BWR STABILITY ANALYSIS WITH SIMULATE-3K

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ABSTRACT

SIMULATE-3K is a two group, advanced nodal reactor analysis transient code. It has been used by many utilities for the prediction and analysis of BWR stability events. In recent years, several enhancements of the SIMULATE-3K channel and vessel thermal-hydraulic model have been made. This paper summarizes the status of the SIMULATE-3K core and vessel models. It presents results for the Ringhals-1 Stability Benchmark and for regional instability in a large BWR. Finally, modeling sensitivities to space and time discretization are discussed.

1. INTRODUCTION

SIMULATE-3K, a two group, advanced nodal reactor analysis transient code has been described in references [1 - 3]. In recent years, several enhancements of the SIMULATE-3K channel and vessel thermal-hydraulic model have been made. The most extensive changes that have occurred are related to the BWR vessel models. The implementation of discretized vessel models into SIMULATE-3K extends its range of applicability to operational transients. Therefore, the main application areas for SIMULATE-3K belong to the following classes of transients: reactivity insertion transients, pressurization transients, coolant inventory or flow rate changes transients, coolant temperature transients and instabilities (core wide and regional oscillations).

The objective of this paper is twofold: (1) to summarize the present status of the SIMULATE-3K models and (2) to present some stability analysis results after the implementation of the discretized vessel models. Section 2 is devoted to a brief description of SIMULATE-3K core and BWR vessel models. Section 3 presents the stability analysis results including: (a) the latest calculations for the Ringhals-1 Stability Benchmark [4], (b) results for regional instability in a large BWR, and (c) a sensitivity study to space and time discretization. The application of SIMULATE-3K to an operational transient (Peach Bottom Turbine Trip Transient [5]) is presented as a separate paper in this proceeding [6].

2. MODELS

2.1 CORE MODELS

The 3-D spatial neutronic model used in SIMULATE-3K is either the QPANDA [7] or SANM [8] advanced nodal model. The temporal neutronic model uses a fully implicit differencing of the frequency-transformed time-dependent diffusion equation.

The 3-D hydraulic core model is nodalized with one characteristic thermal-hydraulic channel per fuel bundle (without cross flow) and variable axial mesh. The hydraulic model [9] in SIMULATE-3K has been extended to a six-equation, 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 condition 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 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 MODELS

Figure 1 shows pictorially 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 2 non-mixing radial zones).

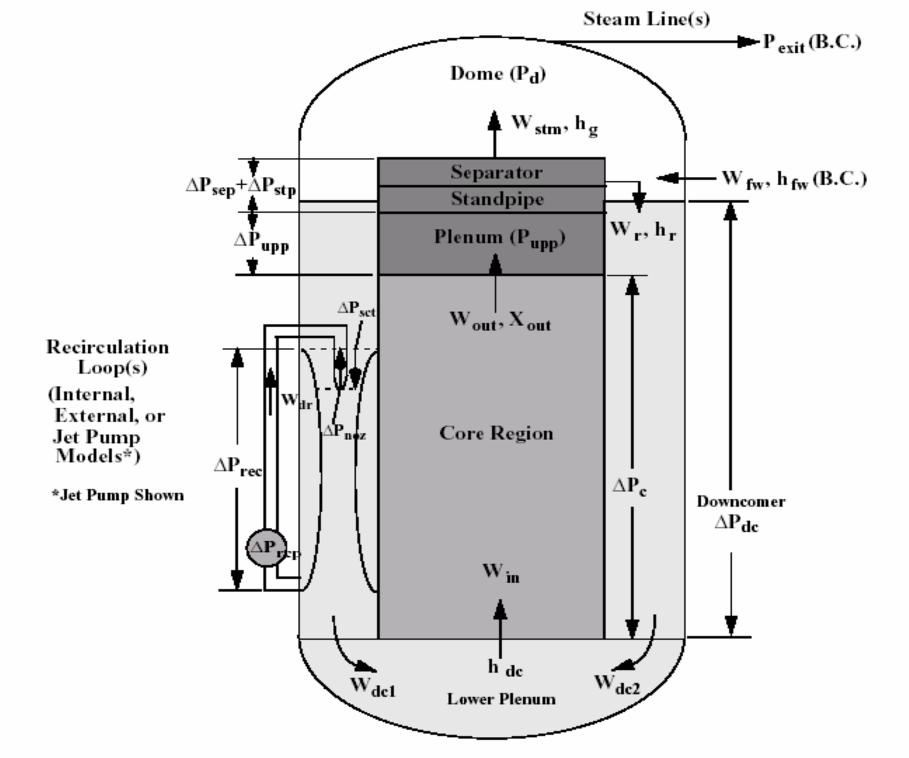

Figure 1. BWR vessel model components.

