ASSESSMENT OF A TRACE/PARCS BENCHMARK AGAINST LEIBSTADT PLANT DATA DURING THE TURBINE TRIP TEST

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ABSTRACT

The Leibstadt Nuclear Power Plant (KKL) participates in the Code Applications and Maintenance Program (CAMP) of the U.S. Nuclear Regulatory Commission (U.S.NRC) to validate the TRACE code for BWR/6 transient analysis. The application of TRACE for the safety assessment of BWRs requires verification and validation using not only experimental data from separate effects and integral tests but also plant data. The purpose of this paper is to review the KKL TRACE/PARCS model and benchmark it against plant data recorded during a turbine trip (TT) test. Turbine trip transients in a BWR are pressurization events, in which the coupling between core-space dependent neutronic phenomena and system dynamics play an important role.

A TRACE/PARCS model has been developed at KKL. The first benchmark against a TT test aimed to test the code capabilities in reproducing the main physical behavior of the plant. This analysis showed potential for additional improvements and highlighted modeling issues that required further investigation. Besides, a qualitative comparison between TRACE/PARCS and the test data was not possible due to the generic core design which was different from the TT core design.

The improvements introduced to the TRACE model, such as modifications of the geometry and the control system are presented in this work, as well as the PARCS model, updated with the specific core loading of the TT test. Additionally, for the steady-state calculations to convergence, the constrained steady-state (CSS) option in TRACE was used, combined with an automated control system to regulate the turbine control valve opening and the feedwater flow rate.

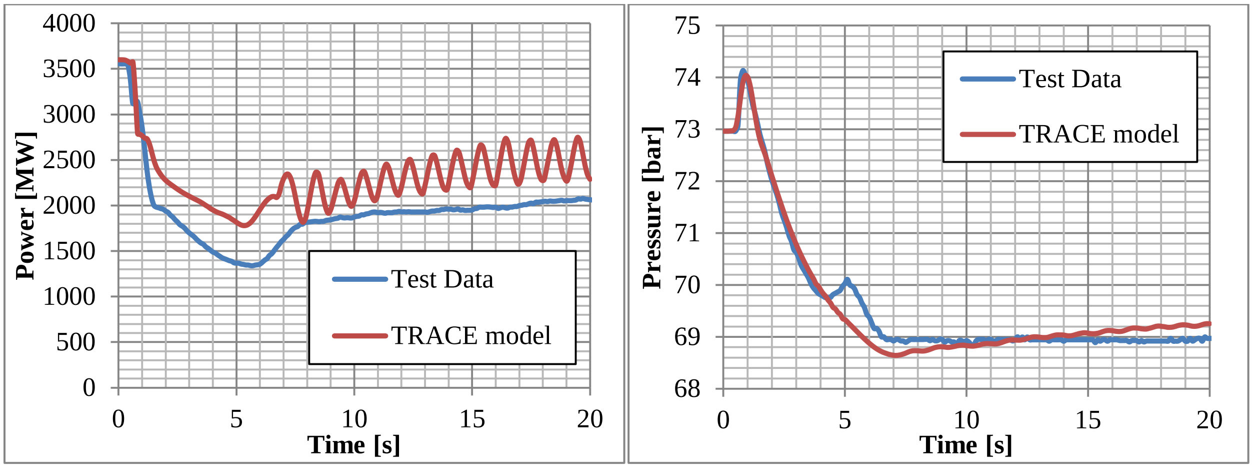
These developments on the TRACE/PARCS model improved the stability steady-state values, and thus, the initial conditions prior to the test. The results obtained during the transient showed excellent agreement with the plant data, capturing the entire behavior of the transient including the magnitudes.

Key Words: TRACE/PARCS, Benchmark, Transient, Code Coupling

1 INTRODUCTION

System codes are widely used nowadays in the nuclear industry to evaluate complex scenarios related to plant safety, for which the analysis of transients is profound. Hence, a system code such as TRACE/PARCS is needed to reproduce the plant behavior and investigate design basis accidents. The Leibstadt Nuclear Power Plant (KKL) and the nuclear energy division of Axpo (Axpo Kernenergie), both members of the U.S.NRC Code Applications and Maintenance Program (CAMP), received access to the TRACE/PARCS code. Therefore, KKL shares its experience on TRACE applications for BWR/6 power plants and benchmarks the code capabilities to predict the plant's physical behavior. One challenging application for TRACE is the benchmark of the model against the turbine trip (TT) test, performed at KKL as part of the plant test programs. In this TT, several safety and control systems are involved, including a power reduction using the selected rod insertion (SRI). In this benchmark, the coupling of TRACE and PARCS was required and the interactions between the two codes were tested.

The thermal-hydraulic (TH) code TRACE was used together with the neutron kinetics (NK) code PARCS to simulate the plant transient behavior. The KKL model is under a verification and validation process. Several applications were modeled using TRACE [1] in order to validate the model against different plant data. For instance, in the previous TRACE benchmark against the plant TT, the aim was to set up the model, including the control systems and the sequence of event. The interaction between TRACE and PARCS was also tested. The outcome of this application was presented in [2]. In Figure 1, the comparison between the TRACE and the TT test data is illustrated for the total core power (a) and the reactor dome pressure (b). It is noticeable that the TRACE calculation predicted power oscillations in the region after 7 seconds. These oscillations are induced due to numerical instabilities and the BWR instability region. The transient underestimated the core flow and settled the core in the KKL instability region. Furthermore, the steady-state calculation preceding the transient did not successfully converge and may have introduced instabilities in the transient. The discrepancies shown in the results of the TRACE simulation compared to the TT data were studied thoroughly.



a) Total Reactor Power **b) Dome Pressure**

Figure 1: Total Reactor Power and Dome Pressure [2]

