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EVALUATION OF GAMMA SCANNING IN OSKARSHAMN2 WITH SIMULATE-5

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ABSTRACT

SIMULATE-5, Studsvik Scandpower's next generation nodal code, has been benchmarked against recent gamma scan measurements of Oskarshamn2, an ABB/Westinghouse design BWR, and results are presented in this paper. Gamma scan measurements following the Cycle-32 operation includes 48 assembly gamma scans of advanced Optima2 and Atrium-10B fuels. Two Optima2 fuel assemblies were disassembled for more detailed gamma scanning of 49 fuel rods. SIMULATE-5 is a three dimensional multi-group analytical nodal code with microscopic depletion capability. Its state of the art neutronic modules have been developed based on first principals with considerations of today's highly heterogeneous cores. SIMULATE-5 has a built in capability of tracking Ba140 isotopics in a node as well as fuel pin level which makes the evaluations of gamma scans straightforward. The assembly gamma scan comparisons reveal that SIMULATE-5 accurately predicts the nodal Ba140 densities, hence nodal/assembly powers, regardless of fuel assembly type, burnup or location of the fuel assembly in the core. Heterogeneities in the axial direction, due to enrichment/burnable absorber zoning, part length fuel and spacer/grids are handled well. Pin gamma scan evaluations show that SIMULATE-5 offers significant improvements in accuracy to calculate pin powers vs. existing methods, especially for the fuel assemblies with control rod which exhibits strong radial power/flux gradients. The last part of this paper summarizes the benchmark results for core tracking calculations for the last 18 cycles of Oskarshamn2.

Key Words: Gamma Scanning, Core Tracking, Assembly Bow, SIMULATE-5

1. INTRODUCTION

Oskarshamn2 is a BWR of ABB/Westinghouse design with 444 assemblies and a thermal output of 1700 MW. With two other Oskarshamn units, it is located on the east coast of Sweden and owned and operated by OKG/EON. An extensive gamma scanning campaign was performed during the outage following the Cycle-32 operation in August of 2007 [1] as a preparation for a power up-rating of the plant.

The Cycle-32 core was made up of 126 Westinghouse/Optima2 and 318 Areva/Atrium-10B fuel assemblies. All once and twice burnt assemblies were of Optima2 design.

The control rod pattern and the reactor power had been stable 30 days prior to the measurements. Core coolant flow was increased during that period to make up for fuel depletion.

19 Optima2 and 29 Atrium assemblies were scanned. A total of 49 fuel pins from two Optima2 assemblies (assembly 26891 with 23 fuel pins and assembly 26899 with 26 pins) were measured individually providing detailed information about the intra assembly power distribution.

In assembly 26891 a control rod was inserted 20%. The channel bow was measured such that the true widths were known for the water gaps surrounding assemblies 26891 and 26899.

The measurement uncertainty was reported to be 1.3 % for assemblies and 1.5 % for pins.

The gamma scanned core has been evaluated with Studsvik's next generation core simulator SIMULATE-5 [2,3,4,5]. Its cross sections are generated by use of CASMO-5[6] based on ENDF/B-VII library.

SIMULATE-5 is, to the largest possible extent, based on true physics and true geometry. Great care has been taken to model pin powers as accurately as possible.

The major features of SIMULATE-5 can be summarized as:

- Any number of energy groups may be used [2].
- The high order SP3 (simplified P3) method is available as an option.
- In the axial direction, the heterogeneities caused by the presence of spacers, control rod material zones, enrichment and BA zoning, and staggered assembly heights are treated explicitly.
- In the radial direction, an assembly is divided into N×N 'submeshes' (typically N=5). For a BWR the water gaps are treated individually. Cross sections are provided for each submesh and the multi-group diffusion (or SP3) equation is solved. For a description on how the 1D axial solution and the 2D radial solutions are coupled, see reference [5].
- The cross sections are described by a hybrid microscopic-macroscopic model [2]. For the whole node, 17 actinides and about 30 fission products are tracked. In addition, for each submesh, the five most important actinides are followed.
- The depletion of control rods is tracked and the reactivity effect of the depleted control rod is accounted for via cross section feedback to the nodal solution.
- The thermal hydraulics models all flow paths carefully. The BWR assembly may be divided into 2×2 subchannels and cross flow is allowed between these channels [4]. The skewed void inside an assembly, especially in the presence of control rods, is thus represented.
- The pin fluxes/powers and the detector readings are based on the fine scale solution obtained via the axial homogenization and the radial submesh approaches [3].

In this report, SIMULATE-5 calculations employing four energy groups are used.

2. GAMMA SCANNING MODEL IN SIMULATE-5

The gamma scanning analysis is performed by a module inside SIMULATE-5. The measured assembly and pin signals are part of the code's input.