Special models are included in SIMULATE-3K to calculate specific flow conditions. They include: recirculation pumps, jet pumps and steam separators. The recirculation pumps, one in each of the 2 recirculation loops, drive the recirculation flow through the recirculation loops into the jet pumps or drive the core flow in a plant with internal 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 the pump flow rate and speed using homologous pump curves. The pump speed may be given as a function of time or can be computed using the motor, hydraulic and friction torques. The jet pump model calculates the pump head in the internal jet pumps. All the jet pumps in one recirculation loop are lumped together. The pressure increase is imposed at the jet pump location as a momentum jump condition, without inertia or gravity effects. No mass is introduced into or taken out from the main hydraulic loop by the pump model. The jet pump model consists of a mixing region in which the drive flow is mixed with the suction flow and one recirculation (drive) loop containing the recirculation pump. The steam separator model takes into account the following effects: flow inertia in the separators, pressure losses in the separators and carry under flow.

The external systems are partially considered. The effect of the turbine and the steam line can be modeled explicitly by means of the steam line model. The steam line model, taken from the RAMONA code [10], 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 line. Figure 2 shows pictorially the components of the steam line model. The steam line, as modeled, consists of a single pipe with specified length and diameter (which may change at branch positions), connecting the steam dome with the turbine valve and two branches at specified axial locations. One branch leads to the pressure relief and safety valves and the other branch leads to the turbine bypass valve. A main steam isolation valve (MSIV) is also modeled. A simple pressure controller may be included in the steam line model to control the turbine and bypass valves. The effect of the feedwater system can be modeled by means of a feedwater controller and/or disturbances in the feedwater flow and temperature.

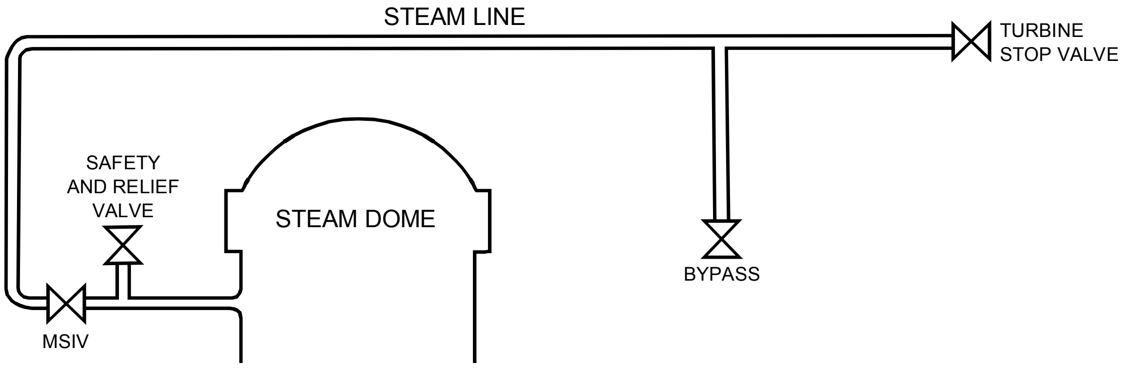

Figure 2. Steam line model.

The vessel thermal-hydraulic is similar to the five equation model for the core hydraulic channels [9]. The conservation equations for all 1-D vessel components are solved using the same linear nodal scheme described previously for 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).

3. RESULTS

3.1 RINGHALS-1 STABILITY ANALYSIS BENCHMARK

The BWR vessel models play an important role in global oscillations because the different pressure drops in the vessel components may damp (or amplify) the core oscillations. Therefore, the influence of the recently implemented vessel models must be assessed. SIMULATE-3K calculations for the Ringhals-1 BWR Stability Benchmark [4] have been presented in reference 2 using a previous version of the vessel models (in which a single node describes each vessel component). The calculations were repeated using the present SIMULATE-3K version. Table 1 summarizes the stability results in terms of the decay ratio and natural frequencies for cycles 14-17. The results from reference 2 are included as a comparison. Note that the mean decay ratios are accurately predicted for all cycles. Recently, stability calculations using the present Ringhals-1 model have been extended to later cycles (20 -24) with similar accuracy.

Table 1. Statistical Summary of the Ringhal-1 Stability Benchmark results.

	Present results				Results reference [2]	
	Decay ratio		Natural frequency (Hz)		Decay ratio	
	Bias	Std. Dev.	Bias	Std. Dev.	Bias	Std. Dev.
Cycle 14	-0.040	0.062	0.005	0.017	-0.028	0.086
Cycle 15	+0.060	0.072	0.028	0.024	+0.038	0.073
Cycle 16	+0.029	0.047	0.02	0.009	+0141	0.056
Cycle 17	+0.006	0.109	0.054	0.049	+0.116	0.058
All cycles	+0.014	0.080	0.021	0.033		

Figures 3 and 4 display the comparison of computed and measured global decay ratios and natural frequencies respectively.

