Transient 3D Methods Validation for cycle specific BWR reload analysis at TVO

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Abstract

The paper describes the application of the SIMULATE-3K code to a class of fast operational BWR transients, that are typically analyzed as part of the core reload design licensing process. The models and methods of the code are presented. Validation results are shown for two recorded fast transient events in the Olkiluoto-1 and –2 reactors. It is concluded that the code adequately captures the complicated interaction between physical processes in the reactor as well as the essential reactor protection and control systems, which qualifies it for applications to this class of fast transients.

1. Introduction

This paper describes the application of the SIMULATE-3K (S3K) code to a class of fast operational BWR transients that are typically analyzed on a cycle-specific basis as part of the core reload design licensing process. These are transients that define the Operating Limit CPR (OLMCPR), which is the primary restriction of the bundle power in the core design. Other reactor specific parameters, such as pressure in the reactor vessel, may have to be verified against safety limits.

S3K is a system code that models the core in 3D with each fuel bundle represented as a flow channel. The core neutronic model is fully compatible with SIMULATE-3, the steady-state code used for core follow and core loading design. The specific reactor systems required to model the thermo-hydraulic processes within the reactor vessel and steam lines, that are essential for the anticipated operational transients, are modeled in S3K. As a consequence of the multi-channel core model, the transient CPR evaluation can be performed explicitly for each bundle. The more approximate method of evaluating one average and one single hot channel, the so-called 1D transient methodology, can be abandoned. The methods of S3K are described in Chapter 2.

S3K has been validated against two fast transient events in the Olkiluoto-1 and –2 reactors. One of the transients is a typical turbine trip combined with a fast flow reduction and partial scram. The other transient is an inadvertent closure of the main steam isolation valves (MSIVs), where the valves closed in sequence with some delay in between. In this transient, the pump speed was partially reduced before final run-down to minimum speed level and full scram. Detailed measurement data had been recorded during both events. The S3K simulation results for the two transient events are shown in Chapter 3.

2. Model Description

SIMULATE-3K, a two group model, advanced nodal reactor analysis transient code has been described in References [1-4, 6]. The present version of the code has been gradually improved with regard to the BWR vessel and system models. The improvement of the vessel model, the steam line model and the addition of controller models makes the code suitable also for operational transients. Besides the analysis of reactivity insertion [1] and stability transients [2, 5], the following classes of transients can be analyzed: pressurization transients [6], coolant inventory or flow change transients using up to two groups of pumps, coolant temperature changes and instabilities that occur during a flow decrease/temperature events. The following sections give an overview of the models.

2.1 Core Model

The 3-D spatial neutronic model used in S3K is either the QPANDA [7] or the semi-analytical [8] advanced nodal model. The temporal neutronic model uses a fully implicit differencing of the frequency-transformed time dependent diffusion solution. The 3-D core model is nodalized with one characteristic thermal-hydraulic channel per fuel bundle (without cross flow) and variable mesh. The hydraulic model [4, 6] in S3K consists of a 5 equations, fully implicit linear 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 (e.g., there is no linearization approximation).

Intra-pin fuel temperatures and heat fluxes are computed using a fully implicit temporal differencing of the standard 1-D 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 non-linear iteration. Thermal-hydraulic feedback to nodal cross sections is computed using a library of 3-D 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 2.2-1 shows schematically the components of the vessel model. The vessel is divided into a series of 1-D components for the upper plenum, standpipes, steam separators, downcomer (with two non-mixing radial zones), two recirculation pump loops, and lower plenum (with two non-mixing radial zones). The steam dome and the bulk water region are modeled as single nodes.