The measured signal is simulated via a sum over the number of fuel pins in the assembly ($=N_f$). For each assembly and node (axial node index is suppressed)

$$S_{asy}^{Calc} = \sum_{i=1}^{N_f} w_i A_i N_i \tag{1}$$

where N_i is the Ba140 number density for pin i, w_i is a weight factor indicating the contribution of pin i to the measured signal, and A_i is the fuel pin area.

For each fuel segment design, a unique set of weights w_i is required. There are no special weights defined for the spacers. The weight factors have been computed by University of Uppsala, Sweden [7].

The Ba140 is tracked explicitly by solving the equation

$$\frac{dN_i}{dt} = \gamma_i^{Ba140} \sum_{g=1}^{G} \Sigma_{f,gi} \phi_{gi} - \lambda_{Ba140} N_i \tag{2}$$

with the solution

$$N_i(t) = N_i(0) e^{-\lambda_{Ba140} t} + \frac{\gamma_i^{Ba140}}{\lambda_{Ba140}} \sum_{g=1}^{G} \Sigma_{f,gi} \phi_{gi} \cdot \left(1 - e^{-\lambda_{Ba140} t}\right) \tag{3}$$

Note, that the fission yield for Ba^{140}, γ_i^{Ba140}, is given per pin. It is calculated with CASMO-5 and tabulated in the cross-section library as functions of important history parameters.

When comparing measured and calculated signals, the core bottom and top nodes are excluded since they are reported to have large measurement uncertainties. Signals for the 48 investigated assemblies are normalized such that both measured and calculated signals average unity. Likewise, when comparing individual pin values, pin signals for respective assembly (26891 and 26899) are normalized to average unity.

In this report, the error is consistently defined as:

$$\varepsilon = (S_x^{Calc} - S_x^{Meas}) \cdot 100 \tag{4}$$

3. GAMMA SCANNING EVALUATIONS OF OSKARSHAMN2

3.1. Evaluation of Assembly Measurements

The main results for the gamma scan evaluation of assemblies are shown in Table I, where also CASMO-4/SIMULATE-3 [8] data are given for comparison purposes. The total RMS is decreased from 4.5 to 3.8 % when going from SIMULATE-3 (S3) to SIMULATE-5 (S5). Results improved both in the axial and the radial directions.

Table I. Assembly gamma scanning evaluation with SIMULATE-3 and SIMULATE-5.

	Assembly RMS (%)		
	Nod	Rad	Axi
SIMULATE-3	4.5	1.7	3.3
SIMULATE-5	3.8	1.4	2.9

The radial assembly average deviations are listed in Fig. 1. Control rods are present in three positions as indicated in the figure. It may be concluded that

- There is no radial tilt.
- The periphery is well predicted.
- Control rod cells are well handled.