The TT test is a moderate pressure increase transient. The turbine control valve is closed and the bypass is opened with a delay time, which results into a pressure rise. The power is reduced by a SRI. The power peaks due to the propagating pressure wave from the steam lines into the core, collapsing the void. By analyzing the main sequence of event of the transient, the main source of the differences in the TT test data and the results of the TRACE simulation can be summarized as follows:

a) The pressure drop through the core was too small in TRACE and made the model very sensitive to pressure changes. The pressure wave travels faster through the core than in the real plant. The TRACE model also caused instabilities in the reactor power because of the underestimated core flow.

b) The dome pressure is driven by the bypass valve opening/closing. The build-in control system does not work properly, and therefore, the closing and opening is not estimated well by TRACE. Besides, there is no data available for the steam flow through the bypass valve, only the valve position is recorded. A review of the valve modeling shall improve the dome pressure predicted by TRACE.

However, TRACE was successfully coupled with PARCS and the coupled model was able to reproduce the general behavior of the TT data. The differences seen in the results of the TRACE simulation have been investigated further and documented in the present paper.

2 PLANT AND TRACE MODEL DESCRIPTION

KKL is a GE design BWR/6 with Mark III containment. The recirculation flow through the core is provided by two external recirculation pumps, connected through 20 internal jet pumps. The initial thermal reactor power was 3012 MW_{th}, which went into several uprates to reach the actual thermal power of 3600 MW_{th}. The reactor core contains 648 fuel elements and 146 control rods.

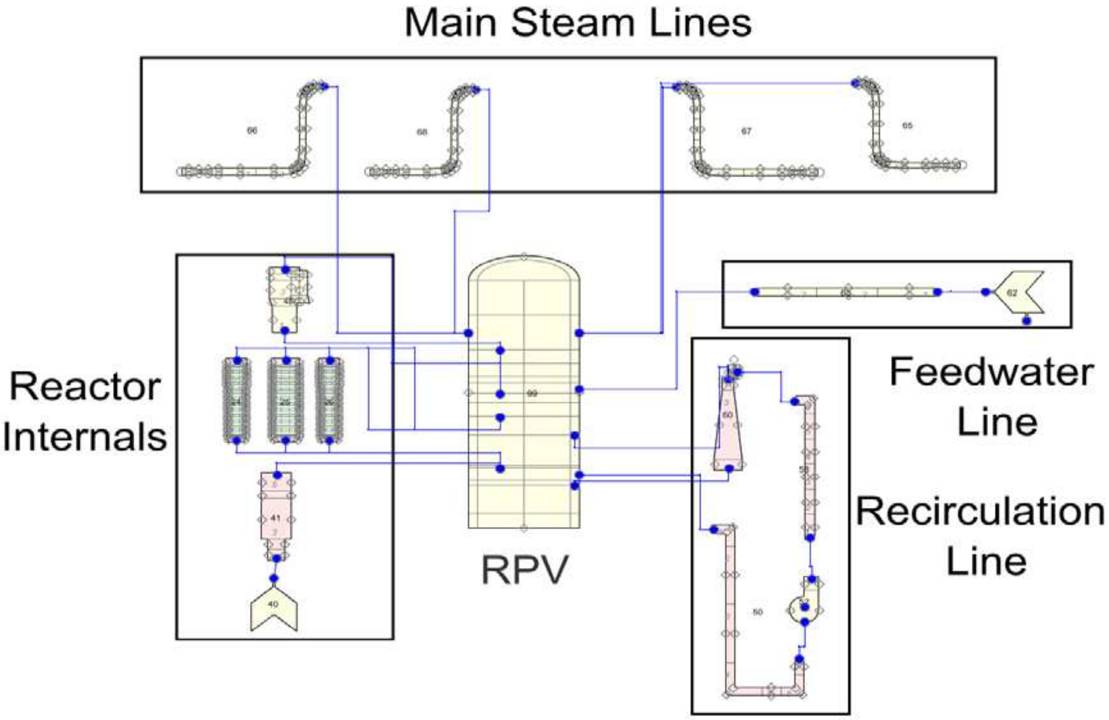


Figure 2: Scheme of the new reactor geometry with four MSL in SNAP

Figure 2 depicts the whole system model in the Symbolic Nuclear Analysis Package (SNAP) [3]. The final TRACE model for KKL includes the following components:

1. A 3-D reactor pressure vessel
2. The reactor internals, including steam separators/dryers and guide tubes

3. The core region, simulated with three channels
4. The feedwater line
5. Two recirculation loops, including jet pumps, recirculation pumps, flow control valves (FCV) and suction pipes
6. Four main steam lines (MSL), namely the main steam isolation valves (MSIV), the safety relief valves (SRV), the manifold and turbine control valves (TCV), the bypass valves (BPV) and the turbine inlet
7. Emergency core cooling system (ECCS), including the high pressure core spray (HPCS) and the reactor core isolation cooling (RCIC)
8. Reactor level measurement instrument
9. Control system (trips, logics, etc.)

In order to improve the TRACE model, an in-depth review of the existing input model was performed. This review can be mainly characterized in three different categories: the geometrical data, the control system and the hydraulics parameters, e.g. the friction terms. Also, further controls were implemented in the new model, which enhanced the robustness of the steady-state conditions. The model has been prepared, based on the plant documentation and existing plant models. The version of the code was TRACE V5.0p3 and PARCSv3.6. The SETS numerical method was used in TRACE. It is worth noting, that SNAP was used for creating graphics only; the actual model was set up in a text editor using the relevant TRACE manuals [4, 5].

2.1 Geometrical Data

The free volume in the RPV was reviewed using KKL drawings and plant documentation. The comparison between the free volume of the old and new model and the reference plant data is illustrated in Figure 3. In the mixing plenum region between 9.5583 m and 11.538 m, the deviation decreased significantly.