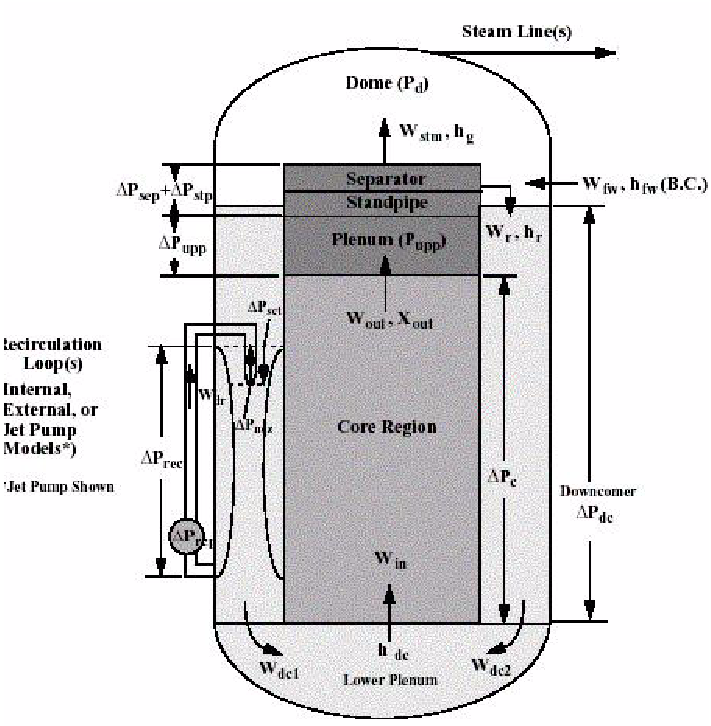


Figure 2.2-1 S3K Vessel model

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 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 descriptions. The pump speed may be given as a function of time or can be computed using the motor, hydraulic and friction torques. The steam separator model takes into account the following effects: flow inertia in the separators, pressure losses in the separators and the carry under flow. The vessel thermal-hydraulic representation is similar to the core model with 5 equations [6]. The conservation equations for all 1-D vessel components are solved using the same linear nodal scheme described previously for the core hydraulic channels. The assumptions employed in the modeling of the BWR vessel components were chosen mainly for applications to BWR stability analysis and operational transients (i.e. non-LOCA).

2.3 BWR Steam Line Model

The steam line model, taken from the RAMONA code [9], 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 2.3-1 shows schematically the components of the steam line model. The steam lines are modeled as up to four parallel lines with a specified length and diameter (which may change at branch locations). Each parallel line connects the steam dome to the turbine stop control valves (TSV/TCV) with two branch-offs at specified locations. One branch leads to the pressure relief and safety valves (SRV) and the other branch leads to the turbine bypass valves (BV). The main steam isolation valves (MSIV) are also modeled. Simplified pressure controller models are also implemented. They correspond to typical existing controller designs for jet pump reactors as well as standard internal/external pump reactors.

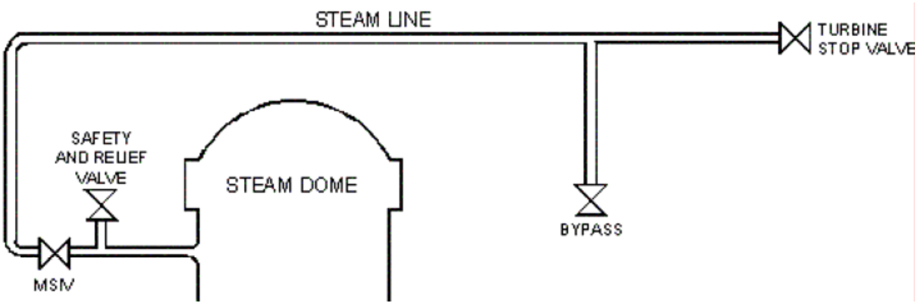


Figure 2.3-1 S3K Steam line model (one out four lines are shown)

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 implied 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. S3K Simulation of Fast Transients

Olkiluoto 1 and 2 are two identical BWR units operated by TVO on the southwestern coast of Finland. Two transient events in these reactors were simulated with S3K for code validation purposes:

In Olkiluoto 2 a turbine trip event, which caused a partial scram, occurred in 2002. The event demonstrates a well-optimized bypass valve opening at the condition of the turbine valve closure. Special focus is on the calculated pressure, power and coolant flow, in comparison with measured data.

