NURETH14-366

TRACE/PARCS VALIDATION FOR BWR STABILITY BASED ON OECD/NEA OSKARSHAMN-2 BENCHMARK

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Abstract

On February 25, 1999, the Oskarshamn-2 NPP experienced a stability event, which culminated in diverging power oscillations with decay ratio greater than 1.3. The event was successfully modeled by TRACE/PARCS coupled code system and the details of the modeling and solution are described in the paper. The obtained results show excellent agreement with the plant data, capturing the entire behavior of the transient including onset of instability, growth of oscillation (decay ratio) and the oscillation frequency. The event allows coupled code validation for BWR with a real, challenging stability event, which challenges accuracy of neutron kinetics (NK), thermal-hydraulics (TH) and TH/NK coupling. The success of this work has demonstrated the ability of 3-D coupled code systems to capture the complex behavior of BWR stability events. The problem is released as an international OECD/NEA benchmark, and it is the first benchmark based on measured plant data for a stability event with a DR greater than one. Interested participants are invited to contact authors for more information.

Introduction

Assessment of coupled nuclear-thermal-hydraulic (CNTH) codes has been enhanced since mid-90s by a series of OECD/NEA coupled code benchmarks based on operating reactor data, including:

- OECD PWR Main Steam Line Break Benchmark (based on TMI-1 Nuclear Power Plant (NPP)) [1]
- OECD BWR Turbine Trip Benchmark (based on Peach Bottom 2 NPP) [2]
- OECD VVER1000 Coolant Transient Benchmark (based on Kozloduy 6 NPP) [3]

The previous OECD benchmarks for CNTH codes have confirmed the codes' capability to model and simulate postulated accidents (PAs) and anticipated operational occurrences (AOOs). The primary objective of the present benchmark is to establish confidence in extending code applications from its original intended use, PAs and AOOs, to more challenging events like unstable power oscillations without scram, when modeling non-linear effects becomes relevant.

The benchmark is based on the Oskarshamn-2 NPP and the transient measurements of the February 25, 1999 event. A loss of feedwater (FW) pre-heaters and control system logic failure resulted in a condition with a high feedwater flow and low feedwater temperature without reactor scram. In addition to the initiating event, an interaction of the automatic power and flow control system caused the plant to move into a low flow – high power regime. Combination of above events culminated in diverging power oscillations, which triggered automatic scram at high power. The power evolution for the event is shown in Figure 1.

The previous BWR stability benchmarks, such as the Peach Bottom 2 stability tests [4], OECD Ringhals 1 [5] and Forsmark [6] benchmarks are based on noise measurements of a stable reactor, where a Decay Ratio (DR) less than 1.0 was measured for all conditions and linear models could be used successfully. The present BWR stability benchmark would be the first benchmark based on measured plant data for a stability event with a DR greater than one, where nonlinear models are required.

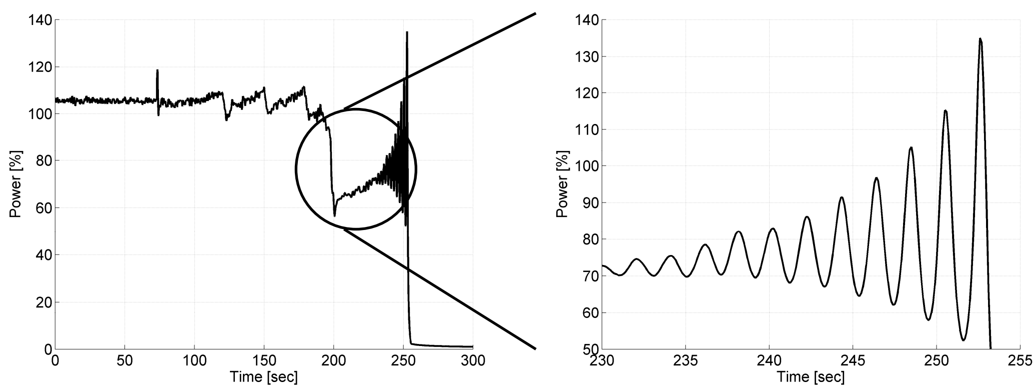

Figure 1 Oskarshamn-2 February 25, 1999 feedwater transient.

