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Validation of the CORD-2 System for the NPP Krško Nuclear Core Design Calculations

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ABSTRACT

The CORD-2 package intended for core design calculations of PWRs has been recently updated with some improved models. Since the modifications could substantially influence the obtained results, a technical validation process is required. This paper presents comparison of some calculated and measured parameters of the NPP Krško core needed to qualify the package. Critical boron concentrations at hot full power for selected cycle burnup points and several parameters obtained during the start-up testing at the beginning of each cycle (hot zero power critical concentration, isothermal temperature coefficient and rods worth) for all 27 finished cycles of operation are considered. In addition, assembly-wise power distribution for some selected cycles is checked. Comparison has shown very good agreement of the CORD-2 calculated values with the selected measured parameter of the NPP Krško core.

Keywords: *PWR, nuclear core design calculations, core simulator*

1 INTRODUCTION

The CORD-2 system [1], developed by the Reactor Physics Department of the Jožef Stefan Institute, is intended for core design calculations of PWRs. The main goal in assembling the computational tools was to provide a package that could be used for simple very fast calculations (such as those frequently required for fuel management) as well as for accurate calculations (for example, reload core design) needed to be executed in acceptable time. The CORD-2 system consists of two basic reactor physics codes: WIMS-D [2], and GNOMER [3]. WIMS-D is a well-known and widely used lattice code. Version WIMS-D5 is available from the NEA data bank in Paris. A 69-group neutron cross-section library based on the ENDFB-VII.0 neutron data files has been used. GNOMER solves the neutron diffusion equation in three-dimensional Cartesian geometry by using Green's function nodal method [4]. It also includes advanced features for cross-section homogenization and a simple thermal-hydraulic module so that thermal feedback can be taken into account. The CORD-2 system enables determination of the core reactivity and power distribution. While average assembly powers come directly from the diffusion equation, a reconstruction procedure is needed, which couples heterogeneous pin by pin distribution with the homogenous nodal solution, to obtain final full core pin by pin distributions. The package has been validated for the nuclear design calculations of PWR cores and has been used for the verification of the NPP Krško reload cores since 1990.

The CORD-2 package has been recently updated with some improved models:

- more elaborate calculation of Dancoff factor in the lattice cell calculations,
- expanded set of nuclides considered explicitly during the fuel cooling period,
- improved neutron reflector cross section determination,
- improved model of burnable poison inserts containing Pyrex glass,
- implementation of the neutron cross-section library based on the ENDFB-VII.0 neutron data files.

Since the modifications substantially influence the obtained results, a validation process is required. This paper presents comparison of some calculated and measured parameters of the NPP Krško core needed to qualify the package.

2 BRIEF NPP KRŠKO CORE DESCRIPTION

The Krško plant is a 2-loop Westinghouse PWR that began electricity production in 1981. The start-up core had a rated thermal capacity of 1,876 MWt, and a 626 MWe gross electric power. Currently, the thermal rating is 1,994 MWt with 727 MWe gross electric power. The core consists of 121 fuel assemblies. Each assembly has 235 fuel rods arranged in a 16×16 array. The remaining 21 positions contain guide tubes and are intended for control rods, neutron source and in-core instrumentation. The core features 33 Reactivity Control Cluster Assemblies (RCCA) arranged in 6 banks (D, C, B and A with the shut-down banks SA and SB). The RCCA locations and bank assignment are shown in Fig. 1.

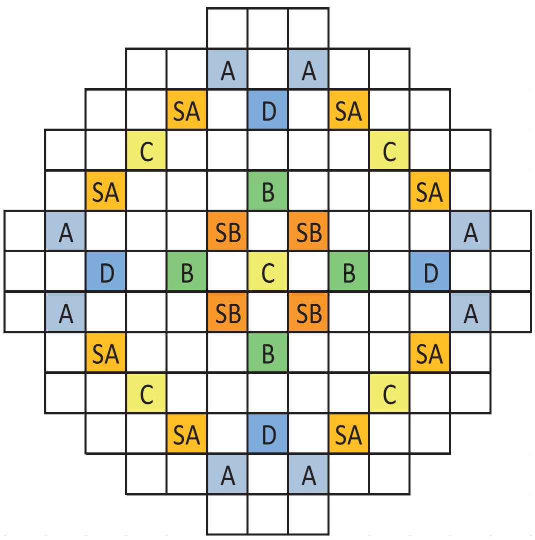

Figure 1: Krško RCCA locations (control bank ID shown)

3 RESULTS AND DISCUSSION

Validation of the CORD-2 system has been accomplished by the comparison of the most important calculated reactor parameters to the available measurement values. All 27 finished plant cycles of operation are considered.

