RB REACTOR BENCHMARK CORES

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Abstract - A selected set of the RB reactor benchmark cores is presented in this paper, The first results of validation of the well-known Monte Carlo MCNP™ code and adjoining neutron cross section libraries are given. They confirm the idea for the proposal of the new U-D_2O criticality benchmark system and support the intention to include this system in the next edition of the recent OECD/NEA Project issue: ***International Handbook of Evaluated Criticality Safety Benchmark Experiment***, in near future.

Key Words: criticality safety benchmarks, uranium, heavy water, RB reactor

1. Introduction

The RB experimental reactor in the Institute of Nuclear Sciences 'Vinča' (former 'Boris Kidrič') was constructed in 1958 as the first Yugoslav nuclear critical assembly [1]. It was designed with natural metal uranium fuel and heavy water, bought in former USSR. Low enriched (LEU, 2% ^{235}U) metal uranium fuel and high enriched (HEU, 80% ^{235}U) uranium dioxide fuel (dispersed in an aluminium matrix) are become available at the RB reactor in 1962 and 1976, respectively. Both types of enriched uranium fuel (EUF) elements are designed in the form of tubular segments ('slug') with the same quantity (mass) of the ^{235}U nuclide. Heavy water is used as moderator, coolant and reflector in the reactor. Up to the end of 1997, more than 580 different RB reactor cores, including coupled fast-thermal ones [2], are investigated, offering a fruitful database for research and evaluation.

Benchmarks are standard problems for which either analytical or accurate experimental data exist. Many valuable benchmark experiments are compiled in well-known books issued by the ANL [3], BNL [4], and, recently, OECD/NEA [5]. But, only few experiments regarding the benchmark uranium – heavy water criticality systems are evaluated in them. The RB reactor numbered cores, mentioned above, offer a fertile and valuable database for miscellaneous research and evaluation. During different analyses of this database, an idea was growing to carefully choose a selected and well-recorded set of the cores and to propose them as a new uranium – heavy water benchmark criticality system. That system could be used for validation of the computer codes and data libraries used for reactor design and criticality safety of fissile materials. That idea is based on fact that rather unusual tubular uranium fuel slugs are used in heavy water forming very 'clean' cores. At the same time, these cores are not easy for computations by routine reactor design codes.

2. RB Reactor Short Description

The RB reactor in the Institute of Nuclear Sciences 'Vinča' was initially designed in 1958 as a bare, U - D_2O critical assembly. The fuel rods (2.5 cm diameter, 210 cm height) from natural metal uranium are protected with 1 mm thick cladding made from 'high purity' aluminium (HpAl). The reactor tank is mounted at a supporting aluminium platform so that minimum distance to the surrounding walls, floor and ceiling is at least 4 m. The tank has ID/OD 200/202 cm, height 230 cm, and bottom/top cover 2.5 cm thick. Two hundred and eight fuel elements were placed in the reactor core in regular square lattice with 12 cm pitch, forming a core (RB core #1/1958) without any reflector.

The first measured heavy water critical level [1] in the RB core #1/1958 was 176.6 ± 0.1 cm at 22.0 ± 0.1 °C. The heavy water used was composed ('purity') of 99.82% mole isotopic pure D_2O; the rest (0.18% mole) was ordinary (light) water.

New, 2% enriched metal uranium fuel and 80% enriched uranium dioxide fuel elements are designed in the same geometry form as tubular segments ('slugs'): 11.25 cm (LEU) or 11.30 cm (HEU) long with 3.7 cm outer diameter (OD). Two millimetres thick fuel layer (10.0 cm long, ID/OD 3.1/3.5 cm) is covered, along the inner and outer side, by 1 mm thick HpAl cladding. The 'stars' at top and bottom of the slug, and the coolant intensifier ('expeller') in the slug are made from the HpAl

