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Transition to CASMO-5M and SIMULATE-3K for Stability Analyses of the Swiss BWRs

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ABSTRACT

For stability analyses of the Swiss operating Boiling-Water-Reactors (BWRs), the methodology employed and validated so far at the Paul Scherrer Institute (PSI) was based on the RAMONA-3 code with a hybrid upstream static lattice/core analysis approach using CASMO-4 and PRESTO-2. More recently, steps were undertaken towards a new methodology based on the SIMULATE-3K (S3K) code for the dynamical analyses combined with the CMSYS system relying on the CASMO/SIMULATE-3 suite of codes and which was established at PSI to serve as framework for the development and validation of reference core models of all the Swiss reactors and operated cycles. This paper presents a first validation of the new methodology on the basis of a benchmark recently organised by a Swiss utility and including the participation of several international organisations with various codes/methods. Now in parallel, a transition from CASMO-4E (C4E) to CASMO-5M (C5M) as basis for the CMSYS core models was also recently initiated at PSI. Consequently, it was considered adequate to address the impact of this transition both for the steady-state core analyses as well as for the stability calculations and to achieve thereby, an integral approach for the validation of the new S3K methodology. Therefore, a comparative assessment of C4 versus C5M is also presented in this paper with particular emphasis on the void coefficients and their impact on the downstream stability analysis results.

Key Words: BWR Stability Analysis, decay Ratio, Resonance Frequency, SIMULATE-3K, CASMO-5.

1. INTRODUCTION

The stability of boiling water reactors (BWRs) is of great importance for optimum plant performance. It has been observed that large BWRs could experience a less stable behaviour under certain conditions which may prevail during startup or shutdown of the plant. Stability analysis of BWRs is usually carried out using large system codes that simulate the nuclear power plant behaviour with a high degree of modelling detail. A particular demand on the system codes used for stability analysis is the integration of a 3D neutron kinetics model for the core, thereby permitting analysis of regional or higher mode stability behaviour. Now due to the operation of BWRs in Switzerland, the availability of a validated coupled 3-D core/plant system computational methodology for stability analyses is one of the missions of the PSI STARS project. In fact, some considerable experience in this area has been accumulated at PSI over the years not only for system code analyses ([1]-[4]) but also in relation to time series analyses of measured neutron noise signals ([5]) as well as to nonlinear dynamical analyses using reduced order models ([6], [7]). And in relation to system codes, the methodology validated so far was based on the RAMONA-3 code. In the meantime, the consolidated CMSYS system, based on the CASMO/SIMULATE-3 suite of codes, was established at PSI to serve as framework for the development and validation of reference core models for all the Swiss reactors ([8], [9]). Using CMSYS as basis, these validated core models are then transferred to the downstream transient codes, among which SIMUKATE-3K (S3K) was recently selected to serve as primary tool for 3-D core dynamical analyses [10]. Consequently, the assessment of S3K for the Swiss BWRs constitutes thus to one central objective at PSI and in that framework, current emphasis is given to the establishment and validation of a stability analysis methodology. In this paper, the first steps undertaken in that direction are presented. More precisely, the new S3K based methodology and its validation for a recent modern BWR core with partial Length Rod (PLR) fuel is outlined. At the same time, since CASMO-5M code is currently being integrated as basis for the 2-D lattice physics calculations within CMSYS, it was considered appropriate to also include an assessment of its impact on BWR stability predictions as part of this paper.

2. PSI STABILITY ANALYSIS METHODOGY

2.1. Overview of New Methodology

The previous stability analysis methodology employed at PSI and the new one being developed and thus for which a first validation is presented in this paper, are compared in Figure 1.

