Advances in Nuclear Fuel Management IV (ANFM 2009)
Hilton Head Island, South Carolina, USA, April 12-15, 2009, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2009)

CYCLE SPECIFIC BWR RELOAD ANALYSIS USING SIMULATE-3K

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Keywords: BWR Transients, SMS, SIMULATE-3K, Coupled Codes, Validation

ABSTRACT

Several organizations, utilities, fuel suppliers and code developers are performing cycle-specific transient predictions for BWRs. The accuracy of the prediction depends on code approximations and code-specific validation results. The penalty that has to be taken in safety analysis depends on the extent and success of the validation method. This paper presents applications of SIMULATE-3K (S3K) to operational transient calculations and results of validation efforts in the Finnish Olkiluoto 1 and 2 plants. The validation models actual events that have occurred at Olkiluoto and includes a fast pressurization and a fast flow reduction that are typical of internal-pump BWRs. Furthermore, the paper discusses the capability that offers S3K to evaluate Operating Limit Minimum CPR (OLMCPR) directly based on 3D transient methods, without the approximations used in traditional 1D evaluations.

1. INTRODUCTION

This paper describes a methodology for Anticipated Operational Occurrences (AOO) in BWR's using the Studsvik Scandpower code SIMULATE-3K[1] (S3K). This class of operational BWR transients is typically analyzed on a cycle-specific basis as part of the core reload design licensing process. Their time span ranges from seconds to a couple of minutes, where the primary acceptance criteria are fuel rod and the reactor vessel integrity. These transients will be referred to here as "fast transients." They define the Operating Limit Minimum CPR (OLMCPR), which is the primary restriction of bundle power in core design. Section 2 describes the S3K models; Section 3 shows the validation against plant measurements at the Olkiluoto 1 and 2 (OL1/2) plants. OL1/2 are two identical BWR units operated by TVO on the southwestern coast of Finland. Section 4 provides a description of the methodology to compute OLMCPR and an example.

2. MODEL DESCRIPTION

S3K[1] is a two group, advanced nodal reactor analysis transient code. It models the core in 3D with each fuel bundle represented as a flow channel. Besides the analysis of reactivity insertion accidents[2] and BWR stability analysis[3], the following classes of operational transients can be analyzed with S3K[4, 5]: pressurizations created in the steam dome and/or the steam lines with valve control and actuation, coolant inventory or flow change transients using the two groups of pumps, coolant temperature changes and instabilities that occur during a flow decrease/temperature event. The following sub-sections give an overview of the models.

2.1 Core Model

The 3D spatial neutronic model used in S3K is the transient version of the QPANDA[6] advanced nodal model. The temporal neutronic model uses a fully implicit differencing of the frequency-transformed time-dependent diffusion equation.

The 3D core model is nodalized with one characteristic thermal-hydraulic channel per fuel bundle (without cross flow). The hydraulic model[7] consists of a 5-equation, fully implicit nodal model for all fields. This model incorporates unknowns at both edges of the control cell (e.g., there is no staggering of the mesh), and there is complete resolution of the nonlinear equations at each time step (i.e., there is no linearization approximation).

Intra-pin fuel temperatures and heat fluxes are computed using a fully implicit temporal differencing of the standard 1D radial finite-difference heat conduction equations, with burnup- and temperature-dependent properties. Heat transfer coefficients and heat fluxes are fully resolved at each time step by nonlinear iteration.

Thermal-hydraulic feedback to nodal cross sections is computed using a library of 3D tables of neutronic parameters versus coolant density, fuel temperature, control rod type, fuel exposure, void history, control rod history, and fission product inventory.

2.2 BWR Vessel Model

Figure 1 shows schematically the components of the vessel model. The vessel is divided into a series of 1D components for the upper plenum, standpipes, separators, downcomer (with two non-mixing radial zones), two recirculation pump loops, and lower plenum (with two non-mixing radial zones).

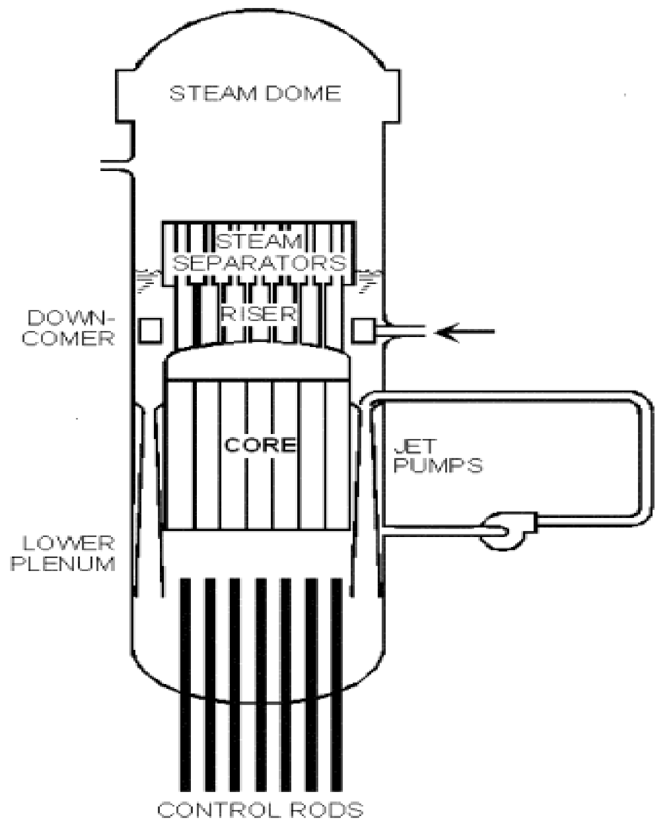

Fig. 1 S3K vessel model.