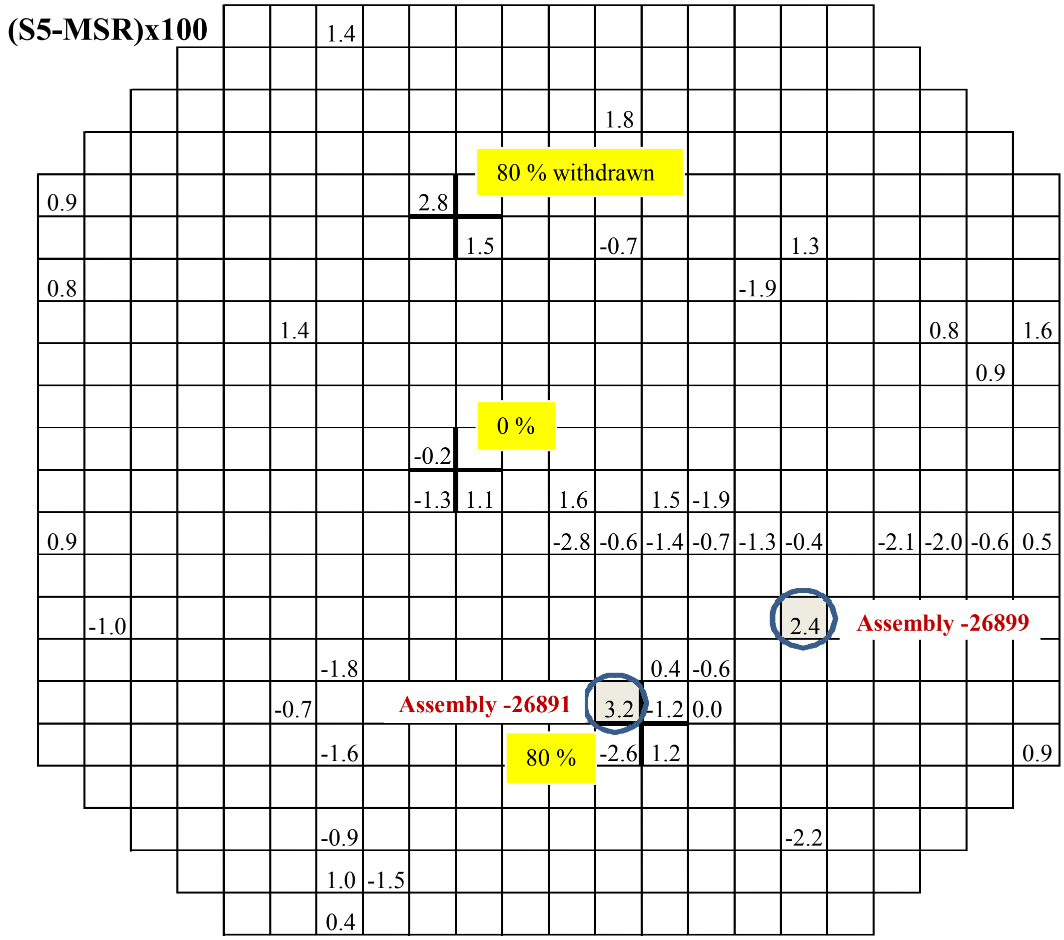

Figure 1. Average deviation (%) per assembly.

The axial profile of the 48 assemblies is displayed in Fig. 2 along with the error curves of SIMULATE-3 and SIMULATE-5. The already small axial error of SIMULATE-3 is further reduced using SIMULATE-5.

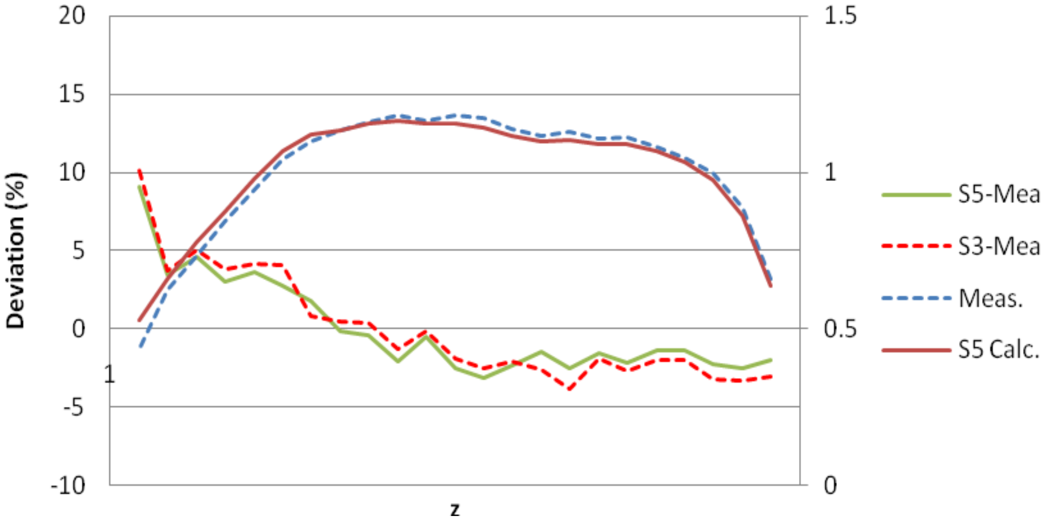

Figure 2. Axial measured and calculated profiles for all assemblies.

The assembly average deviations are plotted versus burnup in Fig. 3. The error has no exposure dependence. The first two clusters in Fig. 3 are mainly due to Optima2 fuel while the remaining dots represent Atrium. The two fuel designs have the same error behavior.

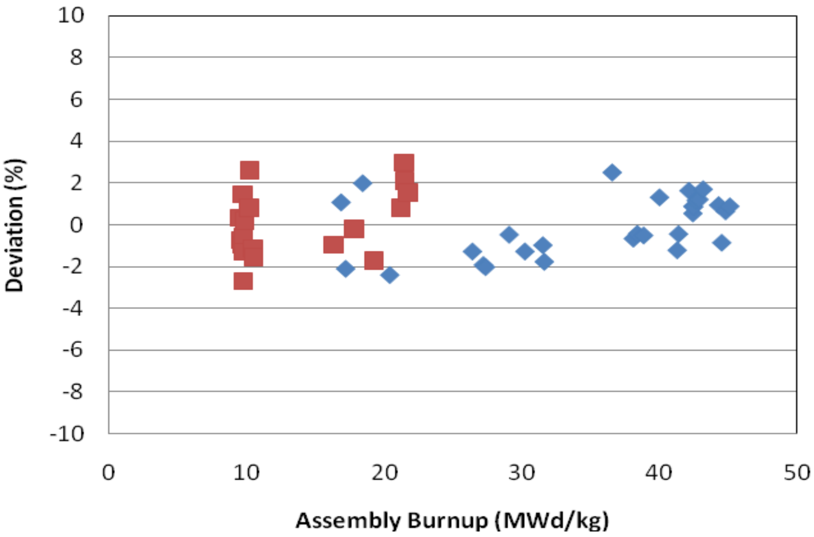

Figure 3. Assembly average deviation (%) as a function of burnup (MWd/kg).