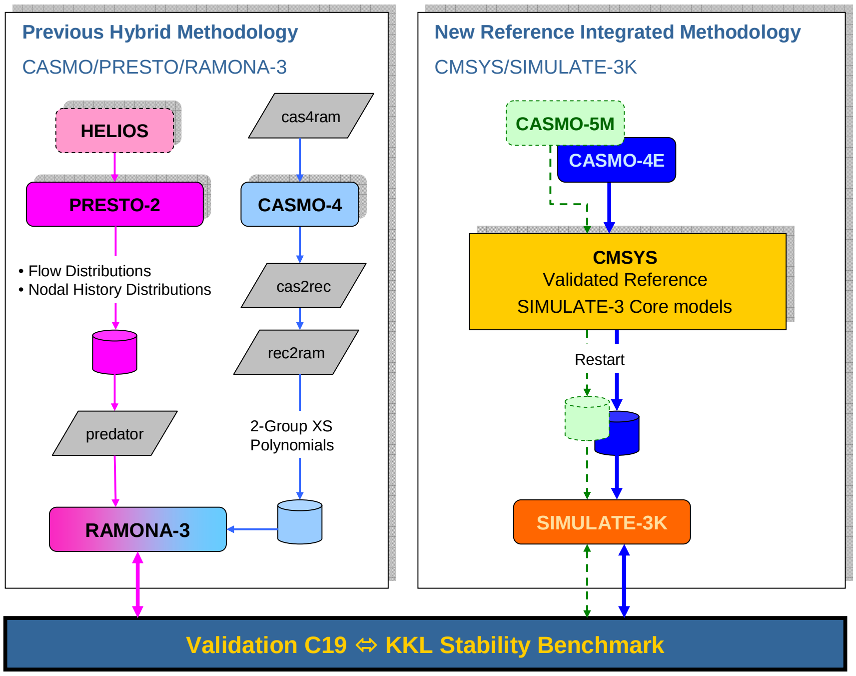

Figure 1. Overview of Previous and New PSI Stability Analysis Methodologies

As can be seen from Figure 1, the previous RAMONA-3 methodology was based on a rather hybrid and complex modelling approach combining PSI produced CASMO-4 cross sections with PRESTO-2 history and flow distributions provided by the plant operator ([1]-[4]). Although the latest validation results carried out for Cycle 19 showed a rather good accuracy [2], a transition to the new S3K methodology was considered as necessary for several reasons. First, S3K provides more state-of-the-art methods compared to the legacy RAMONA-3 code, both in terms of neutronics (e.g. 2-G nodal diffusion, pin power reconstruction, improved cross-section modelling) as well as thermal-hydraulics, e.g. 5 equations instead of 4 equations [10]. Secondly, through its direct "coupling" to the CMSYS system, this new approach allows for greater flexibility and enlarged in-house capacities to carry out stability studies of the Swiss BWRs. Third, since S3K is the time-dependant counter-part of the static core simulator SIMULATE-3, full consistency between the neutronic models (including nodal/pin power method related aspects as well as cross-sections and nodal history data) is ensured between the validated steady-state core models and those employed for the transient simulations. Finally, in the same context, since the 3-D core models are transferred to S3K directly via a single restart file, a complete integral methodology is achieved from the upstream lattice physics code all the way down to the system code dynamical valuations. Among the main advantages, this provides the capability for a systematic assessment of upstream methodology modifications and their propagation to e.g. stability analyses results. This will be addressed in this paper by assessing the impact on the stability results from the 2-D lattice methodology employed for the CMSYS core models.

2.2. Assessment and Validation Target

To launch the transition to the new methodology, the Swiss BWR Leibstadt plant (KKL) was selected as situation target. One main reason is that the plant operator organised recently a benchmark for stability tests carried out in a recent operating cycle characterised by an increased amount of PLR fuel [11]. As within this benchmark, which will be described in more details in Section 2.3, the stability tests had already been analysed at PSI analysed with the previous RAMONA-3 methodology [2] and therefore, it was considered as an adequate choice for a first validation target of the new methodology. The S3K models developed to that aim are briefly outlined in the next sections.

2.2.1 S3K Core Models

The starting point for the new S3K methodology is the CMSYS platform which was established at PSI to serve as framework for the development and validation of reference steady-state core models of all the Swiss reactors including thus the KKL plant ([8], [9]). The main principle of CMSYS is that after completion of each operated cycle, a CASMO/SIMULATE-3 model is developed and a validation is performed, which for BWRs includes two main components. For the cold reference k-*eff*, global as well as local cold critical tests usually carried out at Beginning-of-Cycle (BOC) are analysed. For hot full power cycle depletion conditions, a validation of the calculated 3-D reaction rates is made against TIP measurements carried out at the plant during the cycle. Thereby, Root Mean Square (RMS) statics of the differences between calculated and measured 3-D reaction rates are estimated at the radial, axial as well as nodal level. Currently, the CMSYS core models for KKL are based on the C4E code using a 70 group library structure based on JEF-2.2. However, as a migration to the more advanced C5M code, using a 586-group ENDF/B-VII base library, is currently on-going for the CMSYS KKL models, it was considered appropriate to assess the impact of this migration not only on representative lattice results but also on the overall core analysis accuracy as well as on the stability predictions. Thereby, two CMSYS core models for S3K dynamical simulations will be assessed in this paper, one based on C4E, called S3K-C4E, and the other on C5M, called S3K-C5M. For both these models, as is standard with S3K, a full core representation is applied, using a total of 648 neutronic channels, each one coupled to a single individual T-H channel and discretized into 25 axial nodes with a 1x1 radial assembly mesh. For the bypass, a common T-H channel is used to represent all leakage flows (common peripheral zone, core support plate, assembly lateral leakage) as well as water rod flows. At the radial as well as axial core periphery, explicit reflectors are used.

2.2.2 S3K Vessel Model

To carry out stability analysis, the S3K core model needs to be coupled to a vessel model in order to integrate the momentum balance along the recirculation loop. Thereby, a reference vessel model was developed for KKL comprising all required 1-D “peripheral system” components: upper plenum, steam separators, bulk water region, downcomer, recirculation loop, lower plenum, steam dome and jet pumps [12]. In addition, the following modelling assumptions are made.

- Upper Plenum, standpipes and steam separators are saturated and their properties are evaluated at the upper plenum pressure (noting that the core channel properties are also evaluated using the upper plenum pressure).
- Downcomer, recirculation loops and lower plenum are modelled as single-phase liquid with properties evaluated using the steam dome pressure.
- A perfect mixing of the feedwater flow and recirculation flow is assumed at the interface bulk water region/downcomer.
- For the bulk water region, the properties are evaluated using the steam dome pressure.

This vessel model is applicable for all KKL cycles and operating points. Therefore, it constitutes a “generic” part of the KKL stability methodology and consequently, a change in any of the peripheral systems relative to the reference vessel model used in this work will require a renewed validation and thus an update of the reference vessel model.

2.3. KKL Stability benchmark

At beginning of Cycle 19, stability measurements were carried out at KKL as one of the last commitment the plant had to fulfil to conclude a power uprate from 3138 to 3600 MW (power uprate) [13]. A total of eleven tests were conducted and the operating points are shown in Figure 2. For each of these tests, neutron flux signals were recorded at the LPRM locations shown on the right hand side of Figure 2, noting that there, the locations of TIP strings are also outlined. Recently, KKL invited various organizations to perform a benchmarking of their codes/methodologies on the basis of these Cycle 19 stability tests [11]. All organizations involved in this benchmark study along with the employed codes are summarized in Table I. The calculated stability results, i.e. decay ratio (DR) and resonance frequency (RF), obtained by the different participants are compared to the measured results [14] in Table II.