Special models are included in S3K to calculate specific flow conditions. They include recirculation pumps, jet pumps and steam separators. The recirculation pumps (one in each of the two recirculation loops) drive the core flow through the recirculation loops into the jet pumps or drive the core flow in a plant with internal/external pumps. The purpose of the recirculation pump model is to predict the pressure rise to be used in the momentum conservation equation. The pressure rise is calculated as a function of pump flow rate and speed using homologous pump curves. The pump speed may be entered as a function of time or computed using the motor, hydraulic and friction torques. The steam separator model takes into account flow inertia in the separators, pressure losses in the separators and carry under.

The vessel thermal-hydraulic representation is similar to the 5-equations core model. The conservation equations for all 1D vessel components are solved using the same nodal scheme as the core hydraulic channels.

2.3 BWR Steam Line Model

The steam line model is capable of simulating acoustic effects in the steam line due to sudden valve closures or openings, leading to pressure waves traveling back and forth in the steam lines. Figure 2 shows schematically the components of the steam line: turbine stop/control valve (TSV/TCV), bypass valve (BV), safety/relief valves (SRV), and main steam isolation valve (MSIV). The steam lines are modeled as four parallel lines with a specified length and diameter (which may change at branch locations), connecting the steam dome to the turbine valves with two branch-offs at specified locations. One branch leads to the pressure relief and safety valves and the other branch leads to the turbine bypass valves. Different pressure controller models are implemented, which corresponds to typical controller designs.

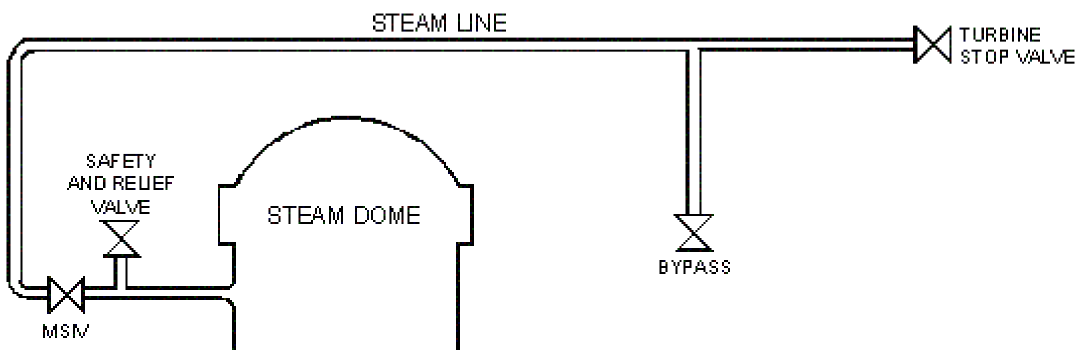

Fig. 2 S3K Steam line model (one out four lines are shown).

The governing equations for the steam line model are the three single-phase equations for the conservation of mass, momentum, and energy. Assuming isentropic expansion of the steam as an ideal gas, the system of equations can be reduced, and the energy equation is imbedded in the momentum and mass equations.

The time integration of the equations uses a highly accurate fourth-order Runge-Kutta explicit solution scheme. The integration of the steam line model is uncoupled from the BWR vessel integration because it requires much smaller time steps to resolve the acoustic effects in the steam line.

3. EVALUATION OF OLMCPR BASED ON 3D TRANSIENT METHODS

The main purpose of the safety analysis for fast transient scenarios is to calculate the OLMCPR. This value will be used as the minimum CPR value allowed in the operation of the plant. Since S3K simulates all the channels in the core, the typical approximations in a 1D methodology, such as mapping of average channel to hot channel power, void reactivity feedback tuning and partial and full scram 3D assumptions, are avoided.

The 3D analysis is more detailed and more accurate and presents new possibilities to determine OLMCPR. It thereby avoids the following drawbacks typical of the 1D methodology:

- The mapping of the time evolution of the core average power distribution to create boundary condition to the hot channel(s) is not required.

- Since all the bundles in the core are evaluated at once, the bundle that first reaches the SLMCPR determines the OLMCPR, compared to a set of possible preselected hot channels in the 1D methodology.

- In the 3D methodology the power distribution changes during the transient. Therefore the relative bundle power changes during the event compared to the typical 1D methodology in which the relative power is assumed constant.