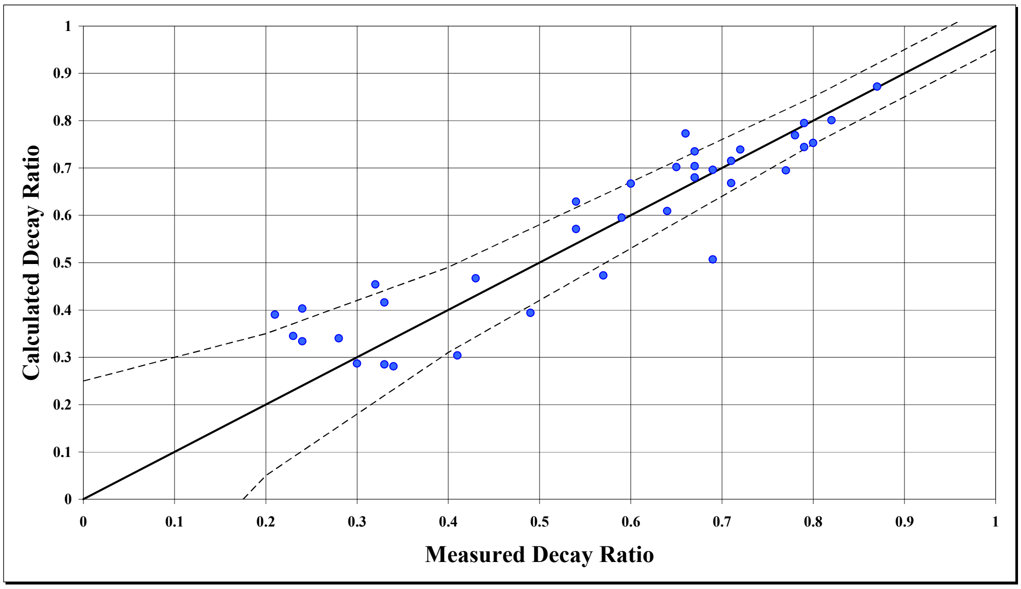

Figure 3. Ringhals-1 Stability Benchmark. Global decay ratios comparison.

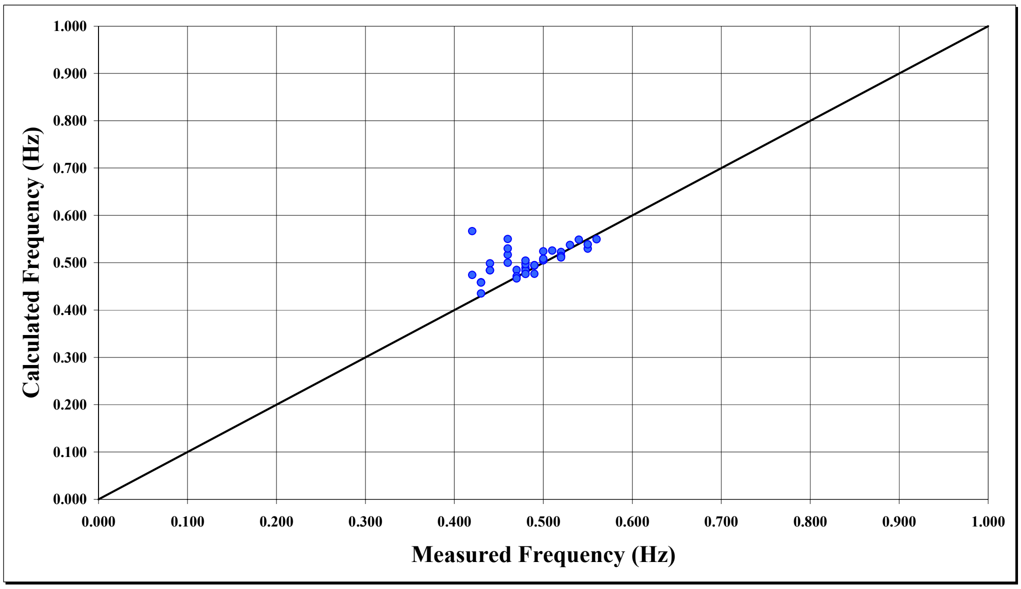

Figure 4. Ringhals-1 Stability Benchmark. Natural frequency comparison.

