RETRAN-3D ANALYSIS OF THE OECD/NRC PEACH BOTTOM 2 TURBINE TRIP BENCHMARK

W. Barten, P. Coddington

This paper presents the PSI results on the different Phases of the Peach Bottom BWR Turbine Trip Benchmark using the RETRAN-3D code. In the first part of the paper, the analysis of Phase 1 is presented, in which the system pressure is predicted based on a pre-defined core power distribution. These calculations demonstrate the importance of accurate modelling of the non-equilibrium effects within the steam separator region. In the second part, a selection of the RETRAN-3D results for Phase 2 are given, where the power is predicted using a 3-D core with pre-defined core flow and pressure boundary conditions. A comparison of calculations using the different (Benchmark-specified) boundary conditions illustrates the sensitivity of the power maximum on the various resultant system parameters. In the third part of the paper, the results of the Phase 3 calculation are presented. This phase, which is a combination of the analytical work of Phases 1 and 2, gives good agreement with the measured data. The coupling of the pressure and flow oscillations in the steam line, the mass balance in the core, the (void) reactivity and the core power are all discussed. It is shown that the reactivity effects resulting from the change in the core void can explain the overall behaviour of the transient prior to the reactor scram. The time-dependent, normalized power for different thermal-hydraulic channels in the core is discussed in some detail. Up to the time of reactor scram, the power change was similar in all channels, with differences of the order of only a few percent. The axial shape of the channel powers at the time of maximum (overall) power increased in the core centre (compared with the shape at time zero). These changes occur as a consequence of the relative change in the channel void, which is largest in the region of the onset of boiling, and the influence on the different fuel assemblies of the complex ring pattern of the control rods.

1 INTRODUCTION

Within the STARS project at PSI, the code environment for the coupled 3-D reactor-kinetics/thermal-hydraulics transient analyses of the Swiss LWRs is based principally on RETRAN-3D and CORETRAN. (It should be noted that other codes are used for specific applications: e.g. RAMONA for BWR stability.) Both codes play distinct roles in this environment: RETRAN-3D is used for the analysis of coupled 3-D core/plant system transients, while CORETRAN is used for core-only dynamic analysis. An important aspect is that both codes are based on an identical neutronics algorithm, allowing the use of CORETRAN as an interface code to help prepare the 3-D core model for RETRAN-3D. This approach forms the basis of the PSI 3-D transient analysis methodology.

Participation in the OECD/NRC Peach Bottom 2 (PB2) Turbine Trip (TT) Benchmark [1] was prompted by the following considerations. Firstly, the PSI methodology has so far only been assessed for neutronically driven transients [2], and for a PWR system transient [3]. Since the Benchmark addresses a BWR transient driven by system thermal-hydraulic perturbations, it extends the range of the codes’ assessment. Secondly, the Benchmark incorporates three different phases, which are, from the PSI point of view, well suited to a comprehensive assessment of all the participating codes. Consequently, PSI participated in all three Phases of the Benchmark.

The first part of the paper presents a summary of the RETRAN-3D results [4] for Phase 1, in which the plant system is modelled with the reactor power taken from the experimental data. In the second part of the paper, a selection of the RETRAN-3D results for Phase 2 are presented, in which a boundary condition model between the lower and upper plena is used with a 3D-core. The results from CORETRAN for Phase 2, which laid the foundations for the 3D core model in RETRAN-3D, are presented in [5]. The third part of the paper summarizes the RETRAN-3D results for Phase 3, with the plant system fully coupled to the core 3D-neutronics and power calculation. More details are given in [6].

2 PHASE 1: FULL PLANT SYSTEM WITH PRE-DEFINED POWER

2.1 The RETRAN-3D Base Model

The RETRAN-3D input model for the Phase 1 calculation was developed from an early RETRAN-02 model for Turbine Trip 1 [7]. From this model, we used the nodalization for the reactor vessel, including the steam separator and downcomer region, the recirculation loop and the steam lines. The reactor core region was re-nodalized (including the accompanying heat structures), to include 24 axial control volumes, in combination with a core exit volume and core inlet volume connected to the core bypass volume.

From the Benchmark specifications [1], we used the time-dependence and axial profile of the pre-defined power, together with the feedwater flow, the turbine inlet flow rate, and the turbine bypass area. In addition, the value of the enthalpy in the steam dome, the dome pressure, and the flow rates at t = 0 were used.
Finally, for the base case, the RETRAN-3D code option of the 4-equation model (thermal equilibrium) was employed. The Zolotar-Lellouche correlation was used to calculate the slip ratio for the two-phase flow, and, although the Chexal-Lellouche correlation is that preferred in RETRAN-3D, it is sometimes difficult to obtain convergence for plant applications, while for the pressures considered here (> 6.0 MPa) the Zolotar-Lellouche correlation has been shown to give equally good agreement with steady-state void-fraction experimental data [8].