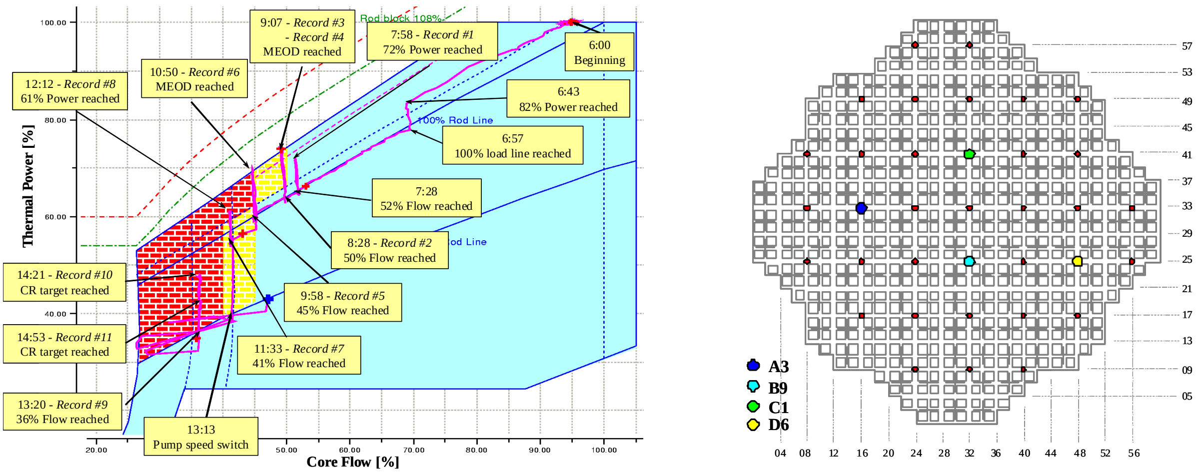

Figure 2. KKL Cycle 19 Stability Tests (Left) and measured TIP/LPRM String Locations (Right)

Table I. Summary of Measured and Calculated Results for Cycle19 [11]

ORGANIZATION	LATTICE CODE	STEADY-STATE CODE	TRANSIENT CODE
PSI	CASMO4	PRESTO-2	RAMONA-3 (PR3)
Areva NP	CASMO4	MICROBURN-B2	RAMONA-3 (AR3)
Studsvik Scandpower	CASMO4	SIMULATE-3	SIMULATE-3K (SR5)
Studsvik Scandpower	HELIOS	PRESTO-2	RAMONA-5 (S3K)
Westinghouse	PHOENIX4	POLCA7	RAMONA-5 (WR5)
Westinghouse	PHOENIX4	POLCA7	POLCA-T (P-T)

Table II. Summary of Measured and Calculated Results for Cycle19 [11]

	DECAY RATIO							RESONANCE FREQUENCY						
	Measured	Predicted by Code						Measured	Predicted by Code					
Case	PSI	PR3	AR3	SR5	WR5	S3K	P-T	PSI	PR3	AR3	SR5	WR5	S3K	P-T
1	0.43±0.07		0.44		0.43	0.45	0.35	0.68±0.02		0.64		0.60	0.64	0.62
3	0.46±0.07		0.54		0.53	0.53	0.45	0.67±0.02		0.66		0.60	0.64	0.65
4	0.55±0.06	0.58	0.53	0.58	0.55	0.57	0.48	0.70±0.01	0.68	0.67	0.60	0.63	0.66	0.71
5	0.49±0.07		0.51		0.48	0.54	0.45	0.65±0.02		0.65		0.59	0.64	0.67
6	0.68±0.09	0.74	0.69	0.67	0.66	0.71	0.65	0.66±0.02	0.67	0.64	0.59	0.59	0.61	0.69
7	0.59±0.06		0.52		0.50	0.59	0.54	0.63±0.02		0.62		0.56	0.61	0.65
8	0.71±0.04	0.72	0.69	0.67	0.64	0.73	0.73	0.63±0.01	0.65	0.61	0.57	0.55	0.59	0.67
9	0.40±0.11		0.41		0.40	0.30	0.37	0.47±0.02		0.48		0.40	0.44	0.45
10	0.64±0.05	0.64	0.58	0.64	0.57	0.57	0.61	0.59±0.01	0.61	0.58	0.52	0.48	0.56	0.59
11	0.54±0.10		0.57		0.53	0.48	0.52	0.54±0.02		0.54		0.45	0.52	0.53

3. STATIC CORE ANALYSES WITH CASMO-5 ASSESSMENT

3.1. Steady-State 3-D Core Analysis

To start, the cycle-average RMS values (radial, axial and nodal) obtained with C4E are shown in the upper part of Fig. 3 and as can be seen, a satisfactory accuracy is thus achieved with nodal RMS typically below or around 5% including for the cycle analysed in this paper (Cycle 19). Next, the absolute RMS differences between C5M and C4E are shown in the lower part of Fig. 3. Some fluctuations are observed between cycles, i.e. in some cases, a slightly better performance is obtained with C5M while for others, C4E provides the best results. However, on an overall basis, the differences are very small (within ± 0.4%) although noting that for Cycle 19, a better accuracy is in fact obtained with the C5M code.

