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VALIDATION OF THE HOR OSCAR4/MCNP MODEL FOR USE IN SAFETY STUDIES

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ABSTRACT

The MCNP model for the HOR research reactor uses material densities obtained from the core follow and depletion code OSCAR4. The model was validated with respect to low and nominal power critical control rod positions, control rod reactivity, two stuck control rod shut down margin and power distribution with sufficient accuracy. The model validation was successful and the model will be used for input data generation for RELAP. This code will be used in safety studies for the new Safety Analyses Report.

1. Introduction

The only university based RR in the Netherlands, HOR, is a 3 MW licenced open pool type RR in operation for 55 years. Since 2005 the reactor uses fuel assemblies utilizing low enriched uranium (LEU) fuel, that having less than 20 weight-% in U^{235}. The fuel is a silicide compound in an aluminum dispersion (U_3Si_2-Al). A complete licence renewal is due since its last revision in 1993. The safety study is to be completely overhauled to conform to current standards. The commonly accepted thermal hydraulics code RELAP5 mod 3.3 will be used to analyse the deterministic postulated initiating events. The kinetic and reactivity data necessary will be supplied by calculation codes MCNP and OSCAR4.

The models used to support analysis and operation are expected to be suitably predictive. To achieve this goal, it is expected that the calculation of reactivity, power distribution, and supporting parameters are not only accurate, but they are also consistent. There are no readily available criteria available on how to judge whether this has been achieved by any particular model. As a consequence, for example, one finds a spread from 0.5 to 1.5% in the bias allowed in the eigenvalue at estimated critical position in models used for RR safety studies [1].

The one available standard available for power reactors is ANSI/ANS-19.6.1-2011 [2]. It requires that the model (for existing facilities) should be validated by comparing historical data at power and low power of at least parameters of importance to assuring safe operation:

- reactivity balance (eg prediction of Keff)
- reactivity control (eg prediction of isothermal temperature coefficient)
- power distribution
- the capability to achieve safe shutdown (eg CR worth and SDM prediction)

The available criteria proposed for power reactors are translated to:

- Calculated bias of critical Keff (Kecp, estimated critical position) should be consistent within 500 pcm.
- Calculated ITC should be within 2 pcm/ºC of the measured value,
- Calculated (relative) local power should be within 10 % of measured and
- Calculated CR worth should be within 15% of measured.

The previous HOR model implemented by the corefollow and depletion code OSCAR3 feeding fuel material composition to MCNP did not fulfil Kecp for showing an unacceptable bias and an inconsistent upwards trend.

Several improvement were implemented (in order of importance):

- reactor power was recalibrated to be 15 % higher,
- Be poisons are modelled and updated for each Be reflector assembly,
- B4C absorber in Control Rods are depleted,
- Fresh fuel uses as build detailed material definitions,
- Construction materials (like AG3NE) are defined including impurities

These improvements were implemented by updating to OSCAR4 corefollow and depletion feeding MCNP.

2. Validation

HOR operates on a weekly schedule, running at 2.3 MW typical for 104 hours and no operation during the weekend. Every 15 weeks one or two spent assemblies are changed for fresh ones and a new reactor cycle is started after shuffling. Each year covers 2 to 3 reactor cycles. This validation covers six recent cycles (beginning of 2013 to end of 2015). The following quantities will be addressed:

- Critical position eigenvalue

- Control Rod worth
- Excess reactivity
- N-2 shut down margin
- Power distribution evaluation

2.1 Critical eigenvalues

In-cycle ECP eigenvalue were calculated at beginning of the cycle at cold zero [Xe] condition, at two mid cycle moments at Xe equilibrium and at a moment near the end of the cycle, also at Xe equilibrium. Typical CR bank settings for these moments are 52 (BOC), 70, 80 and nearly 100% (EOC) out of the core thus covering the complete travel of CR during a reactor cycle.

Temperature corrected k_{ECP} values are reported in Table 2-1, and shown graphically in Figure 2-1.