3.1 Definition of OLMCPR

OLMCPR is defined for each bundle after the limiting transient calculation has been performed. Staying above the safety limit prevents the bundle from going through boiling transition if the analyzed transient would occur. The OLMCPR is defined in S3K by Eq. (1) below:

$$OLMCPR = SLMCPR \times \frac{ICPR}{MCPR} \tag{1}$$

In order to determine OLMCPR, S3K uses a “bundle power increase process.” After the initial 3D dynamic simulation, the core power is increased, using the 3D power shape from the initial dynamic simulation, until the minimum CPR (MCPR) for the limiting bundle coincides with the safety limit for MCPR (SLMCPR). When this condition is fulfilled the initial CPR for the limiting channel, is equal to the OLMCPR.

This is illustrated in Fig. 3, which shows the behavior of CPR during a transient for the reference S3K calculation and the perturbed calculation. OLMCPR corresponds to the initial CPR from the perturbed calculation where the MCPR reached SLMCPR

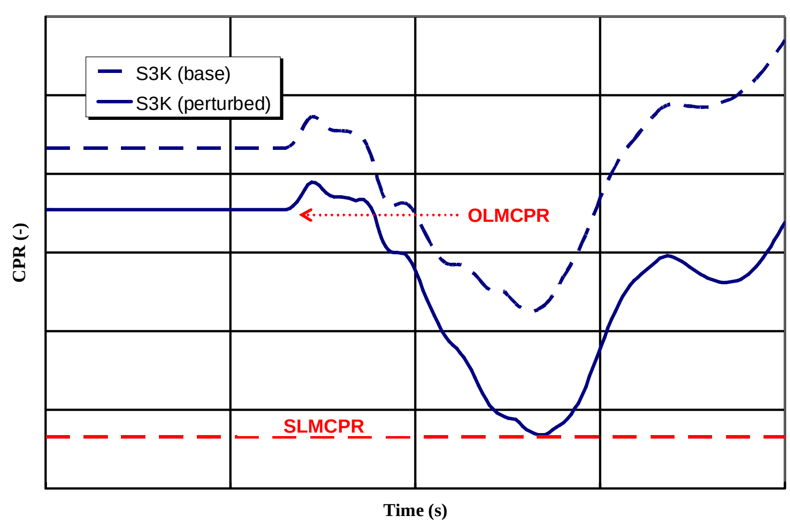

Fig. 3 CPR behavior during a transient after a power increase.

3.2 Proposed 3D Methodology for OLMCPR Calculation

The accepted method often used in 1D transient analysis to determine the OLMCPR is to change the bundle power (for a set of potentially limiting fuel bundles in the core, the so-called hot channels) such that the minimum CPR during the transient calculation is equal to the SLMCPR for each of the selected bundles. When this condition is fulfilled the maximum initial CPR (ICPR), for the analyzed cases, is equal to the OLMCPR.

The traditional hot channel methodology for OLMCPR determination is a two-step calculation. First, the transient is initiated from the operating conditions given by the FSAR or from experience. The typical limiting evaluations are at minimum and/or maximum core coolant flow at nominal power. If the analysis tool is a 1D model, the calculation can only produce the average core response and the CPR is, at this stage, unknown.

Second, a thermal-hydraulic analysis is performed in order to find the power, such that the MCPR, during the transient is exactly the same as the SLMCPR. If a 1D code is used, several thermal-hydraulic calculations are needed to produce the limiting bundle CPR response for the actual core condition. Due to differences in the average channel and the hot channel responses an approximate mapping scheme has to be used to avoid non-conservative results. If the 1D methodology includes a 3D calculation, the results are only used to identify the limiting bundles. A 1D thermal-hydraulic code is then used to recalculate the channel response and increase the power in each of the identified limiting bundles until SMLCPR is reached.

The CPR module in S3K performs automatic MCPR evaluation using the traditional hot channel methodology, described above, but adapted to analyze all the active core channels simultaneously. Since S3K includes 3D neutronic and thermal-hydraulic channel calculation with all bundles represented, accurate transient CPR can be predicted for each bundle in the core as part of the analysis of the reference case.

A perturbation technique is used in which the second pass is done at increased power level without the neutronic model using the same power shape as in the reference case (see next section for more details). The limiting condition is defined directly by the bundle that, during the transient, reaches the SLMCPR.

3.3 S3K Perturbation Technique

First, the desired transient scenario is analyzed at the reference operating conditions. This is the base case or reference case. After the analysis of the reference case has been completed, the transient can be replayed many times at different power levels. These are the replay cases.

When the transient is replayed, the 3D power distribution as a function of time is fetched from the reference case and scaled according to the user request. Appropriate boundary conditions are applied to the core channel to ensure that the pressure drop in the core is the same in the base case and in the subsequent replay cases. The MCPR evaluation is a two-step procedure:

Step # 1 (to be performed only once):

- Initialize the S3K steady state solution (both neutronics and thermal hydraulics).
- Calculate the base case (neutronics and thermal hydraulics) for the desired scenario and evaluate assembly CPR.
- Calculate for all the channels in the core: Minimum CPR during the transient (MCPR), the operating limit MCPR (OLMCPR) and time at which the MCPR occurs (TLMCPR).
- Save the 3D power distribution and core inlet/outlet boundary conditions for later use.

