WWER IN-CORE FUEL MANAGEMENT BENCHMARK DEFINITION, BENCHMARK CALCULATIONS AND COMPARISON ANALYSES

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ABSTRACT

Two benchmark problems for WWER-440 and WWER-1000, including design parameters, operating conditions and measured quantities are discussed in the paper. Some benchmark results for infinitive multiplication factor - Keff, natural boron concentration - C_B and relative power distribution - k_q, obtained by the used code package are represented.

Introduction

The WWER benchmarks have been developed to verify methods and to validate in-core fuel management code systems, related to core physics with actual operating data. It is typical for the reactors of this type that the active core contain low-enriched fuel in hexagonal grid, light water as both moderator and coolant, relatively thick fuel assemblies, due to the short diffusion length of neutrons in the water.

Units 2 (WWER-440/V 230) and 5 (WWER-1000/V 320) of Kozloduy Nuclear Power Plant (NPP) serve as models for providing data for the benchmark specifications [1-4]. The data required for the benchmark problem definition include:

I. Design parameters based on the best estimate design information on two levels:

a) reactor core description: rated thermal and electrical power, specific power density, integral description of the core, coolant, and reflector;

b) fuel and control assembly data - **for each type of fuel assemblies:** enrichment, geometry, number of fuel rods and lattice pitch, total description of the spacer grids and the instrumentation tubes; **for fuel rods:** material compositions of pellets and cladding, geometry, etc; **for control and burnable poison rods:** for WWER-440 - geometry and composition of the absorber, for WWER-1000 - number of control pins per cluster, composition and geometry of the absorber and cladding;

II. Set of realistic experimental reactor data and measured quantities. Experimental data files have been prepared to describe the corresponding first three operational cycles of WWER-1000 [3] and WWER-440 [4] at Kozloduy NPP. Some of the experimental data are measured directly: thermal power, critical boron acid concentration C_B technological pressure value, flow through the core, assemblywise temperature control values, average "cold" and "warm" coolant temperature and warm up data, control rods position, current of the activation detectors.

The experimental data files for WWER-1000 have been prepared by an information system in which the detector set signals were transmitted into physical units. The measurements are obtained by means of self-powered neutron detectors (SPD). They are located in 64 places in radial plane (in given fuel assemblies) and in 7 positions in axial plane: 42.5, 86.2, 130., 173.7, 217.5, 261.2, 305. cm from the bottom of active core. The measured values are used to reconstruct the field W by methods of least squires and is represented by:

$$W = W1 * W2,$$

where W1 - function, describing the microstructure of power field and W2 - a smooth part of power field. The reconstructed field is determined taking into account the dispersion of measurements and setting the inequality:

$$|W - Y| < F,$$

where Y - measurements and F - allowable deviation. Results from code package calculations (three-dimensional diffusion simulation code, based on a version of BIPR code [5]) in 16 points are used to construct the calculational curve. After that, an iteration procedure on the basis of least squires methods is used to minimize the differences between the experimental and calculational curves. The inaccuracy range of calculated data is $\pm 5\%$ and they could be considered as experimental.

This information is collected to be used as input data for running in-core fuel management codes and for performing the benchmark calculations.

III. Operating conditions for the fist three cycles of the WWER-1000 and WWER-440, which contain the corresponding reload patterns and operation histories.

Benchmark calculations have been performed in 60^0 mirror symmetry with 28 assemblies for WWER-1000 and 59 assemblies for WWER-440. A set of steady states, necessary for description of the real operation has been defined for each cycle of each type of reactor.

Based on analysis of the actual core operation during each cycle the validation parameters have been selected for given burnup steps. The following parameters are calculated and compared as a function of burnup: Kinf, critical boron concentration, radial (assemblywise) power distribution, assemblywise burnup distribution and axial average core power distribution.

Calculation codes and methods

To perform benchmark calculations the cross section generating code NESSEL-IV-EC [6] and core simulator code PYTHIA-Q [7] (supplied with appropriate libraries) have been used.

The NESSEL-IV-EC is intended to calculate the local neutron physics characteristics of light water moderated reactor cores. It calculates effective few-group diffusion parameters and depletion not only for a given subzone, but also for the entire assembly, taking into consideration the strong inhomogeneities inherent to this type of reactor cores.

PYTHIA-Q is an asymptotic diffusion theory code for global reactor core analysis. Diffusion equation in three-dimensional hexagonal geometry is solved by coarse-mesh finite-difference scheme of a quadratic order. Iterative solution of the nonlinear problem for the eigenvalue of the algebraic mesh system value is used.