Table 2-1 Validation Moderator Temperature Corrected in cycle k_{ECP}

Cycle	ECP date	Temperature (°C)	Correction (pcm)	Corrected k_{ECP}
1301	BOC	27.74	139	1.00625
	22-02-2013	29.77	100	1.00705
	19-04-2013	32.34	51	1.00723
	05-07-2013	38.11	-59	1.00495
1302	BOC	34.63	7	1.00635
	27-09-2013	35.41	-8	1.00696
	15-11-2013	35.13	-2	1.00702
	24-01-2014	34.03	19	1.00605
1401	BOC	29.90	97	1.00616
	14-02-2014	32.84	41	1.00684
	28-03-2014	34.22	15	1.00669
	16-05-2014	34.99	0	1.00609
1402	BOC	32.22	53	1.00554
	06-06-2014	37.21	-42	1.00616
	05-09-2014	40.35	-102	1.00570
	21-11-2014	33.12	36	1.00578
1403	BOC	30.83	80	1.00705
	12-12-2014	33.69	25	1.00617
	06-02-2015	29.38	107	1.00718
	03-04-2015	32.91	40	1.00583
1501	BOC	28.95	116	1.00607
	17-04-2015	34.70	6	1.00598
	28-08-2015	36.60	-31	1.00578
	23-10-2015	36.50	-29	1.00517
Average k_{ECP} (std. dev. in pcm)				1.00625 (63)

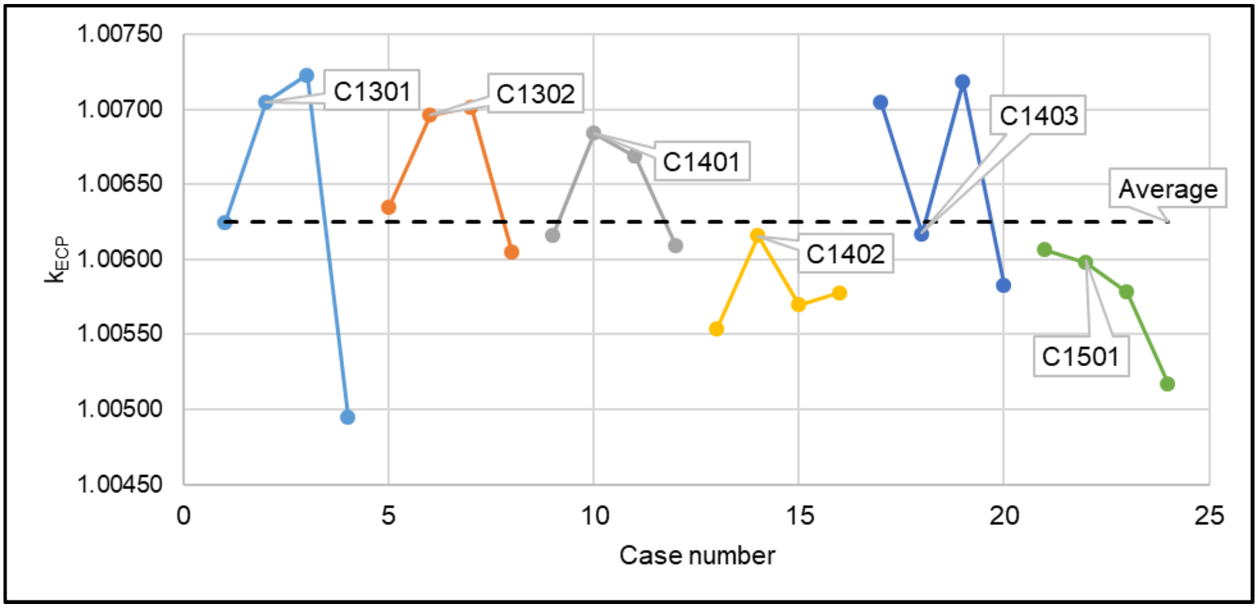

Figure 2-1 Moderator Temperature Corrected MCNP k_{ECP} Values for Validation Cases

The temperature corrections result in an increase of the average k_{eff} values over all of the cycles, from 1.00598 to 1.00625, while the standard is 63 pcm. The model predicts core criticality consistently, with a maximum deviation from the average of 130 pcm.

Apart from the in-cycle ECPs listed above, the starting critical configuration for each trajectory of the control rod worth measurements, reported in the follow section, can also be used to evaluate the model's predictive capability in terms of criticality. These CR reactivity worth measurements are performed after shuffle, typically 1 day before BOC. It must be noted that these critical positions cover extremely skewed CR settings.