3.1 Critical boron concentration

Comparison of the critical boron concentration is shown in Figure 2. Differences from measurements (C-M) are presented for some selected statepoints:

- Hot Zero Power (HZP) at Beginning Of Cycle (BOC)
- Hot Full Power (HFP) at burnup:
  - 150 MWd/tU
  - 500 MWd/tU
  - End Of Cycle (EOC)

Results are showing consistent CORD-2 behaviour. Differences from measurements are within ±50 ppm band, which is usually taken as an acceptable tolerance level at start-up tests. Only in cycle 17 the HZP value of 62 ppm exceeds the imposed limit. Furthermore, for each cycle, the error critical boron concentration spread from BOC to EOC is almost everywhere within 50 ppm.

Averaged differences and standard deviation are presented in Table 1. A slight tilt smaller than 18 ppm from the BOC to EOC critical boron concentration can be observed confirming good CORD-2 burnout prediction capabilities. Standard deviation of results is within 25 ppm, therefore there is the 95% confidence that predicted critical boron concentrations are within ±50 ppm band.

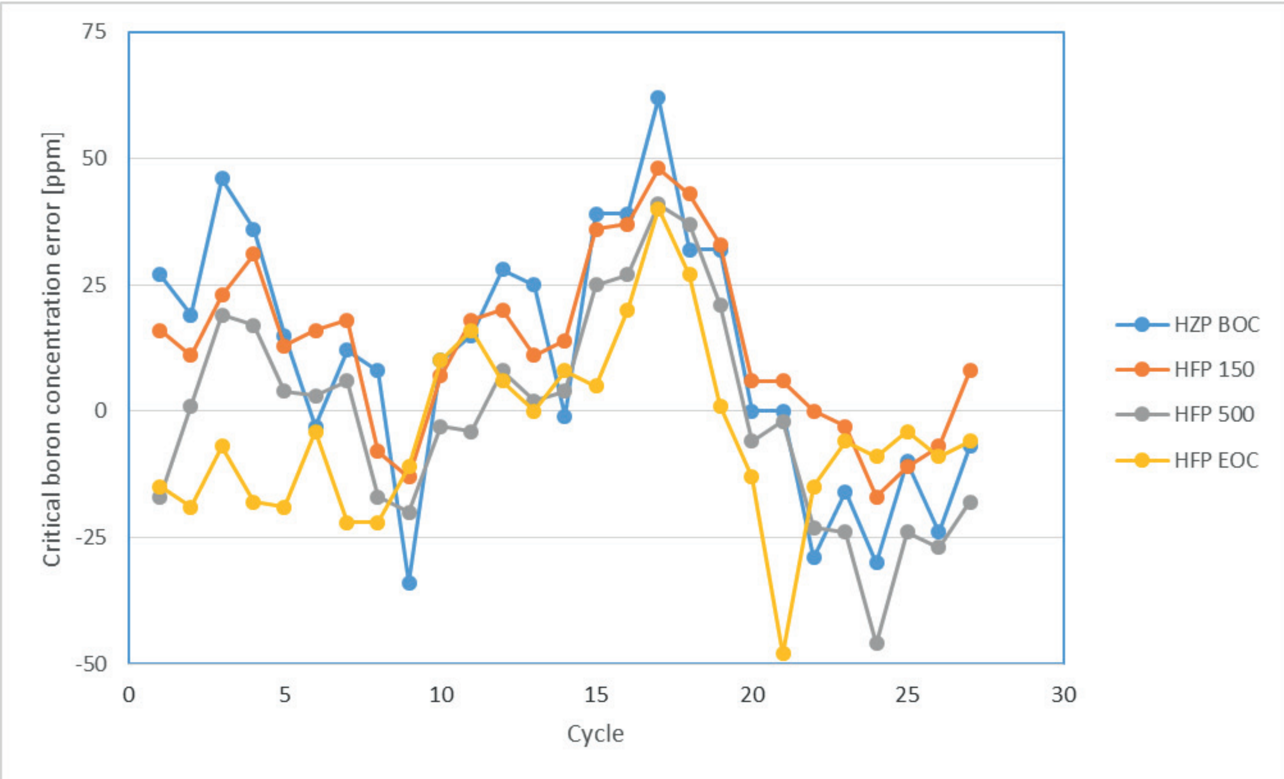

Figure 2: Critical boron concentration differences (C-M)