This problem is challenging to neutron kinetics (NK), thermal-hydraulics (TH) and TH/NK coupling, where high-fidelity coupled TH/NK is a must. The expected benefits of the benchmark are:

- The benchmark provides a framework for coupled code validation for BWR with both large amplitude nonlinear power oscillations and challenging plant transients, including subcooling changes and partial control rod insertions;

- The benchmark challenges accuracy of TH solution – numerical methods, model discretization, constitutive relations, flow regime maps;

- The benchmark challenges accuracy of NK solution – coolant temperature and density feedback, neutronic and kinetic data;

- The benchmark challenges accuracy of TH/NK coupling – tightly coupled transient, oscillatory conditions with feedback, fast multi-physics and strongly coupled problem.

The event was successfully modeled by TRACE/PARCS coupled code system [7]. The details of the modeling and solution are described in the present paper.

1. Plant description and TRACE/PARCS model description

Oskarshamn-2 is an external-loop type BWR reactor designed and built by ASEA Atom (currently Westinghouse). The reactor contains four external recirculation loops and the core consists of 444 bundles. The power was uprated in the early 1980's to 1800 MWth (from original 1700 MWth), with full power in 1999 denoted as 105.9%. The vessel geometry is shown on Figure 3.

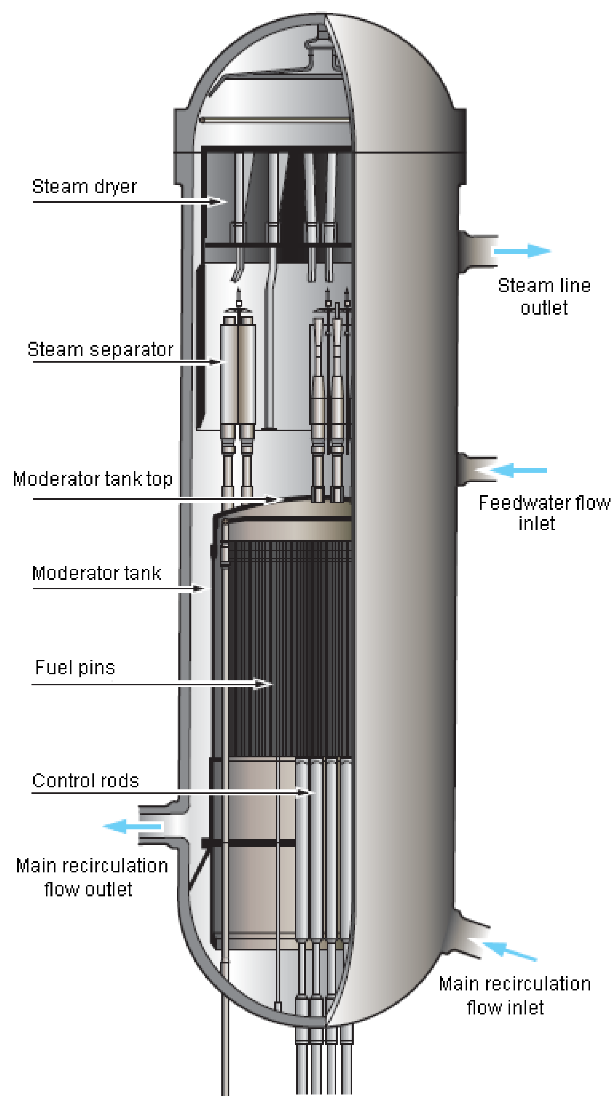

Figure 3 Oskarshamn-2 vessel, system drawing.

The TRACE/PARCS model has been prepared based on the plant documentation and existing plant models. It consists of explicit core, vessel, recirculation loop, separator, feedwater and steam line models. The balance-of-plant was modeled through controllers and boundary conditions. The TRACE nodalization diagram is shown on Figure 4.