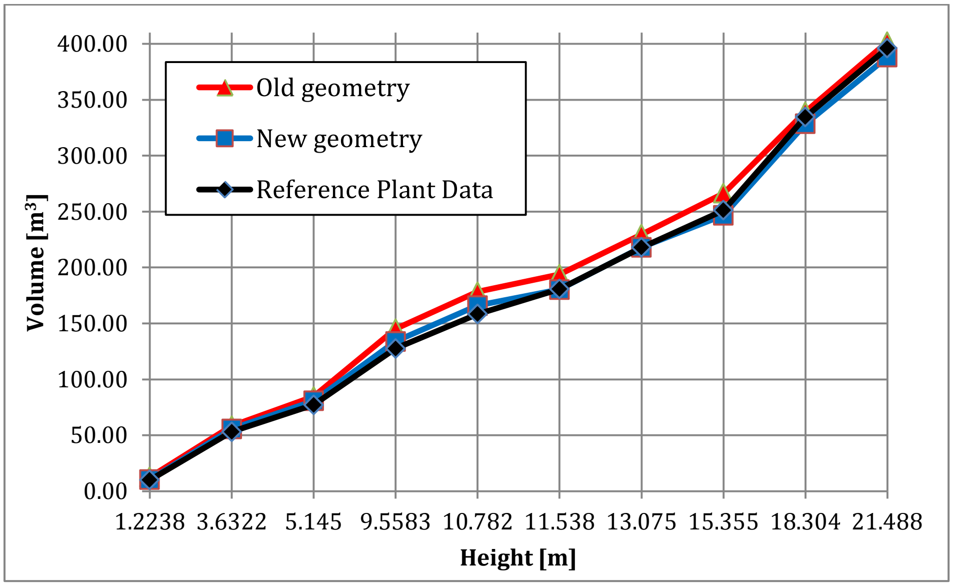


Figure 3: Comparison of the different model geometries in terms of free volume inside the RPV without internals

Furthermore, it has been seen, that the pressure drop and pressure distribution are important to determine the pressure propagation through the steam line, the RPV and eventually the core. For a better prediction of the TT test data during steady-state calculations and transient simulations, it was essential to remodel the appropriate components, i.e. the vessel, the steam separators and the core channels to obtain similar pressure values alongside the RPV as the plant data. The core has been modeled with three lumped channel components and in a second identical model with the full set of 648 channels. The core channels have been divided axially into 25 axial nodes.

In terms of steam lines, the old KKL TRACE model contained two lumped lines instead of four separate ones. This approximation was adopted in the early stage of the model to save computation time. For the proposed TT benchmark, the turbine control valves needed the ability to act independently. A delay time between the four valves was observed, which directly influences the pressure evolvement in the steam dome. For the fast transient analysis, this pressure also defined the power excursion. Thus, some focus had also to be set on the correct design of the pressure drop in the steam and bypass lines.

2.2 Control Systems

The plant balance was achieved using two main control systems, designed in the TRACE model in order to reach steady-state conditions. There is, on the one hand, the feedwater controller to keep the water in the downcomer on a specific level. The downcomer level is calculated with the hydrostatic pressure equation (1), using the parameters illustrated in Figure 4 as input. With the known downcomer level, the built-in level controller (ICBN = 202, [5]) could be used. The controller reads in the estimated downcomer level, the feedwater flow, the main steam flow, the desired level and the nominal feedwater flow rate. The output is the new feedwater flow rate which serves as an input for the feedwater fill component.

$$\Delta p = \rho_g(h_2 - h_l) + \rho_l(h_l - h_1) \tag{1}$$

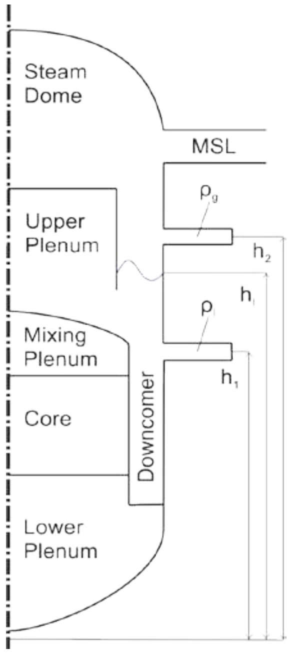


Figure 4: Determination of the Water Level

On the other hand, the pressure controller is a key parameter to achieve stable steady-state conditions. It was observed that the steam flow is very sensitive to power oscillations, which cause convergence problems. The pressure regulator controls the turbine control valve position to maintain the steam dome pressure constant at the desired value. The pressure regulator was implemented by the constrained steady-state (CSS) calculation as described in the next section.

3 STEADY-STATE CALCULATIONS

The changes performed on the TRACE/PARCS model resulted in a stable steady-state behavior. In the turbine trip benchmark, the results of the transient calculation were validated against real plant data of a turbine trip test. The results of the transient calculation will show if the modifications lead to an improved behavior of the TRACE model. As a first step, the setup parameters shall be described before the outcome of the turbine trip sequence of both, the lumped and the full core model is investigated.

3.1 TRACE Stand-Alone

The newly developed stand-alone TRACE model needs firstly a steady-state calculation in order to fulfill the predefined convergence criterion. The criterion should be below 1E-4 to avoid numerically metastable conditions. TRACE supports five different steady-state calculation methods. In the case of the KKL TRACE model, the CSS calculation was applied. The CSS runs the model with the given initial conditions until all significant parameters reach the desired and initially set convergence criterion. Furthermore, the user can add a various number of controllers, such as pressure or velocity controllers for valve components which are only active during the steady-state calculation. Starting a transient simulation leads to the deactivation of all CSS controllers. For the recent TRACE model, the turbine control valves are driven by such a CSS controller to keep the turbine inlet pressure at the desired set point.