In order to determine the dynamical response of the reactor system, it is important to understand the general flow of water in the reactor vessel, and how this is approximated using the RETRAN-3D nodalization (Fig. 1). Water is pumped from the jet pumps into the lower plenum. From there, the flow is directed upwards into the core region, where the water is heated and steam is produced. From the core region, the steam/water mixture flows into the upper plenum and through the standpipes into the steam/water separator. From there, the liquid part of the mixture flows into the "steam-separator-external" volume, while the gaseous fraction (steam) flows through the lower dryer into the steam dome, and from there through the steam line to the turbine.

From the steam-separator-external volume, the liquid flows down into the upper downcomer, while a small amount of steam flows up into the lower dryer volume. From the upper downcomer, where the liquid from the steam-separator-external volume mixes with the feedwater, subcooled water flows down into the jet pumps. The separation of steam and water in the separator region is important for the system behaviour, and will be discussed in more detail below.

A comparison between calculated (base-case) and measured steam dome pressure, Fig. 2, shows generally, good agreement. The calculation reproduces the initial increase in the pressure as the pressure wave propagates along the steam line from the turbine, following the turbine trip and closure of the turbine stop valves. This is followed, between 0.5_s and 0.9_s by a pressure increase as the power increases, and later by the oscillations due to the pressure wave in the steam line, with a periodicity of a little below 1_s. The flattening of the curve after about 3_s, and the beginning of the decrease as a consequence of the power reduction, is also reproduced by the calculation.

The increase in the measured pressure at about 1_s, which is due to the closure of the turbine stop valve, and the power increase is larger than the calculated one by about 0.1 MPa, while after 1_s both curves are almost parallel. In order to investigate the possible reasons for the discrepancy in the initial pressure rise, we looked at two features of the plant representation and physical modelling. This was based on the knowledge that the system pressure is dependant on the energy (steam) production/consumption in the vessel and the pressure loss along the steam line.

When the pressure loss coefficients in the turbine bypass line are increased, the steam dome differential pressure at times later than 3_s is also increased (Fig. 2). Up to about 2_s, however, there is no visible
In the present study, the two-phase steam-water flow, entering the steam dome and upper downcomer regions, is considered. The steam dome pressure is influenced by changes in the turbine bypass pressure losses and internal heat generation. The effects of these factors on the steam dome pressure are significant, especially during startup and shutdown phases.

The steam dome differential pressure, measured by RETRAN-3D, is shown in Figure 2. The pressure is plotted against time, with variations from the base case. The base case represents the standard conditions, while the measured values show deviations due to the influence of operation parameters.

Since the pressure increase after 0.5 s is driven primarily by the additional steam production, it is important to determine the distribution, including any condensation of this steam as it flows through the steam separators into the steam dome and upper downcomer regions. The impact of non-equilibrium effects on the steam dome pressure is discussed in Section 2.2.1.

### 2.2 Investigation of Impact of Non-Equilibrium Effects

#### 2.2.1 Nodalization of Steam Separator Region

In this section, the nodalization of the steam separator region is discussed. The steam-water mixture is divided into smaller volumes to accurately model the pressure changes. The separator vane elements are set to be radially tilted, which helps in further reducing the pressure rise. The pressure rise is then calculated using RETRAN-3D code, and the results are compared with the measured pressure rise.

The main effect of the re-nodalization was a reduction in the energy transfer from the gas phase to the liquid phase, because the volume within which thermal equilibrium can be established is then smaller. Consequently, there is less condensation of the vapour as the pressure increases. To obtain the measured pressure increase, it was necessary to approximately halve the volume of the steam separator and steam separator external control volumes.
2.2.2 Two-Region Non-Equilibrium Model

Another RETRAN-3D code option that can be used to obtain a reduced energy transfer between the liquid and the vapour region is the "two-region, non-equilibrium model". In this model, RETRAN-3D divides the fluid in a bubble-rise control volume at the liquid level interface into two regions, the two regions being internally in thermal equilibrium, but not necessarily in equilibrium with each other. The "liquid" region below the interface, and the "vapour" region above the interface, have the same pressure, but in general have different temperatures; for example, because of superheated steam in the vapour region. The application of this model to the steam separator volume and the steam separator external volume, CV 1 and CV 4 in Fig. 3, also produced an increased pressure rise at about 1 sec (Fig. 4). A sensitivity study showed that the effect in the steam separator volume is negligible, and that the increased pressure rise at 1_s comes mostly from the steam separator external volume. The reason for this is that, in the steam separator external volume, the pressure increase after 0.3_s leads to an increase in the steam temperature in the vapour region but, because of the non-equilibrium model, the energy transfer between the vapour region above the interface and the liquid region below the interface is reduced, thus maintaining the superheated steam in the vapour and dryer regions. In the steam separator region, however, there is a transfer of vapour from the liquid region at the level interface, because of the rising bubbles through the liquid region, and, relative to this, reduction in the energy transfer across the interface due to the non-equilibrium model has only a small effect.

Fig. 3 Nodalization diagram of the steam separator/downcomer region.