Every EUF element ('fuel channel') of the RB reactor is forming in a separate 'low purity' aluminium (LpAl) tube (ID/OD 4.1/4.3 cm, 225 cm height). The fuel slugs are placing, one above the other, inside the tube, (usually from 9 to 16), with the aim to obtain desired core (fuel) height. Reactor cores with only one type or mixed types of EUF elements are possible to design in regular square lattices with few different 'basic' pitches: a [cm] = 7.0, 8.0, 9.0, 12.0, 13.0, and, also, $n \times a$, $n \times \sqrt{a}$, or $a \times \sqrt{(n+1)}$, where n is a whole number (1,2,...). The RB core lattices with irregular fuel positions can be formed too. The EUF slugs have offered a possibility to design radically (usually) or axially (rarely) heavy water reflected cores, as well.

During the RB reactor operation there are none control or monitoring devices in the core. The criticality and power changing are acquired and maintained by running a pump to achieve a fine adjustment of the heavy water level. The current D_2O height in the reactor tank is continuously measured by an automatic probe with maximum error of ± 0.2 mm. Manually operating another (precise calibrated) probe, this absolute error in determination of the D_2O level in the reactor tank could be reduced to ± 0.1 mm.

The RB reactor still operates as the critical system with the fission power range from 10 mW to 50 W (rarely at power levels up to 10 kW for short time). The total generated fission energy in the core (for all three types of uranium fuel) during the reactor's 40 years history is estimated [6, 10] at 16 kWh, i.e., the fuel burn-up is insignificant and, consequently, not included in the calculations.

The isotopic 'purity' of the heavy water is measured [7] in the Chemical Laboratory of the 'Vinča' Institute, at least once per year. The major 'impurity' in the heavy water is ordinary water (H_2O) absorbed from the humidity in the air, while other impurities are negligible [8].

Nuclide composition [9, 10] of the reactor construction's major materials (uranium fuel, heavy water, Al cladding, Al channels, Al reactor tank) is known up to the impurities content to the lowest weight fraction of 0.0001%. The impurities in the metal natural U fuel are measured [7, 10] for the first time in 1989, but they are neglected in the calculations. Type and content of impurities in the fuel layer of the EUF slugs are not known yet.

Temperature of the heavy water in the reactor core is measured by using a platinum resistance probe connected to a direct current bridge calibrated in degrees of Celsius with the maximum absolute error of ± 0.1 °C. Because the reactor operates at low power, the temperatures of the fuel and cladding are equal to the temperature of the heavy water.

In some experiments, the EUF slugs could be placed in the LpAl 'fuel channels' (ID/OD 4.1/4.3 cm) filled with air instead the D_2O moderator. Few vertical experimental channels (VK) or one horizontal experimental channel (HK), made from the LpAl, with various diameters and length, could be placed at several positions in the core. The reactor tank, new Al cladding of the natural uranium fuel elements and the fuel supporter plates are made from LpAl.

3. Proposed RB Reactor Benchmark Cores

As it was mentioned above, near 600 different cores are examined at the RB experimental reactor up to the end of 1997. In this paper, the first proposal of the new U-D_2O benchmark examples, based on a selected set of a few 'clean' and 'mixed' RB reactor cores is given. The adjoining measured criticality data for 19 evaluated RB cores are given in Table I. Horizontal cross sections for some of the proposed cores are given at Figure 1. All selected cores, except the RB cores #05/1973, #311/1968 and #39/1978, are designed without the axial heavy water reflector. These three last mentioned cores have thin top axial reflector above the uppermost EUF slugs

Many other feasible RB reactor cores are surveyed too. But, due to uncertainties (of various origins) discovered in the data required or due to duplicity, these cores are rejected temporarly from the proposed U-D_2O criticality benchmark set.