The feedwater controller is acting independent from the CSS and is, therefore, not taken into account in the convergence criterion. Hence, the water level must be verified separately. The new feedwater controller was configured to keep the water level at 14.35m height. In Figure 5, the nominal water level is depicted against the TRACE steady-state simulation time. It is noticeable, that the two values meet after around 150 seconds.

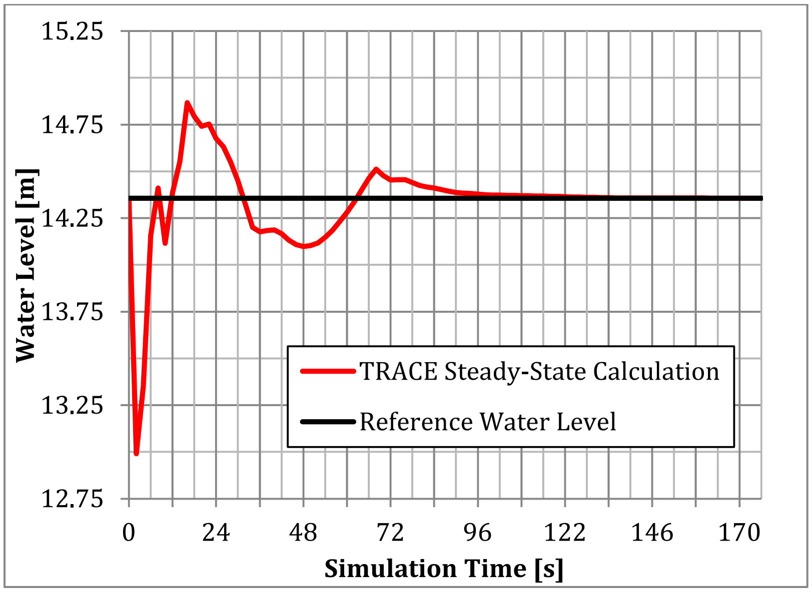


Figure 5: Evolution of the water level during steady-state calculation

In Figure 6, the evolution of the water level of the old and the new TRACE models is shown against the number of time steps. The old model was able to converge after 900 time steps with a criterion of 1E-3. The model did not manage to reach the criterion of 1E-4, even after 1500 time steps. In fact, it starts to reveal a repetitive pattern of oscillations which indicates numerical instabilities. The new TRACE model on the other hand achieved convergent conditions within less than 100 time steps with a criterion of 1E-4 and converged even with a 1E-5 criterion. Nonetheless, according to best-practice, a 1E-4 criterion is sufficient to assure numerical stable conditions. In this case, only the evolution of the water level during the steady-state calculation is exemplary illustrated in Figure 5, but the same behavior has been observed for the other parameters too, such as dome pressure, main steam flow and all other parameters.

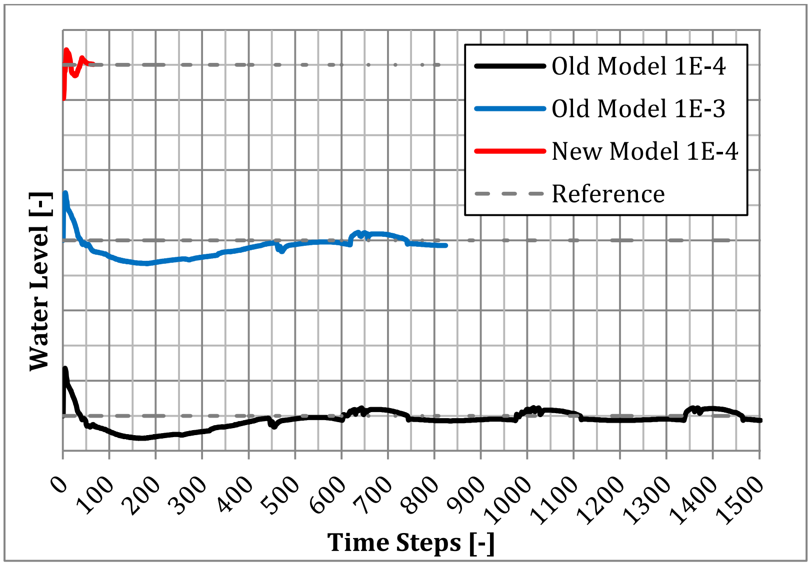


Figure 6: Evolution of the water level during steady-state calculation

3.2 PARCS Stand-Alone

The results in [2] were created with a generic core configuration. The turbine trip test was performed during cycle 18. The generation of the new cross sections was necessary for the proper simulation of the turbine trip transient. The data set was created by Axpo Kernenergie in CASMO-3 and transformed with the SIMTAB methodology [6] to PARCS. The created data set was validated with the SIMULATE3 [7] reference case for KKL. The comparison of the axial power profile between SIMULATE3 and PARCS v3.6 in Figure 7 showed a good agreement of the two simulations, as the root mean square error for the total axial profile is 2.93 %.