Results

Comparisons between calculated and experimental data for critical boron concentration have been carried out and results for given cycles of WWER-440, unit 2 and WWER-1000, unit 5 of NPP Kozloduy are presented in

Table 1. The corresponding differences have been analyzed statistically and it has been established that they have got Gaussian distribution on χ^2 criteria. The standard deviation if this distribution is σ = 0.04 g/kg, e.g. 13% of the experimental inaccuracy, which is approximately 0.3 g/kg.

The comparison between calculated and experimental radial and axial core power distributions have been performed with evaluation of the averaged differences (from the experimental data) and the standard deviations in per cent. For all assemblies the averaged differences have been calculated according to the formulae:

$$\overline{\delta k_q^j} = \frac{\sum_{i=1}^{n} \delta k_q(i)^j}{n}, \ \%, \quad n = 28$$

where:

n - number of steady states per cycle

$\delta k_q(i)^j$ - relative differences, presented as:

$$\delta k_q(i)^j = \frac{|k_q(i)^j|^E - |k_q(i)^j|^C}{|k_q(i)^j|^E} \ 100, \ \%$$

$(k_q(i)^j)^E$ and $(k_q(i)^j)^C$ are the values for k_q for assembly i, and for steady state j, determined experimentally and calculated by PYTHIA-Q, and their standard deviations according to the formulae:

$$\overline{\delta k_q(i)} = \frac{\sum_{j=1}^{m} \delta k_q(i)^j}{n}, \ \% \qquad \begin{array}{l} m = 32 \text{ for the I cycle} \\ m = 20 \text{ for the II cycle} \end{array}$$

Statistical characteristics of $\overline{\delta k_q}$ distribution for WWER - 1000, unit 5 of NPP Kozloduy cycle 1 are shown in Table 2.

Statistical analysis of the comparison results show the following:

- calculated radial power distributions are in a good agreement with the corresponding measured data;

- some disagreements, in axial core power distribution observed in the beginning of cycles, are a ground to analyze this problem in the future.

Kinf calculation of the fuel assemblies with four different enrichments as a function of the state parameters have been carried out by the NESSEL-IV-EC code. The average fuel temperature has been chosen to be 727°C. The water density at 302°C is 0.71442 g/cm^3. The average Boron-10 concentration during the first operation cycle is 718 ppm. As an illustration in Table 3 is shown Kinf investigation results for an assembly with enrichment of 3.3% U-235, profiled with 3% U-235.

The main conclusion is that both formulated benchmarks for WWER-440 and WWER-1000 can successfully serve for verification and validation of the developed methods and codes for in-core fuel management code systems. The accuracy of the calculations has been found satisfactory from the viewpoint of the directly measured data accuracy. The difference distributions are normal with standard deviation in the range of experimental inaccuracy.

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Tabl.1. Kozloduy NPP comparison critical boron concentration [gB/kg H_2O]

WWER-440, Unit 2 Cycle 2			WWER-1000, Unit 5 Cycle 2		
FPD	$C_B^{krit.}$		FPD	$C_B^{krit.}$	
	calc.	meas.		calc.	meas.
8.4	0.79	0.803	1.18	1.362	1.243
13.	0.78	0.790	1.36	1.362	1.344
34.7	0.578	0.609	1.39	1.323	1.400
40.	0.65	-	1.61	1.207	1.250
93.2	0.386	0.381	2.18	1.227	1.246
101.3	0.40	0.391	11.9	1.127	1.131
104.	0.35	-	25.1	1.078	1.062
104.3	-	0.381	35.5	1.166	0.889
120.	0.30	-	35.7	1.150	1.078
120.2	-	0.350	36.7	1.083	1.103
143.5	0.19	0.259	65.5	0.891	0.889
155.7	0.19	0.205	67.0	0.938	1.302
160.	0.18	-	68.2	0.938	1.160
160.7	-	0.217	71.8	0.803	0.875
188.2	0.09	0.109	76.8	0.961	1.031
189.5	0.07	0.151	98.5	0.836	0.856
191.4	-	0.151	109.1	0.789	0.838
191.9	0.11	-	111.6	1.003	1.925
196.4	-	0.119	138.3	0.723	0.723
196.9	0.07	-	165.4	0.601	0.625
204.2	-	0.075	205.2	0.273	0.376
211.4	0.04	0.052	206.3	0.574	0.711
213.2	-	0.035	213.3	0.448	0.336
213.3	0.04	-	218.4	0.318	0.397
235.6	-	0.008	224.4	0.289	0.270
244.6	-	0.008	250.3	0.245	0.259
261.6	-	0.002	285.3	0.108	0.088
273.4	0.001	0.000	300.4	0.096	0.049
279.5	0.001	0.000	324.1	0.021	0.005
284.8	0.001	0.000	324.5	0.020	0.005

