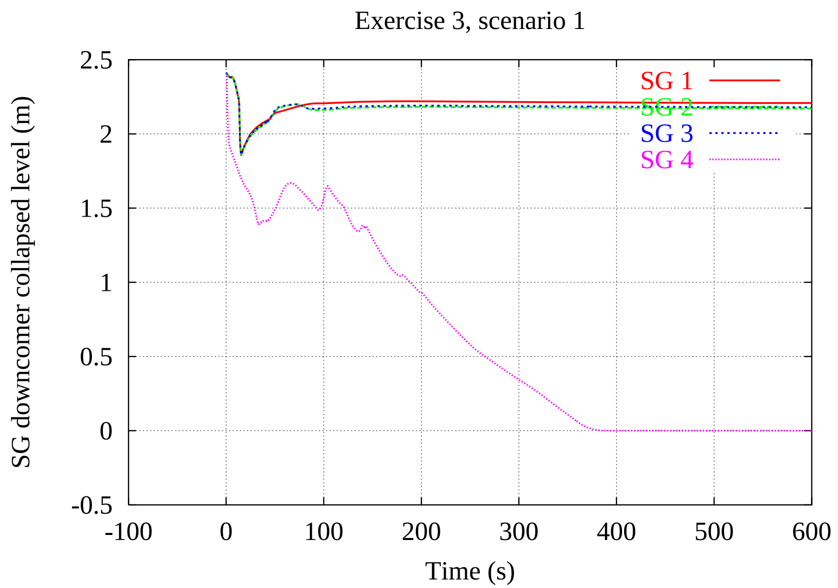

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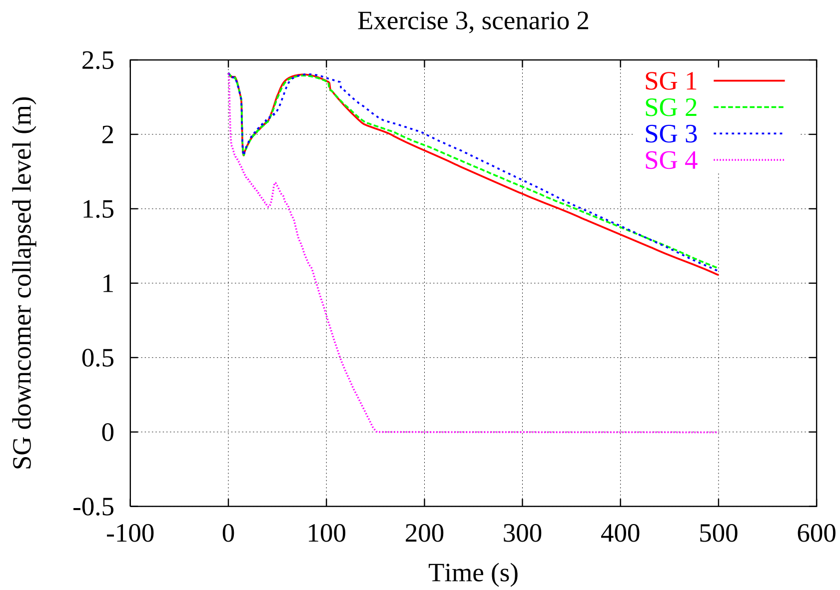

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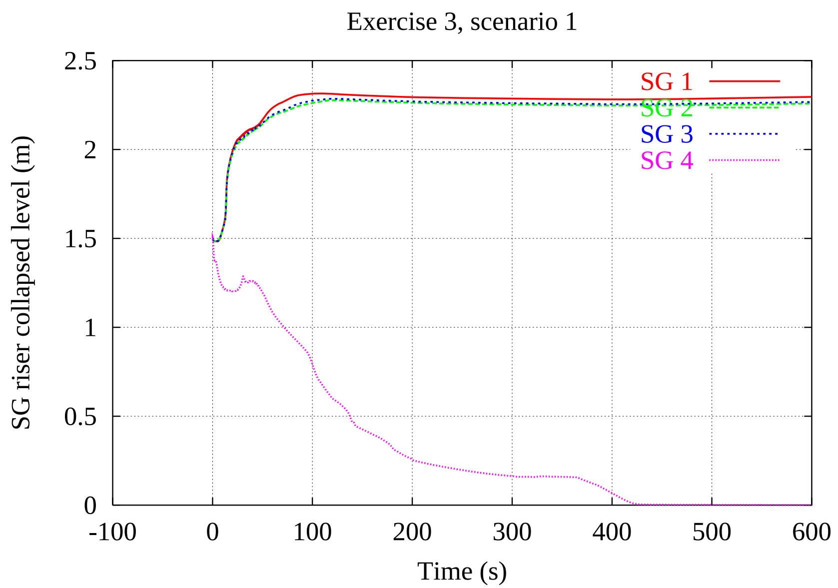