In Olkiluoto 1 a closure of one main steam isolation valve occurred in 2004. The consecutive steam load perturbation closed the other MSIVs in sequence and created a significant pressure increase event. The decrease of steam flow in one steam line and the increase in the other three steam lines are of special importance in this transient and has to be captured by the code.

3.1 Turbine Trip with Fast Flow Reduction

Besides the general objective of validating the system response to pressure and flow perturbations, of special interest in this validation is to demonstrate the applicability of the pressure controller model in the typical situation of power and flow fast reduction. The turbine trip, control valve closure with simultaneous bypass valve opening, is a typical condition that appears after e.g. a pump trip. Secondary objectives are to verify the 3D power impact on the partial scram and the coolant flow prediction during the pump run-down.

A turbine trip created a pump speed reduction from nominal to minimum in about five seconds in Olkiluoto 2 on the 14 February 2002. The pressure is perturbed when the four turbine valves close and the bypass valves open. The pressure reaches a maximum of 70.1 bar(g) and a minimum of 67.8 bar(g). After the initial perturbation the pressure levels off at the pressure set-point, which is a result of the control of the bypass valve. The total steam flow is measured in the steam lines close to the reactor. The steam flow oscillates due to the pressure disturbance created by the turbine valve closure and the bypass valve opening. When the power is reduced (due to the pumps rundown and insertion of a control rod group) the steam flow decreases to a minimum value and stays close to this minimum.

The calculated results are shown below. The turbine control valve closure starts at time 46.5 sec. The bypass valve opening (Figure 3.1-1) starts at the same time. The calculated pressure (see Figure 3.1-2) is in good agreement with the measured pressure during the initial perturbation phase.

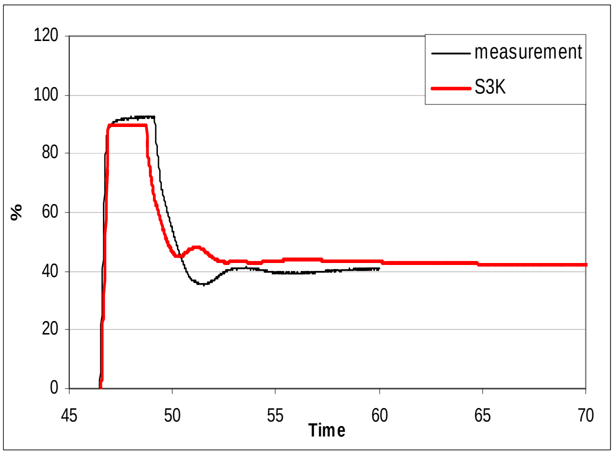


Figure 3.1-1 Bypass valve position

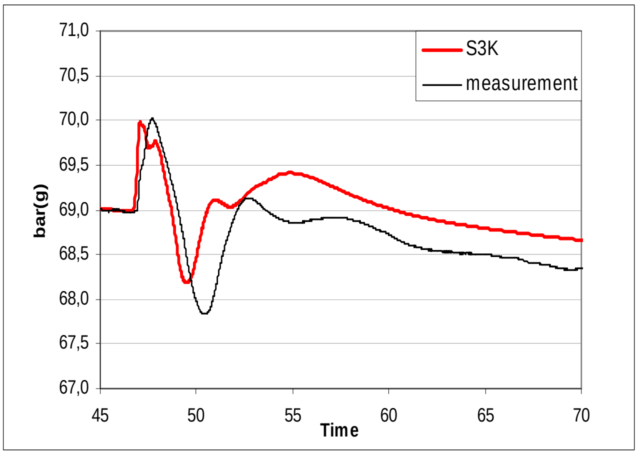


Figure 3.1-2 Steam dome pressure response

The power (see Figure 3.1-3) depends on the partial scram and the reduction of the main recirculation flow. The power is in excellent agreement with the measurement.