Step # 2 (to be performed as many times as desired):

- Initialize the S3K steady state solution at the same power level as the base case.
- Set the power level to the requested value and scale the 3D power distribution accordingly.
- Set core inlet and exit pressures and core inlet temperature equal to their values in the base case.
- Run a null transient to achieve a new steady state at the requested power.
- Replay the transient scenario at a requested power level, using only the thermal hydraulic module (core thermal hydraulics and fuel pin).
- Calculate MCPR, OLMCPR and TLMCPR for all channels in the core.

At the end of the run, a number of edits are produced:

- Maps with the assembly initial and final CPR
- Maps with the assembly MCPR during the transient and the time at which MCPR occurs for each channel
- Map with the assembly R-factors
- Map with the assembly OLMCPR
- Requested edits for selected assemblies and a summary per fuel type in the core

3.4 S3K CPR Result Example

The example below is taken from an evaluation of OL1 inadvertent closure of all four turbine control valves transient. [4] Figure 4 compares the MCPR evolution for the reference case and the replay case (20% power increase). Note that the MCPR is reduced in the replay case due to the power increase and core flow decrease.

More details are given in Fig. 5. MCPR and CPR in three selected assemblies are plotted in Fig. 5 with an inset showing the transition of MCPR from assembly 1 to assembly 2 and then to assembly 3. The MCPR in this last assembly is the smallest during the run; OLMCPR for this run is thus the ICPR in assembly 3 scaled by the ratio of SLMCPR to MCPR. A summary of the values from this run are extracted from the S3K output file and displayed in Table 1 below.

Figure 6 shows a map of MCPR, OLMCPR and the TLMCPR 2D distributions for the replay case. The assembly in which MCPR reaches SLMCPR during the transient is highlighted by the red box.

Table 1 MCPR calculation summary.

Assembly Name	MCPR	Initial CPR	OLMCPR	Time MCPR
MCPR in run	1.068	1.448	1.465	2.683
Bundle 1	1.085	1.355	1.348	2.583
Bundle 2	1.070	1.449	1.462	2.663
Bundle 3	1.068	1.448	1.465	2.683

SLMCPR value used in this analysis = 1.080

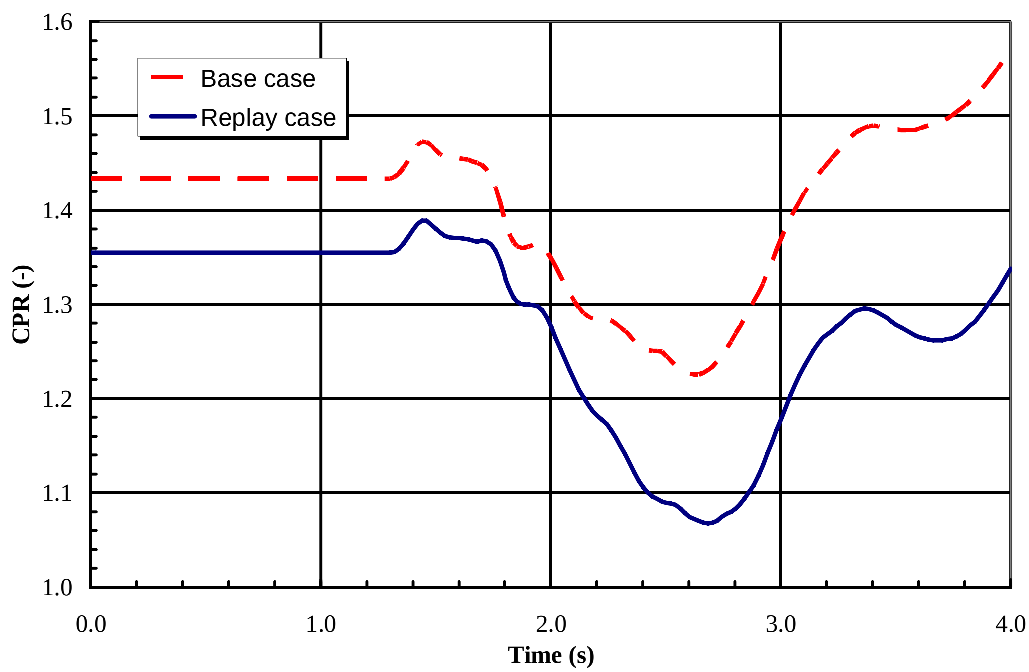

Fig. 4 Minimum CPR for base case and replay case with 20% power increase.