3.2. Evaluation of Pin Measurements

The evaluation of the gamma scanning of individual pins in Optima2 assemblies 26891 (20 % controlled) and 26899 are summarized in Table II. The total, radial and axial RMS deviations are shown for SIMULATE-3 and for SIMULATE-5 with nominal water gaps and with measured assembly bow corrected ones. The maximum assembly bow, in mm, at assembly midpoint is shown in Fig. 4. A positive number indicates widening water gap size. The bowing is assumed to have a cosine shape axially and to be zero at the end points.

Table II. Pin gamma scanning evaluation with SIMULATE-3 and SIMULATE-5. RMS errors (%)

	Pins of assy 26891			**Pins of assy 26899**		
	Nod	**Rad**	**Axi**	**Nod**	**Rad**	**Axi**
SIM-3	6.6	4.1	4.7	2.8	1.6	1.7
SIM-5 nom. gaps	3.8	3.1	1.4	2.5	1.2	1.6
SIM-5 corr. gaps	3.0	2.1	1.4	2.5	1.1	1.8

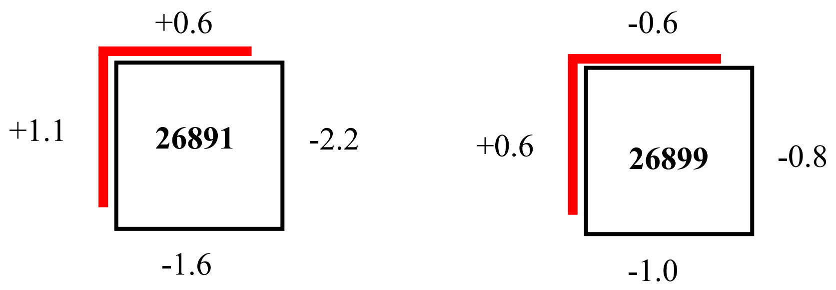

Figure 4. Channel bow at assembly midpoint. A positive number indicates a wider gap.

The average deviation for each pin is shown by Figures 5 and 6. SIMULATE-5 calculations based on nominal and corrected gaps are presented. The bow correction in SIMULATE-5 is done by modifying the nodal cross-sections and pin data by interpolation on delta gap branch data, which is generated with CASMO-5 and tabulated in the library, for the given 3D delta gap distribution.

The axial profiles for the sum of the scanned pins are displayed in Figures 7 and 8. These figures contain information about the position of control rod, spacers, and the end point for part length fuel rods (PLR). The lower, middle, and upper assembly regions of the Optima2 design contain 96, 92, and 84 fuel pins, respectively.

SIMULATE-5 with nominal gaps provides considerable improvement compared to SIMULATE-3. The use of true gap widths further reduces the error to levels not far from the reported measurement uncertainty (1.5 %). The tilt from control rod corner to detector corner, observed in the controlled assembly, is considerably mitigated by the use of correct inter-assembly widths.

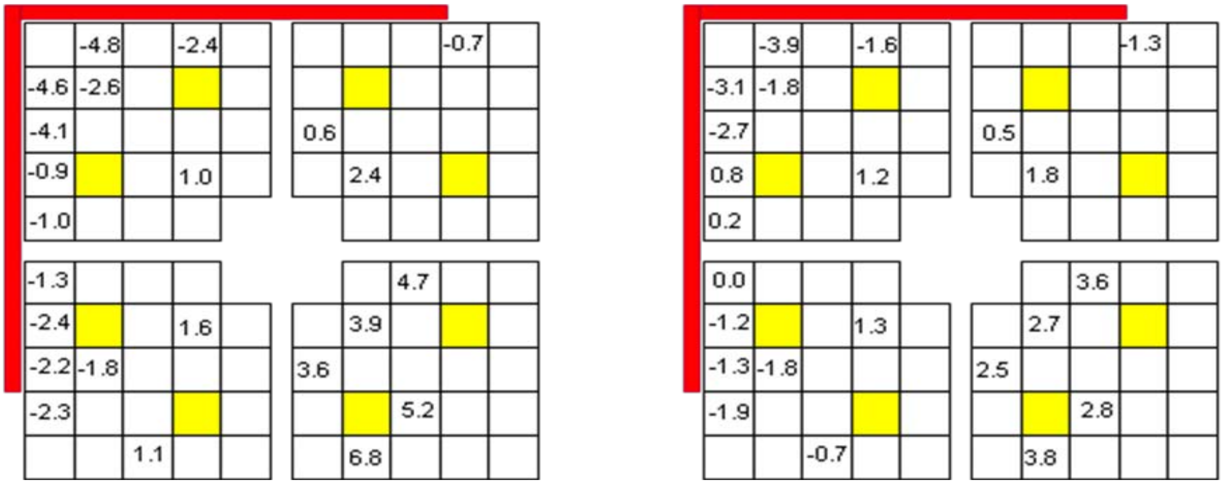

Figure 5. Average pin deviations for assembly 26891. Nominal and corrected gaps.