Figure 5 compares two sets of computed global decay ratios for all measurements with decay ratio greater than 0.4. The cases with low decay ratio were left out because their statistic is very poor. The first set of calculations was performed including the vessel models (standard stability calculations), and the second set was computed with a core model imposing fixed plenum pressures as hydraulic boundary conditions.

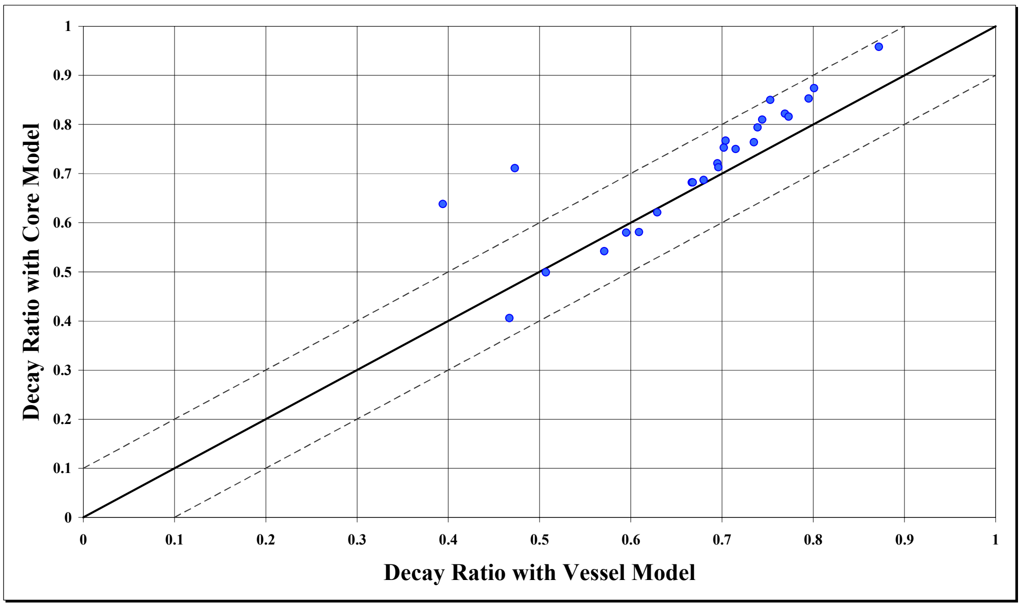

Figure 5. Comparison of global decay ratios computed with the vessel model and with a core model.

This comparison shows that the vessel models damp the core global oscillations for most of the cases. The results from other plants confirm this observation. Results from several plants show that in general the damping (core decay ratios vs. vessel decay ratios) is a function of the decay ratio itself.

3.2 CORE REGIONAL INSTABILITY

As mentioned before, the effect of the vessel model is very important for core global oscillations, where the different pressure drops in the vessel model may amplify or damp the flow oscillations. However, for core regional oscillations the effect of the vessel models is much less significant, as illustrated below.

A divergent regional instability case in a large BWR was simulated using three different models: (a) a complete vessel model, (b) a core model with imposed core inlet flow and channel pressure balance as hydraulic boundary conditions and (c) the same core model as in (b), but imposing fixed lower and upper plenum pressures as hydraulic boundary conditions.

Figure 6 displays results of computations (a) and (b) while Figure 7 compares the results of computations (a) and (c). The SIMULATE-3K vessel model predicts the growth rate of the oscillations quite close to that measured. One interesting result presented in Figure 6 is that the regional instability can be well predicted without a vessel model. Computations with just the core model predict nearly the same growing oscillations as with the vessel model, provided appropriate boundary conditions are used.

Note that if the traditional assumption of constant plenum pressure is made, the computed results do not have the correct growth rate (Figure 7). Moreover, a global pattern of oscillation will develop, even if the initial perturbation is non-symmetric. However, if a constant total inlet flow and a spatially uniform (but not temporally constant) channel pressure drop condition are imposed, the regional instability can be accurately modeled.