Table 1: Statistical data of critical boron concentration differences

	HZP BOC [ppm]	HFP 150 [ppm]	HFP 500 [ppm]	HFP EOC [ppm]
Average	10.8	13.2	-0.6	-4.2
St. Dev.	24.6	16.9	20.7	17.3

3.2 Isothermal temperature coefficient and control rods worth

Isothermal temperature coefficient (ITC) and control rods worth at HZP are measured during the start-up test at the beginning of plant operation following each fuel reload. Comparison of the CORD-2 results is presented in Table 2. Since the ITC is very sensitive to the boron concentration, the coefficients are calculated at the measured critical boron concentration.

ITC is almost everywhere lower than the 1.8 pcm/K value, which is usually considered as a measurement uncertainty. Larger difference is found only in Cycle 7. However, all values are well inside the ±5.4 pcm/K tolerance band, which is usually imposed at start-up tests. Average value of 0.72 pcm/K is showing small overprediction of the CORD-2 system. Standard deviation of all 27 values is less than 1 pcm/K.

Control rods worth differences are mostly below 10%. Somewhat larger differences are observed in cycle 7, where rod swap technique with significant higher measurement uncertainty was applied. In other cycles boron dilution and rod insertion methods were applied. Average values of all control rods worths are below 10%, with standard deviation lower than 6%. However, the average value of the differences for the sum of all control rods worths is -2.6%, which is significantly lower than 10% acceptance criteria usually taken at start-up tests.

Table 2: ITC and control rods worth differences

Cycle	ITC [pcm/K]	D	C	B	A	Sum
1	1.17	0.1%	2.4%	-1.4%	-2.2%	-0.5%
2	-0.67	-11.0%	-3.9%	0.9%	-7.5%	-5.7%
3	-1.10	-3.5%	6.0%	4.3%	-1.7%	0.8%
4	-0.06	-2.8%	-2.6%	6.5%	-6.0%	-2.5%
5	0.70	1.2%	3.7%	5.1%	3.9%	3.6%
6	1.81	6.8%	6.8%	20.1%	0.2%	5.7%
7	4.47	-1.6%	-19.8%	-14.5%	-22.0%	-16.5%
8	1.12	4.6%	0.0%	9.4%	-11.3%	-1.3%
9	1.05	0.3%	-0.6%	5.0%	-8.0%	-2.7%
10	0.00	-2.6%	-1.7%	5.4%	-9.3%	-3.8%
11	-0.51	3.1%	-4.9%	10.5%	-11.5%	-2.8%
12	0.21	-2.0%	0.4%	5.3%	-12.9%	-2.2%
13	1.02	1.3%	1.4%	3.5%	-10.2%	-1.8%
14	1.45	-0.5%	-1.5%	6.0%	-14.7%	-4.2%
15	0.46	-0.8%	0.4%	5.9%	-8.0%	-1.7%
16	0.53	2.7%	-3.4%	1.8%	-8.8%	-3.1%
17	0.10	4.8%	-2.4%	5.7%	-9.2%	-2.1%
18	0.75	6.1%	-3.1%	8.8%	-10.7%	-1.1%
19	0.48	0.3%	-1.1%	8.8%	-4.9%	-1.0%
20	0.85	3.8%	-0.2%	12.7%	-9.5%	-1.1%
21	0.91	-8.4%	-1.7%	1.6%	-7.1%	-3.5%
22	0.45	-4.8%	-4.4%	2.6%	-6.0%	-3.5%
23	0.25	-1.5%	-4.6%	3.3%	-3.9%	-2.0%
24	1.11	-4.0%	-5.1%	2.5%	-4.9%	-3.0%
25	0.69	-3.1%	-8.5%	-0.8%	-9.2%	-5.8%
26	1.02	-3.1%	-3.5%	-0.4%	-5.1%	-3.0%
27	1.26	-7.7%	-5.5%	-0.4%	-8.7%	-5.5%
Average	0.72	-0.8%	-2.1%	4.4%	-7.7%	-2.6%
St. Dev.	0.98	4.3%	4.9%	5.9%	4.9%	3.7%

3.3 Power distributions

HFP radial power distribution comparison with assembly powers derived from measured in-core flux distributions (C-M) at several burnup points are provided in Tables 3-7. Burnup steps and maximal differences are listed in the lower right corner. The first cycle and a few last cycles are presented. Cyclic quadrant symmetry was respected in all calculations.