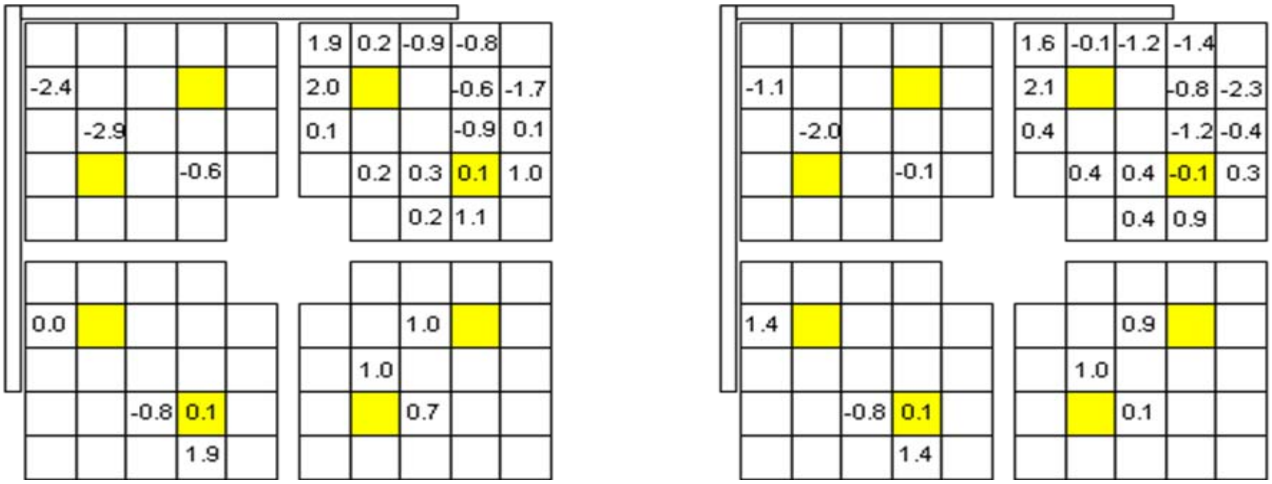

Figure 6. Average pin deviations for assembly 26899. Nominal and corrected gaps

The highlighted squares of Figures 5 and 6 mark burnable absorber pins. There is no indication that such pins have larger errors than other pins. (At the time of the gamma scan measurements, the gadolinium is depleted to insignificant levels.)

The SIMULATE-5 prediction of the flux shape at the control rod (covering the first 5 nodes of the assembly) is excellent as seen in Fig 7. The striking improvement at the control rod locations compared to SIMULATE-3 can be explained by a number of model developments:

- Control rod history and void history are accurately handled by tracking of a large number of nuclides.

- The submesh model provides a detailed flux solution that does not depend on 'conventional' cross sections and discontinuity factors that are generated with the zero net current boundary condition.
- The submesh model accounts for the local build-up of important actinides.
- The sub-channel thermal hydraulics gives a realistic coolant density distribution in the radial direction of an assembly.
- The depletion of the control rod is tracked.

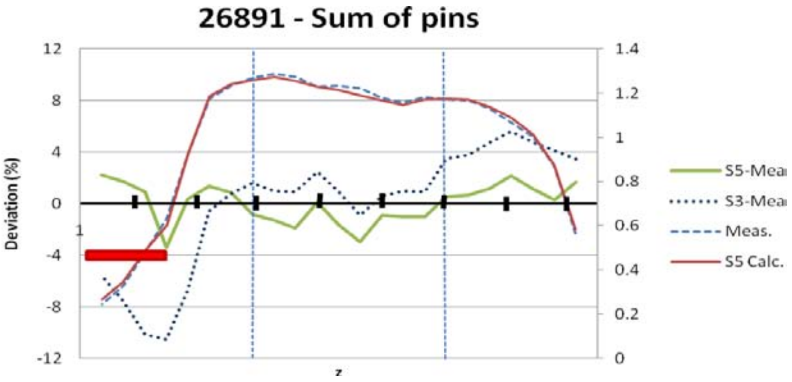

Figure 7. Average axial profile for measured pins of assembly 26891. CR, Spacers and PLR transitions indicated in figure.

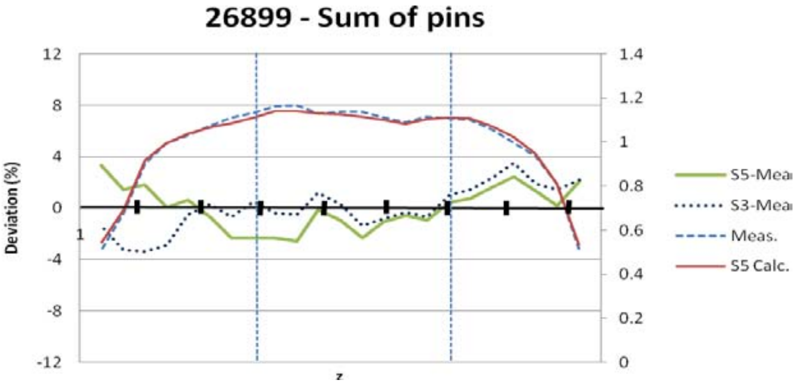

Figure 8. Average axial profile for measured pins of assembly 26899.