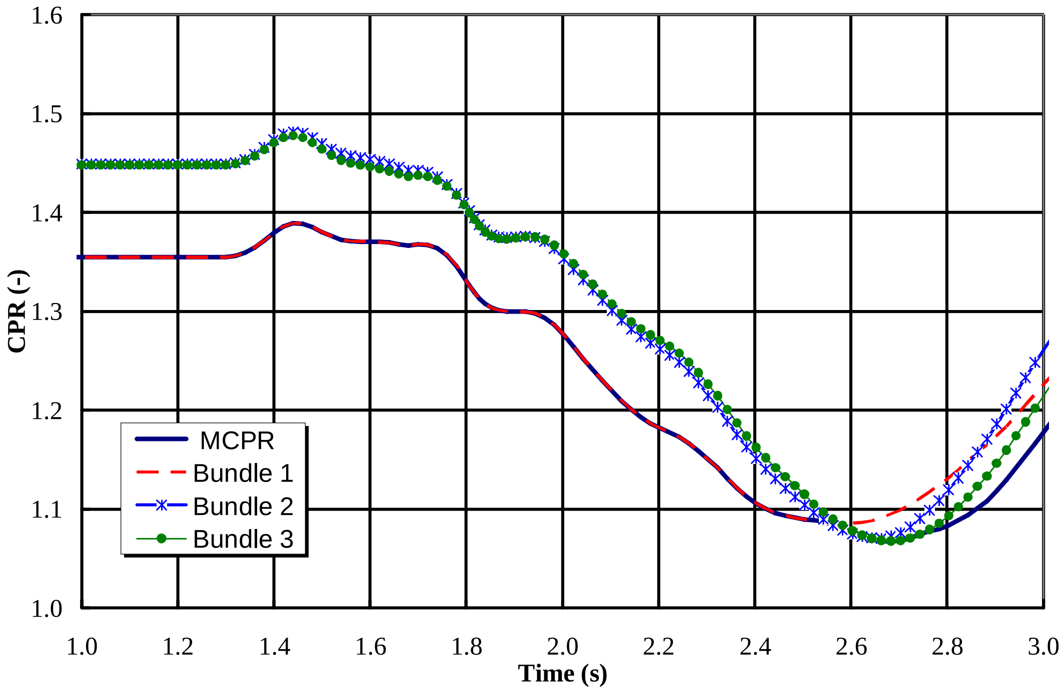

Fig. 5 MCPR, OLMCPR and TMCPR distributions for replay case.

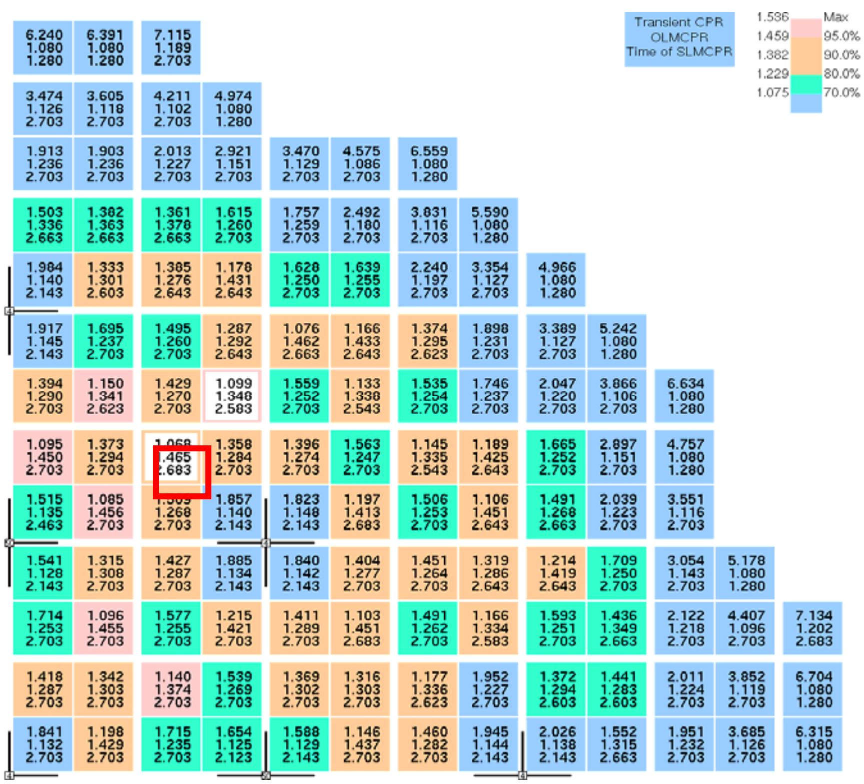

Fig. 6 MCPR, OLMCPR and TMCPR distributions for replay case

4. S3K VALIDATION

The validation of S3K against plant measurements has the following general objectives: (1) verify that S3K can be used for the specified reactor design (e. g. jet pump plant, internal/external pump plant), and (2) verify that the utility has the required knowledge and the technical methodology to be able to perform transient analysis.

The transient validation has the following technical objectives:

- Verify that the specific model is a correct representation of the reactor.
- Verify that the global parameters (e.g. power, coolant flow, pressure, and inlet temperature) are predicted accurately.
- Verify the 3D power distribution response.
- Verify the radial flow distribution response.

