SIMULATE-3K stability benchmarking and predictive calculations of Leibstadt

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Abstract

SIMULATE-3K (S3K) has been used to investigate the stability margins of Leibstadt. The model has been benchmarked against stability measurements in Cycle 19 and used for predictive calculations in Cycle 23. The paper presents results of the Cycle-19 benchmark and verification of stability exclusion and surveillance regions for the Cycle 23 core in the presence of an increasing use of modern fuel bundles with partial-length rods. The close agreement between calculations and measurements helps establish the S3K model as a reliable tool for predictive stability calculations in Leibstadt.

1. Introduction

This paper presents the benchmarking of the SIMULATE-3K (S3K) (Grandi 2006) Leibstadt (KKL) model against the Cycle 19 stability measurements (Aguirre 2003) and the predictive calculations for Cycle 23 for a number of cases defined by KKL (Aguirre 2006).

S3K has been benchmarked against stability measurements in Scandinavia and Germany (internal and external pump plants) (Grandi and Smith 2002, Gorzel 2005). However, no measured data exist for jet pump plants, except for KKL. The Cycle 19 set of calculations fills the gap in the S3K stability benchmark database.

The aim of the Cycle 23 calculations was to verify the validity of the stability exclusion and surveillance regions for a core entirely loaded with part length rod assemblies including SVEA 96 Optima, SVEA 96 Optima 2, and ATRIUM 10XP, and to observe the evolution of the stability of KKL with increasing amount of modern fuel with partial-length rods.

The CMS model was developed by Studsvik Scandpower (SSP) starting from Cycle 14. Depletion from Cycle 14 to Cycle 23 was performed together with comparison to Traversing In-Core Probe (TIP) measurements performed periodically at full power. CMS stands for Studsvik in-core fuel management system.

Note that other authors have used another dynamic code, RAMONA (3 and 5), to assess the stability of the KKL core (Hennig 1999, Grandi 2005) and to investigate the nonlinear aspects and limit cycle characteristics of the oscillations (Dokhane 2007). This paper does not attempt to

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address model differences between RAMONA and S3K and is strictly concerned with linear stability predictions.

2. Stability measurements

Stability measurements were performed at the beginning of Cycle 19. This was part of a commitment that KKL made to conclude the power upgrade to 3600 MWth. The test points were chosen based on earlier tests to validate the Maximum Extended Operating Domain (MEOD) line as well as the stability monitoring and exclusion zones in the power-flow map. The tests were also used to qualify the stability monitoring system COSMOS, which calculates online decay ratio (DR) and oscillation frequency using noise analysis of 29 LPRM and 2 APRM signals.

A total of eleven test recordings were conducted, each lasting about 10 minutes, eight performed with the recirculation pumps running at high speed and three with the pumps in low speed. Digital signal recordings of eight LPRM signals, all APRM signals, and a number of process signals (pressure, coolant flow, steam flow, etc.) were made using the data acquisition system GETARS with a 40-Hz sampling frequency. These were later analyzed to extract DR and frequencies (Dokhane 2005). At the same time, the DR from COSMOS was also recorded. Also, at each measurement point, during the recording phase, four simultaneous TIP campaigns were performed with the aim to test the code performance at off-rated conditions.

Table 1 gives a summary of the measurements, power and flow conditions together with the stability parameters produced by COSMOS and noise analysis of the APRM signals. Note that Recording #2 was not included in the analysis. It was found to be inappropriate because it was too short. Also 100% power and flow correspond to 3600 MWth and 11151 kg/s, respectively.