2.2.3 "5-Equation" Model

Using the RETRAN-3D "constrained non-equilibrium" or "5-equation" model in the steam separator and steam separator external control volumes also reduces the heat transfer between the vapour and the liquid phase. Thus, the pressure at about 1_s in the steam dome is increased (Fig. 4). This increase, however, is much smaller than for the two-region, non-equilibrium case. The reason for this is that the 5-equation model, when used in conjunction with the bubble-rise model, influences only the heat transfer within the regions above and below the liquid level, and does not consider the heat transfer across the liquid-level interface. The smaller pressure rise of the 5-equation model is also in line with the properties of the different models. While the homogeneous equilibrium model for a two-phase mixture constrains all phasic temperatures to the saturation temperature at the respective pressure, the 5-equation model constrains the vapour phase to the saturation temperature only and permits the liquid temperature to float freely. It is clear that, since there is no mechanism for sub cooling the liquid in CV 1 and CV 4 (Fig. 3), a major impact on the pressure increase through the use of this model is not to be expected.

2.3 New Version of RETRAN-3D

The calculations presented above were performed using RETRAN-3D MOD003.0 [10]. Recently, RETRAN-3D has been updated to MOD003.1 [11], thereby correcting the area-change pressure drop for the case of multiple junctions. The influence of this update, for example for the calculation with the two-region, non-equilibrium model, is shown in Fig. 5, which confirms that the calculations using MOD003.0 and MOD003.1 are nearly identical.

It should be noted that the combination of the two-region, non-equilibrium model with the 5-equation model in the same control volume is currently not...
available in either code version, and the 4-equation model is always used in the code in combination with the two-region non-equilibrium model. Therefore, calculations using the 4-equation and 5-equation options in the steam separator and steam separator external volumes, together with the two-region non-equilibrium model, always produce the same results (Fig. 5). Such a combination, allowing non-equilibrium between the liquid and the vapour regions in combination with non-equilibrium between the liquid and the vapour phases in the liquid region, would usefully extend the modelling capabilities of the code.

![Fig. 5: Steam dome differential pressure versus time: a comparison of the 4-equation and 5-equation models, and different RETRAN-3D versions.](image)

**2.4 The Non-Equilibrium Model and Parameter Variations**

In the previous Sections, we saw that the two-region non-equilibrium model gave improved agreement with the measured pressure in the steam dome. We have also seen that the agreement at later times can be improved by increasing the pressure losses in the turbine bypass line (Fig. 2). That is, when the change in the bypass line is combined with the two-region, non-equilibrium model in the steam separator regions, the calculated pressure after 3_s is in excellent agreement with measured data, while there are still some differences between 1s and 3_s (Fig. 6). However, as described above, the change in the bypass line has almost no effect on the differential pressure in the steam dome for times up to 2_s.

Finally, we investigated a further feature of the steam separator region: the steam separator fluid inertia. Because of the complex flow behaviour in the steam separator volume, i.e. flow in a vortex, there is no unique value for the inertia appropriate for all conditions and transients. To analyse the sensitivity to fluid inertia, we approximately doubled the value in the steam separator inlet, and more than doubled the value in the steam separator exit to the lower dryer (see Fig. 3). These values were chosen based on an early analysis of this transient [7], together with recent discussions [April 2002] in the e-mail forum of the Benchmark. The effects of these changes on the steam dome differential pressure are relatively small (Fig. 6) for the case considered here, i.e. with a pre-defined power.

![Fig. 6: Steam dome differential pressure versus time: the two-region, non-equilibrium models and variations.](image)

**2.5 Summary of RETRAN-3D Analysis of PB2TT Phase 1**

In summary, we saw in the above Sections that the manner in which the heat transfer between the liquid and vapour phases is treated in the two-phase regions (steam separator and steam-separator external volumes in Fig. 3) had the most influential impact on the transient pressure prediction. Two sensitivity calculations were subsequently performed: firstly, to understand the importance of the volume of liquid with which the vapour is brought into equilibrium as the pressure increases (re-nod separator sensitivity); and secondly, the importance of heat transfer across the free surface in the steam separator external volume. Since these two effects relate to two different physical phenomena, a final calculation was performed (Fig. 7) showing their combined effects. The result is very close agreement between the calculation and measurement up to about 2_s, after which (as...
discussed above), the modelling of the pressure losses along turbine bypass line become important.

![Graph](image)

**Fig. 7:** Steam dome differential pressure versus time: sensitivity to non-equilibrium conditions.

3 PHASE 2: PRE-DEFINED CORE BOUNDARY CONDITION MODEL

The principal aim of Phase 2 of the Benchmark was to define the 3D core for the Phase 3 calculation. Consequently, flow and/or pressure boundary conditions at the lower and upper plenum were provided in the Benchmark specifications for the generation of a “core-only” model. Since, in Phase 2, these (calculated) boundary conditions were stipulated by the Benchmark co-ordinators, no comparison with measured data was possible.