Table 2-2 shows the k_{ECP} values for each of the starting critical configurations, as well as the temperature correction applied to these values. Both the uncorrected and temperature corrected values are shown graphically in Figure 2-2 and Figure 2-3.

Table 2-2 Moderator Temperature Corrected k_{ECP} for Control Rod Calculations

Cycle	k_{ECP}	Std. Dev. (pcm)	Temp. (°C)	Correction (pcm)	Corrected k_{ECP}
	1.00453	15	20.74	272	1.00725
	1.00474	15	20.78	272	1.00746
	1.00402	15	20.53	276	1.00678
1301	1.00462	17	20.51	277	1.00739
	1.00471	16	20.53	276	1.00747
	1.00425	16	20.55	276	1.00701
	1.00385	16	20.16	283	1.00668

	1.00454	15	20.33	280	1.00734
	1.00422	15	20.33	280	1.00702
	1.00346	15	20.19	283	1.00629
	1.00463	15	20.14	284	1.00747
	1.00485	16	19.82	290	1.00775
1302	1.00470	16	29.94	97	1.00567
	1.00512	15	29.83	99	1.00611
	1.00455	17	29.87	98	1.00553
	1.00491	15	29.78	100	1.00591
	1.00528	16	29.85	98	1.00626
	1.00457	15	29.71	101	1.00558
	1.00521	16	29.69	101	1.00622
	1.00512	15	29.70	101	1.00613
	1.00488	15	29.85	98	1.00586
	1.00427	14	29.70	101	1.00528
	1.00494	16	29.60	103	1.00597
	1.00579	16	29.60	103	1.00682
1401	1.00403	16	22.64	236	1.00639
	1.00415	16	22.09	247	1.00662
	1.00347	15	22.13	246	1.00593
	1.00376	16	22.07	247	1.00623
	1.00402	15	22.00	248	1.00650
	1.00321	16	21.93	250	1.00571
	1.00378	16	21.74	253	1.00631
	1.00400	15	21.77	253	1.00653
	1.00384	15	21.79	252	1.00636
	1.00318	17	21.65	255	1.00573
	1.00408	15	21.72	254	1.00662
	1.00368	15	21.65	255	1.00623
1402	1.00523	15	27.51	143	1.00666
	1.00498	16	27.56	142	1.00640
	1.00375	16	27.54	142	1.00517
	1.00413	16	27.65	140	1.00553
	1.00471	17	27.61	141	1.00612
	1.00421	15	27.67	140	1.00561
	1.00449	16	27.74	139	1.00588
	1.00464	16	27.58	142	1.00606
	1.00493	16	27.65	140	1.00633
	1.00331	16	27.70	139	1.00470
	1.00418	15	27.70	139	1.00557
	1.00497	16	27.63	141	1.00638
1403	1.00400	16	24.43	202	1.00602
	1.00484	16	25.52	181	1.00665
	1.00445	15	25.54	181	1.00626
	1.00408	15	25.50	181	1.00589
	1.00500	16	25.38	184	1.00684
	1.00430	15	25.40	183	1.00613
	1.00483	16	25.38	184	1.00667

	1.00504	16	25.38	184	1.00688
	1.00466	16	25.30	185	1.00651
	1.00429	15	25.11	189	1.00618
	1.00472	17	25.25	186	1.00658
	1.00495	15	25.32	185	1.00680
	1.00431	17	24.31	204	1.00635
	1.00448	17	24.24	206	1.00654
	1.00406	16	24.99	191	1.00597
	1.00419	16	24.26	205	1.00624
	1.00428	15	24.29	205	1.00633
1501	1.00390	14	24.26	205	1.00595
	1.00429	16	24.31	204	1.00633
	1.00432	16	24.35	203	1.00635
	1.00442	15	24.38	203	1.00645
	1.00399	15	24.22	206	1.00605
	1.00466	16	24.33	204	1.00670
	1.00452	15	24.29	205	1.00657
Average (Std. Dev. pcm)					1.00633 (57)