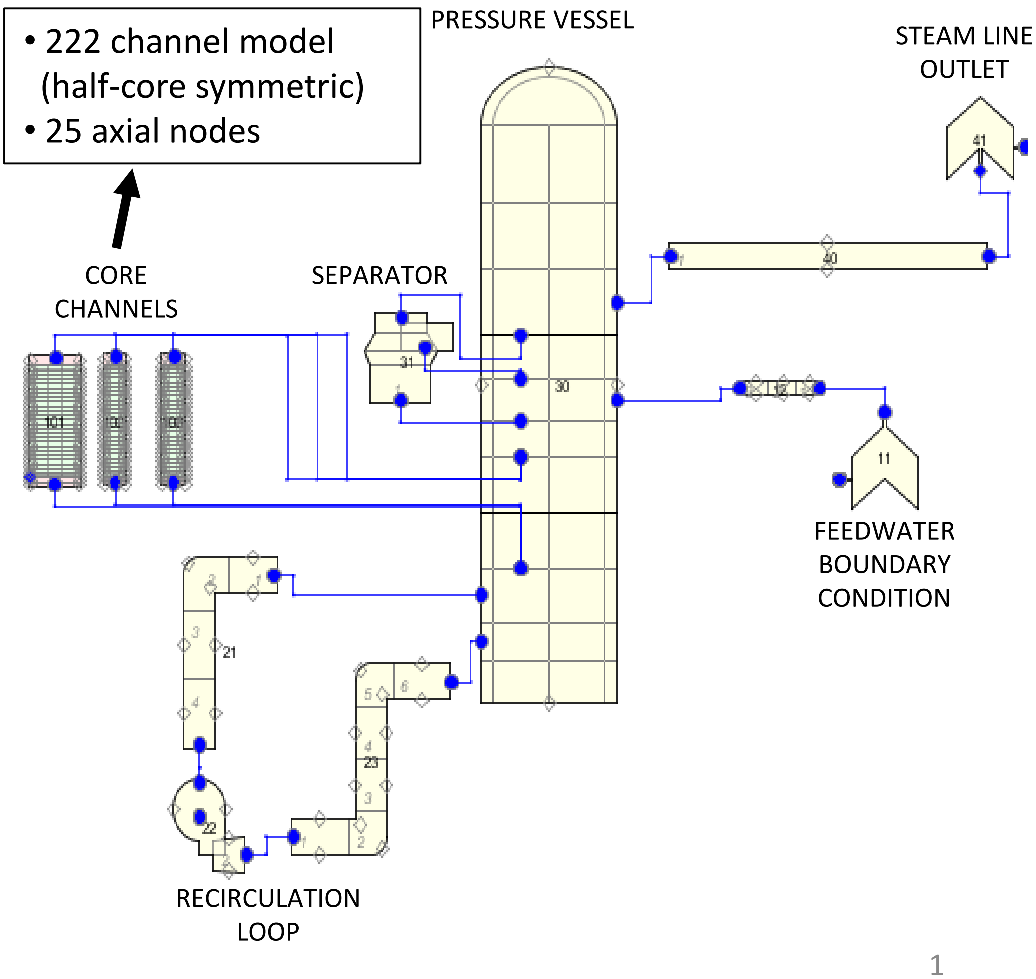

Figure 4 Oskarshamn-2 TRACE nodalization diagram.

The core has been modeled with 222 core channels, corresponding to half-core symmetry. Axially, the core channels have been divided into 25 axial nodes, with node size proportional to the maximum vapor velocity (larger nodes at top of the core) to stay as close as possible to the Courant limit in all cells. This minimizes numerical diffusion, which has a strong dampening effect on any oscillations predicted by the codes. The fine meshing at the bottom of the core also has the side benefit of a well-resolved boiling height, important for prediction of BWR stability. Semi-implicit numerical method (nosets=1) was used in TRACE.

PARCS was coupled with TRACE for neutronics calculations. Two-to-one mapping of PARCS neutronic nodes to TRACE thermal-hydraulics channels was used, exploiting core half-core symmetry. The plant provided cross-section libraries, and burnup and history distribution were converted to PMAXS format [8] used in PARCS. The core loading pattern used in PARCS is shown in Figure 5.

				RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE				
			RE	RE	SO	SP	SQ	SQ	SQ	SQ	SQ	SQ	SQ	SP	SQ	SQ	SP	SQ	RE	RE			
		RE	RE	SQ	SR	SR	SS	SS	SS	SQ	SP	SS	SS	SR	SS	SR	SS	SQ	SO	RE	RE		
	RE	RE	SP	SO	SS	QD	SS	QC	QC	SR	QC	QC	QC	QC	QC	SS	QC	SS	SP	SR	RE	RE	
RE	RE	SO	SO	QC	QC	SR	QD	QE	SS	QD	SR	QE	QD	SS	QE	SR	SS	QC	QC	SO	SP	RE	RE
RE	SQ	SS	QC	QC	SR	QE	QC	SR	QD	QC	QD	SS	SR	QD	SR	QD	QE	SP	QC	QC	SS	SQ	RE
RE	SQ	SS	QC	SQ	QE	QD	SO	SR	QC	QD	SR	QD	QD	SO	QC	SS	QD	QE	SR	QD	SQ	SO	RE
RE	SQ	SO	SS	QC	QD	SS	QE	QA	QA	QA	QC	QA	QA	SR	SR	QD	SR	QC	QD	QC	SO	SQ	RE
RE	SQ	SS	LT	QE	SR	QD	SS	QD	QA	QA	QA	QD	QD	SR	QD	SQ	QD	SQ	QE	QC	SO	SQ	RE
RE	SQ	SR	LT	SS	QD	QA	QD	SQ	SS	SS	QD	QA	QC	QC	QA	QA	QC	QC	SR	QC	SR	SQ	RE
RE	SQ	SR	SS	QC	SR	QD	SR	QD	QC	QD	QA	QC	QD	QB	QA	QA	QD	SR	QD	QC	SS	SP	RE
RE	SQ	SR	SR	QE	SS	QD	SR	QD	QB	QC	QA	QA	QA	QC	SR	SR	SR	QD	SR	QC	SR	SQ	RE
RE	SQ	SR	QC	SR	QD	SR	SR	SR	QC	QA	QA	QA	QC	QB	QD	SR	QD	SS	QE	SR	SR	SQ	RE
RE	SP	SS	QC	QD	SR	QD	QA	QA	QB	QD	QC	QA	QD	QC	QD	SR	QD	SR	QC	SS	SR	SQ	RE
RE	SQ	SR	QC	SR	QC	QC	QA	QA	QC	QC	QA	QD	SS	SS	SQ	QD	QA	QD	SS	LT	SR	SQ	RE
RE	SQ	SO	QC	QE	SQ	QD	SQ	QD	SR	QD	QD	QA	QA	QA	QD	SS	QD	SR	QE	LT	SS	SQ	RE
RE	SQ	SO	QC	QD	QC	SR	QD	SR	SR	QA	QA	QC	QA	QA	QA	QE	SS	QD	QC	SS	SO	SQ	RE
RE	SO	SQ	QD	SR	QE	QD	SS	QC	SO	QD	QD	SR	QD	QC	SR	SO	QD	QE	SQ	QC	SS	SQ	RE
RE	SQ	SS	QC	QC	SP	QE	QD	SR	QD	SR	SS	QD	QC	QD	SR	QC	QE	SR	QC	QC	SS	SQ	RE
RE	RE	SP	SO	QC	QC	SS	SR	QE	SS	QD	QE	SR	QD	SS	QE	QD	SR	QC	QC	SO	SO	RE	RE
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				RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE				

Figure 5 Oskarshamn-2 core loading pattern during 1999 cycle.
SO, SP, SQ, SR, SS, QA, QB, QC, QD, QE, LT – fuel assembly
RE – reflector

2. December 1998 stability tests calculation

The model has been validated with two stability measurements done in December 1998, approximately 3 months before the event. The results are shown in Table 1.

Table 1 TRACE/PARCS model validation with December 1998 stability measurements

	Power	Flow	Measured Decay Ratio[1]	TRACE/PARCS Decay Ratio
Point 1	84.5%	58.6%	0.53	0.44
Point 2	81.8%	54.8%	0.45	0.42

[1] The decay ratio was read from the on-line stability monitor, which used AR-models to calculate DR from the APRM signal. The DR value from the monitor fluctuates somewhat and at that time the operators read the maximum value obtained during the minutes they had stable power and flow conditions. The plant own simulations indicates that such measured values are higher than the expected (calculated) DR value. Unfortunately, at that time the plant did not collect APRM signal noise to do an offline evaluation of the DR.

TRACE/PARCS decay ratio was evaluated using Control Rod perturbation and calculating DR from the obtained power signal. The axial node sizes were proportional to the vapor velocity as described above; this increased the decay ratio by 0.10 versus the case of uniform nodalization, confirming that the axial nodalization is important for minimizing numerical diffusion. The agreement with the measurements was found to be satisfactory, and the modeling proceeded to the February 1999 transient.

3. February 1999 feedwater event description

On February 25, 1999 a maintenance work was performed on the switchyard outside of the Oskarshamn power plant unit 2. After finishing this task, the normal electric supply was restored, during which the power supply to a bus bar was unexpectedly interrupted for 150 milliseconds. The control logic for the main breaker connecting the unit to the main grid interpreted this as a load rejection. The load rejection signal was transmitted to the turbine and caused a turbine trip. However, due to a failure in relay circuit, the load reject signal was never transmitted to the reactor.

The output power level of the generator decreased by about 40 MWe, from 625 MWe to 585 MWe, steam lines bypass valves opened allowing the excess steam to main condenser, while maintaining the full reactor power. As the load rejection signal was never received by the reactor, the expected automatic control such as automatic insertion of a control rods and main recirculation pump trips never occurred.