Some cores in the proposed benchmark U-D_2O system are with the experimental channels in the reactor core. Only one horizontal experimental channel (made from LpAl, ID/OD 1.70/2.00 cm, 101.0 cm or 202.0 cm long) could be placed in the reactor core along the tank diameter at height (measured from the tank bottom) of 61.0 cm. It is filled with the air at the atmospheric pressure and temperature in the reactor hall. Central axial vertical channel in the RB core #1/1958, used in 1958 for injection of the neutron external source [1], is neglected in the calculations. The selected cores of the RB reactor, labelled in range #19...#23/1976, are designed (and calculated) with the horizontal channel (Table I). Folis, cadmium covers (if any) and supporter (made from LpAl) for the foils are neglected in the calculation by the MCNP.

4. Verification of the Computer Codes

As the first step of the verification of the computer codes and data libraries, the well-known Monte Carlo based MCNP™ code (Version 4B2) [11] with the ENDF601 (based on the file ENDF/B-VI), RMCCS1 (ENDF/B-V) and BMCCS1 (ENDF/B-IV) continuous energy neutron cross-sections data libraries [12] is used. Neutron

Table II. MCNP criticality results for RB benchmark cores

Core # /Year	Al Impurities	Basic/Optional Neutron Libraries	#NH /#AC	$k_{eff} \pm 1\sigma$
#1 / 1958	yes	ENDF601/RMCCS1	1000 / 500	0.99201 ± 0.00083
			2000 / 500	0.99368 ± 0.00058
			4000 / 500	0.99434 ± 0.00041
#23 / 1976	yes	ENDF601/RMCCS1	1000 / 500	0.99616 ± 0.00105
			2000 / 500	0.99668 ± 0.00078
			4000 / 500	0.99518 ± 0.00055
	no		2000 / 500	1.02969 ± 0.00075
#34 / 1978	yes	ENDF601/RMCCS1	1000 / 500	0.99507 ± 0.00102
#5 / 1973	yes	ENDF601/RMCCS1	2000 / 500	0.99423 ± 0.00067
#32 / 1977	yes	ENDF601/RMCCS1	1000 / 500	1.00289 ± 0.00128
			2000 / 500	1.00361 ± 0.00090
			4000 / 500	1.00387 ± 0.00062
	no		2000 / 500	1.04155 ± 0.00092
#330 / 1978	yes	ENDF601/RMCCS1	1000 / 500	0.99934 ± 0.00097
#185 / 1978	yes	ENDF601/RMCCS1	1000 / 500	0.99463 ± 0.00105
#19 / 1976	yes	ENDF601/RMCCS1	1000 / 500	0.99616 ± 0.00105
#20 / 1976	yes	ENDF601/RMCCS1	1000 / 500	0.99018 ± 0.00105
#21 / 1976	yes	ENDF601/RMCCS1	4000 / 500	1.00883 ± 0.00052
#22 / 1976	yes	ENDF601/RMCCS1	4000 / 350	1.01086 ± 0.00062
#33 / 1976	yes	ENDF601/RMCCS1	1000 / 500	1.00256 ± 0.00105
#311 / 1968	yes	ENDF601/RMCCS1	1000 / 500	0.99109 ± 0.00105
#12 / 1963	yes	ENDF601/RMCCS1	1000 / 500	0.99597± 0.00108
#76 / 1963	yes	ENDF601/RMCCS1	1000 / 500	1.00626 ± 0.00104
#300 / 1967	yes	ENDF601/RMCCS1	1000 / 500	1.01069 ± 0.00109
#10 / 1963	yes	ENDF601/RMCCS1	2000 / 500	1.00571 ± 0.00075
#39 / 1978	yes	ENDF601/RMCCS1	4000 / 800	0.99309 ± 0.00042