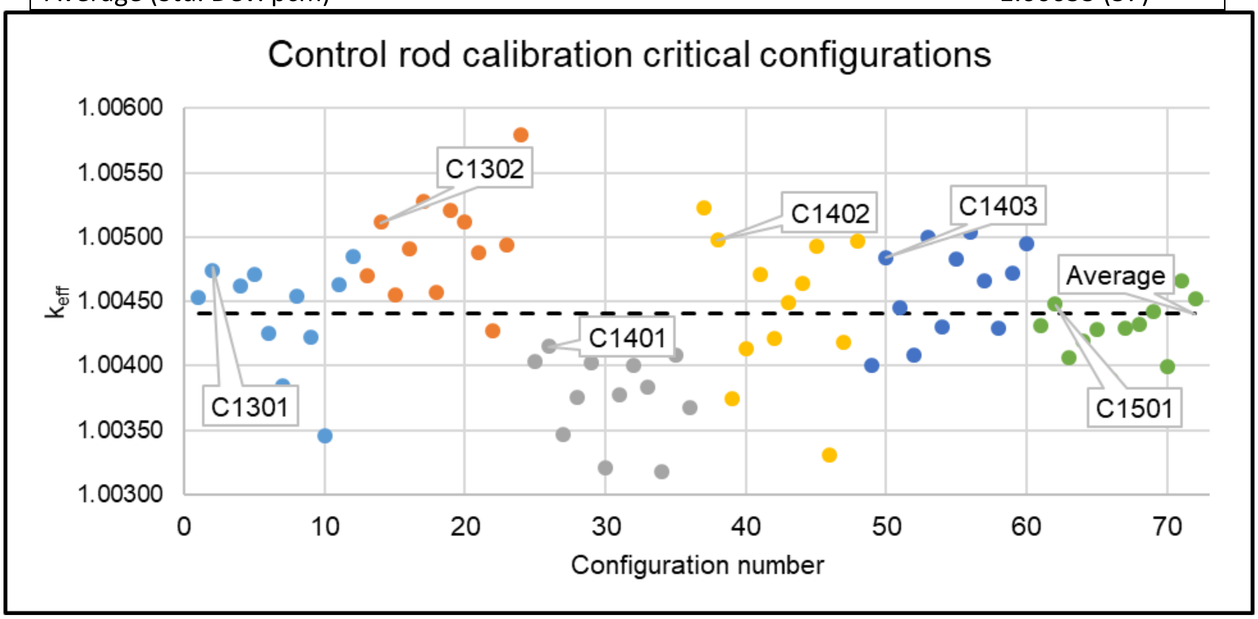

Figure 2-2 MCNP k_{ECP} Values Before Moderator Temperature Correction

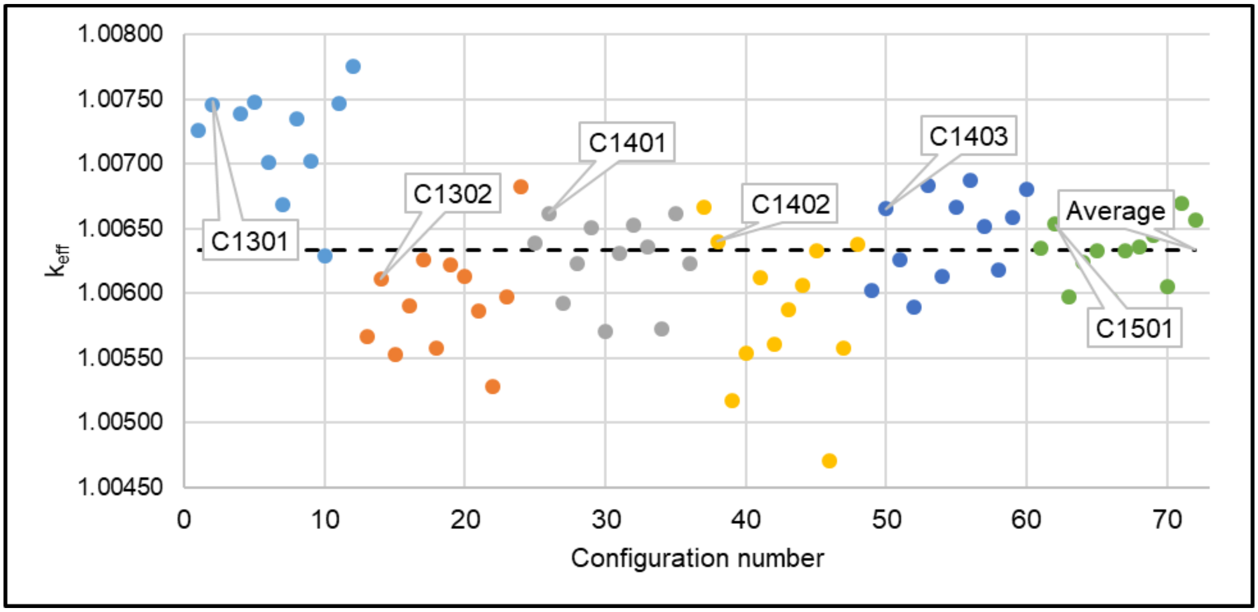

Figure 2-3 MCNP k_{ECP} Values After Moderator Temperature Correction

The model consistently predicts the k_{eff} value for different critical configurations over multiple cycles, with the maximum in-cycle standard deviation of 55 pcm and an overall standard deviation of 57 pcm. For cycle C1301 there is a systematic off-set from the overall average k_{eff} value, which could be a result of an incorrect temperature used to apply the temperature correction, as this systematic off-set is not seen in the uncorrected values. Nonetheless, the average k_{ECP} value of 1.00633 corresponds well with the average value of the ECPs of 1.00625 throughout the validation period. It is apparent that MCNP calculations of ECPs should typically expect an eigenvalue of ~1.00633. This is the bias applicable to ECP calculations.

2.2 Rod Worths

At the beginning of each reactor cycle the control rod worths are determined, by measuring the reactivity effects of moving each individual control rod through the following trajectories: from 100% to 60%, 60% to 30% and finally 30% to 0%, where the percentage here indicates the extraction of the control rod. The reactivity effect of moving an individual control rod is compensated by the remaining three control rods, and each trajectory is started