Because of turbine trip and opening of the steam line bypass valves, the feedwater pre-heater system was no longer functional, and the feedwater temperature decreased by 75 ^{o}C over a period of 150 seconds. The feedwater temperature decrease caused the colder water to enter the reactor vessel and created a positive reactivity feedback, increasing the core power level.

A pump controller, controlling the rotation of the recirculation pumps, reduced the main recirculation flow when the reactor power increased more than 2% above the nominal power and thereby reducing the power. The controller was activated 45 seconds after the turbine trip when the power reached 108% (the nominal power level at the time of the event was 105.9%), reducing the pump speed at a rate of 640 rpm/min until the power level decreased below 108%. However, the cold water continued entering the vessel causing the power level to increase once more above 108% activating the pump controller. This sequence was repeated one more time (the third time).

Due to the nature of the event involving increase in reactor power and decrease in reactor flow, the operators partially scrammed the reactor by fully inserting 7 predefined control rods and reducing recirculation flow to minimum, at about two minutes after the initiation of the event. After the partial scram, the power was reduced to 65% and the flow was 3200 kg/sec. However, the flow of the cold feedwater continued, causing the reactor power to increase and enter the unstable region of the power/flow map. The reactor power started to oscillate with successively increasing amplitudes over a period of 20 seconds.

The reactor scrammed due to the high power at 3 minutes and 6 seconds after the initial load rejection event, when the power exceeded 132 % at 2500 kg/s recirculation flow. The scram proceeded according to the design, opening the generator breaker two seconds after the scram, disconnecting it from the main grid and moving the reactor into hot shut down state.

The most important thermal-hydraulic parameters (power, pressure, flow, temperature, level) measured during the transient are shown on Figure 2.