S3K has been validated against the Frigg experiment[8], against the Peach Bottom turbine trip[5], and against a number of events in the OL1/2 reactors.[4] The OL1/2 transients include a load rejection without bypass, several turbine trips (with selected rod insertion, with coolant temperature transient, with feedwater temperature decrease, and with active pressure controller), and a sequential MSIV closure. Two of the transient events, namely, the load rejection without bypass and the fast flow reduction, are presented in this paper. Other scenarios are discussed in detail by Jönsson et al.[4]

4.1 Load Rejection without Bypass

The objective of this validation was to demonstrate the accuracy of the reactor and steam line modeling. The parameters of interest are the steam dome pressure and the APRM and LPRMs. The turbine valve closure without bypass valve opening is a typical limiting event in most BWR.

A pressurization transient occurred September 10, 1985 at full power, 2160 MW and 7250 kg/s core flow in Olkiluoto 1 (operation was prior to the Olkiluoto reactor power increase). A failure in the pressure controller system caused a fast closure of the turbine control valves. All valves were closed in 0.5 sec. and no bypass valves opened. A pressure pulse was created which traveled through the steam lines and caused a fission power increase when the pulse reached the core. Automatic scram and pump speed decrease mitigated the second part of the event. The measured fission power (APRM and LPRM) exceeded the measurement scale during a fraction of a second. The steam dome pressure increased from 7.00 to 7.85 MPa.

The boundary conditions to the event are the valve closure and the scram boundary conditions (control rod insertion at 125% APRM and pump speed decrease at 118% APRM).

Measured and calculated steam dome pressures are shown in Fig. 6 below. Figure 7 compares one of the LPRM signals. Note the cutoff value in the measurement system for LPRM.

The comparison demonstrates the realistic timing of the pressure wave, which causes the LPRM peak. The steam dome pressure increase and oscillation frequency are also in good agreement. The core flow (not shown) is also captured adequately.

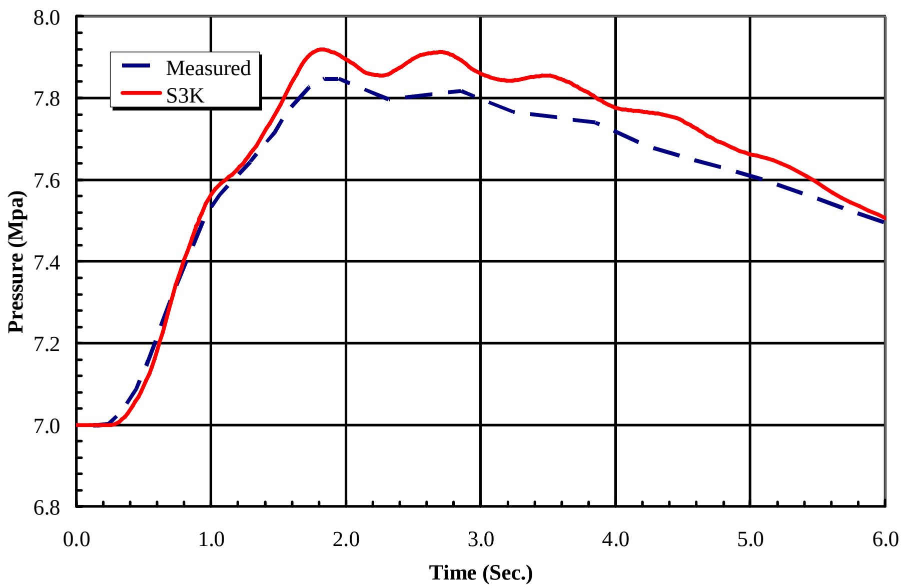

Fig. 6 Steam dome pressure.

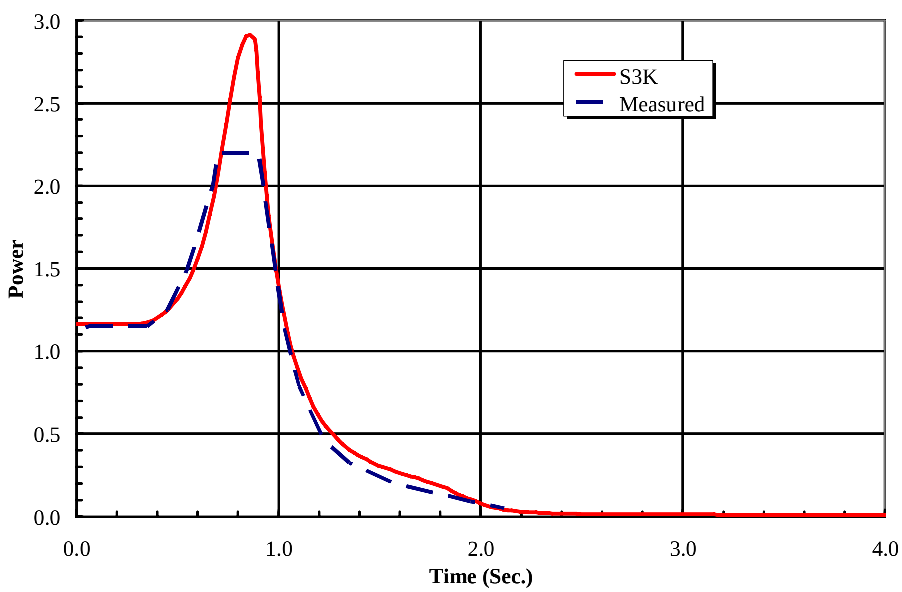

Fig. 7 Level 2 LPRM response.