Figures 7 and 8 show that the spacer grids, which are modeled explicitly in SIMULATE-5, are treated adequately. No error discontinuities are seen at the PLR transitions. This is not an obvious result since the boiling process is affected by the area expansion above PLRs. Thus SIMULATE-5 models the voiding well.

Finally, the error curves (no gap correction) for all pins of assembly 26891 are shown in Figures 9 and 10. The pins adjacent to the control blade have an error bias compared to interior pins. The power of the pins at the blades is under-predicted. This could be due to either the modeling in SIMULATE-5 and/or gap width uncertainties.

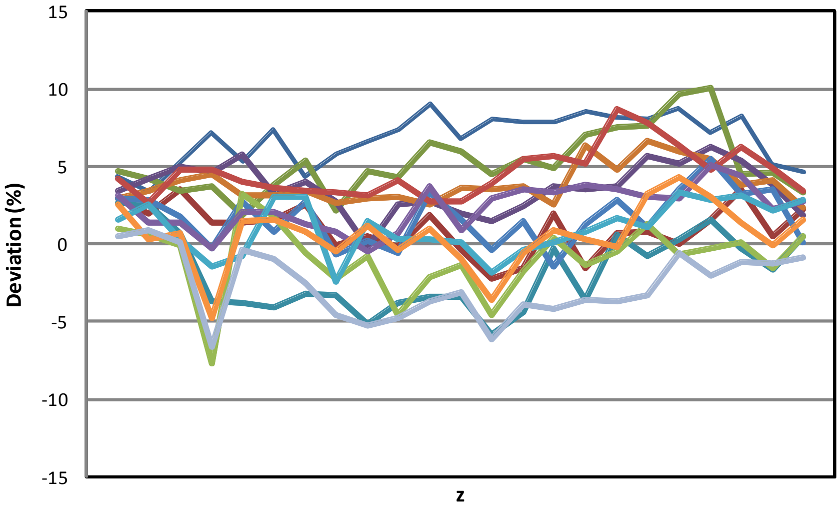

Figure 9. Axial error profiles for interior pins of assembly 26891.

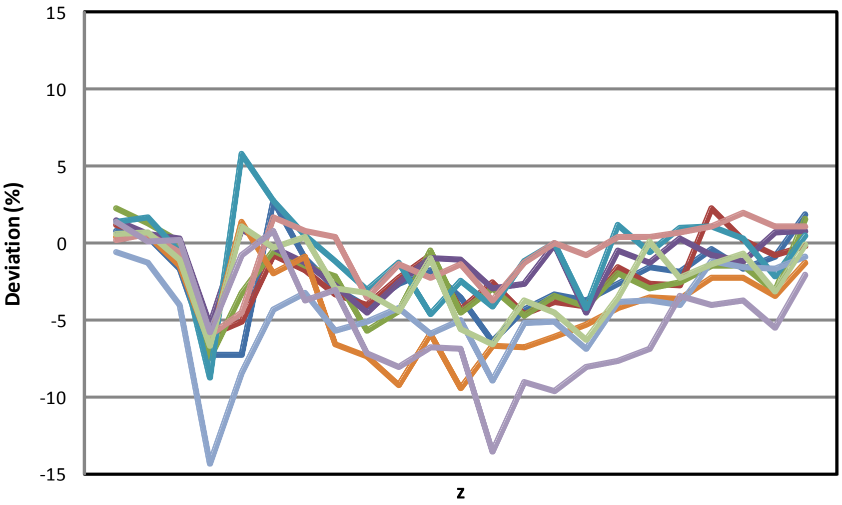

Figure 10. Axial error profiles for pins of assembly 26891 adjacent to CR blade.

For the interior pins there is no obvious systematic error trend, apart from an over-prediction caused by the under-prediction of the pins adjacent to the gaps. Gadolinium, part length pins and water holes, seem to have no strong, visible affect on the accuracy.

4. TIP AND keff EVALUATION OF OSKARSHAMN2

4.1. Tip and Hot Eigenvalue Evaluation

Oskarshamn2 is equipped with gamma TIPs. The detector evaluation of cycles 15 to 32 with SIMULATE-5 is summarized in Table III. The SIMULATE-5 keff and total TIP RMS values for all measurements of cycles 21-32 are displayed in Fig. 11.

The average total TIP RMS for cycle 32 is 3.0%. For the last TIP evaluation of that cycle, the total RMS is 2.5%. These numbers are lower than the error of the gamma scanning. This is to be expected since the TIP trace is an average of the flux of four assemblies, thus averaging out individual assembly errors.