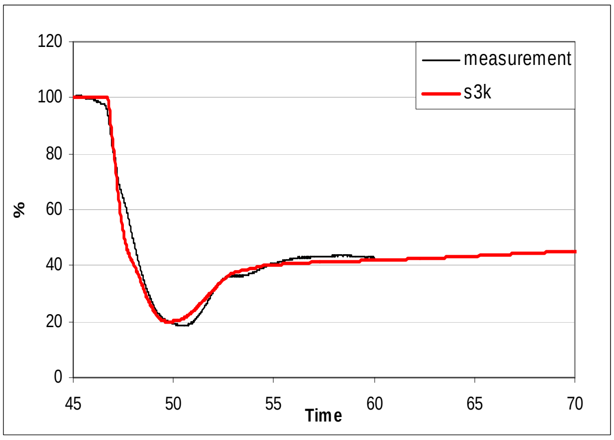


Figure 3.1-3 Core power response

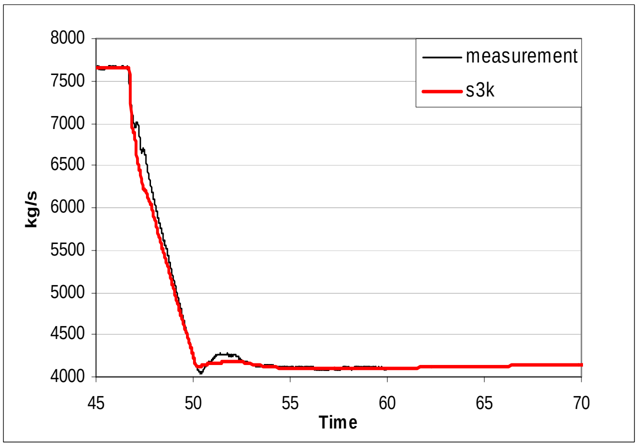


Figure 3.1-4 Core flow response

The pump speed ramp and the initial coolant flow are specified boundary conditions. The initial pump speed is calculated nearly exact and the calculated and measured main recirculation flow transients (Figure 3.1-4) are in good agreement. The minimum flow is, e.g. captured very well. The pump model in S3K captures the event accurately.

The validation result is summarized as:

- The pressure controller captures the pressure variations in an adequate way.
- The minimum core flow is very well predicted, indicating that the general pump and reactor models are accurate.
- The global power is in good agreement with the measurements, indicating that the combined effects of 3D control rod effects and coolant flow reduction are accurately modeled.

3.2 Sequential Main Steam Isolation Valve closure

The objective of this validation is to verify that the parallel steam line model can capture the asymmetrical steam flow behavior in the steam lines.

The MSIVs (See Figure 3.2-1) are normally fully open and close at conditions when reactor or turbine conditions exceed specific thresholds. A magnet holds each MSIV in the open position. If, e.g. the steam flow through the valve becomes very high the force of the magnet is exceeded and the MSIV will close immediately.

On the 7:th March 2004, starting from nominal conditions, one (out-of-four) MSIV closes erroneously (valve V1) in Olkiluoto 1. During the following second, first valve V3 closes then right after the V4 valve closes, due to the higher steam flow. Valve V2 had a stronger magnet: allowing more steam flow. However all three valves closed due to high steam flow (see Figure 3.2-1). The valve closures caused the reactor pressure to increase. Due to the void collapse and positive reactivity insertion, the fission power increased as well.