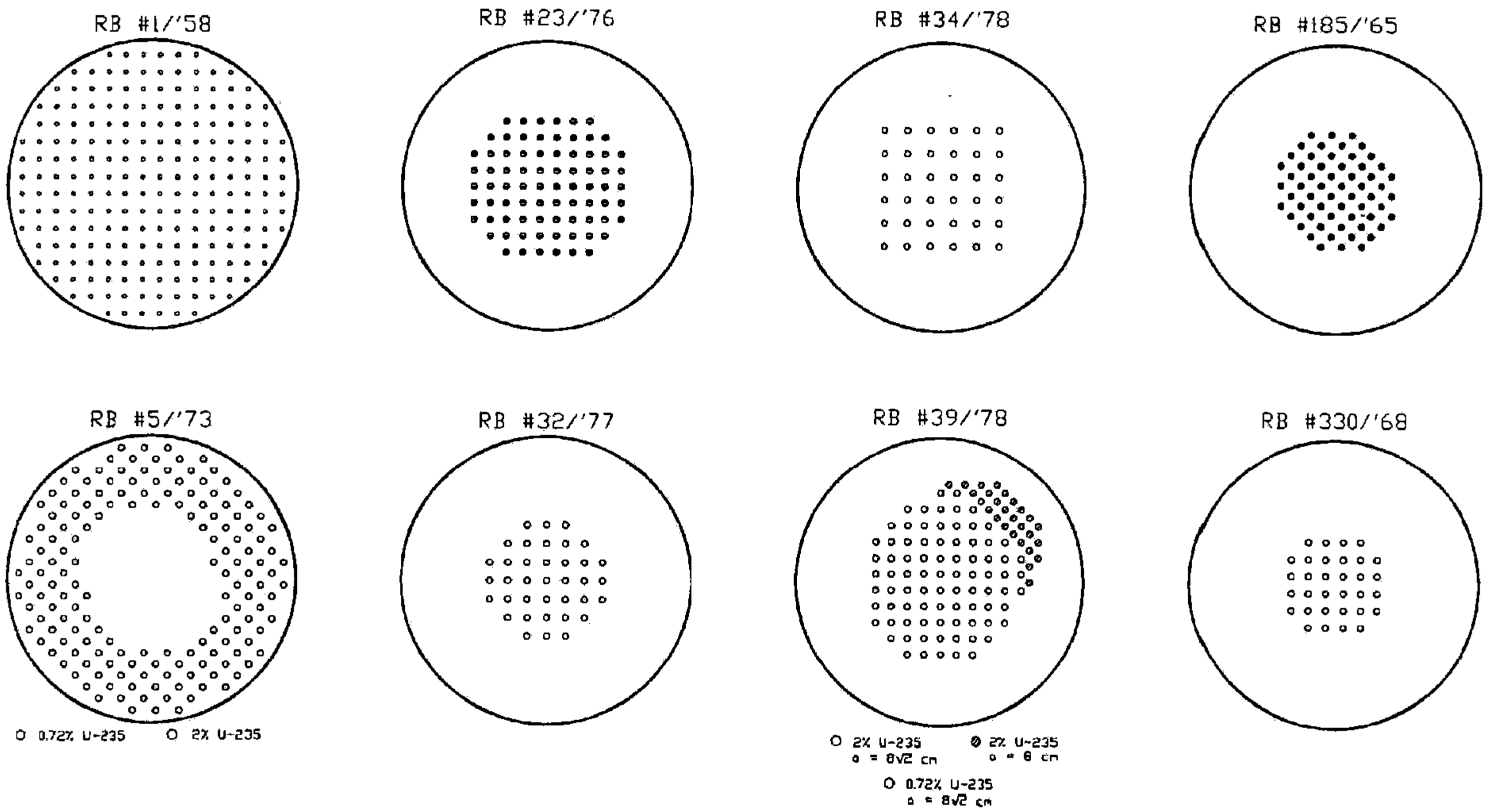

Figure 1. Horizontal cross sections few of proposed RB bechmark cores

scattering at hydrogen atoms bounded in H_2O molecules and at deuterium atoms bounded in D_2O molecules in thermal energy range is described by using corresponding $S(\alpha,\beta)$ laws given in the TMCCS1 library [12].