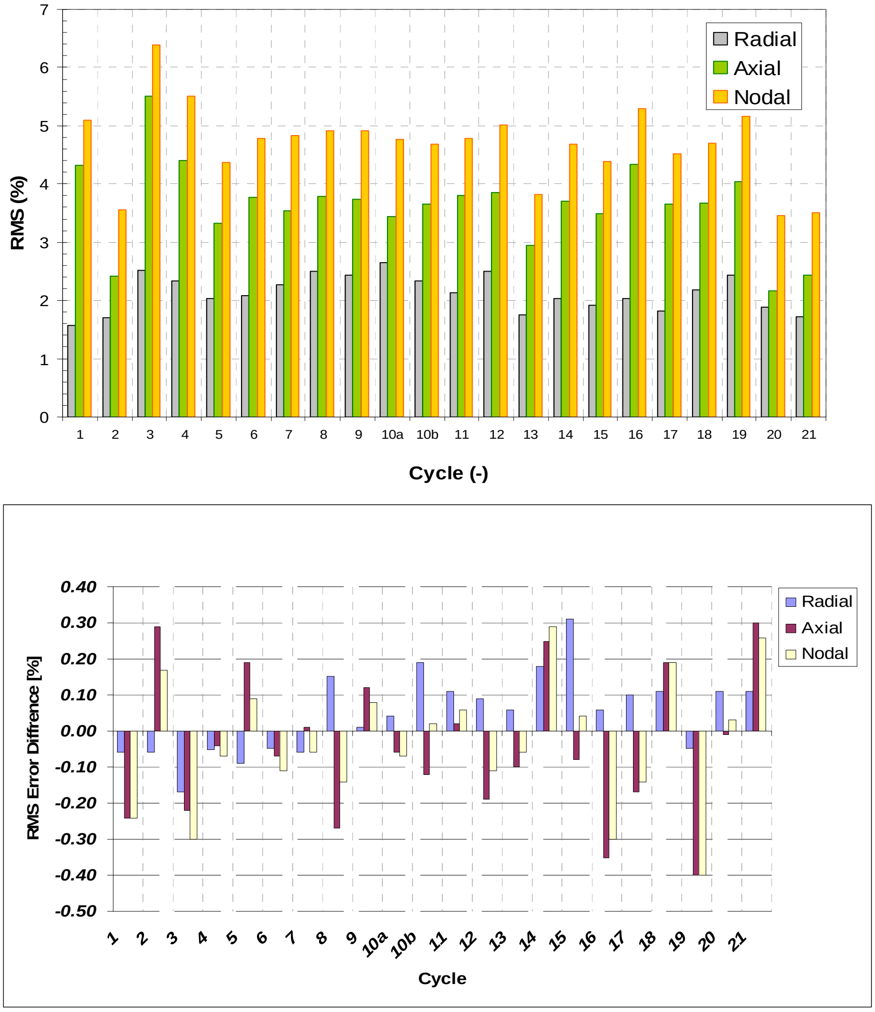

Figure 3. CMSYS Accuracy with C4E (Top) and Differences [C5M-C4E] (Bottom)

3.2. Effect on Void Reactivity Coefficients

The results shown in the previous section have illustrated that on an overall basis, the transition to C5M does not affect very much the accuracy of the 3-D power distributions calculated for all the modelled cycles of KKL in the CMSYS system. For stability analyses however, an important parameter is the void reactivity coefficient (VRC) since it represents one of the dominant feedback components of a thermal-hydraulic perturbation on the neutron fluxes. Thereby, it was considered appropriate to compare for selected fuel assembly segments of the Cycle 19 core, the VRC between both codes. To this aim, the absolute VRC differences (pcm/%void) between C5M and C4E were thus compared as function of void content, burnup, and control rod insertion for a lower (L) and upper (U) segment of two dominant fuel assembly designs in the Cycle 19 core, namely a full-length-rod (FLR) design, referred to as fuel type 1 (FT-1), and a partial-length-rod (PLR) design, referred to as fuel type 2 (FT-2). Note that a one-to-one comparison between both FTs can not be made due to different enrichments and Gd loadings. Instead, the objective here is to assess the trends between both codes for given FTs, in this case the two dominant ones of the Cycle 19 core. The results for the FT-1 assembly are shown in Figure 4.