At low power and core flow rates, keff drops by several hundred pcm and the TIP RMS value increases to six percent as shown in Fig. 11. This operating regime is an area where future model improvements are expected.

Table III. Summary of TIP and hot keff results, cycle15-32.

Cycle	Mean keff	keff RMS (pcm)	Nod avg RMS	Rad avg RMS	Axi avg RMS
15	1.00334	124	5.61	2.30	3.96
16	1.00265	84	5.67	2.10	3.68
17	1.00196	89	3.64	2.02	1.51
18	1.00017	58	8.85	1.62	7.99
19	1.00115	87	4.91	1.97	3.59
20	1.00062	125	5.10	1.41	3.75
21	1.00148	104	3.82	1.71	2.95
22	1.00147	74	3.91	1.67	3.08
23	1.00079	61	3.75	1.81	2.84
24	1.00126	58	3.70	1.43	2.94
25	1.00291	47	4.78	1.50	3.66
26	1.00155	69	4.42	1.71	3.60
27	1.00171	64	4.04	1.21	3.43
28	1.00213	52	4.36	1.67	3.53
29	1.00161	25	4.56	1.39	3.75
30	1.00243	36	4.02	1.37	3.26
31	1.00201	36	3.73	1.76	2.65
32	1.00259	43	3.04	1.02	2.08

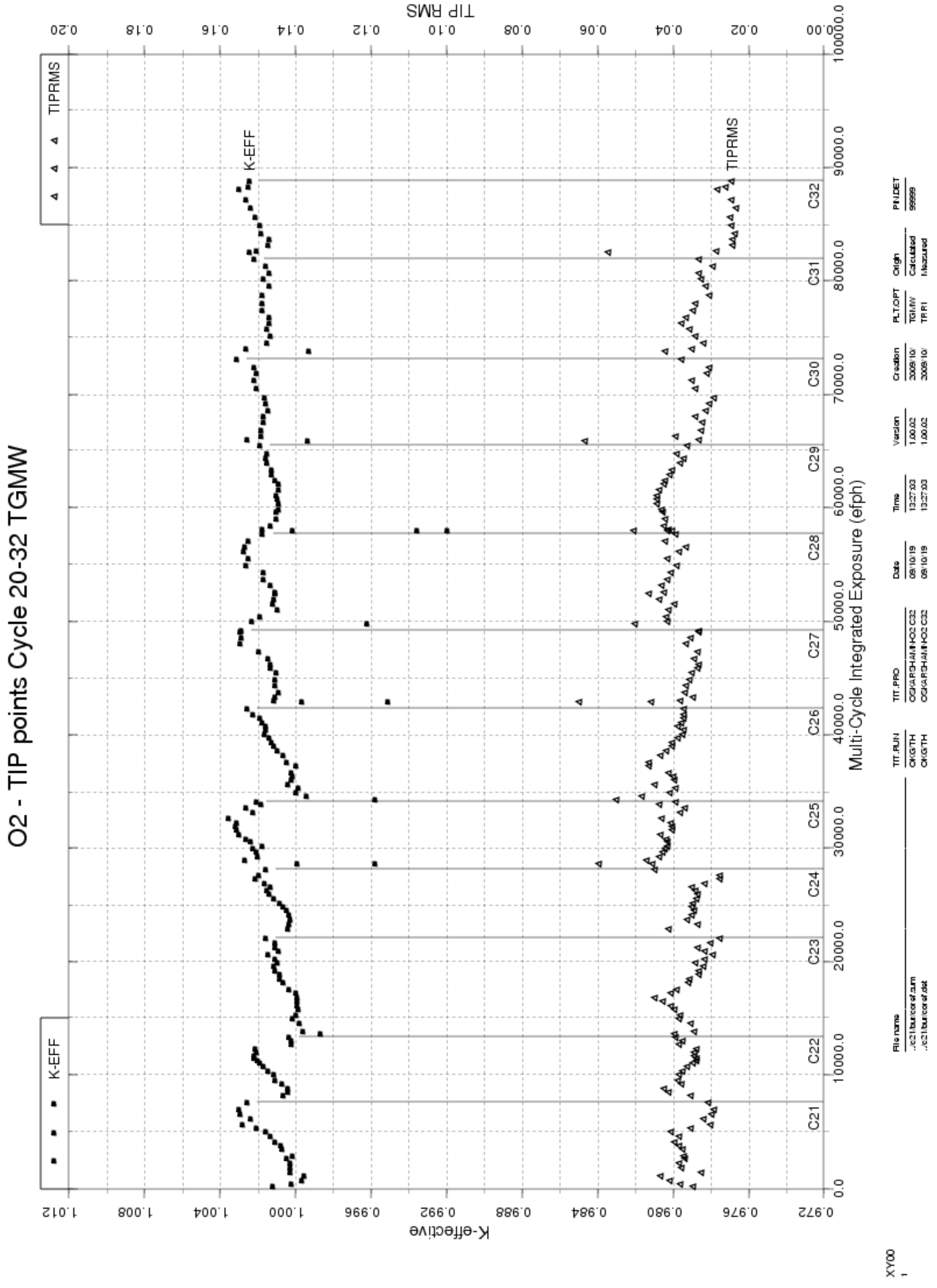

Figure 11. keff and TIP node RMS for cy21-c32.