Each proposed the RB reactor core, including the reactor tank, is modelled in the 3D geometry of the MCNP code as close as possible to the real ones. Only minor approximations in the 3D model of the enriched uranium fuel slug are included: e.g., the HpAl 'stars' and top parts of fuel cladding and the 'expeller' are, separately, homogenised (by using volume fractions) with surrounding parts of the heavy water or air. Corresponding volume fractions are determined in the independent measurements. Neutron interactions with the reactor's supporting platform (aluminium), the concrete walls, floor and ceiling of the reactor hall, are neglected in the calculations.

The parts of the fuel elements surrounded by the air (i.e., that lie above the critical level in the reactor tank) are adequately modelled in the 3D geometry of the MCNP code as well.

For measured critical heavy water level in the particular core (Table I), the criticality is calculated by the KCODE option [11, 13] of the MCNP code with the initial neutron source placed in each fuel slug/element. Nominal number of neutron histories (#NH) per cycle and number of active neutron cycles (#AC) after 15 initial ones for determination of distribution of the neutron steady state source are given in Table II. Number of the active neutron cycles (#AC) is selected to obtain the average effective neutron multiplication factor (k_{eff}) with the statistical error of 1σ less than 0.2 %, i.e., it was 500 in most of the cases. Analyses of the k_{eff} convergence chart, obtained from the MCNP code output, show that the k_{eff} is reached an asymptotic level when the first 100 - 150 cycles are already completed, regardless what value for the #NH is selected within the range (1000 - 4000). Influences at the result of the calculations of nominal number of neutrons histories per cycle (#NH = 1000, 2000, 4000) and impurities in the low purity and high purity aluminium are examined for few proposed reactor cores and presented in the Table II as well.

The 'basic' neutron cross section library is used for data for all possible nuclides if they are contained in that library file. Neutron cross section data for remaining nuclides are taken from the 'optional' library. Generally, the ENDF601 library is selected as the 'basic' one, and only neutron cross section data for nuclides of some impurities are selected from the 'optional' libraries: e.g., RMCCS1 (for natural Mg, Cr, Mn, Ni, Cu, Cd in the LpAl and HpAl) and the BMCCS1 (for natural Ar in air).

Inclusion of the real composition of the LPAl and HpAl materials in the calculations is shown in the Table II in the column labelled 'Al impurities' (answer: 'yes'). If the impurities are neglected, i.e., pure natural metal aluminium material is used in the calculation, the answer in that column is 'no'. It can be concluded, from the results obtained that knowledge of the exact contents of the impurities in the RB reactor materials has essential significance in the RB reactor criticality determination.

Two examples given in Table II show that contribution of the impurities to decreasing of the RB reactor reactivity is about 0.038 for the core #32/1977 ('clean' 80% UO_2 fuel) and about 0.033 for the core #23/1976 ('clean' 2% U fuel). These reactivity values correspond, roughly, to deviation in the core critical height for about 10 cm.

5. Conclusions

The first results obtained in the validation process of the MCNP code and data libraries against the proposed set of the RB reactor benchmark cores are very satisfactory.

The k_{eff} values calculated by the MCNP code for the measured critical levels of the proposed RB reactor cores, using modern neutron cross section libraries, are very close to 1. The $\Delta k_{eff} = 1 - k_{eff}$ values obtained for most of the cases of the calculations are in range from 0.00050 to 0.00600, corresponding to the difference in the D_2O critical level of 0.2 - 1.5 cm, depending on the reactivity gradient value of the particular core. The higher differences, obtained in Δk_{eff} in few cases, need further data evaluation (influences of the HC, temperature, or the $S(\alpha,\beta)$ law for D connected in the heavy water), and these cores are temporarily excluded from the proposed benchmark system

It is shown that the knowledge of the exact material composition is very important for the criticality calculations.

The preliminary results, given in Table II, confirm that the selected set of the RB reactor cores could be chosen for the new U-D_2O benchmark criticality system for validation of reactor design computer codes and data libraries.