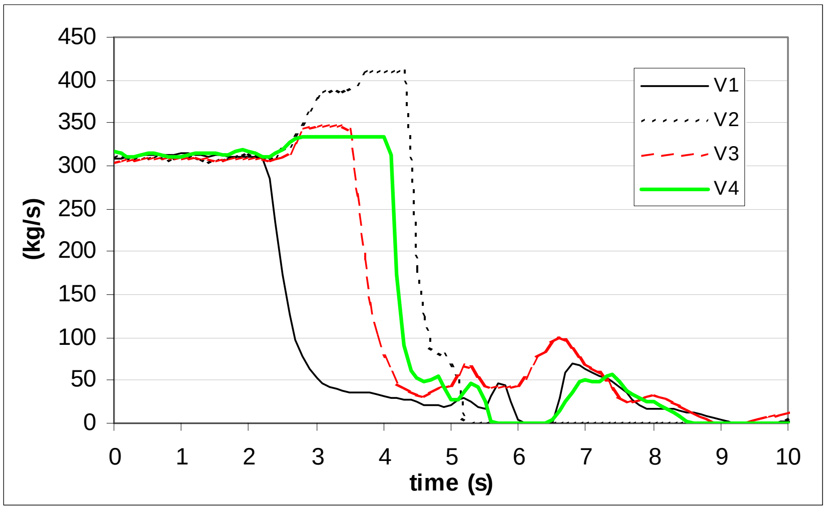


Figure 3.2-1 Measured steam flow response

The automatic pump speed reduction started when the power reached 116 % (and ended when the power decreased below 116%). The following flow reduction stopped the power increase due to increased voiding. Due to the second, third and fourth MSIV closures the power increased above the 122 % scram limit causing a complete control rod scram and fast pump run-down. The pressure in the reactor reaches a peak of 76.8 bar(g).

The steam flow is practically constant during the first part of the valve closure (1.3 sec) and the effective steam flow decrease takes place during the last 0.1 seconds of the closure. The increase of steam, in the other steam lines, is dependent on the increase in steam dome pressure and the pressure controller acting on the turbine control and bypass valves. The measured steam flow passes the measurement saturation levels for the other three steam lines. The exact self-closing steam flow threshold is therefore unknown.
In the simulation the initial event (first valve closure) and the measured times for the other three closures is defined in input. The calculated steam flows and global parameters such as flow, power, pressure, water level, etc, are compared with the measured parameters in order to verify that the event is well understood and that S3K can capture the important physical effects.

The core coolant flow decreases due to the first violation of the 116% power threshold (see Figure 3.2-2 and 3.2-3). At the time of the repeated MSIV closures both the 116% and the 122% (scram) lines are violated and a non-stoppable pump speed reduction to minimum level is initiated.