Tabl 2. Statistical characteristics of $\overline{\delta k_q}$ distribution and σ_{kq} for each steady sta
and for each assembly,
WWER-1000, Unit 5, cycle 1

FPD	$\overline{\delta k_q}$, %	σ_{kq} %
37.2	0.47	0.64
38.8	0.83	0.92
42.4	1.93	0.98
45.0	-2.04	1.30
54.4	-0.02	1.40
55.1	-2.25	0.89
56.6	-0.47	1.03
59.5	-0.96	0.68
63.1	-0.78	0.67
71.3	0.04	0.96
88.7	-2.33	1.23
197.7	-0.19	0.50
206.6	-0.09	0.63
213.6	0.50	1.07
238.5	0.07	0.87
242.5	-0.16	0.55
248.3	0.12	0.55
254.2	-0.22	0.51
271.3	-0.06	0.34
280.8	-0.26	0.54
286.8	0.29	0.63
288.7	-2.15	0.60
289.2	0.70	0.62
289.7	0.30	0.69
291.2	0.32	0.61
291.7	-0.16	0.62
292.2	-0.25	0.66
292.7	0.69	0.58
295.2	-0.01	0.68
295.7	-0.10	0.61
296.2	0.16	0.58
296.7	0.76	0.45

Ass. №	$\overline{\delta k_q}$ %	σ_{kq} %
1	2.73	1.06
2	2.89	0.56
3	4.47	0.49
4	3.98	0.59
5	1.50	0.22
6	-0.06	0.25
7	-3.99	0.48
8	5.03	0.40
9	5.34	0.39
10	0.37	0.37
11	0.35	0.36
12	-3.94	0.58
13	-2.82	0.66
14	3.70	0.40
15	1.10	0.34
16	-0.77	0.33
17	-4.64	0.56
18	-4.11	0.67
19	1.14	0.31
20	-0.38	0.24
21	-1.38	0.90
22	-3.40	0.55
23	1.38	0.49
24	-2.86	0.20
25	-3.33	0.42
26	-2.77	0.37
27	-3.38	0.38
28	-2.31	0.55

Table 3. Kinf of 3.3% fuel assembly, profiled with 3% U-235 as a function of state parameters

state number	Fuel temperature, °C	Cladding temperature, °C	Cooland temperature, °C P = 160 at	Average core power density kw/l	Xe-135 (equilibrium)	Sm-149 (equilibrium)	Bororn concentration pm	Control rod	(***) Burnable rod	Fuel burnup Mwd/t	Kinf
1	120	120	120	-	-	-	0	-	-	0	-
2	120	120	120	-	-	-	0	-	-	0	-
3	280	280	280	-	-	-	0	-	-	0	1.30567
4	280	280	280	-	-	-	1000	-	-	0	1.19263
5	280	280	280	-	-	-	0	yes	-	0	1.03267
6	280	280	280	-	-	-	0	-	yes	0	-
7	302	302	302	-	-	-	0	-	-	0	-
8	302	302	302	-	-	-	1000	-	-	0	-
9	302	302	302	-	-	-	0	yes	-	0	-
10	302	302	302	-	-	-	0	-	yes	0	-
11	727	302	302	108	-	-	0	-	-	0	1.28901
12	727	302	302	108	yes	-	0	-	-	0	1.24873
13	727	302	302	108	yes	yes	0	-	-	0	1.24016
14	727	302	302	108	yes	yes	718	-	-	0	1.16463
15	727	302	302	108	yes	yes	718	-	-	1	1.15613
16	727	302	302	108	yes	yes	718	-	-	2	1.14718
17	727	302	302	108	yes	yes	718	-	-	3	1.13793
18	727	302	302	108	yes	yes	718	-	-	4	1.12825
19	727	302	302	108	yes	yes	718	-	-	6	1.10865
20	727	302	302	108	yes	yes	718	-	-	8	1.08955
21	727	302	302	108	yes	yes	718	-	-	10	1.07127
22	727	302	302	108	yes	yes	718	-	-	12	1.05383
23	727	302	302	108	yes	yes	718	-	-	16	1.02162
24	727	302	302	108	yes	yes	718	-	-	20	0.99183
25	727	302	302	108	yes	yes	718	-	-	24	0.96409
26	727	302	302	108	yes	yes	718	-	-	28	0.93816
27	727	302	302	108	yes	yes	718	-	-	32	0.91389
28	727	302	302	108	yes	yes	718	-	-	36	0.89123
29	727	302	302	108	yes	yes	718	-	-	40	0.87013
30	727	302	302	108	yes	yes	718	-	-	44	0.85061