Table 1
Summary of measured results in Cycle 19

Case	Power (%)	Flow (%)	Mean COSMOS DR	APRM Noise Analysis (PSI)	
				DR	Freq
1	72.3	51.2	0.40 ± 0.06	0.43 ± 0.07	0.68 ± 0.02
3	74.3	48.9	0.42 ± 0.04	0.46 ± 0.07	0.67 ± 0.02
4	74.2	49.2	0.43 ± 0.04	0.55 ± 0.06	0.70 ± 0.01
5	59.6	44.9	0.46 ± 0.05	0.49 ± 0.07	0.65 ± 0.02
6	70.0	44.6	0.64 ± 0.06	0.68 ± 0.09	0.66 ± 0.02
7	54.5	41.4	0.59 ± 0.07	0.59 ± 0.06	0.63 ± 0.02
8	61.1	41.0	0.74 ± 0.05	0.71 ± 0.04	0.63 ± 0.01
9	35.1	36.1	0.45 ± 0.04	0.40 ± 0.11	0.47 ± 0.02
10	47.6	36.2	0.62 ± 0.06	0.64 ± 0.05	0.59 ± 0.01
11	43.1	36.1	0.52 ± 0.06	0.54 ± 0.10	0.54 ± 0.02

3. SIMULATE-3K calculations of the Cycle-19 measurements

3.1. Steady-state results

A detailed SIMULATE-3 (S3) model of the test period was set up using the recorded operating conditions. This included calculating the total bypass flow based on the bundle geometries and thermal-hydraulic data. The Martinelli-Nelson (MN) two-phase friction multiplier has been used. Note that the use of the explicit bypass flow fraction calculation and the MN correlation gave the closest agreement with PRESTO-2 (P2) in terms of flow distributions and the best agreement with the stability measurements. P2 is the code used for core design and online monitoring at KKL.

TIP comparisons for Recordings 4, 6, 8, and 10 were performed. An example of TIP comparison is given in Figure 1 which shows S3K distributions together with measured data for Recording #8 at the four core locations monitored during the tests. The S3K results agree well with the measurements.

3.2. Stability calculations

The standard S3K options for stability calculations were used: 25 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 (upper plenum, steam separators, downcomer and lower plenum) is discretized into 50 nodes. The stability calculations were 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).

Comparisons to the measured decay ratios are shown in Table 2 and Figure 2 below. Overall, the decay ratio agrees well with the measurements. However, the frequency is systematically under predicted. This was observed by others in the application of RAMONA to the Cycle 19 benchmark. The reason for the bias in resonance frequency is still under investigation. There is no bias in the decay ratio and the standard deviation of the differences for all the recordings is 0.06. The results provide confidence in the model and its applicability to predictive calculations.