from a critical state. Measured control rod worths are determined using inverse points kinetics by analyzing the time rate of change of the neutron population as measured by a fission chamber. While partial CR worths are available, only total CR worth is presented.

Table 2-3 1301 Comparison of Predicted and Measured Control Rod Worths

Rod	MCNP	σ	Meas.	Diff. (pcm)	Diff. (%)
CR1	2998	38	2830	168	6%
CR2	3294	39	3093	201	6%
CR3	2985	38	2951	34	1%
CR4	3311	38	3271	40	1%
Total	12588	76	12145	443	4%

Table 2-4 1302 Comparison of Predicted and Measured Control Rod Worths

Rod	MCNP	σ	Meas.	Diff. (pcm)	Diff. (%)
CR1	3099	38	2998	101	3%
CR2	3378	38	3152	226	7%
CR3	2758	38	2748	10	0%
CR4	2905	38	2990	-85	-3%
Total	12139	76	11888	251	2%

Table 2-5 1401 Comparison of Predicted and Measured Control Rod Worths

Rod	MCNP	σ	Meas.	Diff. (pcm)	Diff. (%)
CR1	3121	38	2982	139	5%
CR2	3149	38	2996	153	5%
CR3	2811	38	2702	109	4%
CR4	3005	39	3142	-137	-4%
Total	12087	77	11822	265	2%

Table 2-6 1402 Comparison of Predicted and Measured Control Rod Worths

Rod	MCNP	σ	Meas.	Diff. (pcm)	Diff. (%)
CR1	3127	38	2914	213	7%
CR2	3409	39	3259	150	5%
CR3	2972	38	2814	158	6%
CR4	3194	38	3306	-112	-3%
Total	12702	77	12293	409	3%

Table 2-7 1403 Comparison of Predicted and Measured Control Rod Worths

Rod	MCNP	σ	Meas.	Diff. (pcm)	Diff. (%)
CR1	3101	38	3043	58	2%
CR2	3526	39	3332	194	6%
CR3	2776	40	2644	132	5%
CR4	2998	38	3065	-67	-2%
Total	12401	77	12084	317	3%