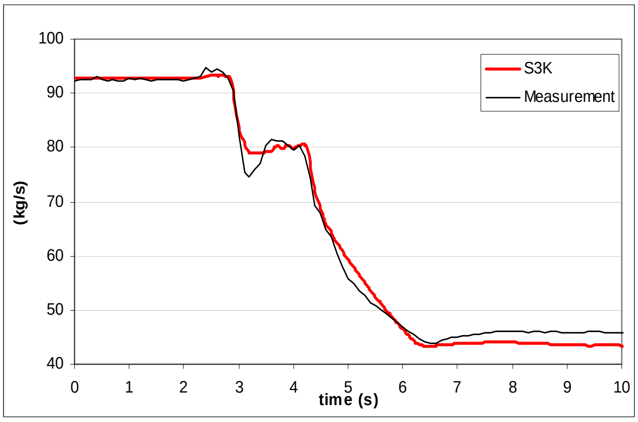


Figure 3.2-2 Core coolant flow response

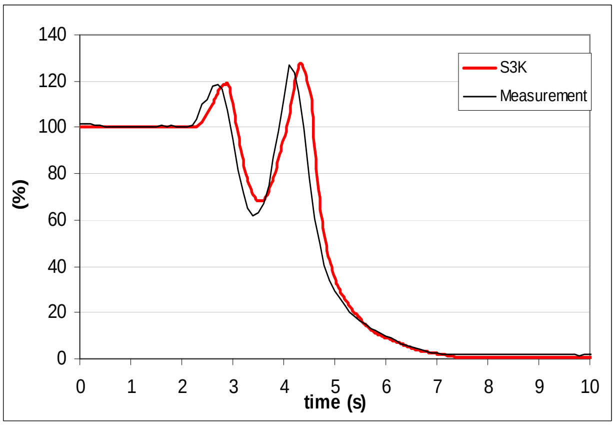
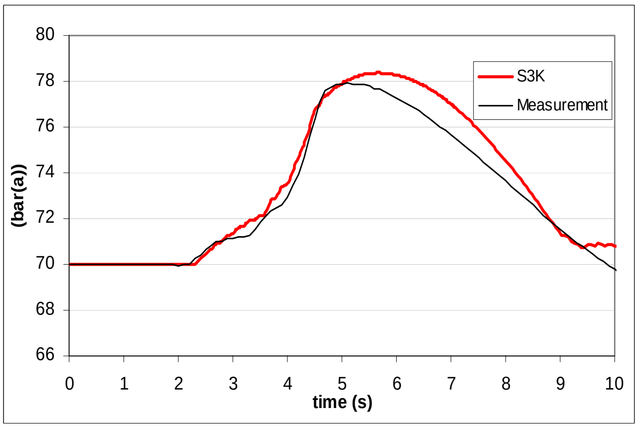


Figure 3.2-3 Total power response

The S3K calculation captures the essential flow reduction.

The power transient is a delicate combination of reactivity insertion, caused by pressure increase, and flow reduction caused by the passing of the 116% power threshold. When the power for the first time passes 116%, a temporary pump speed decrease is initiated, during the time the 116%-line is violated. The power decreases to a level just above 60% (see Figure 3.2-3). The second time the power starts to increase, due to the sequential MSIV closure both the 116% and the 122% lines are violated. The scram (on power 122%) and the recirculation pump speed decrease terminate the transient. The S3K calculation captures the essential power variation.

The relief valves open after the pressure passes 74 bar(a). The resulting pressure transient is shown in the Figure 3.2-4.



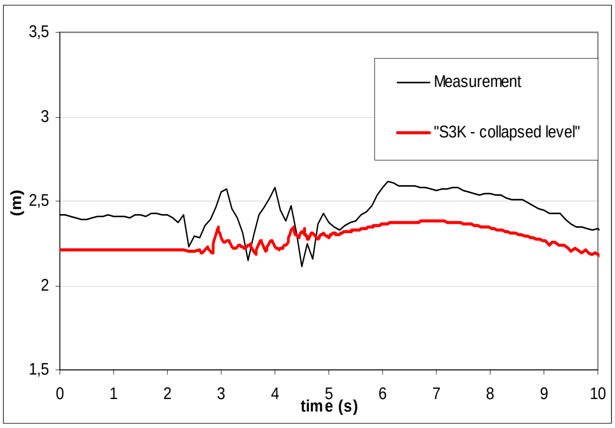


Figure 3.2-4 Steam dome pressure response

Figure 3.2-5 Water level response

The pressure transient is reasonably captured in the simulation. The measured and calculated water levels (see Figure 3.2-5) are also in reasonable agreement.

The validation result can be summarized as:

- The MSIV closure event is well understood and can be modeled by the code. The detailed power, flow and pressure transients are well captured.
- The turbine stop valves, bypass valves, MSIVs and the safety valves are modeled adequately.

4. Summary and Conclusions

SIMULATE-3K is proven to be a flexible and accurate tool for simulating fast transients for typical cycle-specific safety analysis (CPR-limiting operational transients). The chosen pressurization, flow decrease and power increase events demonstrate the applicability and accuracy of the code.

More specifically, the validation shows:

- The S3K pump model can be used to simulate threshold driven changes and combinations of tripped and controlled pumps.
- The calculated power and pressure increase events are well captured by the code.
- The S3K steam line model accurately models the pressure waves after valve closures/opening of MSIVs, turbine valves, safety&relief valves as well as bypass valves.
- The S3K pressure controller is appropriate for the turbine trip situation that appears in many fast transients.

The fast transient analysis, using S3K, is an on-going effort, where several validation and CPR comparisons are included. The methodology is targeted to the reload analysis of the Anticipated Operational Occurrences as one part of the cycle specific safety analysis.

5. References

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