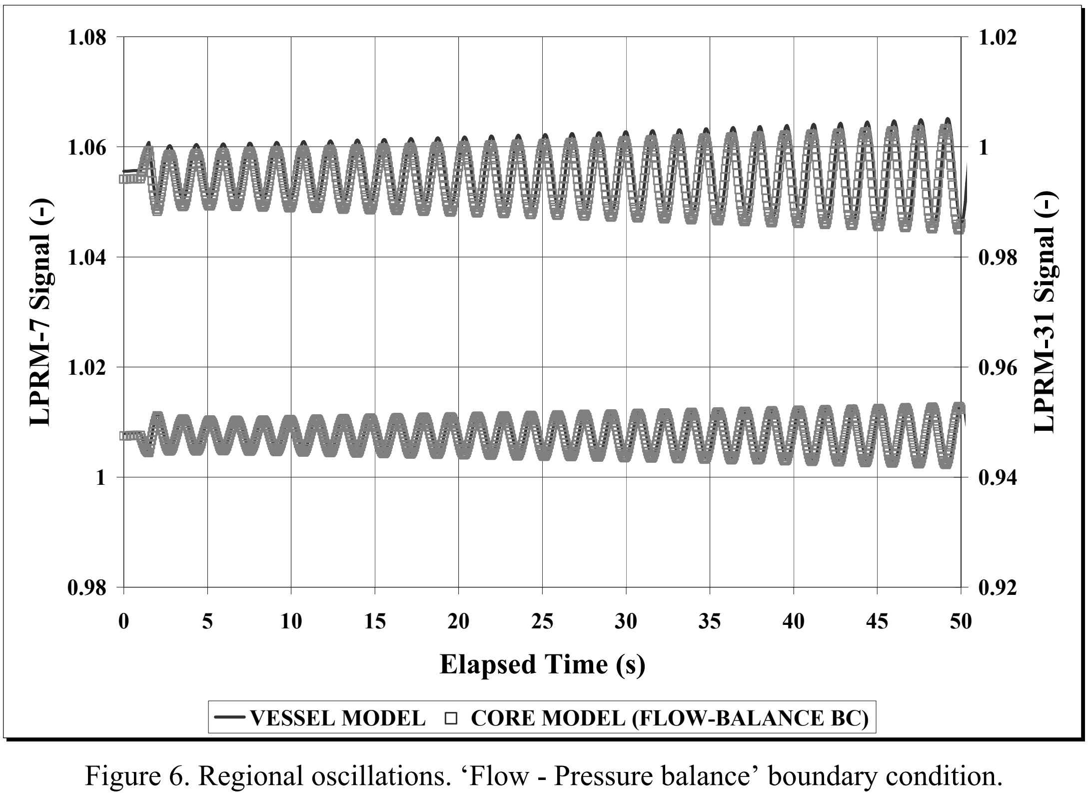

Figure 6. Regional oscillations. ‘Flow - Pressure balance’ boundary condition.

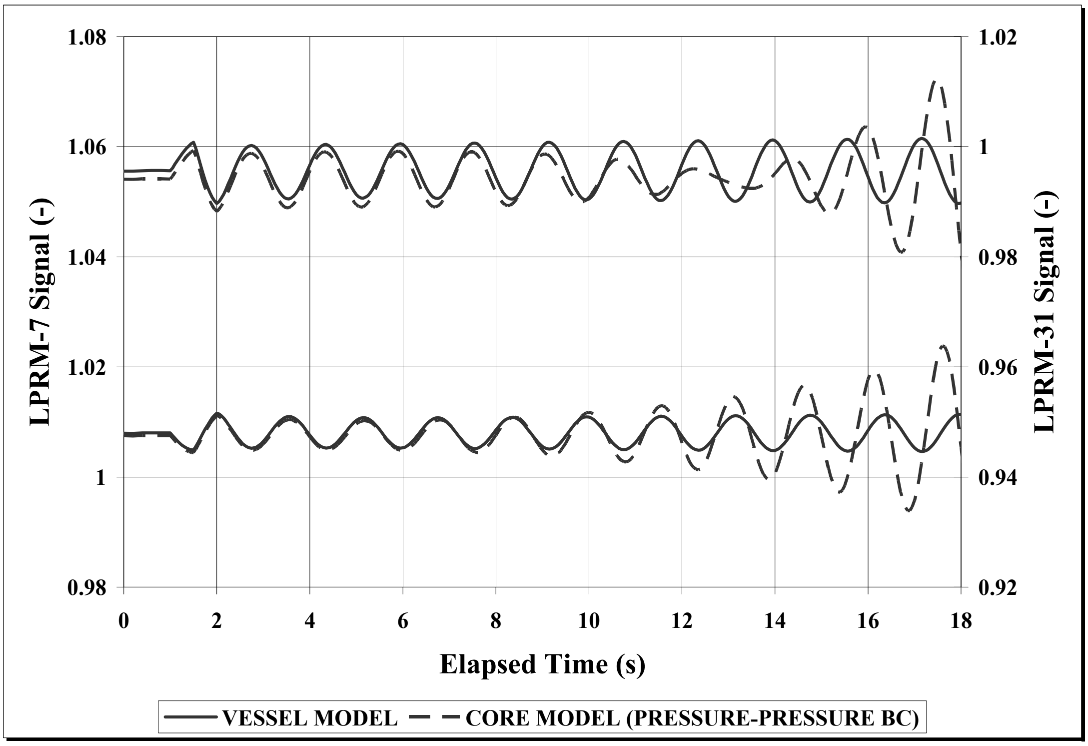

Figure 7. Regional oscillations. 'Pressure – Pressure' boundary condition.