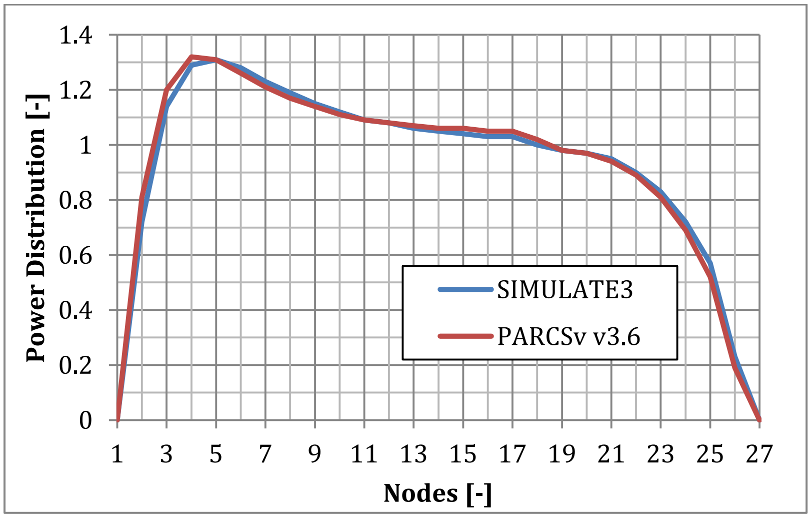


Figure 7: Comparison of the axial power profile in SIMULATE3 and PARCS v3.6 of cycle 18 cross sections at begin of cycle [6]

The difference of the k_{eff} values of the two system codes in Table I is equal to 304 pcm. This deviation is still in the acceptable range of about 300 pcm. In the further validation analysis with different core configurations in [6], this deviation remained constant through the different core configurations. This indicates no error propagation in the methodology.

Table I: Comparison of k_{eff} between SIMULATE and PARCS of cycle 18 cross sections at begin of cycle [6]

System Code	k_{eff} [-]	Absolute Deviation [pcm]
SIMULATE3	1.00529	-
PARCS v3.6	1.00225	304

The radial power distributions of PARCS and SIMULATE are, in general, in good compliance with relative errors, mostly between 0 and 5%. Some peripheral nodes though deviate between 5 and 7%. This is due to the correction of the axial nodes in the SIMTAB methodology. The conclusion in [6] states for those cases the necessity to check the segment distribution.

3.3 Coupled TRACE/PARCS Steady-State

In order to couple the PARCS data with the TRACE model, the fuel elements in TRACE had to be linked with the core geometry in PARCS. The assignment of the channels was done in a MAPTAB file, which is read in by PARCS. The MAPTAB of the lumped model with the three CHANs (24, 25 and 26) is illustrated in Figure 8. In this file, the radial weighting factors are also defined to compensate the power differences in different fuel elements. In case of the KKL input, the weighting factors were all equally normalized to 1.0.

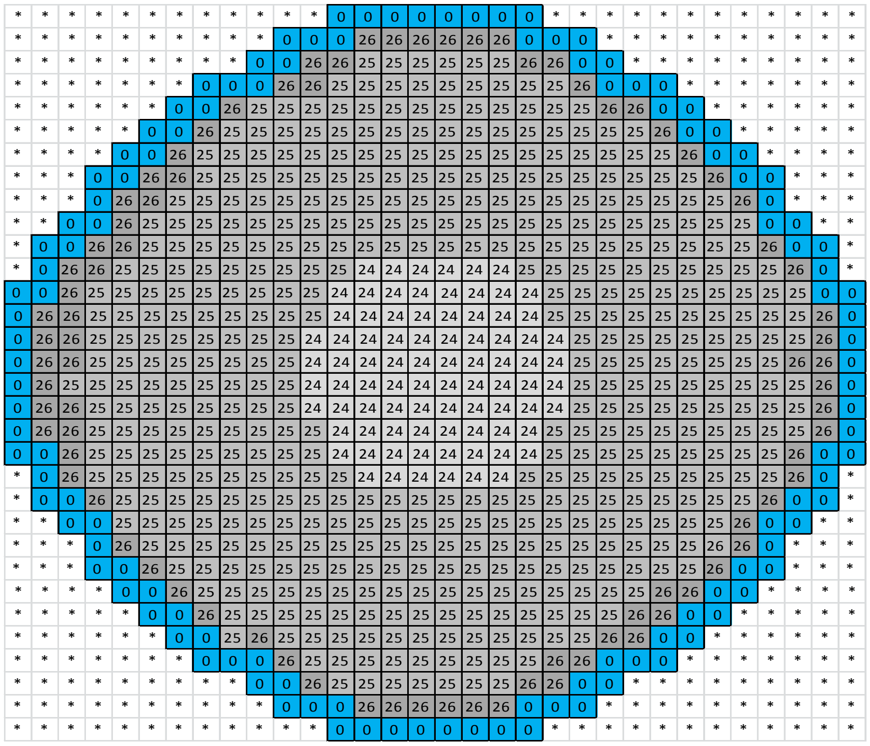


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Figure 8: Mapping of the three channels of the lumped core TRACE model with PARCS cross sections 24 – Inner core channels, 25 – Intermediate channels, 26 – Outer channels, 0 – Reflector

The coupled TRACE/PARCS model needed to undergo another steady-state calculation to take the NK feedback into account. Again, a global convergence criterion of 1E-4 was a good stability index for the new steady-state conditions. This is of high importance, since instabilities, carried on in the transient simulation, may lead to wrong conclusions in the analysis.

4 TURBINE TRIP BENCHMARK

The changes performed on the TRACE/PARCS model resulted in a stable steady-state behavior. In the turbine trip benchmark, the results of the transient calculation were validated against real plant data of a turbine trip test. The results of the transient calculation would show if the modifications improves the behavior of the TRACE model. Firstly, the setup parameters shall be described, before the outcome of the turbine trip sequence of both, the lumped and the full core model is investigated.

4.1 Steady-State Conditions Priory to the Turbine Test

The accuracy of the steady-state conditions of the coupled steady-state calculation was very important for the quality of the transient results. The results of the coupled simulation were compared with the reference plant data of the turbine trip test in Table II. The relative deviation of all seven characteristic values for the lumped core model was less than 1%. The maximum deviation of the full core model was less than 3%, a very good result too. Both models reached a convergence criterion of 1E-4.