Table 2-8 1501 Comparison of Predicted and Measured Control Rod Worths

Rod	MCNP	σ	Meas.	Diff. (pcm)	Diff. (%)
CR1	3091	40	2991	100	3%
CR2	3324	37	3188	136	4%
CR3	2857	39	2789	68	2%
CR4	3052	38	3185	-133	-4%
Total	12323	77	12153	170	1%

In the validation model, the estimated total worth of the individual control rods agree well with the measured worth, with a maximum error of 7% of the measured worth. The total control rod worth of all of the control rods combined agree to within 4% of the total measured worth. These results show that the MCNP model can reliably predict the individual as well as the total control rod worth. It also demonstrates that there is no particular need for biasing the calculations of individual control rod worths.

2.3 Excess reactivity

The measured excess reactivity is calculated by summing the reactivity swing of each rod going from 100% out of core to critical (cold, zero Xe) position. In the MCNP model excess reactivity is calculated as the difference between all-rods-out and all rods at critical position.

A comparison of the calculated and measured excess reactivity of cycles 1301 – 1501 is given in Table 2-9, and shows that the calculated excess reactivity compares well with the measured values to within 5%. The small deviations between measured and calculated values indicate that there is no particular need to bias the results.

Table 2-9 Comparison of Predicted and Measured Excess Reactivity

Cycle	MCNP	σ	Meas.	Diff. (pcm)	Diff. (%)
1301	4699	17	4602	97	2%
1302	4155	17	3971	184	5%

1401	3917	17	3732	185	5%
1402	4726	17	4624	102	2%
1403	4203	17	4106	97	2%
1501	4648	17	4481	167	4%

2.4 N-2 shutdown margin

HOR is subject to a very strict 2 stuck-rod principle. The quantification demands that N-2 Shut down margin be larger than 100 pcm. Experimentally, after each shuffle the N-2 rod combination of highest worth is determined and sub sequentially driven to 100% out of core. The core is made critical by driving the other rods to critical banked position. The reactivity worth of driving these banked rods completely into the core is then measured and documented as the N-2 shutdown margin. The MCNP calculated N-2 shutdown margin mimics this closely: the reactivity swing is calculated between the N-2 critical position and the N-2 inserted position.

Calculated and measured values (pcm) for the N-2 shut-down margins for cycles 1301 through 1602 are compared in Table 2-10.

Table 2-10 Comparison of Predicted and Measured N-2 Shut-Down Margin

Cycle	MCNP	σ	Meas.	Diff. (pcm)	Diff. (%)
1301	-568	22	-472	-96	20%
1302	-941	22	-786	-156	20%
1401	-1182	24	-1028	-154	15%
1402	-579	22	-519	-60	12%
1403	-1129	22	-916	-213	23%
1501	-623	22	-501	-122	24%
1502	-295	21	-237	-58	24%
1601	-890	22	-738	-152	21%
1602	-1184	22	-1096	-88	8%

The N-2 shutdown margin is consistently overestimated by about 20%. The worst case absolute difference (213 pcm) is within the error to be expected considering 4 %, or 120 pcm, average CR worth difference between measurement and calculation (2.2).

2.5 Power Distribution Evaluation

Copper and cobalt foil activation measurements are performed after each shuffle. Copper foil activation are performed at very low power at 128 positions (8 axial positions in a predefined channel in each of the 16 standard fuel assemblies). The copper activation results in relative reaction rates. MCNP simulation of the copper foil activation uses fmesh tallies at the foil positions. Fmesh tallying thermal flux upto 1 eV gave the same result as fmesh with the reaction rate multiplier for Cu-63 (n,γ). Normalization was by the average of all 128 foil reaction rate values. While comparison was performed for 6 cycles, only results for one cycle is shown here.

The measured and calculated data are shown for the cycle 1301 in Figure 2-4.