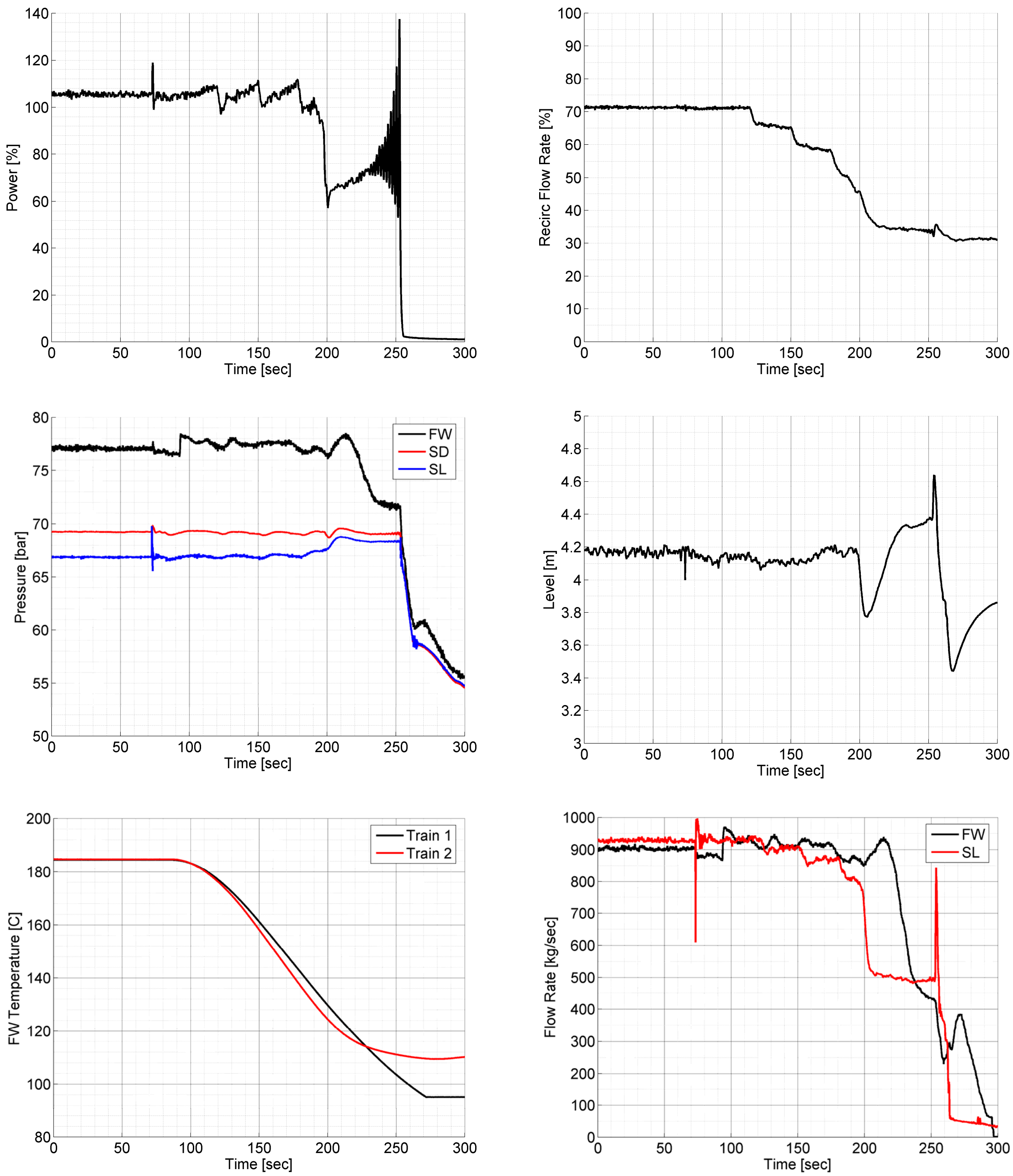

Figure 2 Oskarshamn-2 February 25, 1999 feedwater transient measurements.

4. February 1999 feedwater transient initial conditions

The complete initial and boundary conditions necessary for modeling of the February 1999 feedwater transient (stability event) have been made available by the plant. The initial steady-state conditions measured or calculated by the plant were compared with TRACE/PARCS in Table 2.

The comparison of the plant-calculated radial flow and radial power with TRACE/PARCS solution is shown on Figure 6.

Table 2 Comparison of initial conditions at the beginning of the transient.

	Oskarshamn-2 NPP	TRACE/PARCS
Reactor Power (MW)	1802^{m}	1802
Steam Dome Pressure (MPa)	7.0^{m}	7.0
Core Inlet Pressure (MPa)	7.166^{c}	7.1626
Core Outlet Pressure (MPa)	7.067^{c}	7.0611
Core Pressure Drop (kPa)	98.8^{c}	101.6
Channel Pressure Drop (kPa)	52.8^{c}	54.7
Orifice & Lwr plate dP (kPa)	46^{c}	46.8
Core Average Void	0.42^{c}	0.37
Core Average Fuel Temp (K)	816.67^{c}	823.44
Feedwater Temperature (K)		457.58
Core Inlet Temperature (K)	548.05^{c}	543.93
Pump Speed (rad/s)		101.81
Total Core Flow Rate (kg/s)	5515.9^{m}	5515.9
Active Core Flow Rate (kg/s)	4793.5^{c}	4803.2
Steam Flow Rate (kg/s)	976^{m}	904.5
Downcomer Water Level (m)		8.402
K-eff	1.0026^{c}	0.9973

m – measured
c – plant calculation

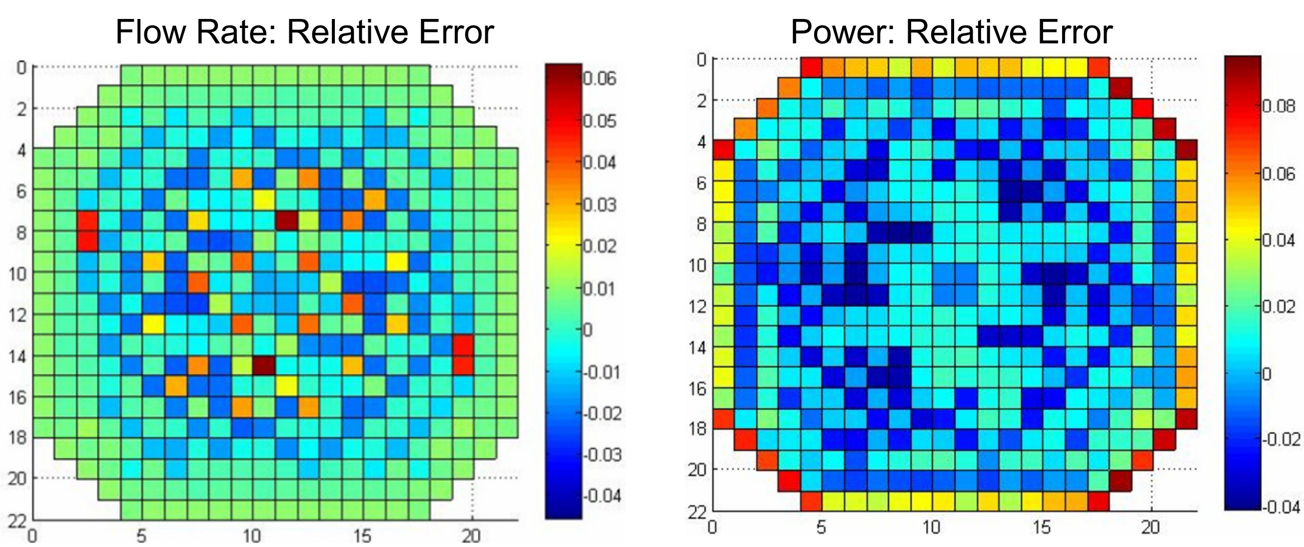

Figure 6 Relative error comparison for the channel flow rate (left) and the assembly power (right).