Table II: Initial conditions prior the turbine trip test

	Plant Data	TRACE/PARCS model Lumped Core / Full Core	Relative Deviation [%] Lumped Core / Full Core
Core Power [MW]	3557.63	3539.99 / 3539.99	-0.496 / -0.496
Core Flow [kg/s]	10170.88	10239.98 / 10461.03	0.679 / 2.853
Dome Pressure [bar]	72.96	72.92 / 72.88	-0.055 / -0.109
Recirculation Flow [kg/s]	3370.85	3391.84 / 3391.84	0.623 / 0.623
Steam Flow [kg/s]	1955.02	1955.12 / 1910.19	0.005 / -2.293
Feedwater Flow [kg/s]	1952.99	1952.99 / 1952.99	0.0 / 0.0
Water Level [m]	14.357	14.356 / 14.356	0.007 / 0.007

4.2 Analysis Results

In Table III, the sequence of the turbine trip test is compared with the TRACE/PARCS input. Except for the recirculation runback, all other measures were initiated in both model versions at the same time as the TT plant data. The reason for the earlier recirculation runback is explained later in this section.

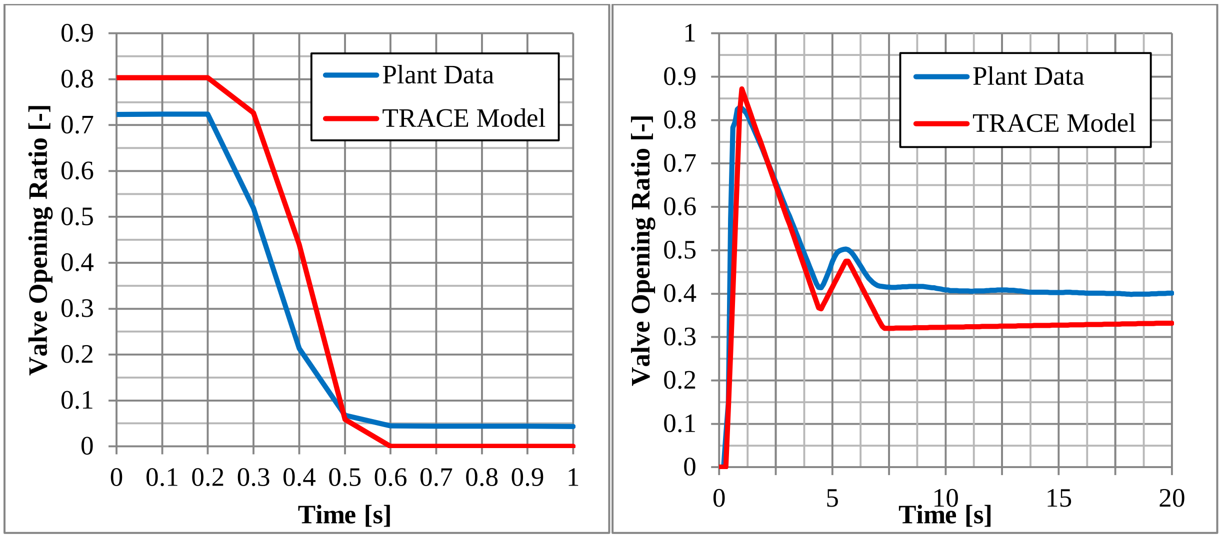
The turbine control valve closing and the bypass opening sequence is shown exemplary in Figure 9 on the TCV B (a) and the BPV N (b) against the plant data. The opening ratios followed the general behavior of the reference data with a small deviation. This discrepancy comes from the different geometrical opening areas of the valve components. Because of the time consuming implementation of a real valve behavior in TRACE, the valve opening areas were slightly adjusted during the modeling phase to compensate this effect. The overestimated initial value of the TCV in Figure 9 a) is a direct effect of the CSS calculation as described before. The minimum and maximum of the TRACE/PARCS simulation are, however, synchronous with the plant data.

The sequence of the valves was very important in this fast transient, since they define the pressure build-up, the wave propagation and eventually the dome pressure. The bypass valve component was connected to a break pressure boundary with sub atmospheric pressure in the condenser. The bigger the open area of these bypass valves is, the faster the RPV depressurizes. In the real plant, a pressure controller regulates the opening area ratio of the bypass valves.

Table III: Sequence of event against TRACE input data

Event	Initiation after trip [s]	TRACE [s]
Turbine Control Valve closing	0.20	0.20
Bypass opening	0.24	0.24
Selected Rod Insertion	0.30	0.30
Recirculation Runback	0.31	0.20

Unfortunately, there is no plant data available for each independent bypass line. Only the cumulative bypass flow could be obtained from the measurement data. Therefore, the steam flow had to be estimated by the valve specifications (steam flow-pressure-diagram), which lead to the results depicted in Figure 9 b).



a) Turbine Control Valve B **b) Bypass Valve N**

Figure 9: Closing of TCV B and Opening of the Bypass Valve N

The response of the dome pressure in Figure 10 verified the sequence of the opening area of the four TCVs and four BPVs to be correct. A working pressure controller would still be appropriate for the handling of the area fraction and could also keep the pressure constant during the steady phase after 7 seconds as the plant does. Nevertheless, both model performances are in very good compliance with the measured plant data. The difference between the lumped and the full core model comes from the different pressure and core flow distribution in the full core. Since all trip initiated sequences are the same in both cases, the results are expected to reflect this difference.

The core flow was one of the tunable input parameters, and was defined by the opening position of the flow control valve. The recirculation flow drives the jet pumps which determined the total core flow. It is alongside the rod insertion one of the possibilities to strongly reduce the reactivity in the core. The results in Figure 11 confirm that the TRACE valve component is not able to reproduce the non-linearity at the beginning and the end of the closing. The effect of non-linearity is compensated by the trip sequence as described in Table III. Thus, the lumped core model succeeds to match the linear closing phase and the starting and ending point with a high accuracy.