Further, even for more complex RB reactor cores, containing large zones filled with air and/or cadmium, it is shown, for the first time, that it was possible to find out the D_2O critical level reliably, i.e., k_{eff}, by using the MCNP code with the ENDF601 data library.

It is expected that even better results of the validation could be achieved by the MCNP code if the $S(\alpha,\beta)$ law for the D in the D_2O, derived for the neutron incoherent scattering, could be replaced by new $S(\alpha,\beta)$ law based on neutron coherent scattering, since the discrepancies in the measured values and model used up to now for low thermal neutron energies are reported [14, 15]. New evaluation of the thermal scattering law libraries, done recently [16], did not include any modification of the $S(\alpha,\beta)$ law for D connected in the heavy water.

Table I. Criticality data for proposed RB reactor cores

Core # /Year	U enrich. [%]	No. fuel el. /slugs	Lattice pitch [cm]	D_2O compos. [%]	$H_{critical}$ [cm]	Experimental channel	T [°C]
#1 / 1958	0.720	208	12.0	99.82 ± 0.02	177.6 ± 0.1	-	22.0 ± 0.1
#23 / 1976	2	78/9	$8\sqrt{2}$	99.57 ± 0.03	100.01 ± 0.01	HC	17.1 ± 0.1
#34 / 1978	2	36/17	16.0	99.43 ± 0.03	153.46 ± 0.01	-	19.0 ± 0.1
#5 / 1973	0.720 & 2	90 & 70/15	$8\sqrt{2}$	99.70 ± 0.01	179.22 ± 0.01	-	27.3 ± 0.1
#330 / 1968	2	32/16	12.0	98.50 ± 0.03	171.83 ± 0.01	-	19.1 ± 0.1
#185 / 1965	2	60/11	$7\sqrt{2}$	99.25 ± 0.03	112.19 ± 0.01	-	23.3 ± 0.1
#32 / 1977	80	37/12	13.0	99.43 ± 0.03	94.46 ± 0.01	-	23.0 ± 0.1
#19 / 1976	2	82/9	$8\sqrt{2}$	99.57 ± 0.03	98.95 ± 0.01	HC	19.5 ± 0.1
#20 / 1976	2	52/13	8.0	99.57 ± 0.03	138.74 ± 0.01	HC	19.3 ± 0.1
#21 / 1976	2	52/13	16.0	99.57 ± 0.03	132.17 ± 0.01	HC	19.3 ± 0.1
# 22 / 1976	2	40/16	16.0	99.57 ± 0.03	148.60 ± 0.01	HC	19.7 ± 0.1
#33 / 1977	2	57/11	13.0	99.43 ± 0.03	115.28 ± 0.01	-	19.0 ± 0.1
#311 / 1968	2	52/16	7.0	98.75 ± 0.03	186.26 ± 0.01	-	23.5 ± 0.1
#12 / 1963	2	52/12	14.0	99.75 ± 0.02	117.16 ± 0.01	-	19.0 ± 0.1
#76 / 1963	2	52/13	$\sqrt{(14^2 + 7^2)}$	99.62 ± 0.02	129.55 ± 0.01	-	21.6 ± 0.1
#300 / 1967	2	80/13	16.0	98.85 ± 0.03	127.80 ± 0.01	-	24.0 ± 0.1
#10 / 1963	2	52/13	$\sqrt{(16^2 + 8^2)}$	99.83 ± 0.02	142.13 ± 0.01	-	18.6 ± 0.1
#39 / 1978	0.720 & 2	31 & 78/9	$8\sqrt{2}$ & $8\sqrt{2}$ / 8	99.40 ± 0.03	103.65 ± 0.01	-	21.0 ± 0.1

Selection of new, more complex, the RB reactor benchmark cores from the RB criticality database will be continued, followed by validation of the MCNP and other modern computer codes based on usage of different cross section data libraries.

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