3.3 SENSITIVITY ANALYSIS TO THE TIME AND SPATIAL DISCRETIZATIONS

Decay ratios are sensitive to many model parameters, among the most important ones are: (a) the time step used to solve the neutronic and hydraulic equations, (b) the axial neutronic and hydraulic mesh and (c) the radial discretization. The effect of the radial discretization will not be discussed here because all the fuel assemblies are always explicitly represented by one neutronic and one hydraulic channel in the SIMULATE-3K calculations (i.e. there is no lumping in the radial direction).

SIMULATE-3K standard stability calculations, use 24 axial neutronic and hydraulic nodes in the core (i.e. a node size of approximately 15 cm). Each of the 1-D components in the vessel model is discretized into 50 nodes. The calculations are performed with neutronic time steps of 50 ms and 4 hydraulic time steps per neutronic time step (i.e. a hydraulic time step of 12.5 ms).

Table 2 summarizes the results from a time step size sensitivity study performed for 4 cases of Ringhals-1 cycle 16. The cases were selected because they represent decay ratios in the region of interest for core design applications (0.5 – 0.9). The results are summarized as 'delta decay ratios', i.e. the difference between the calculated decay ratio for each selected time discretization and the decay ratio predicted by the standard calculations (neutronic time step of 50 ms, hydraulic time step 12.5 ms).

Figure 8 displays the effect of changing the hydraulic time step for a fixed neutronic time step (50 ms), and Figure 9 displays the effect of changing the neutronic time step for a given hydraulic time step (12.5 ms). Note that an increase in the hydraulic time step has a clearly damping effect while the neutronic time step has the opposite effect.

Table 2. Effect of the time discretization. Delta decay ratio vs. time step size.

	Hydraulic time step (ms)	Neutronic time step (ms)		
		12.50	25.00	50.00
Case 9	6.25	-0.02	0.00	0.04
	12.50	-0.06	-0.04	**0.00**
	25.00		-0.11	-0.07
	50.00			-0.18
Case 11	6.25	-0.02	0.00	0.04
	12.50	-0.06	-0.04	**0.00**
	25.00		-0.10	-0.07
	50.00			-0.17
Case 04	6.25	-0.02	0.00	0.03
	12.50	-0.05	-0.03	**0.00**
	25.00		-0.08	-0.06
	50.00			-0.15
Case 01	6.25	-0.02	0.00	0.03
	12.50	-0.04	-0.03	**0.00**
	25.00		-0.07	-0.04
	50.00			-0.12