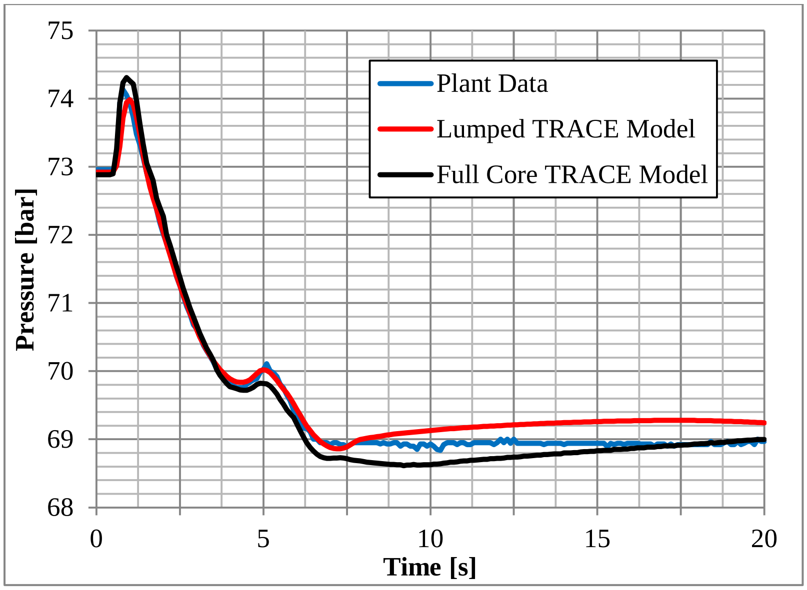


Figure 10: Dome pressure behavior of the TRACE/PARCS model against plant data

The full core model started with a slightly higher core flow. Since the core is no longer simplified, the core flow distribution and friction inside the fuel elements is determined for each fuel assembly independently. Therefore, the flow control valve needed some adjustment to take this into account. For this reason, it is not surprising to reach a higher final value as well.

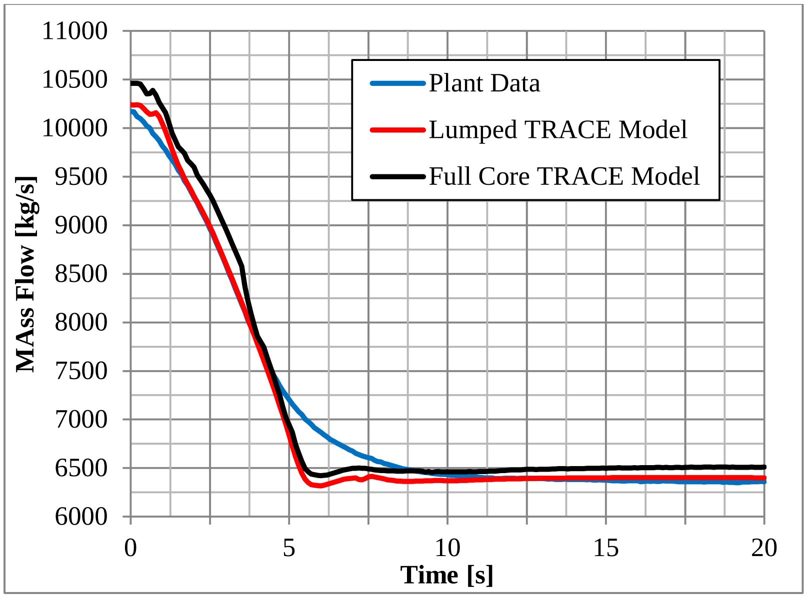


Figure 11: Core flow behavior of the TRACE/PARCS models against plant data

With the results shown by the core flow and dome pressure behavior, the core power was expected to show good results as well. The only reactivity action left that could have an impact on the core power, is the selected control rod insertion which was defined in the PARCS input according to the turbine trip test procedure. The core power response in Figure 12 meets the expectations. The core power of the lumped core model shows a big improvement compared to the initial model response in Figure 1. The area between 1 and 6 seconds remains overestimated, even though it improved significantly.

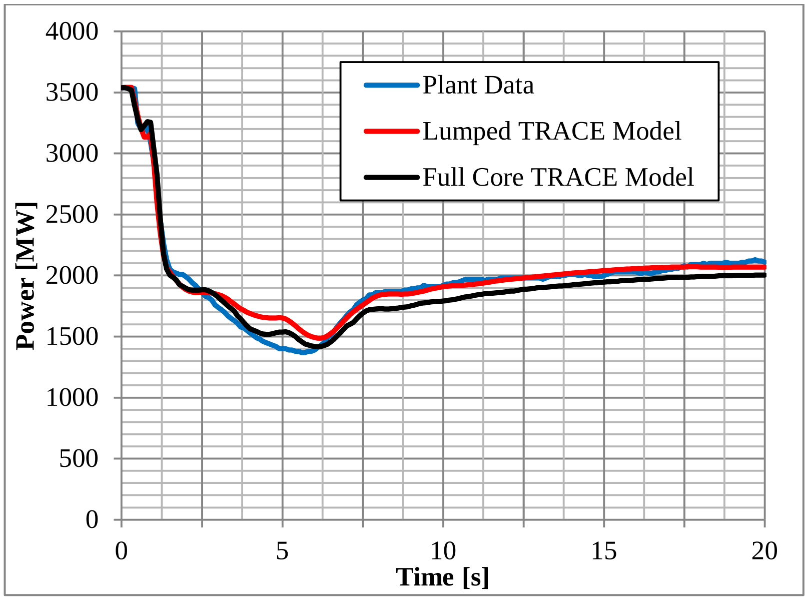


Figure 12: Core power behavior of the TRACE/PARCS models against plant data

The full core model reacted better in this respect. A closer look at the dome pressure of the full core model gives a reasonable explanation for the origin of this effect. The pressure in the full core model is slightly underestimated most of the time. A smaller pressure has a direct effect on the core power, resulting in a higher void inside and therefore a worse moderation. This explains also the underestimated core power in the recovery phase after 7.5 seconds. The pressure induced power bump at 5 seconds in both models may have its origin in the underestimated pressure drop in the steam separators.