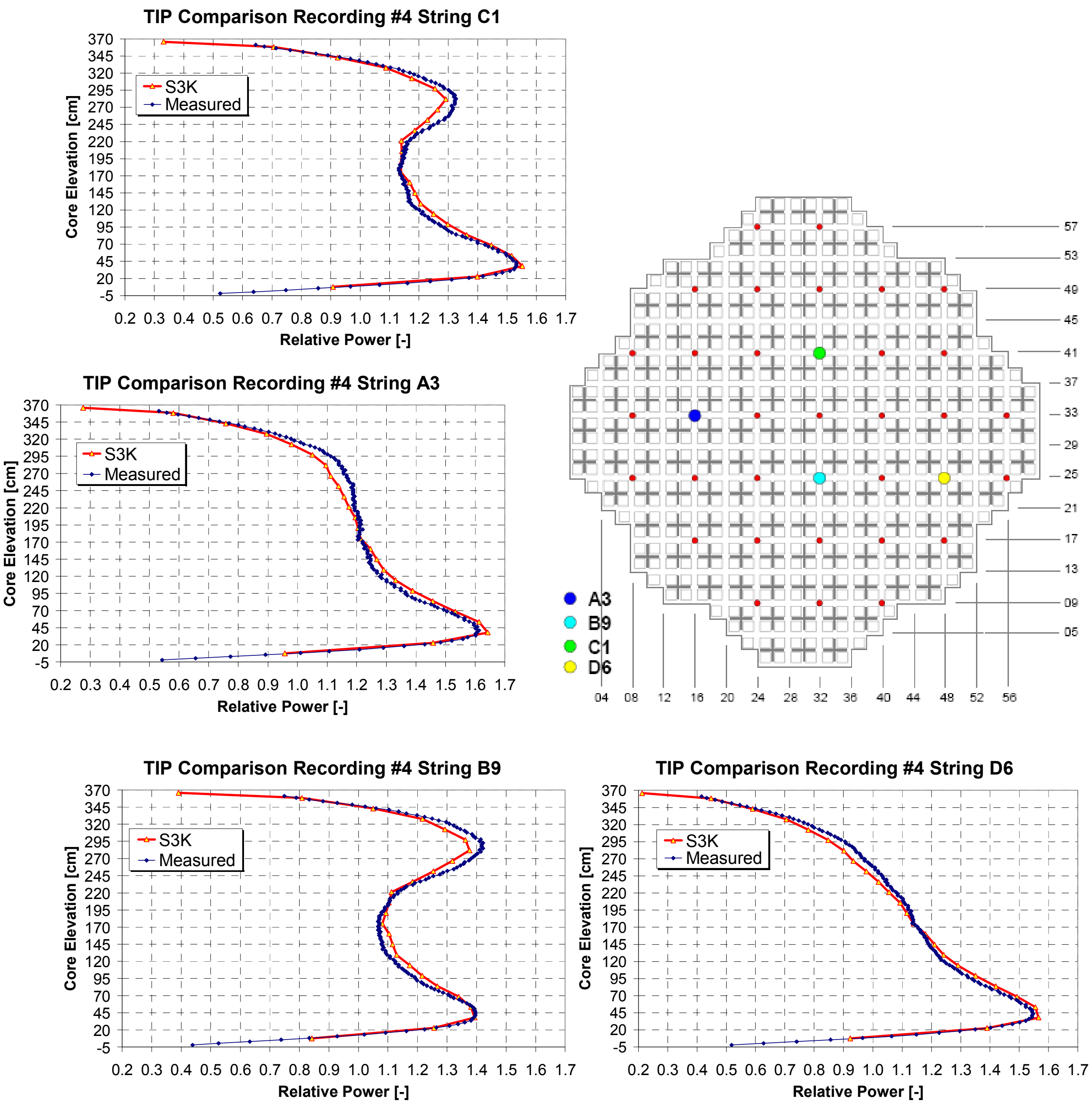

Fig. 1. TIP comparisons for Recording #8

Table 2
Calculated vs. measured decay ratios in Cycle 19

Case	APRM Noise Analysis (PSI)		S3K		C - M	
	DR	Freq	DR	Freq	DR	Freq
1	0.43 ± 0.07	0.68 ± 0.02	0.45	0.64	0.02	-0.04
3	0.46 ± 0.07	0.67 ± 0.02	0.53	0.64	0.07	-0.03
4	0.55 ± 0.06	0.70 ± 0.01	0.57	0.66	0.02	-0.04
5	0.49 ± 0.07	0.65 ± 0.02	0.54	0.64	0.05	-0.02
6	0.68 ± 0.09	0.66 ± 0.02	0.71	0.61	0.03	-0.05
7	0.59 ± 0.06	0.63 ± 0.02	0.59	0.61	0.00	-0.02
8	0.71 ± 0.04	0.63 ± 0.01	0.73	0.59	0.02	-0.04
9	0.40 ± 0.11	0.47 ± 0.02	0.30	0.44	-0.10	-0.04
10	0.64 ± 0.05	0.59 ± 0.01	0.57	0.56	-0.07	-0.03
11	0.54 ± 0.10	0.54 ± 0.02	0.48	0.52	-0.06	-0.03

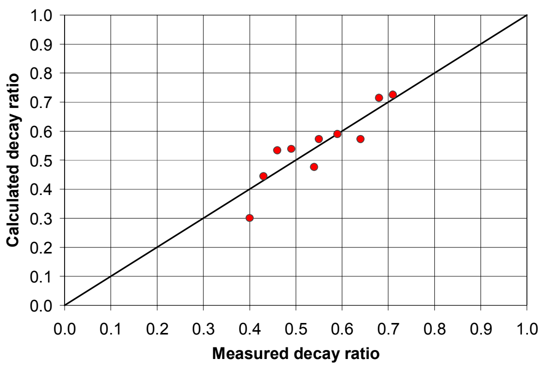

Fig. 2. Calculated vs. measured decay ratios in cycle 19

4. Cycle-23 predictive calculations

4.1. *State points*

The Cycle 23 cases were set using the operating conditions and control rod patterns specified in Aguirre (2006). A total of 15 cases were investigated at the beginning of cycle (BOC), middle of cycle (MOC), and end of full power (EOFP, corresponding to exposures of 0.0, 5.615, and 10.433 GWD/MT. In all cases the xenon inventories were kept constant at their full power concentrations. Figure 3 shows the selected operating points in the power-flow map.