Comparison of the initial steady-state conditions was in excellent agreement with the measured or plant-calculated results, therefore the transient modelling was attempted.

5. February 1999 feedwater transient results

Once the model has been validated with the December 1998 stability measurements and February 1999 event initial conditions, exactly the same model has been used for the February 1999 transient, changing only the relevant transient boundary conditions.

The measured transient feedwater flow, feedwater temperature, pump speed and steam line pressure time histories (see Figure 2) have been used as boundary conditions for the simulation of the February 25, 1999 event.

The solution obtained with the provided boundary conditions is shown on Figure 8, marked as “original” (blue line). The solution clearly deviates from the measured power already after the first pump runback at around 120 sec, and continues to under-predict the power by about 10% through the transient, missing the oscillation growth. Since the deviation occurs early in the transient, this indicated model or code deficiency related to pump runback or FW transient, not to the stability itself.

The deviation could be explained only by miss-prediction of recirculation flow, core inlet temperature or the neutronic feedback. Knowing that the recirculation flow is easily measured, even in transient conditions, and assuming neutronic feedback is accurately modeled with modern nodal methods and high-quality cross-sections (as confirmed by the obtained steady-state results at different power/flow and burnup conditions), the remaining suspect is the core inlet temperature.

Deeper investigation of this issue revealed the limitation of the time-dependent feedwater temperature measurement. The FW temperature was measured by the Resistance Temperature Detectors (RTD), which are mounted on wells that go inside the FW flow (the RTDs do not penetrate the pipe, they cannot be part of the pressure boundary). The RTDs are very accurate, but in such configuration the signal is first filtered by a slab of steel before being measured. The reactor operator is mainly interested in the steady-state temperature, so it is not a problem for normal operation if the sensor has some delay.

However, for this type of event accurate FW temperature is necessary. Using the inverse conduction problem, i.e. with known RTD-measured temperature on the outside of the FW well and assuming 0.5” pipe thickness, the real FW temperature can be calculated. The original (measured) and the corrected FW temperature calculated by the inverse conduction problem through 0.5” of steel is show on Figure 7. As it can be seen, the FW temperature decreases faster and to a lower level than indicated by the plant measurement.

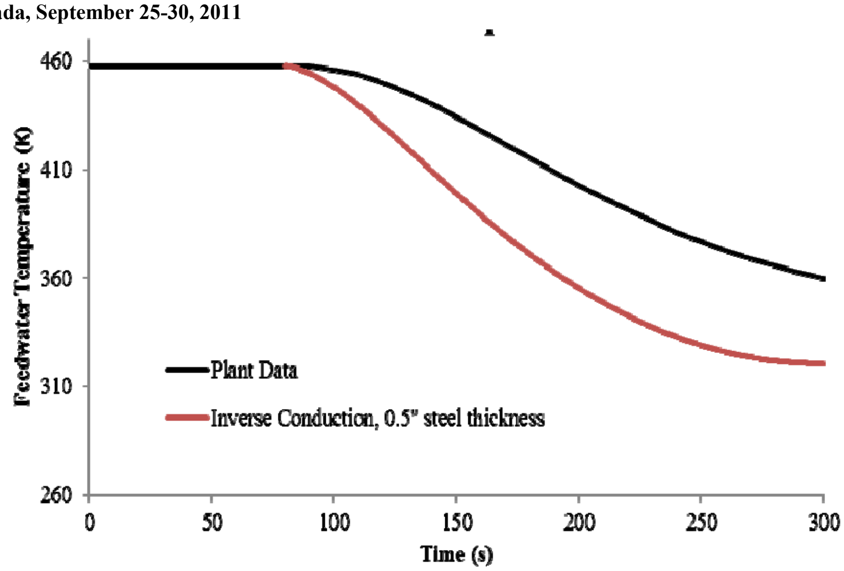

Figure 7 Original and corrected transient FW temperature.