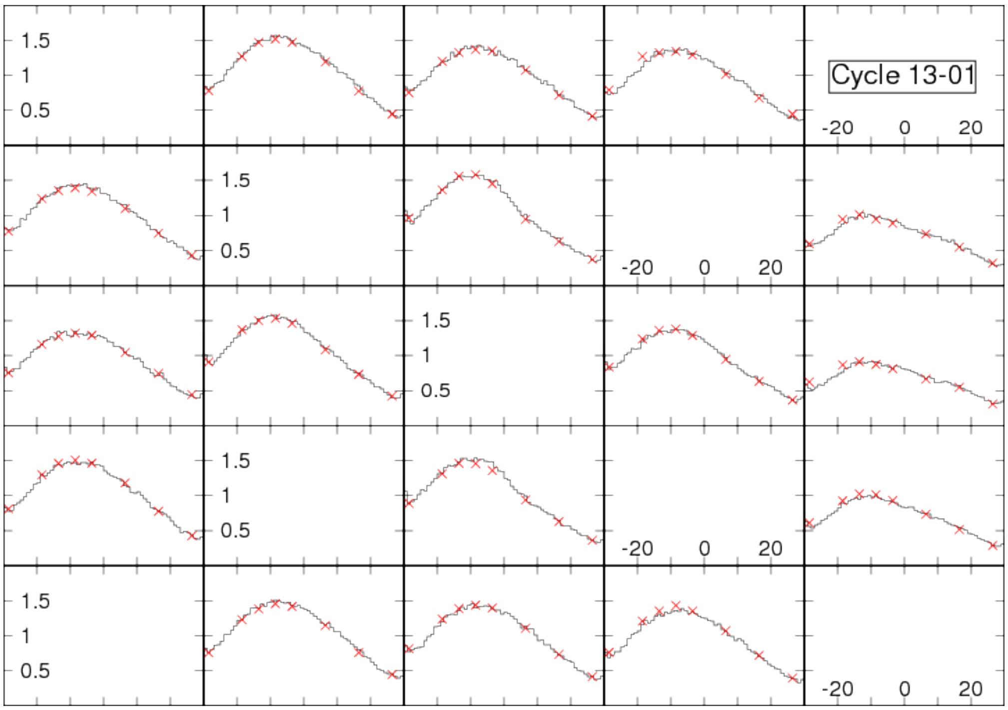

Figure 2-4 Calculated (black line) and measured (red crosses) results for Cu foil activation in cycle 1301, in relative units

Overall good agreement is found for copper foil relative distribution.

Cobalt foil activation is performed at 12 positions in the two least burned standard fuel assemblies of which typically one is fresh (no burnup). This activation is performed at 1% of nominal power for typically 20 minutes. Recoding the power time-trace during activation enables to calculate the reaction rate at the recorded power.

MCNP calculation of the absolute Cobalt reaction rate was performed by modeling the foil explicitly to incorporate considerable self shielding of Co. The MCNP source multiplier was calculated by Pv/epf where P is (effective) reactor power during activation v=neutrons per fission and epf is the energy release per fission.

The measured Cobalt activation reaction rate was well reproduced in the MCNP model, the difference was 2% per cycle (average of 12 foils).

Conclusions

For the several cycles validated the average k_{ECP} value calculated is consistently higher than 1.0. It is apparent that MCNP calculations of ECPs should typically expect an eigenvalue of ~1.00633 +/-0.001 (2σ). This is the bias applicable to all ECP calculations for HOR.

The estimated total worth of the individual control rods agrees well with the measured worth, with a maximum error within 7% of the measured worth. The total control rod worth of all of the control rods combined agree to within 4% of the total measured worth. These results show that the MCNP model can reliably predict the individual as well as the total control rod worth. It also demonstrates that there is no particular need for biasing the calculations of individual control rod worths.

A comparison of the calculated and measured excess reactivity of cycles 1301 – 1501 shows that the calculated excess reactivity compares well with the measured values to within 5%. The small deviations between measured and calculated values indicates that there is no particular need to bias the results.

The N-2 shut-down margin is overestimated by 19% on average, for the cycles considered in this validation report.

The results for the copper foil activation show that the flux, and hence power, distribution over the core is consistently well reproduced by the calculations thus not indicating any need to bias the results of MCNP power distribution calculations.

The cycle depletion fuel densities supplied by OSCAR4 substituted in the MCNP model give consistent in-cycle and cycle to cycle results of HOR reactor conditions.

The MCNP model is suitably predictive for reactivity, control rod worth, and power distribution. Ancillary calculations of reactivity coefficients and kinetics parameters are also acceptable.