The investigated cases fall in three categories: (1) same conditions as some of the recording from Cycle 19, (2) border of the exclusion region, and (3) conditions after a trip of one of the recirculation pumps. These chosen conditions represent power and flow following pump runback. The MEOD line was reached either by adjusting the control rod pattern (BOC and MOC) or decreasing the feedwater temperature (EOFP).

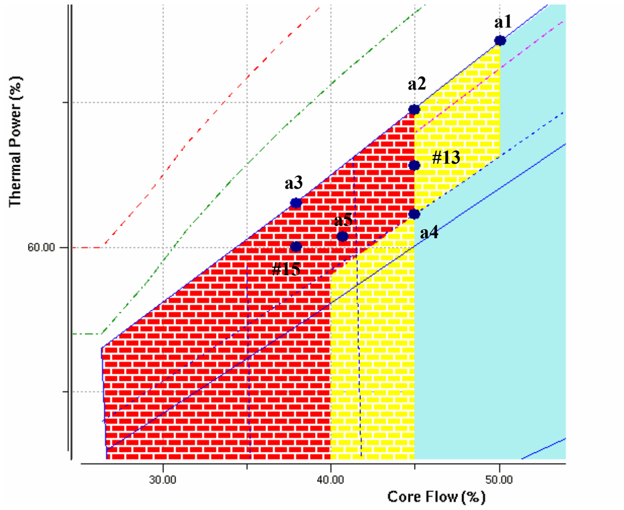

Fig. 3. Selected operating points for stability evaluation

4.2. *Steady-state calculations*

The S3 model of the test cases was set up to use the same options as for the Cycle 19 benchmark calculations. Comparison between P2 and S3K for the stability cases shows about a 2% bias in the bypass flow fraction between the two codes. This was also observed during the Cycle 19 benchmark calculations. The impact on stability of this difference in bypass flow fraction is discussed in Section 4.4.

At each stability case S3 restart files were created to be later accessed by S3K for the stability calculations

4.3. *Stability calculations*

Calculated decay ratios and frequencies for all analyzed Cycle 23 cases are given in Table 3. Cases 1, 2, and 4, which are meant to correspond to the conditions of Cycle-19 recordings 4, 6, and 8, respectively, show decay ratios that are close to those obtained before, although with somewhat reduced margins (0.69 vs. 0.57, 0.80 vs. 0.71, and 0.81 vs. 0.73). The differences are acceptable considering the difference in core loading, control rod patterns, and xenon distributions.

The cases that correspond to the border of the exclusion region have decay ratios of 0.67 (Case 3, BOC), 0.73 (Case 9, MOC), and 0.73 (Case 12, EOFP). Although all three cases are stable, there seems to be a trend toward less stability margin with core exposure.

Using the specified conditions that would correspond to the trip of one of the recirculation pumps takes the core deeper in the exclusion region. These cases (5, 11, and 15) exhibit all three decay ratios close to or above 1.0.

Table 3
Stability parameters for Cycle-23 cases.