3.1 The RETRAN-3D Model

In the PSI methodology, the input required for RETRAN-3D to perform a 3D core calculation consists of three separate input files, two of which are prepared by CORETRAN, and the remaining one forms part of the normal RETRAN-3D input structure. The two files prepared by CORETRAN consist of a transient cross-section (tcs) file, and a file containing geometric information for all the individual fuel assemblies (cdi or CORETRAN Data Interface file). The additional information contained within the standard RETRAN input includes a “map” which allocates each reactor fuel assembly to a given RETRAN core hydraulic channel (a total of 34 such channels were used in the present analysis, see below). Thus, prior to the RETRAN-3D calculation, a CORETRAN analysis [5] of Phase 2 was performed to provide well-founded parameters for the 3D core. The Phase 2 calculation is described briefly below, while more information is given in the Section describing Phase 3 of the Benchmark.

If we now consider the flow in the core region, we see that the flow from the lower plenum is mainly to the core inlet volume, with a small fraction of the total core flow flowing through the core bypass volume (Fig. 8).

From the core inlet volume, most of the coolant flows into the core, while again a small amount enters the core bypass volume. The core region is represented by 34 thermal-hydraulic channels, each with 24 axial nodes, and the flow through each channel corresponds to the combined flow through a certain number of fuel assemblies. The steam/water mixture flowing out of the top of the core channels flows into a single core exit volume, and from there into the upper plenum, where it mixes with the core bypass flow.

![Diagram](image)

**Fig. 8:** Core region nodalization (not to scale).

In the current (Phases 2 and 3) calculations, the neutronics parameters of each of the 764 fuel assemblies have been entered at 24 axial levels. The combining, or “lumping”, of the flow through these assemblies into the 34 thermal-hydraulic channels is that suggested in the Benchmark specification (Ref. [1], Fig. 3.2.2), except that for numerical reasons Channel 26 was subdivided into two different channels, with numbers 26 and 34; see Section 4 for more information. The neutronics parameters for the fuel assemblies and control rods were generated in a manner similar to the PSI CORETRAN analyses of Phase 2 of the Benchmark.

3.2 Selected Results

In the Benchmark specifications, different options were provided for boundary conditions for the Phase 2 calculations. In all of these options, the upper plenum
pressure is used as (outlet) boundary condition, and the same lower plenum fluid enthalpy is used. In one option, the total flow rate through the lower plenum into the core region, i.e. the sum of the core and bypass flows, is used as the inlet boundary condition (Fig. 9a, dashed line), which completes the information needed to calculate the power (Fig. 9c). We can compare this with a second option in which the pressure in the lower plenum is used as the inlet boundary condition. With this option, a slightly smaller inlet flow rate (Fig. 9a, solid line) for the core region (relative to the flow boundary condition case) is calculated. In addition, the core exit flow rate is also reduced. Together, this results in a slightly reduced net flow of water into the core region before the time of the power maximum (Fig. 9b), which in turn means a smaller increase in the (void) reactivity. These slight differences in the flow behavior lead to a power peak for the pressure boundary condition case about 20% lower than that for the flow boundary condition case.

Fig. 9: Flow rates and normalized power of Phase 2 calculations around the power peak for two different sets of boundary conditions.

This illustrates the sensitivity of the power peak to small changes in the system parameters; namely, in the lower plenum flow rate and pressure. The dynamic response of the system with close interaction of the thermal-hydraulic properties with the core power is discussed in more detail in the following Sections for Phase 3.

4 PHASE 3: FULL PLANT SYSTEM COUPLED WITH THREE-DIMENSIONAL CORE

4.1 The RETRAN-3D Model for Phase 3

The RETRAN-3D input model of the reactor system for Phase 3 of the Benchmark exercise is based on the model for the Phase 1 calculation [4], described above in Section 2. In the Phase 1 calculation, however, the core was represented by a single thermal-hydraulic channel with 24 axial control volumes, and the reactor power was taken from the experimental data, but in Phase 3 a 3D core model is used instead. The region between the lower and upper plena is the same as that in the Phase 2 calculation.

4.2 Comparison with Measurements

The results of the RETRAN-3D Phase 3 calculation are presented in this Section. The calculation (Fig. 10, solid lines) was performed using the same model and code options as for Phase 1, including the two-phase, two-region, non-equilibrium model (see Section 2). Results are generally in good agreement with the measured data (Fig. 10, dotted lines). The calculated maximum of the normalized power, $\bar{P}(t)$, occurs only slightly earlier, and is slightly smaller, than measurement (Fig. 10a).