Differences are showing pretty consistent behaviour. CORD-2 is mostly underpredicting power in the core centre and at some specific assemblies bordering the reactor baffle. The zone in between experiences higher power compared to measurements. Maximal differences are inside ±0.05 band.

Table 3: Assembly-wise power differences (C–M) for the cycle 1

-0.041	-0.027	-0.017	-0.002	0.003	-0.005	0.015
-0.038	-0.022	-0.011	0.006	-0.004	-0.007	0.011
-0.032	-0.016	-0.008	0.006	0.003	-0.007	0.010
-0.029	-0.017	-0.007	0.007	-0.001	-0.011	0.005
-0.025	-0.015	-0.005	0.006	-0.005	-0.010	0.005
-0.024	-0.009	-0.005	0.009	-0.006	-0.011	0.002
-0.022	-0.008	-0.003	0.010	0.003	-0.009	0.004
-0.018	-0.004	0.000	0.008	0.001	-0.013	0.002
-0.024	-0.015	-0.007	0.006	0.005	-0.004	0.007
-0.028	-0.029	-0.015	-0.003	0.000	-0.002	0.010
-0.022	-0.019	-0.005	0.003	-0.001	-0.008	0.005
-0.016	-0.018	-0.005	0.006	0.000	-0.006	0.004
-0.017	-0.021	-0.007	0.001	0.003	-0.005	0.004
-0.016	-0.018	-0.007	0.003	0.003	-0.005	0.004
-0.010	-0.016	-0.002	0.007	0.005	-0.007	0.001
-0.009	-0.012	-0.001	0.006	0.004	-0.006	0.001
-0.005	-0.009	-0.002	0.006	-0.002	-0.009	-0.001
-0.015	-0.019	-0.009	0.004	0.004	-0.006	0.001
-0.014	-0.012	-0.006	0.006	0.006	0.002	
-0.009	-0.004	0.001	0.006	-0.001	-0.006	
-0.005	-0.004	-0.001	0.006	0.003	-0.004	
-0.005	-0.004	-0.003	0.004	0.009	0.000	
-0.003	-0.005	0.000	0.005	0.010	0.001	
-0.003	0.000	0.002	0.006	0.007	-0.004	
-0.001	0.000	0.001	0.007	0.005	-0.005	
0.002	0.000	0.003	0.007	0.005	-0.005	
-0.005	-0.007	-0.002	0.002	0.008	-0.004	
-0.002	-0.006	0.005	0.008	0.004	0.007	
0.006	0.001	0.005	0.007	0.002	0.003	
0.006	0.001	0.001	0.004	0.000	0.002	
0.007	0.000	0.005	0.010	0.006	0.004	
0.006	0.001	0.004	0.009	0.006	0.003	
0.009	0.005	0.006	0.009	0.004	0.000	
0.009	0.004	0.005	0.004	0.002	-0.003	
0.007	0.005	0.010	0.004	0.002	-0.003	
0.006	0.003	0.005	0.003	0.007	-0.003	
0.003	0.003	0.013	0.014	0.005		
-0.005	0.001	0.009	0.012	0.006		
0.002	0.001	0.008	0.007	0.000		
-0.002	0.001	0.010	0.013	0.003		
-0.006	0.001	0.009	0.012	0.000		
-0.008	0.001	0.009	0.011	-0.002		
0.001	0.001	0.007	0.009	-0.003		
0.000	-0.001	0.010	0.013	-0.002		
0.004	0.003	0.011	0.014	-0.002		
-0.005	0.000	0.009	0.010			
-0.007	-0.004	0.005	0.009			
-0.007	-0.004	0.004	0.006			
-0.011	-0.010	0.000	0.006			
-0.009	-0.010	-0.001	0.002			
-0.011	-0.012	-0.004	0.000			
-0.009	-0.010	-0.005	-0.002		**Burnup**	**Maximal**
-0.013	-0.013	-0.005	-0.002		**[MWd/tU]**	**diff.**
-0.004	-0.005	0.002	-0.001			
0.016	0.014				4099	-0.041
0.012	0.010				5249	-0.038
0.011	0.008				6427	-0.032
0.006	0.003				7781	-0.029