4.2 Fast Flow Reduction with Fast and Slow Partial Control Rod Insertion

The objective of this validation was to demonstrate the accuracy of the 3D power calculation and the channel flow prediction. Secondary objectives included the global parameters (flow, power, inlet enthalpy) during the pump speed decrease phase of the event.

A turbine trip test was conducted June 6, 1998 at full power in the uprated operating domain, i.e. 2500 MW and 8060 kg/s core flow. The turbine trip caused partial scram and scram actuation such that the scram group 2 (defined in Figure 8) was hydraulically injected (fast insertion) and group 3 electro-mechanically inserted (slow insertion) in four minutes. The turbine trip created a minor pressure disturbance. The control rod insertion at different speeds creates a 3D disturbance in the core power distribution. Recorded data of APRMs and LPRMs exist for comparison.

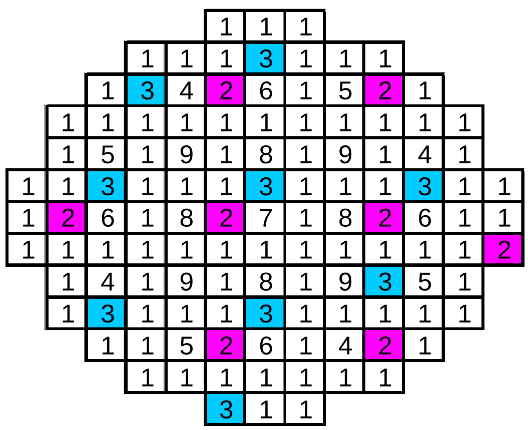

Fig. 8 Partial scram groups.

The calculated results are shown in Figs. 9 through 11. The calculated global parameters (not shown here) are in good agreement with measurements. The LPRM strings and axial levels, in close proximity to control rods that are initially inserted, differ significantly from the average power transient and are well captured by S3K. The bundle flow response before and after the flow reduction, represented in Fig. 11 by one of the eight bundle inlet flow measurement signals, is in good agreement as well.

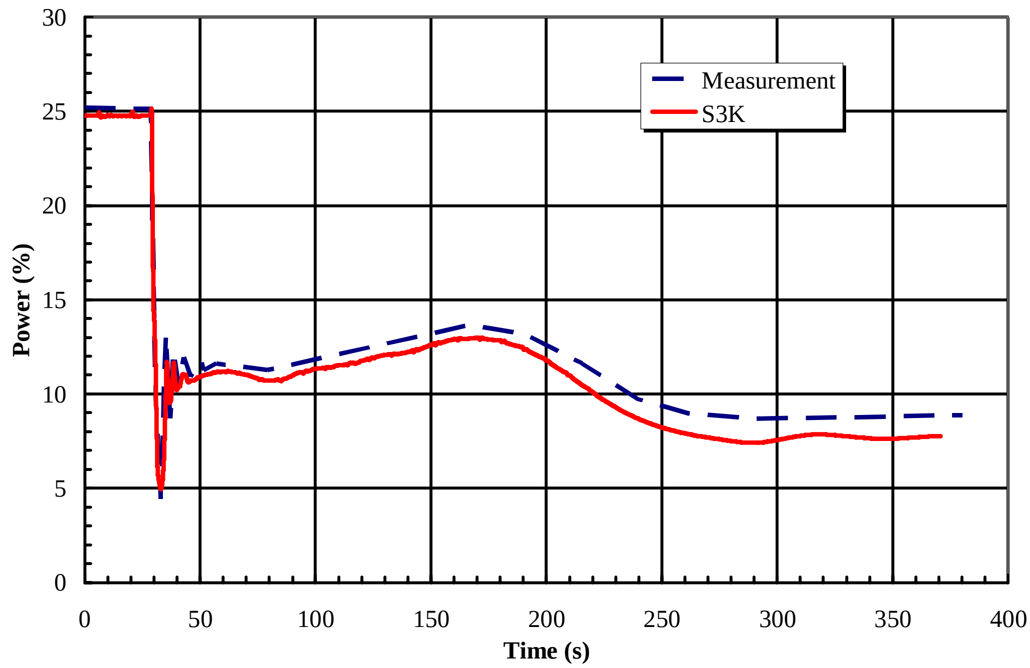

Fig. 9 Top LPRM detector response.