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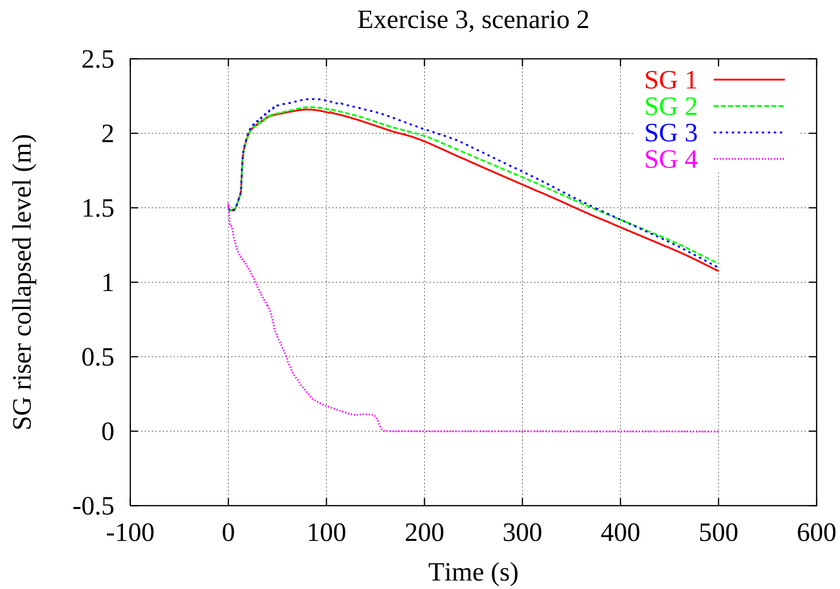

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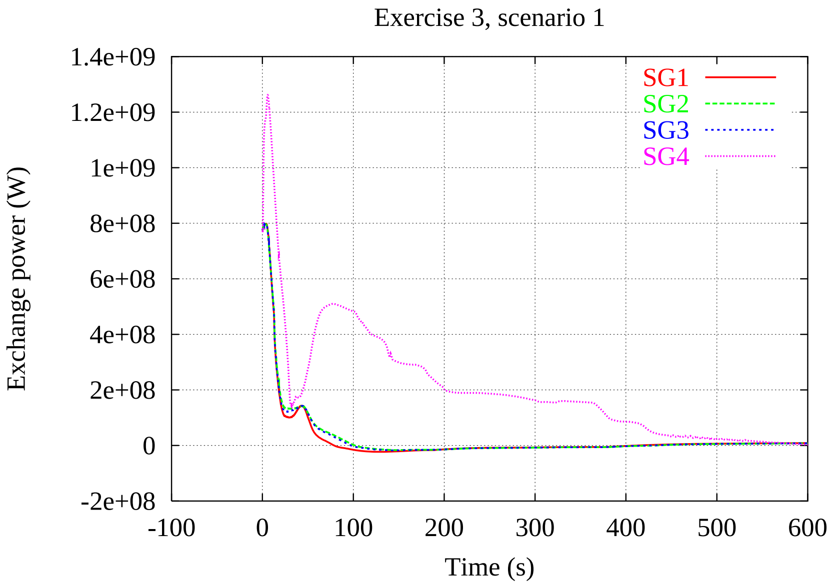