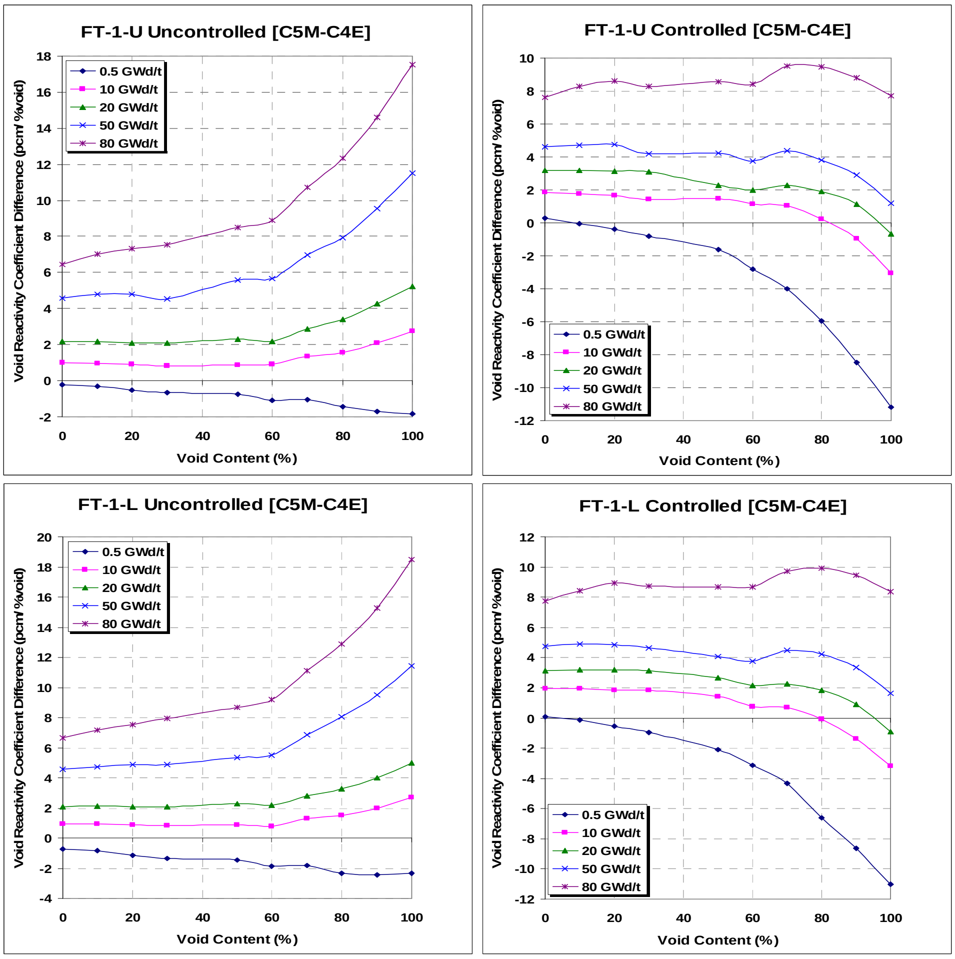

Figure 4. Differences in VRC between C5M and C4E – Full-Length-Rod Assembly Design

As can be seen in Fig. 4, the same trends are observed for the lower and upper segments, something expected in this case since the FT-1 is a FLR assembly design. The main trends are that at low burnup, C5M predicts a slightly more negative VRC while as the burnup increases, the VRC becomes increasingly less negative compared to C4E. This effect is moreover seen to become slightly more pronounced at very high voidages (80-100%). But overall, for a typical core-average burnup of 25 GWD/MT and void fraction of 40%, the C5M VRC is only about +2.5 pcm/% void less negative and such difference can be considered as small. Concerning the controlled case, the differences between both codes are almost similar to those of the uncontrolled case. However, there is a clear opposite trend at very high voidages, i.e. a monotone decrease in the difference between C5M and C4E indicating a more negative VRC for C5M.

The corresponding results for the PLR assembly are shown in Fig. 5. Overall, the same trends as for the FLR FT-1 design are seen. However, it is observed that for the upper “overmoderated” zone, the differences between C5M and C4E will for the uncontrolled configuration increase i.e. the former producing even lees negative VRCs than C4E. For the controlled case, the spectrum hardening mitigates slightly the less negative VRCs with C5E i.e. the differences between the codes are smaller in the upper core zone compared to the lower zone.

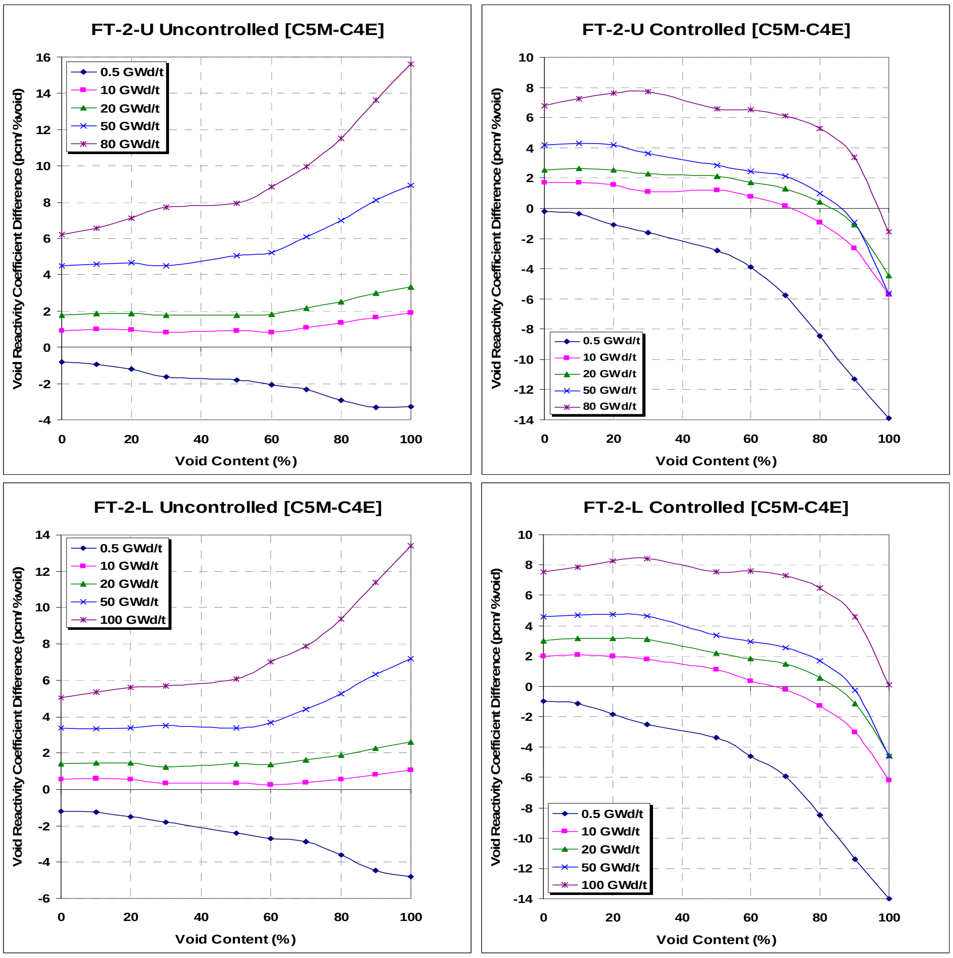

Figure 5. Differences in VRC between C5M and C4E – Partial-Length-Rod Assembly Design