0.006	0.002
0.002	0.000
0.004	0.000
0.002	-0.001
0.008	0.003

8988	-0.025
9727	-0.024
11689	-0.022
12996	-0.018
13320	-0.024

Table 4: Assembly-wise power differences (C–M) for the cycle 24

0.010	0.010	0.016	0.005	-0.007	0.000	-0.004
-0.012	-0.002	0.007	-0.004	0.001	0.006	-0.004
-0.033	-0.020	-0.005	-0.007	0.017	0.020	0.000
-0.042	-0.026	-0.014	-0.012	0.020	0.026	0.002
-0.043	-0.026	-0.013	-0.009	0.023	0.025	0.003
-0.041	-0.024	-0.011	-0.007	0.023	0.023	0.001
0.010	0.011	0.008	0.007	-0.001	-0.003	-0.016
-0.002	-0.001	-0.003	-0.001	0.003	0.002	-0.016
-0.020	-0.015	-0.013	-0.008	0.015	0.011	-0.014
-0.026	-0.022	-0.019	-0.013	0.015	0.015	-0.013
-0.026	-0.022	-0.016	-0.011	0.017	0.015	-0.013
-0.024	-0.023	-0.015	-0.011	0.015	0.012	-0.013
0.016	0.010	0.007	0.007	0.004	-0.008	
0.007	0.000	0.002	0.004	0.011	-0.005	
-0.005	-0.012	-0.005	0.002	0.016	-0.002	
-0.014	-0.018	-0.008	0.000	0.018	0.002	
-0.013	-0.016	-0.008	0.001	0.016	0.001	
-0.011	-0.014	-0.009	0.000	0.014	0.003	
0.005	0.006	0.006	0.015	0.007	-0.011	
-0.004	0.000	0.005	0.024	0.015	-0.008	
-0.007	-0.008	0.001	0.027	0.016	-0.008	
-0.012	-0.012	0.001	0.028	0.018	-0.006	
-0.009	-0.011	0.002	0.024	0.014	-0.008	
-0.007	-0.010	0.003	0.023	0.013	-0.007	
-0.007	0.000	-0.005	-0.001	-0.017		
0.001	0.006	0.003	0.008	-0.013		
0.017	0.016	0.009	0.010	-0.012		
0.020	0.018	0.015	0.014	-0.012		
0.023	0.020	0.014	0.012	-0.013		
0.023	0.022	0.016	0.011	-0.013		
0.000	-0.004	-0.013	-0.015			
0.006	0.002	-0.010	-0.011			
0.020	0.012	-0.007	-0.011			
0.026	0.016	-0.002	-0.010		Burnup	Maximal
0.025	0.016	-0.002	-0.011		[MWd/tU]	diff.
0.023	0.014	0.000	-0.011			
-0.004	-0.018				164	-0.018
-0.004	-0.018				3148	0.024
0.000	-0.015				6555	-0.033
0.002	-0.014				10177	-0.042
0.003	-0.014				13570	-0.043
0.001	-0.013				17010	-0.041