The thermal-hydraulic behaviour of the reactor, as represented by the steam dome (Fig. 10b) and the core exit relative (Fig. 10c) pressures, are well predicted. The calculation shows, between $t = 0.5$ s and $t = 0.9$ s, the initial increase in the pressure as the pressure wave propagates along the steam line from the turbine, followed by the pressure rise as the power increases. The calculation also shows the pressure oscillations due to pressure wave propagation back and forth along the steam line, with a periodicity of about 1 s. The flattening of the pressure curve after about 3 s, and the beginning of the pressure decrease as a consequence of the power reduction, is also reproduced by the calculation. After about 1 s the calculated pressures are about 0.05 MPa below the measured ones, and are in very close agreement with the Phase 1 predictions with the pre-defined core power (dashed lines).
In the analysis of Phase 1 (Section 2 above and [4]), sensitivity of the model to the original base case was investigated, in particular with respect to non-equilibrium effects in the steam separator region and to pressure losses in the turbine bypass line. The improvements with respect to the non-equilibrium effects were included in the 3D model, since they influence the magnitude and timing of the power maximum, while those relating to pressure losses in the turbine bypass line, becoming effective only after $t = 2_s$, were not included.

The Phase 3 calculation, which is a culmination of the analytical work of Phases 1 and 2, shows that it is possible, using RETRAN-3D, to perform an accurate analysis of a system-driven transient with a 3D core on the basis of the PSI analytical methodology of preparing the transient neutronics cross-sections and core geometry within the CORETRAN code.

![Graphs](image)

**Fig. 10**: Comparison of calculated and measured powers and pressures.

### 4.3 Dynamic Response of the System

In this Section, we analyze the dynamics of the reactor system during the transient, in particular around the time of maximum power.

#### 4.3.1 Before Scram

We first discuss the behaviour before $t = 0.75_s$, i.e. prior to control rod insertion. The transient is initiated at $t = 0$ when the turbine is tripped and the turbine stop valve starts to close. The flow rate from the steam line to the turbine reduces quickly from the steady-state value of $\sim 1000\,\text{kg/s}$ to zero at $t = 0.096_s$ when the turbine stop valve is completely closed. Simultaneously, at $t = 0.06_s$, the turbine
bypass valve begins to open, and is full open at \( t_\text{=} _{0.852 \text{ s}} \). The flow through the turbine bypass is choked, and has a 100% capacity of \(~600 \text{ kg/s}\). The steam line exit flow (Fig. 11a, dashed line), which is the sum of the (rapidly decreasing) flow through the turbine and the (slowly increasing) flow through the turbine bypass, is determined up to \( t_\text{=} _{0.1 \text{ s}} \) by the flow through the turbine, and later by that through the turbine bypass. Thus, at \( t_\text{=} _{0.1 \text{ s}} \), there is almost no flow at the steam line exit, but at the same time there is still the full flow rate of \(~1000 \text{ kg/s}\) from the steam dome into the steam line (Fig. 11a, solid line). These two effects generate a net mass flow into the steam line. Consequently, the pressure in the steam line increases, at first close to the exit to the turbine. The pressure rise then propagates as a pressure wave back along the steam line to the steam dome, leading \(~0.25 \text{ s}\) later to a reduction of the steam flow at the steam line inlet. After \( t_\text{=} _{0.3 \text{ s}} \), the flow at the steam line inlet begins to decrease, and eventually falls below zero. Between \( t_\text{=} _{0.4 \text{ s}} \) and \( 0.65 \text{ s}\), there is a reverse flow of steam from the steam line into the steam dome (Fig. 11a, solid line), with a maximum of \(-600 \text{ kg/s}\) at \( t_\text{=} _{0.46 \text{ s}} \).

The reduced mass flow between the steam dome and the steam line after \( t_\text{=} _{0.3 \text{ s}} \) causes the pressure to rise in the steam dome (Fig. 10b). A pressure wave then propagates through the steam separator external volume to the lower plenum (Fig. 1). The pressure rise at the core inlet (Fig. 8), then leads to an increase in the mass flow into the core (Fig. 11b, solid line), with a maximum at \( t_\text{=} _{0.5 \text{ s}} \). In addition, the pressure rise in the steam dome produces a wave, which propagates down through the steam separator to the upper plenum (Fig. 1). The pressure rise at the core exit (Fig. 8) results in a reduced mass flow from the core exit (Fig. 11b, dashed line), with minimum flow occurring at about \( t_\text{=} _{0.55 \text{ s}} \). The response of the flow at the core exit is slower than that at the core inlet because the pressure wave propagates faster through the liquid in the path from the steam separator external to the lower plenum than through the (more compressible) steam/water mixture in the path from the steam separator to the upper plenum. The increased core inlet flow and the decreased core exit flow together produce a net positive mass flow into the core (Fig. 11b, dash-dotted line). The maximum of this net mass flow is about \( 4000 \text{ kg/s}\) at \( t_\text{=} _{0.55 \text{ s}} \), which is more than twice the maximum flow rate reduction at the steam line inlet.

![Fig. 11: Flow rates, reactivities and power around the time of maximum power.](image-url)
The “squeezing” of the core by the pressure wave propagation through the lower and upper plena results both in an increase in the liquid (mass) content of the core and an increase in the core pressure. The net mass flow into the core increases the void (or density) reactivity (Fig. 11c, dashed line).