From the previous figures, the overall conclusion is that although a tendency for slightly less negative VRCs is observed with C5M, the differences remain rather small and do therefore not point out any significant changes due to the finer neutron group structure (586 g instead of 70-group) or to the underlying neutron data library (E7 instead of J2) except at higher burnups where the C5M VRCs becomes increasingly less negative. To understand this would require reactivity decomposition in order to compare the codes with regards to the behaviour of two major contributors to the VRC, namely the ^{137}Gd and ^{238}U capture reaction rates. This is outside of the scope of the studies presented here noting however in this context that because of the increasingly less negative VRCs at high burnup, the impact of C5M on stability can be expected to become more visible at the end of cycle (EOC) compared to beginning-of-cycle (BOC) conditions.

4. DYNAMICAL ANALYSES WITH S3K VALIDATION

4.1. Validation of Steady-State Power Profiles

A key parameter for a reliable stability analysis is an accurate prediction of the initial steady-state 3-D power and void distributions. To that aim, the steady-state performance of the two PSI-S3K core models, i.e. using C5M and C4E, is assessed here by carrying out a comparison against an available TIP measurement (string B9, see Figure 3) from one of the Cycle 19 stability tests [11]. For this configuration, the obtained local (normalised) power profiles are compared in Figure 6 against both measured data as well as against steady-state solutions obtained by the previous participants. As can be seen from Figure 6, the PSI S3K results agree for that particular string as good if not better than most of the other solutions. This applies to both the C4E and C5M based models although the later is observed to predict a slightly more bottom peaked power distribution.

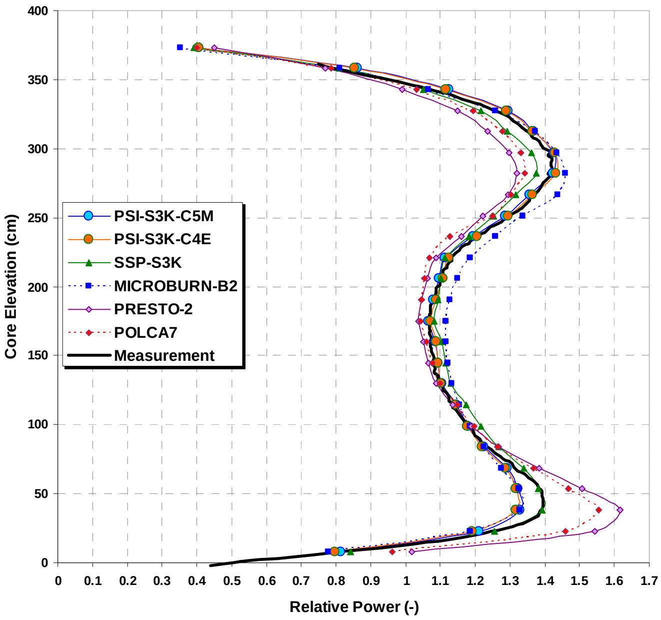

Figure 6. Code Benchmarking for TIP Comparison for REC8, String B9

4.2. Validation of Dynamical Calculations

This section presents the results of the PSI S3K model for the dynamical stability simulations i.e. the validation results obtained for the C19 stability tests. The results of the S3K stability calculations are presented and compared with measurements in Table III.

Overall, the PSI-S3K results show a very good agreement with the measured values for both DR and RF, and almost all fall inside the uncertainty range. More specifically, the average DR bias is -0.01 while the standard deviation is 0.04 for both models. For the RF, the bias and the standard deviation are -0.02 and 0.01 for both models. Therefore, all in all, this points to a very good performance and provides thus confidence in the current S3K model regarding its prediction capabilities of the stability parameters. Coming to the comparison between S3K-C5M and S3K-C4E, the differences are very small which, from the point of view of the VRCs discussed previously, could to some extent be expected since these stability tests were performed at BOC conditions.