Table 5: Assembly-wise power differences (C–M) for the cycle 25

0.019	0.003	0.006	0.003	-0.003	0.007	0.001
-0.019	-0.016	-0.004	-0.003	0.012	0.013	-0.003
-0.035	-0.028	-0.016	-0.006	0.024	0.026	0.001
-0.036	-0.029	-0.019	-0.002	0.025	0.026	0.002
-0.036	-0.026	-0.015	0.002	0.025	0.020	-0.001
-0.033	-0.021	-0.011	0.007	0.023	0.015	-0.004
0.003	0.009	0.018	0.017	0.000	0.003	-0.006
-0.016	-0.007	0.004	0.005	0.012	0.011	-0.008
-0.028	-0.020	-0.011	-0.004	0.017	0.016	-0.009
-0.029	-0.024	-0.016	-0.006	0.017	0.017	-0.008
-0.026	-0.021	-0.013	-0.005	0.016	0.012	-0.010
-0.021	-0.016	-0.009	-0.003	0.014	0.007	-0.011
0.006	0.019	0.028	0.014	-0.002	-0.009	
-0.004	0.007	0.025	0.013	0.009	-0.007	
-0.016	-0.010	0.013	0.004	0.014	-0.003	
-0.019	-0.015	0.009	0.002	0.013	-0.002	
-0.015	-0.013	0.007	0.001	0.013	-0.003	
-0.011	-0.011	0.006	0.001	0.010	-0.002	
0.003	0.013	0.012	0.000	-0.008	-0.017	
-0.003	0.004	0.013	0.017	0.001	-0.015	
-0.006	-0.004	0.005	0.016	0.009	-0.012	
-0.002	-0.007	0.005	0.018	0.011	-0.010	
0.002	-0.006	0.004	0.019	0.011	-0.009	
0.007	-0.004	0.004	0.018	0.010	-0.010	
-0.003	-0.006	-0.012	-0.018	-0.035		
0.012	0.006	0.002	-0.007	-0.029		
0.024	0.017	0.009	0.000	-0.024		
0.025	0.018	0.010	0.005	-0.020		
0.025	0.017	0.011	0.007	-0.021		
0.023	0.017	0.010	0.006	-0.020		
0.007	-0.002	-0.014	-0.019			
0.013	0.001	-0.015	-0.020			
0.026	0.015	-0.006	-0.014			
0.026	0.016	-0.006	-0.012			
0.020	0.013	-0.006	-0.011			
0.015	0.010	-0.004	-0.012			
0.001	-0.010					
-0.003	-0.014					
0.001	-0.011					
0.002	-0.010					
-0.001	-0.011					
-0.004	-0.011					

Burnup [MWd/tU]	Maximal diff.
190	-0.035
3185	-0.029
7160	-0.035
10850	-0.036
14542	-0.036
17660	-0.033

Table 6: Assembly-wise power differences (C–M) for the cycle 26

-0.009	-0.005	-0.009	-0.006	-0.012	-0.004	-0.004
-0.041	-0.027	-0.017	-0.011	0.003	0.011	-0.002
-0.046	-0.033	-0.020	-0.012	0.017	0.019	-0.002
-0.050	-0.035	-0.024	-0.015	0.023	0.025	0.002
-0.050	-0.029	-0.021	-0.014	0.023	0.026	0.003
-0.048	-0.026	-0.017	-0.013	0.023	0.024	0.003
-0.005	0.002	0.003	0.000	0.003	-0.003	-0.015
-0.027	-0.019	-0.011	-0.007	0.014	0.008	-0.013
-0.033	-0.026	-0.017	-0.010	0.019	0.014	-0.012
-0.035	-0.028	-0.022	-0.012	0.018	0.017	-0.011
-0.029	-0.023	-0.022	-0.012	0.016	0.019	-0.010
-0.026	-0.021	-0.020	-0.012	0.012	0.018	-0.009
-0.009	0.007	0.008	0.017	0.011	-0.009	
-0.017	-0.007	0.003	0.013	0.019	-0.008	
-0.020	-0.015	-0.002	0.006	0.020	-0.004	
-0.024	-0.018	-0.005	0.003	0.019	-0.002	
-0.021	-0.016	-0.002	0.003	0.016	-0.002	
-0.017	-0.016	-0.005	-0.002	0.012	-0.002	
-0.006	0.003	0.015	0.033	0.018	-0.008	
-0.011	-0.004	0.007	0.043	0.025	-0.009	
-0.012	-0.006	0.005	0.039	0.022	-0.009	
-0.015	-0.010	0.004	0.035	0.021	-0.008	
-0.014	-0.009	0.004	0.032	0.018	-0.009	
-0.013	-0.008	0.003	0.029	0.016	-0.009	
-0.012	-0.007	0.002	0.017	-0.012		
0.003	0.003	0.007	0.028	-0.010		
0.017	0.014	0.014	0.022	-0.010		
0.023	0.017	0.016	0.021	-0.010		
0.023	0.016	0.015	0.016	-0.012		
0.023	0.017	0.015	0.017	-0.009		
-0.004	-0.008	-0.011	-0.008			
0.011	0.001	-0.007	-0.006			
0.019	0.008	-0.008	-0.008			
0.025	0.014	-0.003	-0.008		**Burnup**	**Maximal**
0.026	0.014	-0.004	-0.010		**[MWd/tU]**	**diff.**
0.024	0.015	0.000	-0.009			
-0.004	-0.018				259	0.033
-0.002	-0.017				3421	0.043
-0.002	-0.016				6740	-0.046
0.002	-0.013				10435	-0.050
0.003	-0.013				13012	-0.050
0.003	-0.011				16710	-0.048