The increase in reactivity then leads to a power rise (Fig. 11d, solid line). The enhanced heat generation, and consequently the heat transfer to the coolant, promotes vaporization of water in the core, which in turn causes a further increase in the core pressure. This balances the pressure at the core inlet and exit and reverses the mass flow into the core, so that, after 0.65_s, there is, for a period of 0.15_s, a net mass flow out of the core. The result of this is that the void reactivity peaks at 0.65_s, and then slowly decreases. The Doppler reactivity effect is small (Fig. 11c, dash-dotted line), and acts only as a second-order correction. Thus, the total reactivity \( \dot{\rho}(t) \) seen in Fig. 11c (solid line) is dominated by the void reactivity, and also peaks at about \( t_1 = 0.65_s \). The maximum in the normalized power, \( \bar{\rho}(t) \), follows closely at \( t = 0.68_s \) (Fig. 11d, solid line). For comparison, the measured power is also included (Fig. 11d, dotted line). Note that the reduction in power begins well before the insertion of the control rods at 0.75_s.

The power behaviour can be understood in qualitative terms for this fast transient by a “prompt jump approximation” [12], which predicts the normalized power to be

\[
\bar{\rho}(t) = \frac{\dot{\rho}}{\bar{\rho}(t)_{\text{max}}}.
\]

The total delayed neutron fraction at the start of the transient is \( \bar{\rho} = 0.005526 \) [1, Table 2.3.1]. The power calculated from the prompt jump approximation (Fig. 11d, dashed line) rises slightly earlier than the power calculated by RETRAN-3D because it assumes an immediate response of the power with respect to the reactivity. The power maximum is also slightly earlier than that calculated by RETRAN-3D, and coincides with the time to the reactivity maximum. It is also smaller, because the increased level of delayed neutrons due to the power rise has not been taken into account. The sensitivity of the power maximum to the core inlet flow rate, observed in the Phase 2 calculations, can be seen in the prompt jump approximation of the power \( \bar{\rho}(t) \) considering that the total reactivity approaches the delayed neutron fraction.

### 4.3.2 After Scram

The reactor scram is activated at \( t_1 = 0.63_s \), but since the control rods have a response time of 0.12_s, control rod insertion begins at \( t_2 = 0.75_s \). (It should be noted that the scram activation at 0.63_s was part of the Benchmark specification, and is not connected to any plant signal.) The total reactivity is then further reduced by the control reactivity (Fig. 11c, dash-dot-dot-dash line). At \( t = 0.85_s \), the total reactivity falls below zero. With its further decline, the power is also reduced. This means that less vapour is being produced in the core, which leads to a net inflow of water. A continuous net mass flow into the core, however, begins only after \( t_1 = 1.3_s \) (i.e. beyond the time scale given in Fig. 11). The (mostly) negative values of the core flow balance between \( t = 0.7_s \) and \( t_1 = 1.3_s \) occur as a consequence of the power increase, which leads to an increase in the heat transfer into the coolant, and thereby enhanced vaporization and core pressurization. Superimposed on the general behaviour of the core mass balance (Fig. 11b) are the oscillations which occur as a consequence of the pressure wave propagations (back and forth) along the steam line. In addition, the oscillations of the steam line inlet flow relative to the exit flow also continue, in line with the pressure oscillations in the steam line after the time frame presented in Fig. 11, but with decreasing amplitude.

### 4.4 Analysis of the Three-Dimensional Core

In the previous Section, we analyzed the reactivity and total power of the core. In this Section, we determine the 3-dimensional power shape by examining the power in different thermal-hydraulic channels, concentrating on the time before scram.

#### 4.4.1 Thermal-Hydraulic Channel Radial Map and Control Rod Map

In the Phase 3 calculation of the core behaviour, the combining, or “lumping”, of the flow through the different fuel assemblies into the 34 thermal-hydraulic channels is that suggested in Ref. [1], except that since RETRAN-3D will not combine assembly types with different numbers of fuel rods within the same hydraulic channel, Channel 26 in [1, Fig. 3.2.2] was subdivided into two separate channels: Number 26 (for the 4 outermost fuel assemblies with Assembly Design 5 [1, Fig. 2.4.2]), and Number 34 (for the 4 innermost fuel assemblies with Assembly Design 4). Figure 12 is a radial map of the thermal-hydraulic channels; those mentioned above have been highlighted. The neutronics parameters of the fuel assemblies and control rods are generated in a manner similar to the PSI RETRAN-3D and CORETRAN analysis of Phase 2 of the Benchmark, already described in Section 3.

The reactor core consisted of a complex pattern of control rods prior to the initiation of the transient (Fig. 12), with a significant number of partially inserted rods. The details of the control rod pattern are given in [1, Fig. 5.2.1]. Some important features of this pattern are a bank of 4 control rods inserted to 1/3 of their length surrounds the inner part of the core. This region is surrounded by another bank of 8 control rods, which are almost fully (11/12) inserted. Outside of this is a ring of 24 control rods, which are between
1/4 and 1/2 inserted. Finally, on the outside, there is a ring of 24 control rods consisting of 8 fully inserted control rods: 12 control rods with ~1/4 insertion, and 4 with 1/6 insertion.