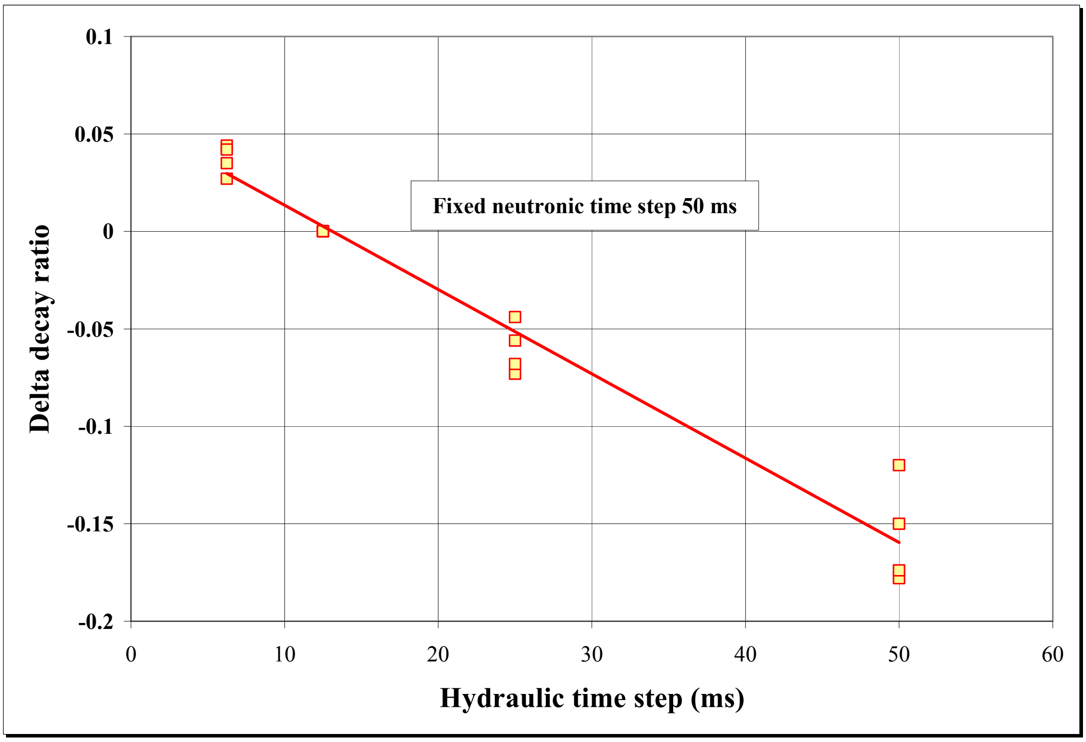

Figure 8. Effect of the time discretization. Delta decay ratios vs. hydraulic time step for a given neutronic time step (50 ms).

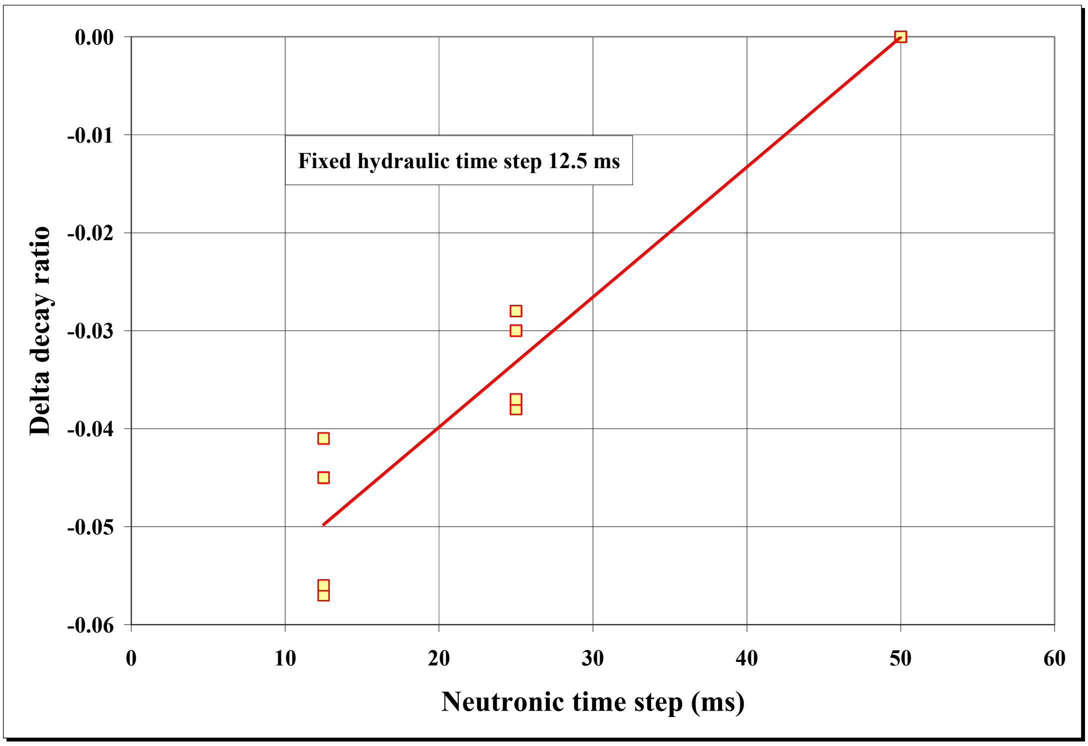

Figure 9. Effect of the time discretization. Delta decay ratios vs. neutronic time step for a given hydraulic time step (12.5 ms).

Overall, the time step combinations in the standard solution (neutronic time step 50 ms and hydraulic time step 12.5 ms) differ no more than 0.02 from the most refined time step discretization (neutronic time step 12.5 ms and hydraulic time step 6.25 ms).

Table 3 summarizes the results from an axial nodalization sensitivity study performed for three of the cycle 16 cases, namely case 9, case 4 and case 1. The results are again presented as 'delta decay ratios', i.e. the difference between the calculated decay ratio for each axial discretization and the decay ratio predicted by our standard calculations (24 axial neutronic nodes and 24 hydraulic nodes). Figure 10 displays the results for case 9 as an example.

It can be seen that results are very sensitive to the hydraulic axial mesh, and decay ratios predicted with 8 or 12 axial hydraulic nodes are far from converged. The axial nodalization of the fuel assembly into 24 nodes introduces a damping effect of no more than 0.05 in decay ratio when compared with 96 axial nodes. The effect of the spatial discretization can be removed for all practical purposes by using 48 nodes. The increase of the number of neutronic nodes from 24 to 48 changes the decay ratio less than 0.02.