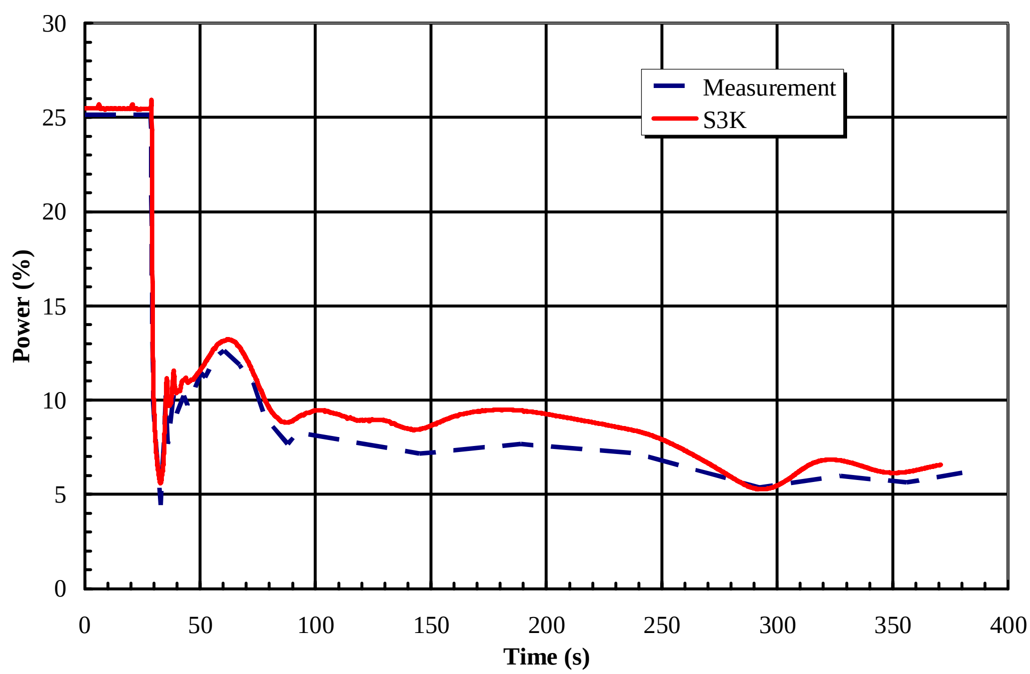

Fig. 10 Bottom LPRM detector response.

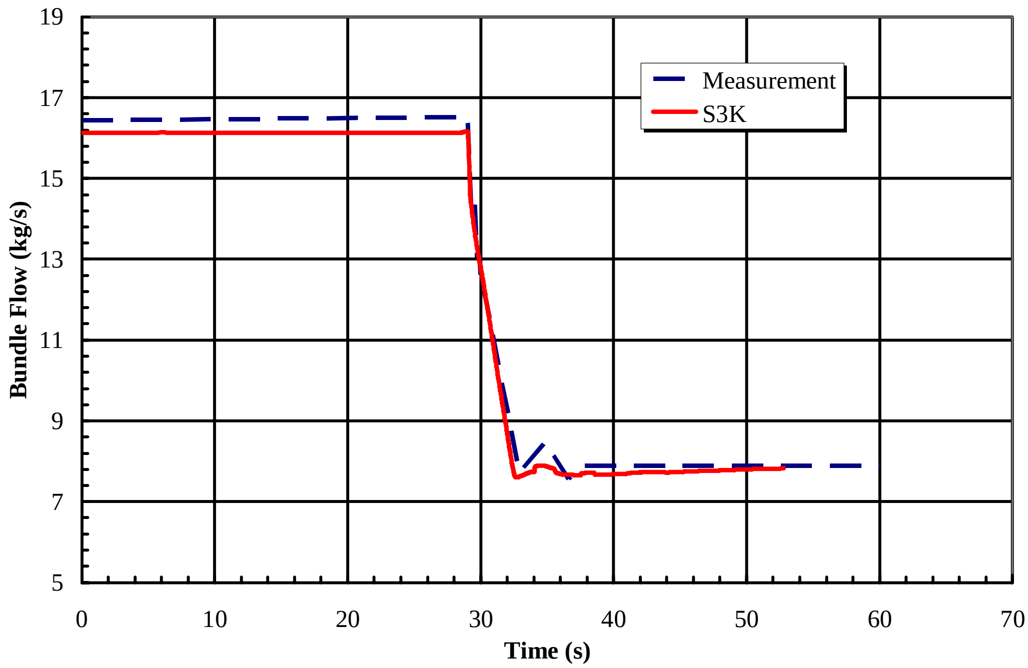

Fig. 11 Bundle inlet flow response.

5. CONCLUSIONS

S3K provides a flexible and accurate tool for simulating fast transients (Anticipated Operational Occurrences with OLMCPR requirements) during typical cycle-to-cycle safety analysis. Results from typical BWR pressurization, flow decrease, and enthalpy events, presented in this paper and in Jönsson et al.[4], demonstrate the applicability and accuracy of S3K to this class of transients and the introduction of OLMCPR evaluation based on 3D transient methods.

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