Table III. Calculated vs. Measured Stability Parameters of Cycle 19

	DECAY RATIO					RESONANCE FREQUENCY				
CASE	**Meas**	**S3K-C4E**	**DIFF1***	**S3K-C5M**	**DIFF2¥**	**Measured**	**S3K-C4E**	**DIFF1***	**S3K-C5M**	**DIFF2¥**
1	0.43±0.07	**0.43**	-0.01	**0.43**	0.00	0.68±0.02	**0.68**	0.00	**0.68**	0.00
3	0.46±0.07	**0.49**	0.03	**0.48**	0.02	0.67±0.02	**0.67**	0.00	**0.67**	0.00
4	0.55±0.06	**0.58**	0.03	**0.58**	0.03	0.70±0.01	**0.68**	-0.02	**0.68**	-0.02
5	0.49±0.07	**0.53**	0.04	**0.52**	0.03	0.65±0.02	**0.64**	-0.01	**0.64**	-0.01
6	0.68±0.09	**0.64**	-0.04	**0.63**	-0.05	0.66±0.02	**0.63**	-0.03	**0.63**	-0.03
7	0.59±0.06	**0.58**	-0.01	**0.57**	-0.02	0.63±0.02	**0.61**	-0.02	**0.61**	-0.02
8	0.71±0.04	**0.67**	-0.04	**0.66**	-0.05	0.63±0.01	**0.60**	-0.03	**0.60**	-0.03
9	0.40±0.11	**0.33**	-0.07	**0.32**	-0.08	0.47±0.02	**0.47**	0.00	**0.47**	0.00
10	0.64±0.05	**0.62**	-0.02	**0.61**	-0.03	0.59±0.01	**0.55**	-0.04	**0.55**	-0.04
11	0.54±0.10	**0.50**	-0.04	**0.49**	-0.05	0.54±0.02	**0.52**	-0.02	**0.51**	-0.03
Std.dev			**0.04**		**0.04**			**0.01**		**0.01**
Bias			**-0.01**		**-0.01**			**-0.02**		**-0.02**

***DIFF1=Cal_S3K-C4E – Meas**

¥ DIFF2=Cal_S3K-C5M - Meas

The above dynamical results obtained for Cycle 19 are compared next to the solutions provided by the previous benchmark participants, underlining that the new PSI-S3K solutions added here were in fact made in a complete independent manner from this benchmark i.e. using as only basis, the in-house CMSYS KKL core models.

Figures 7 and 8 present the DR and RF results. As can be seen, the PSI-S3K results show a performance well in-line with most other benchmark solutions. And in that context, it is noted that the C5M based S3K model predicts systematically lower DRs.

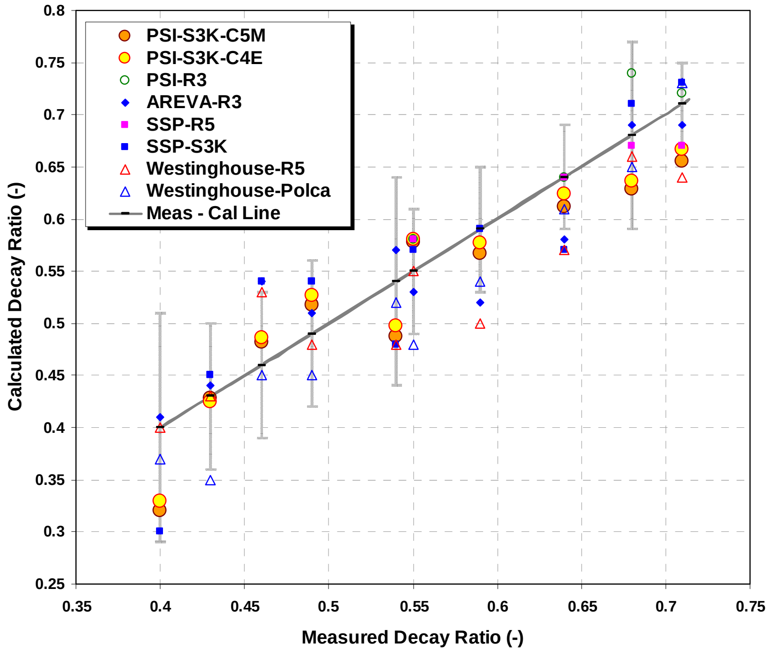

Figure 7. KKL Cycle 19 Benchmark-Decay Ratio

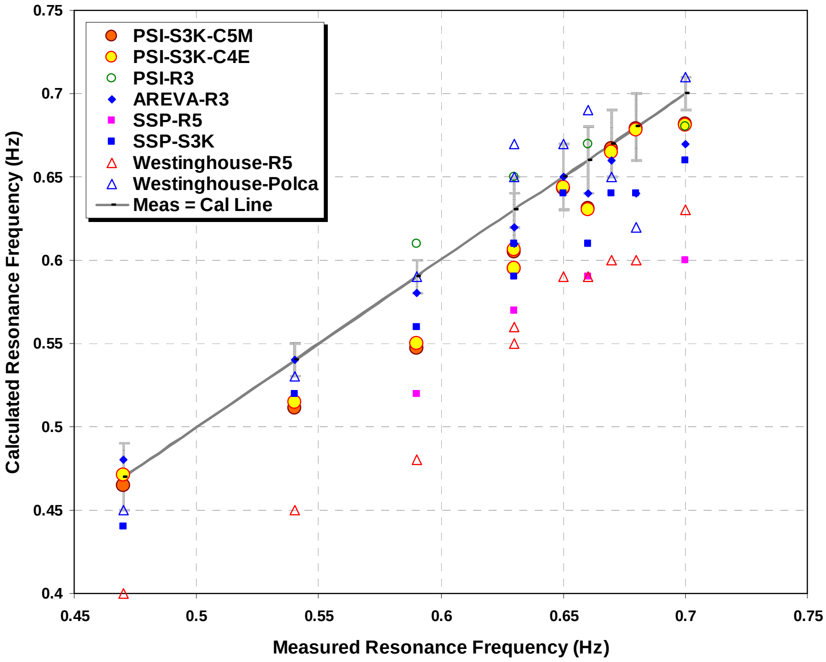

Figure 8. KKL Cycle 19 Benchmark-Resonance Frequency

Although the differences are not large, this is consistent with the expectations from the studies presented in Section 3.2 which indicated a tendency for less negative VRCs with the C5M code. Concerning the RF results, similarly to most other methodologies, a tendency to underestimate the core natural frequency is observed (Fig. 8). The reason for such bias in the predicted resonance frequency is thus not clear and will require further investigations in an attempt to address this generic difficulty of system codes to capture adequately the resonance frequency. This is however outside the scope of this paper.