4.2 Cold Critical Eigenvalue Evaluation

The cold critical keff has been evaluated for Cycles 15 to 32. The results are summarized by Figure 12 where cycle average keff is plotted for SIMULATE-3 with CASMO-4 and SIMULATE-5 with CASMO-5, and by Figure 13 where the spread in respective cycle is displayed.

The following observations are made:

- The keff of SIMULATE-3 and SIMULATE-5 have a very similar behavior over the cycles, but SIMULATE-3 lays 200-400 pcm below unity while S5 is closer to one.
- The difference between hot and cold keff is about +350 pcm for SIMULATE-3 and about +100 pcm for SIMULATE-5.
- From Cycle 21 to 25 there is a rise in keff of roughly 300 pcm that coincides with the introduction of Atrium fuel. When Optima2 is introduced in Cycles 31-32, keff drops by about 300 pcm.
- The RMS spread in keff for a given cycle is around 100 pcm for SIMULATE-5, cf. Fig. 13. For SIMULATE-3 the spread is higher.

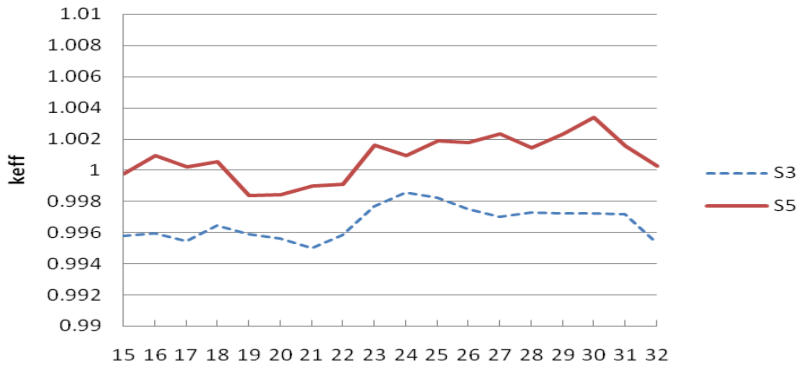

Figure 12. Cold critical keff for cycles 15-32, SIMULATE-3 and SIMULATE-5.

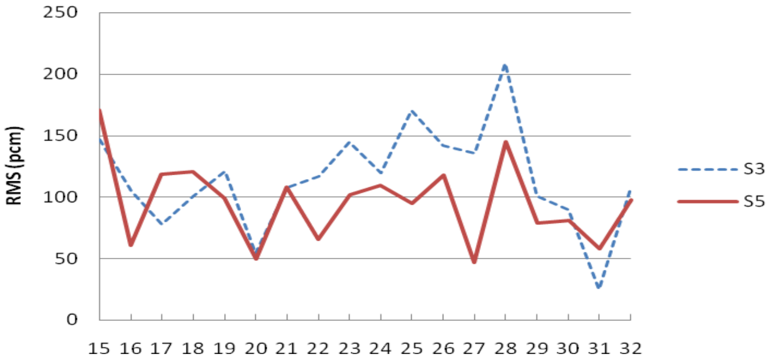

Figure 13. RMS of cold critical calculations for cycles 15-32.

5. CONCLUSIONS

The following conclusions can be drawn from the evaluation of the Oskarshamn2 gamma scanning:

- SIMULATE-5 predicts the assembly flux shape of Oskarshamn2 EOC cycle 32 with a total RMS of around 3-4 %.
- The RMS of the assembly average error is 1.5 %.
- The total RMS error for a normalized pin distribution is roughly 2.5 to 4 %, the lower of these two numbers being valid for uncontrolled assemblies.
- SIMULATE-5 offers significant improvement compared to SIMULATE-3, especially for pin power calculations.
- The assembly average error shows no apparent dependence on control rods.
- The assembly average error shows no radial tilt. The periphery poses no problem.
- In the axial direction, spacers are well handled.
- The axial error is fairly evenly distributed. No error bumps are seen at the transition to part length fuel rods. Thus, the thermal hydraulic and neutronic treatment of PLRs is satisfactory.
- The pin results show no error dependence on burnable absorbers or water rods.
- The pin results have a significant dependence on the gap widths.
- SIMULATE-5 with CASMO-5 has a smaller discrepancy between cold and hot eigenvalues than SIMULATE-3 with CASMO-4.
- SIMULATE-5 cold keff values have a smaller spread than SIMULATE-3.

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