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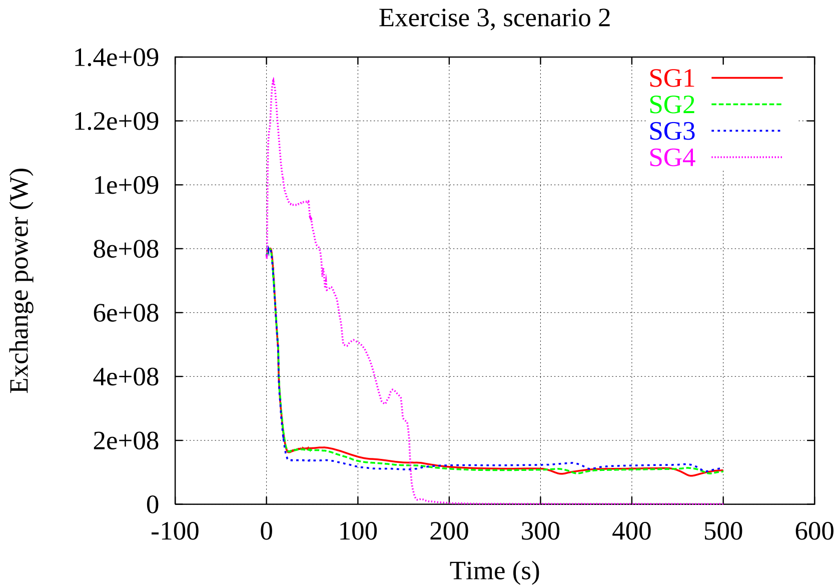

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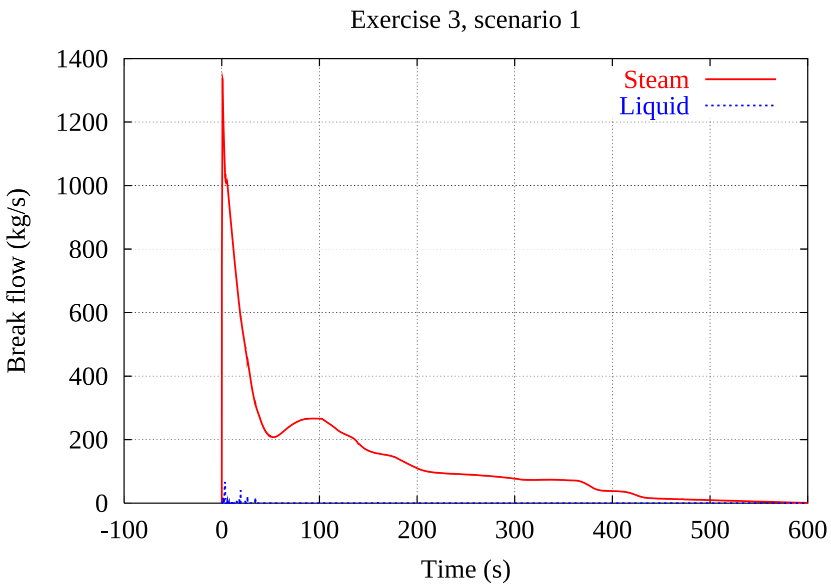

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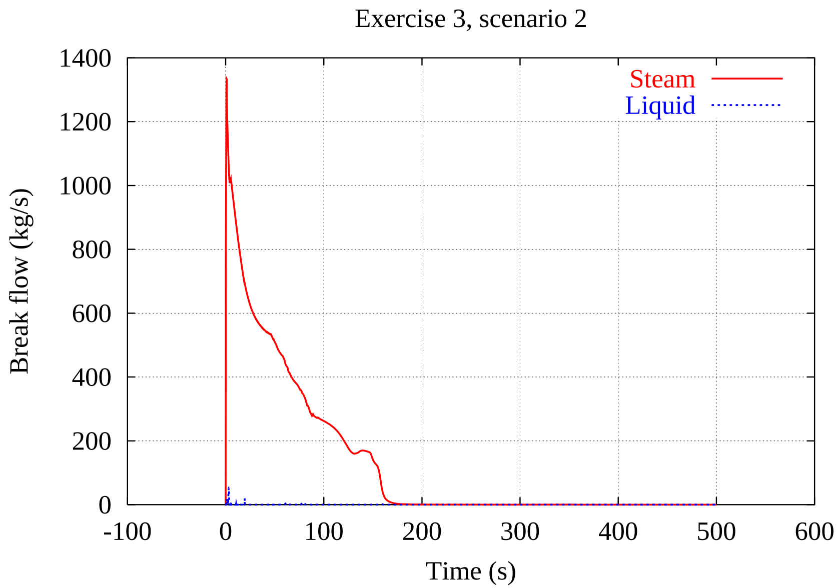

Figure 31.