![Figure 12](image)

**Fig. 12:** Thermal-hydraulic channel radial map, with Channels 1, 10, 26, 34 highlighted. The + symbols represent differently inserted control rods.

### 4.4.2 Channel-Averaged Power

The change in the power production as a function of time in the different fuel assemblies is almost homogenous. To illustrate this, the normalized power distributions of the fuel assemblies in Channels 1, 10 and 26 are shown in Fig. 13. Channel 1 is representative of those inside the ring of 8 nearly fully-inserted control rods. Channel 10 is typical of the channels outside this ring, and at the time of maximum power it has the highest power density of all the channels in the core. Channel 26 is close to the periphery of the core, and is the furthest away from the region with control rods.

Figure 13a gives the power \( t = 0 \) to \( t = 1.2 \text{ s} \), while Fig. 13b shows the detailed behaviour close to the maximum. The time-dependency of the power in the individual channels is almost identical. The rise of the normalized power in Channel 10 (Fig. 13b, dotted line) is slightly larger than that in Channel 26 (dashed line), which again is larger than that in the centre of the core: Channel 1 (dash-dotted line). However, the differences are only a few percent.
4.4.3 Axial Profiles of Channel Power

Figure 14a shows the axial distribution of the normalized power density, $\hat{Q}_{ch,0}(t = 0)$, at time zero for Channels 1, 10 and 26. As can be immediately noticed, the axial profiles are different, both in shape and magnitude. Channels 1 and 10 have their power maxima at about mid-height, with asymmetry around the maxima such that the power increase below the maximum is steeper than the power decrease above it. This is typical behaviour for most of the channels in the core. Channel 26, and some others at the periphery of the core have their power maxima close to the core inlet.

The power profile for Channel 26 is typical of those far away from the control rod banks, and in particular from those banks with partially inserted control rods. The power profile in the fuel assemblies in the centre of the core, surrounded by the second, nearly fully inserted, ring of control rods, is of similar shape to Channel 1, with a plateau at the lower end of the core. This reflects the influence of the innermost bank of control rods, which are 1/3 inserted, and surround the centre of the core. Channel 10 shows the typical axial power profile of the channels outside the second ring of control rods, where the power in the lower half of the channel is depressed, but where there is no identifiable signature for the location of the tip of an individual control rod. On the other hand, Channel 10 is surrounded by control rods which are inserted by different amounts: ~1/4, 1/3, 1/2.

The overall observation, therefore, is that, because of the complex control rod pattern present in the core prior to the transient initiation, there is a large range of different channel/fuel assembly axial power profiles.

At the time of the power maximum, the axial shapes of the channel power densities are similar to those at time zero, though with some small variations (Fig. 14b). On the average, the normalized power density $\hat{Q}_{ch,0}(t_{\text{max}})$ in Channel 1 is decreased by about 4%, and in Channel 26 by about 1.5%, while in Channel 10 it is increased by about 1.5%. Channel 10 has the highest axially-averaged power density, and also the highest node-based power density at the time of the power maximum. The relative decrease in the centre (Channel 1) is due to the higher control rod density.

The axial redistribution of the normalized power densities is similar for all channels, where, for example, the relative power density is increased at mid-height, but reduced at the lower and upper ends. This can best be seen in Fig. 14c, where the change in normalized power density, $\hat{Q}_{ch,0}(t_{\text{max}}) - \hat{Q}_{ch,0}(t = 0)$, is shown. The power maximum of Channel 10 is increased by about 9%, Channel 1 by about 3%, while the axial location of the power maximum of Channel 26 is displaced towards mid-height.

As noted before, there is no movement of the control rods before the scram. Thus, all these changes, and in particular the redistribution of the axial power density are induced by changes in the void reactivity, and the influence of the complex ring pattern of control rods. In fact, the highest change in local void occurs immediately above the onset of boiling (Fig. 14d).
This is produced as a result of the combination of the following effects. Firstly, prior to the increase in the core power, the increased flow rate of water at the core inlet, and the increase in subcooling as the pressure increases, moves the boiling boundary upwards, while, as a consequence of the compressibility of the two-phase mixture, the relative change in the void fraction increases as the density increases. As the power increases, additional steam is produced as a result of the enhanced heating, which of course approximately follows the axial power profile. This point is discussed in greater detail in [6].

5 CONCLUSIONS

The paper describes the PSI RETRAN-3D analyses of the Peach Bottom BWR Turbine Trip Benchmark, Phases 1, 2 and 3. The CORETRAN analysis of the Benchmark Phase 2 is presented elsewhere [5]. The main goal of the Benchmark participation was to assess the capability of RETRAN-3D for application to the coupled 3-D core/plant system transient, defined in Phase 3 of the exercise. In preparation for this, analyses of Phase 1, in which the RETRAN-3D plant system was initialised, and Phase 2, where the 3-D core model was developed, were also performed.