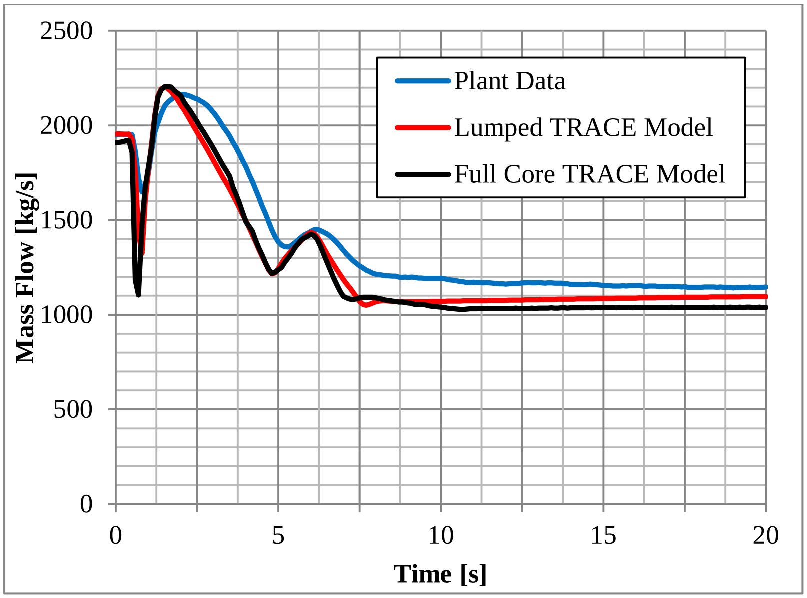


Figure 13: Steam flow behavior of the TRACE/PARCS model against plant data

Finally, the total steam flow was compared against the plant data. Figure 13 gives insight into the results of the simulation. The general behavior of the steam flow follows the plant behavior in good agreement, particularly the maxima. Like in the core flow, the non-linear characteristic of the bypass valves could not be reproduced by the TRACE simulation. Hence, the mass flow showed a sharper increase and decrease during the bypass valve action. The choked flow model of TRACE could also have contributed to this divergence. Both indications demand a more thorough investigation in future work.

A small summary of the final conditions of the initial variables are shown in Table IV to conclude the benchmark. In the lumped core model, all values except for the recirculation flow and the steam flow still differ less than 1%. The error source in the recirculation flow is well known. The tuning parameters in the jet pumps were configured for the nominal operation set point. In the transient case, the conditions in the jet pumps change and thus the flow ratio. In order to keep the core flow at within the correct range, the recirculation flow rate was adjusted. A further review could be done to adapt the tuning parameters for a wider range of working areas.

The full core model shows some significant differences in multiple values. As described before, the transient sequence of the turbine trip was not adjusted for the full core model. The different core pressure drop and the influence of the higher accuracy in the power calculation and core flow distribution lead therefore to different results. Still, the deviation and accuracy of the calculation are in good compliance with the plant data. With some additional tuning of the opening ratios of the different valves, the deviation could be decreased to similar values as in the lumped core model.

Table IV: Final conditions after the turbine trip test

	Plant Data	TRACE/PARCS model Lumped Core / Full Core	Relative Deviation [%] Lumped Core / Full Core
Core Power [MW]	2063.48	2069.19 / 2004.24	0.277 / -2.871
Core Flow [kg/s]	6358.01	6399.39 / 6509.16	0.651 / 2.377
Dome Pressure [bar]	68.97	69.24 / 69.00	0.391 / 0.043
Recirculation Flow [kg/s]	1912.36	1996.54 / 1998.07	4.402 / 4.482
Steam Flow [kg/s]	1148.76	1096.12 / 1038.68	-4.582 / -9.583
Feedwater Flow [kg/s]	1102.78	1103.61 / 1110.06	0.075 / 0.660
Water Level [m]	14.39	14.47 / 14.46	0.556 / 0.486

5 CONCLUSIONS

A TRACE/PARCS model has been developed for the KKL reactor and validated with the TT test data for both steady state and transient. The first attempt to model the TT showed the successful coupling between the TH model in TRACE and the NK model in PARCS. The coupled model reproduced a total plant behavior but a qualitative comparison was not possible because of the generic core loading, and modeling issues, such as steady-state convergence problems and geometry flaws, have been identified.

The assessment of the TRACE/PARCS model included the use of the correct core configuration to reflect the real plant state of the core. The geometry model was also reviewed using existing plant documentations and drawings. The control systems added and the use of the CSS calculation together with the pressure drop changes were essential for a successful steady-state calculation. The pressure drop correction on the steam lines, the RPV and the core improved the model prediction during the transient analysis.

With the corrected boundary conditions and the improved plant modeling, the results obtained for the TT test showed an excellent agreement with the plant data. The original numerical instabilities of the old model were eliminated and the characteristic parameters, i.e. dome pressure, core flow, core power and steam flow, were able to follow and to a high degree also match the test data. The discrepancy of the valve opening and closing behavior with the real valves could not be resolved. The built-in pressure controller in TRACE for the bypass valves could not be properly configured either and needed manual adjusting. The success of this work demonstrated the ability of 1-D coupled code systems to capture the complex behavior of the KKL TT test.

6 ACKNOWLEDGEMENTS

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