Case	PF Map Point	Corelife	Power[%]	Flow[%]	DR	NF	Remark
1	a1	BOC	74.1	50.0	0.69	0.71	comparison with Cycle 19 Rec #4
2	a2	BOC	69.6	45.0	0.80	0.66	comparison with Cycle 19 Rec #6
3	a4	BOC	62.3	45.0	0.67	0.68	exclusion region border
4	a5	BOC	61.1	41.0	0.81	0.64	comparison with Cycle 19 Rec #4
5	a3, p.trip	BOC	63.2	38.0	1.01	0.60	trip one recirculation pump
6	a1	MOC	74.1	50.0	0.79	0.71	MEOD surveillance region border
7	a2	MOC	69.6	45.0	0.86	0.66	MEOD exclusion region border
8	a2	MOC	69.6	45.0	0.85	0.67	same as 7 with mono rod sequence
9	a4	MOC	62.3	45.0	0.73	0.68	exclusion region border
10	a5	MOC	61.1	41.0	0.85	0.64	exclusion region
11	a3, p. trip	MOC	63.2	38.0	0.99	0.61	trip one recirculation pump
12	a4	EOFP	62.3	45.0	0.73	0.60	exclusion region border
13	-	EOFP	65.3	45.0	0.79	0.60	exclusion region border
14	a5	EOFP	61.0	41.0	0.85	0.57	exclusion region
15	p trip	EOFP	60.0	38.0	0.93	0.55	trip of one recirculation pump

4.4. *Effect of bypass flow fraction and two-phase flow multiplier*

The effects of the bypass flow fraction differences between S3K and P2 and the use of the Chisholm-Baroczy instead of Martinelli-Nelson correlation were investigated. The results are given in Figures 4 and 5. "S3 BYP" refers to using the bundle geometry to calculate the flow distributions and "P2 WLT" uses the bypass flow fraction from the KKL P2 model. The two-phase flow multiplier (TPM) options are "MN" for Martinelli-Nelson and "CB" for Chisholm-Baroczy.

The larger bypass flow fraction from P2 results as expected in higher decay ratios. The "CB" multiplier decreases the friction pressure drop in the two-phase region of the core compared to "MN". This is stabilizing and the decay ratios are smaller.

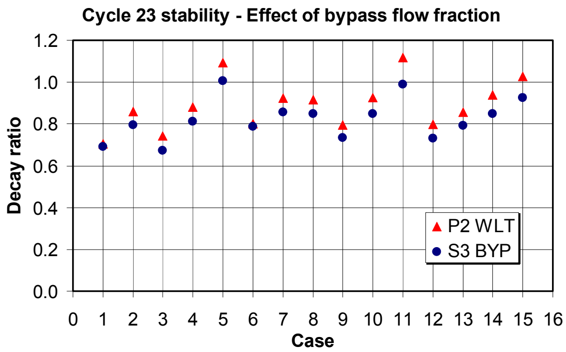

Fig. 4. Effect of bypass flow model.

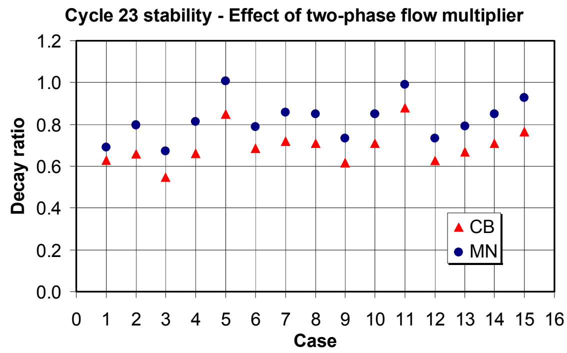

Fig. 5. Effect of two-phase flow multiplier.

5. Conclusions

At the off-rated conditions of the stability cases the S3K axial power distribution fits the TIP measurements very well. Consequently, S3K produced good values of the decay ratio with no discernable bias and a small standard deviation, well within the error bands of the measurements. The resonance frequency is systematically under predicted as has already been observed in past RAMONA analyses. The decay ratio is well estimated both outside and inside the exclusion region. The results provide confidence in the model and its applicability to predictive calculations.

The Cycle 23 results for the operating points that were part of the Cycle 19 measurements were acceptably close to the measurements, when one takes into account the differences in core loading, power distributions, and xenon inventory. No significant difference between the two cores was evident.

The stability results for all the Cycle 23 cases specified by KKL show that the calculated points outside or on the border of the exclusion zone have decay ratios well below 1.0. The trip of one recirculation pump pushes the operating point into the exclusion zone, where the calculations predict instability or a decay ratio close to 1.0.

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