In the first part of the paper, the RETRAN-3D analysis of Phase 1 is presented. In this Phase, a RETRAN-3D plant system model was developed to predict the steam dome pressure using the pre-defined transient core power distribution. The results of the calculations are in good agreement with the measured data, in particular the steam dome pressure. In the paper, we have demonstrated that the modelling of the steam separator/downcomer region is crucial if the pressure increase during the first 2 s is to be correctly predicted. Changes in the turbine bypass line pressure loss distribution also influence the system pressure, but only after the first 2 s.

In order to demonstrate the importance of the modelling of the steam separator region, and to highlight the important physical processes we analysed and compared the impact of: re-nodalizing this region; using the 4-equation and 5-equation models; using a two-region, non-equilibrium model; and finally of changing the fluid inertia within the steam separator. For this Phase, in which the experimental power is used as a boundary condition, the calculation in which the steam separator/downcomer region is re-nodalized, and if a two-region, non-equilibrium model is used, provide the closest predictions to the measured system parameters (expressed in terms of the steam dome pressure). These results help to show that one of the most important mechanisms controlling the magnitude of the initial pressure rise, and therefore the power prediction in Phase 3, is the thermal dis-equilibrium in the separator and dryer region. Using the 5-equation model, or changing the inertia in the steam separator region, has a smaller effect. We also show that the most recent version of the code, RETRAN-3D MOD003.1, gives results very close to those obtained using the previous version.

The second part of the paper presents a selection of the RETRAN-3D results for Phase 2. The analyses of the CORETRAN calculations for this Phase [5,13] provided confidence in the 3D core model, which was then transferred to RETRAN-3D. The RETRAN-3D calculations show that the 3D core was well integrated into the boundary condition model of Phase 2. Comparison of the results obtained with two (pre-defined) sets of pressure and flow boundary conditions illustrate the sensitivity of the power maximum to changes in the system parameters influencing the core inlet and exit flow rates.

Finally, in the third part of the paper, the results for Phase 3, using RETRAN-3D with the system model developed in Phase 1 and the 3D core from Phase 2, are presented. The RETRAN-3D core model used the Benchmark-specified, thermal-hydraulic channel “lumping” scheme, for which the flow through the 764 fuel assemblies was represented by just 34 channels. The calculated reactor system behaviour for Phase 3 is in excellent agreement with that for Phase 1 and with the measured data, while there is a small under-prediction of the core power response.

The Phase 3 calculation, therefore, which is a culmination of the analytical work of Phases 1 and 2, shows that it is possible to perform an accurate analysis of a BWR system-driven transient using RETRAN-3D with a 3-D core using the PSI analytical methodology of preparing the transient neutronics cross-sections and the core geometry within the CORETRAN code.

The results for Phase 3 of the Benchmark are in good agreement with the measured data, in particular the power, the steam dome pressure and the core exit pressure. The following sequence of events in the transient are all well predicted by the code. The closure of the turbine stop valve, causing the interruption of the steam flow, leads to a pressure wave in the steam line which propagates back to the reactor vessel. The pressure wave then propagates down into the reactor vessel, leading to an increase in the flow from the lower plenum into the core, and a reduction in the flow out of the core into the upper plenum. These two effects combine to produce a net mass flow into the core, the amplitude of which is more than double the reduction in the flow into the steam line. The net mass flow into the core increases the void reactivity, which subsequently generates a power excursion. The power increase enhances the heat transfer into the coolant, which increases the core pressure, and so leads to a mass flow out of the core. This then reduces the void reactivity, and consequently also the power. After the power peak, the plant is shut down with a reactor scram. The reactivity effects resulting from the change in the core
void can therefore explain the overall behaviour of the transient prior to the time of the reactor scram. The Doppler reactivity provides a second-order contribution to the termination of the power increase.

Finally, the 3D nature of the core power distribution was investigated by analyzing the power density of the different thermal-hydraulic channels. It was found that the time-dependence of the channel-averaged power was similar for all the channels, while the differences in the relative channel powers, at the time of the power maximum, were within a few percent of each other. The axial distribution of the channel powers at the time of the maximum power, compared to that at time zero, show a relative increase in the power at the core centre, but by a different amount for each channel. The changes in the power shape occur as a consequence of both the change in the void profile in each of the different channels, and the influence on the different fuel assemblies of the complex ring-pattern of the partially and fully inserted control rods.

ACKNOWLEDGMENTS

The introduction of the 3D neutronics parameters into the RETRAN-3D model by our PSI colleague, Hakim Ferroukhi, is gratefully acknowledged. We also wish to thank both him and Garry Gose (CSA/USA) for their implementation of the effective core bypass density correction in the RETRAN-3D code. We have also benefited from discussions with Garry Gose and Andy Olson (Exelon/USA) on the RETRAN-3D model and aspects of the experimental data. This work was partly funded by the Swiss Federal Nuclear Safety Inspectorate (Hauptabteilung für die Sicherheit der Kernanlagen, HSK) and the Swiss Federal Office of Energy (Bundesamt für Energie, BFE).

REFERENCES