Table 3. Effect of the space discretization. Delta decay ratio vs. number of axial nodes.

	Number hydraulic axial nodes	Number neutronic axial nodes	
		12	24
Case 9	8		-0.23
	12	-0.17	-0.05
	24	-0.08	**0.00**
	48	-0.06	0.04
	96		0.05
Case 4	8		-0.16
	12	-0.12	-0.05
	24	-0.04	**0.00**
	48	-0.03	0.03
	96		0.04
Case 1	8		-0.15
	12	-0.08	-0.05
	24	-0.04	**0.00**
	48	-0.03	0.02
	96		0.03

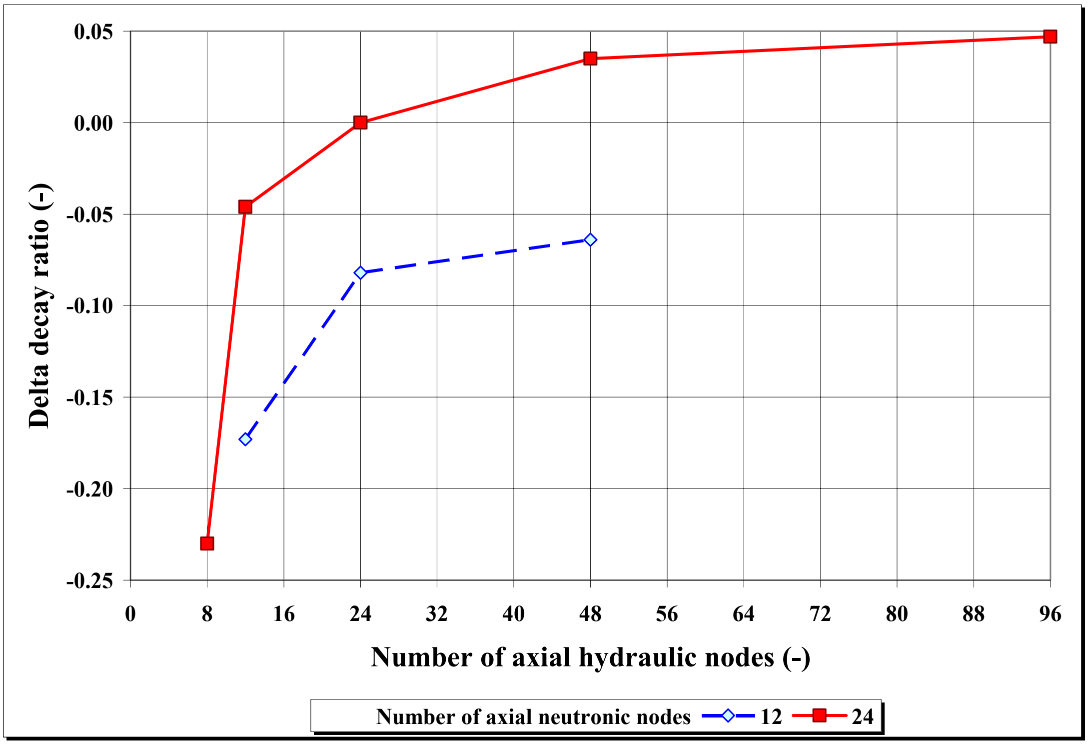

Figure 10. Effect of the space discretization. Delta decay ratio vs. the number of axial nodes for case 9.

CONCLUSIONS

SIMULATE-3K provides a very flexible and accurate tool for BWR stability analysis. The results of the Ringhals-1 Stability Benchmark [4] as well as other stability calculations performed by utilities allow us to conclude that decay ratios and natural frequencies are well predicted by SIMULATE-3K. SIMULATE-3K is also capable of accurately predicting instability events [11], including regional instabilities.

The influence of the BWR vessel model has been assessed. The vessel models damp the core global oscillations. The damping effect cannot be described as a single bias. Instead, it is a function of the decay ratio. In contrast, it is interesting to note that core regional oscillations can be computed accurately using only a core model if appropriate hydraulic boundary conditions are imposed. The methodology presented in this paper allows the calculation of both global and regional modes in a straightforward manner.

The standard time discretization (50 ms neutronic time step and 4 hydraulic time steps per neutronic time step) introduces a small damping effect (0.02 in decay ratio). The standard axial spatial discretization (24 or 25 axial nodes) has a damping effect of at no more than 0.05 in decay ratio. The effect of the space discretization can be removed, if desired, by increasing the number of axial from 24 to 48. But for all practical purposes a core model with 24 axial nodes is accurate enough.

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