Overall, it can thus be concluded that the validation of the PSI-S3K models presented here for Cycle 19 provides confidence in the applicability of these models for KKL core.

4.3 Sensitivity Study

The previous results have illustrated an overall very good performance of the new S3K stability methodology for the analysis of the KKL Cycle 19 tests and no major difference could be observed between the two core models using 2-group homogenised cross-section as well as nodal history data based on C4E and C5M respectively. But as these tests were conducted at BOC while the lattice physics studies (see Section 3.2) indicated a probably stronger impact at EOC, a sensitivity analysis was carried out here where the same tests were analysed but assuming burnup conditions corresponding to end-of-cycle 19. The results are shown in Fig. 9 where the relative differences between S3K-C5M and S3K-C4E are compared at both cycle exposures (BOC and EOC).

As can be seen, C5M produces in most cases lower DRs (more stable core conditions) but the relative differences are indeed stronger at EOC. This is well in-line with the observation that C5M would produce less negative VRCs compared to C4E and this trend would become relatively stronger at higher burnups. The impact on the RF is on the other hand negligible in all cases. Since the RF is related to the void transit time across the core, these results show that the modifications of the upstream lattice physics code did not introduce any major shift/time-delay in this transit time.

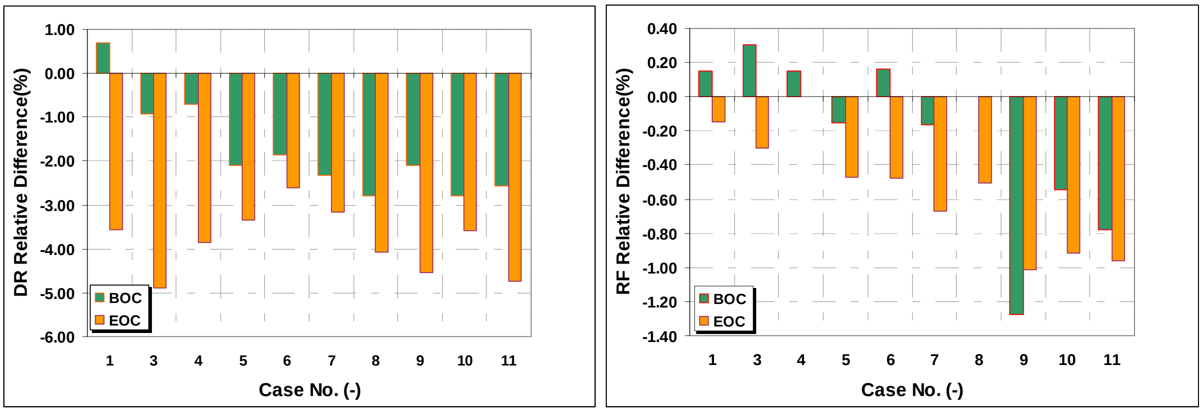

Figure 9. Relative Difference Results between S3K-C5M and S3K-C4E Models: DR (Right) and RF (Left)

5. CONCLUSIONS

The development of a new BWR stability analysis methodology based on SIMULATE-3K (S3K) has recently been launched at PSI and as first situation target for validation purposes, the KKL reactor was selected. For this plant, an S3K vessel model was developed including principally, a series of 1-D components for the recirculation loop: upper plenum, steam separators, bulk water region, downcomer, lower plenum, steam dome and jet pumps. Regarding the 3-D core model, it is in this new methodology directly obtained from the PSI CMSYS system where reference core models are developed, maintained and validated for all the Swiss reactors and operated cycles. For the KKL reactor, the CMSYS models have so far been based on the CASMO-4E (C4E) code with a JEF-2.2 70-group library combined with the SIMULATE-3 two-group three-dimensional nodal diffusion steady-state code. But since a transition to CASMO-5M (C5M) using a 586-group ENDF-B/VII based library is currently being undertaken within CMSYS for BWR analyses, it was considered appropriate to also include and assess the effect of this transition on the stability analysis results.

As a first validation case, stability tests conducted for the KKL Cycle 19 core, containing an increased amount of Partial-Length-Rod fuel assemblies, were analysed in this paper using two variant of the S3K core models, namely one based on C4E and one on C5M. The obtained results were then compared to both stability measurements as well as to a wide range of methodologies relying on other system codes and previously submitted as solutions to a benchmark study organized by the plant in relation to these specific stability tests. This comparison confirmed that the PSI-S3K models are able to adequately predict the core stability characteristics for all the investigated tests i.e. with results close or well in-line with most of the other benchmark solutions. Concerning the effect of the transition from C4E to C5M, this was studied with particular emphasis on the void feedback reactivity coefficient (VRC) and subsequent effects on the stability parameters, i.e. the decay ratio (DR) and resonance frequency (RF). Overall, this study showed a tendency for slightly less negative VRCs with C5M especially at high burnups although the differences were rather small. Nevertheless, as a consequence of less negative VRCs, a trend for lower decay ratios with C5M was obtained for the investigated beginning-of-cycle stability tests noting that the agreement against measurements remained nevertheless satisfactory. But for completeness, a sensitivity study was carried out for end-of-cycle conditions and confirmed that in this case, the trend for more stable results with C5M becomes more pronounced.

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