Using the corrected FW temperature, the TRACE/PARCS calculated power is shown on Figure 8, marked as the "inverse conduction" (red line). As it can be observed, the TRACE/PARCS solution is in excellent agreement with the plant data. The FW temperature correction is confirmed by the fact that the power behavior during the 2nd and 3rd pump runbacks at around 150 and 180 seconds is now correctly captured.

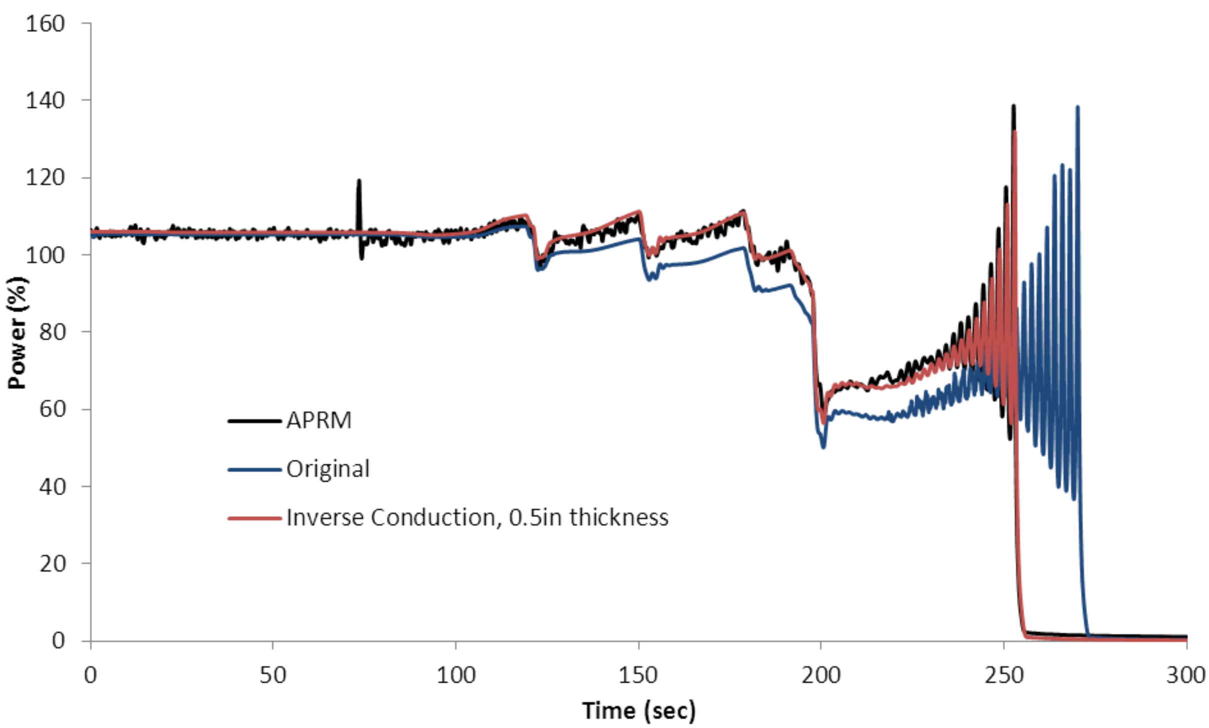

Figure 8 Oskarshamn-2 February 25, 1999 feedwater transient, TRACE/PARCS solution.

With only one corrected parameter (FW temperature), the final TRACE/PARCS solution completely captures the entire behavior of the transient, including power behavior during pump runback, partial scram, onset of instability, growth of oscillation (decay ratio), the oscillation frequency and the scram.

6. Conclusions

A TRACE/PARCS model has been developed for the Oskarshamn-2 reactor and validated with the December 1998 stability tests and February 1999 steady-state conditions. Calculated decay ratios for the December 1998 stability tests match reasonably well with the measured data, and the February 1999 steady-state conditions are in a very good agreement with the measured or plant-calculated data.

The initial attempt to model the event exposed limitation of RTD well instrumentation to measure and capture dynamic effects. With the correct boundary conditions, the obtained results for the February 1999 event show excellent agreement with the plant data, capturing the entire behavior of the transient including onset of instability, growth of oscillation (decay ratio) and the oscillation frequency. The success of this work has demonstrated the ability of 3-D coupled code systems to capture the complex behavior of BWR stability events.

Oskarshamn-2 1999 stability event allows coupled code validation for BWR with a real, challenging stability event, which challenges accuracy of TH solution, NK solution and TH/NK coupling. The problem is released as an international OECD/NEA benchmark and interested participants are invited to contact authors for more information.

7. References

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