Table 7: Assembly-wise power differences (C–M) for the cycle 27

0.032	0.008	0.001	0.002	0.022	0.006	-0.003
0.020	0.003	0.001	-0.008	-0.001	0.003	-0.005
-0.006	-0.017	-0.013	-0.015	0.012	0.016	-0.002
-0.013	-0.019	-0.017	-0.016	0.017	0.019	-0.002
-0.016	-0.019	-0.017	-0.016	0.018	0.022	0.000
-0.016	-0.016	-0.014	-0.016	0.014	0.021	-0.001
0.008	0.010	0.006	0.016	0.007	0.000	-0.013
0.003	0.009	0.002	0.005	0.005	-0.001	-0.015
-0.017	-0.010	-0.013	-0.003	0.014	0.008	-0.012
-0.019	-0.014	-0.017	-0.009	0.017	0.008	-0.014
-0.019	-0.015	-0.018	-0.009	0.017	0.013	-0.011
-0.016	-0.012	-0.015	-0.009	0.015	0.012	-0.010
0.001	0.005	0.015	0.011	0.006	-0.011	
0.001	0.003	0.020	0.013	0.010	-0.011	
-0.013	-0.011	0.009	0.010	0.018	-0.005	
-0.017	-0.015	0.003	0.004	0.023	-0.002	
-0.017	-0.015	0.001	0.005	0.017	-0.002	
-0.014	-0.012	0.001	0.005	0.014	-0.001	
0.002	0.014	0.008	-0.004	-0.003	-0.012	
-0.008	0.006	0.015	0.011	0.006	-0.010	
-0.015	-0.003	0.010	0.018	0.013	-0.007	
-0.016	-0.006	0.007	0.017	0.016	-0.003	
-0.016	-0.007	0.006	0.017	0.013	-0.005	
-0.016	-0.007	0.007	0.016	0.011	-0.003	
0.022	0.002	-0.007	-0.014	-0.028		
-0.001	0.003	0.004	0.000	-0.023		
0.012	0.013	0.013	0.009	-0.019		
0.017	0.017	0.015	0.010	-0.017		
0.018	0.018	0.015	0.011	-0.017		
0.014	0.015	0.014	0.011	-0.016		
0.006	-0.003	-0.017	-0.019			
0.003	-0.002	-0.015	-0.016			
0.016	0.007	-0.010	-0.013			
0.019	0.013	-0.007	-0.012		**Burnup**	**Maximal**
0.022	0.012	-0.007	-0.011		**[MWd/tU]**	**diff.**
0.021	0.011	-0.006	-0.011			
-0.003	-0.016				210	0.032
-0.005	-0.017				2610	-0.023
-0.002	-0.015				6060	-0.019
-0.002	-0.013				9750	0.023
0.000	-0.013				13160	0.022
-0.001	-0.012				16854	0.021

4 CONCLUSION

All 27 completed operational cycles of the NPP Krško plant have been reanalysed using the most recent core simulator package CORD-2 of the Jožef Stefan Institute. The package has been recently updated with some improved models. The key core parameters, such as critical boron concentrations, control rods worth, isothermal temperature coefficient and assembly power distributions are compared to the measured values. Differences in critical boron concentration are less than 50 ppm. The predicted isothermal temperature coefficient is within the ±1.8 pcm/K review criteria. The individual bank worths are mostly inside ±10% criteria, while the sum of all control rods worths is inside 6%. Assembly-wise power differences are within the ±0.05 band.

The results confirm satisfactory performance of the CORD-2 code system and its adequacy to support the core design and fuel loading optimization for the Krško NPP.

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