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A PROPOSAL FOR A NEW U-D$_2$O CRITICALITY BENCHMARK: RB REACTOR CORE 39/1978

by

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In 1958, the experimental RB reactor was designed as a heavy water critical assembly with natural uranium metal rods. It was the first nuclear fission critical facility at the Boris Kidrič (now Vinča) Institute of Nuclear Sciences in the former Yugoslavia (now Serbia). The first non-reflected, unshielded core was assembled in an aluminum tank, at a distance of around 4 m from all adjacent surfaces, so as to achieve as low as possible neutron back reflection to the core. The 2% enriched uranium metal and 80% enriched uranium dioxide (dispersed in aluminum) fuel elements (known as slugs) were obtained from the USSR in 1960 and 1976, respectively. The so-called "clean" cores of the RB reactor were assembled from a single type of fuel elements. The "mixed" cores of the RB reactor, assembled from two or three types of different fuel elements, were also positioned in heavy water. Both types of cores can be composed as square lattices with different pitches, covering a range of 7 cm to 24 cm. A radial heavy water reflector of various thicknesses usually surrounds the cores.
Up to 2006, four sets of clean cores (44 core configurations) have been accepted as criticality benchmarks and included into the OECD ICSBEP Handbook. The RB mixed core 39/1978 was made of 31 natural uranium metal rods positioned in heavy water, in a lattice with a pitch of 8 2 cm and 78 9 low enriched uranium metal slugs placed in heavy water in lattice pitches of 8 cm and 8 2 cm. This RB multipart core has now been proposed to the ICSBEP as a possible new U-D$_2$O criticality benchmark, due to its complex irregular lattice which is almost impossible to simulate by computer codes that require axial symmetry or a regular lattice.
Criticality results presented in this paper were obtained in calculations carried out by using recent versions of the MCNP5 and KENO V.a computer codes and various libraries of the neutron cross-sections data. Our results confirm that the proposed RB reactor complex core, RB 39/1978, may well prove to be a new U-D$_2$O benchmark criticality system for validating reactor design computer codes and data libraries recommended by the ICSPEP.

Key words: RB critical assembly, heavy water, criticality benchmark

INTRODUCTION

Benchmarks are standard problems for which either analytical or accurate experimental data exist. Many valuable benchmark criticality experiments are compiled in well-known reports issued by the ANL (1968, [1]), BNL(1974, [2]), PNNL(1978, [3]), LLNL (1983, [4]) and have recently been systematically evaluated by the OECD/NEA(1997-2011, [5]). Only a few (about 2% from the total number of around 4500) benchmark experiments regarding uranium-heavy water criticality systems were evaluated in these evaluations. Numbered RB reactor cores [6, 7] offer a fertile and valuable database for general research and evaluation of reactor physics data and criticality

benchmark studies. Various analyses of the RB reactor database show that is possible to choose, carefully selected and well recorded, a few sets of these cores and to propose them as uranium-heavy water criticality benchmarks. Four sets of the RB reactor clean cores, a total of 44 core configurations, have been evaluated, accepted as benchmarks and included into the ICSBEP Handbook [5, 8, 9] up to 2006. These RB reactor cores could be used for the validation of computer codes and neutron data libraries used for reactor design and criticality safety of uranium fissile materials placed in regular square lattices filled with heavy water.

The RB experimental nuclear reactor was designed as a bare critical assembly with natural uranium metal rods (2.5 cm diameter, 210 cm height) and heavy water. It was commissioned at the Boris Kidrič Institute of Nuclear Sciences, in late April 1958 [10]. The

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fuel rods cladding was made in 1961 of "low purity" aluminum, 1 mm thick. The RB reactor's core was designed as a bare aluminum cylindrical tank (ID/OD 2.00/2.02 m, height 2.30 m) mounted on an aluminum support platform, 3.75 m high. The entire RB reactor assembly, along with the supporting platform, was placed in the centre of a dry, box shaped pool (dimensions 8 m × 8 m × 1.5 m) in the large hall of the reactor. This type of construction provides as low as possible (less than 0.4%) reflection back to the core of neutrons escaping the bare reactor core (fig. 1). Later, in 1960 and 1976, the 2% enriched uranium metal fuel elements and 80% uranium dioxide (dispersed in aluminum) fuel elements of the TVR-S shape were obtained from the USSR, respectively. These LEU and HEU fuel elements have the same geometric shape (known as the "slug" shape, fig. 2) and a similar content of mass of the nuclide ^{235}U: 7.25 g per LEU slug and 7.67 g per HEU slug. The aluminum alloy used in the fuel slug design is known as the "high purity" SAV-1 alloy with low contents of neutron absorbing impurities (like boron and cadmium). The volume of the TVR-S fuel slug is about 60 cm^3, while the volume of the fuel layer (10 cm height and 2 mm thick) is about 20 cm^3.

Several fuel slugs (from 7 to 18) can be placed, one above the other, at the bottom of the fuel assembly aluminum tube (ID/OD = 41/43 mm, 210 cm long) to build an RB enriched uranium fuel assembly. Fuel rods and fuel assemblies can be placed in square lattices with basic pitches a = 7 cm, 8 cm, 9 cm, 12 cm, and 13 cm. Lattices with pitch values na, $na^{1/2}$, or $a(n+1)^{1/2}$, where n is a whole number (1, 2,...), can be created, too.

Figure 1. View of the RB reactor in 2000

RB cores with fuel assemblies positioned in irregular lattices can be created, as well. These enriched uranium fuel slugs offer a possibility to design radial (usually in experiments) or axial (rarely in experiments) heavy water reflected cores, as well. Heavy water is, thus, used as a moderator, coolant and reflector in the RB reactor.

During the operation of the RB research reactor, no control or neutron monitoring devices were present
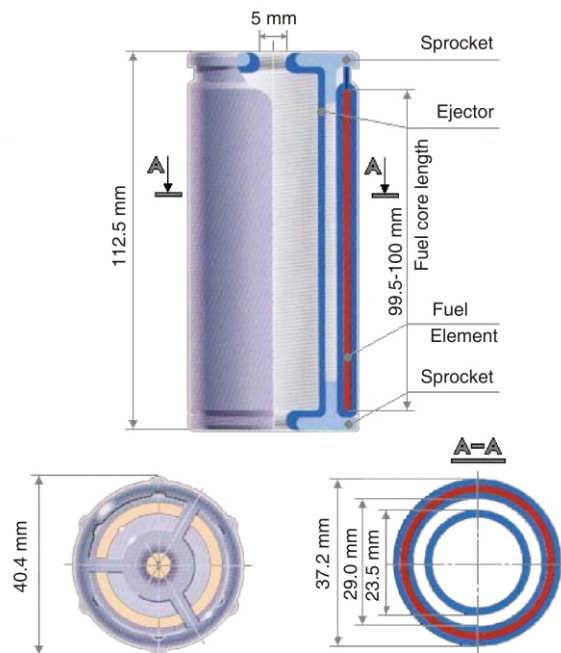

Figure 2. Size, shape, and drawing of the LEU and HEU TVR-S fuel slugs (according to http://www.nccp.ru/ir/tvr-s.html)

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in the core. Criticality and power changes were acquired and maintained by running a pump to achieve a fine adjustment of the heavy water level. The D_2O current height in the reactor tank was continuously measured by a platinum needle of an automatic probe with the maximum error of 0.2 mm. By manually operating another (precisely calibrated) probe, this absolute error in the determination of the D_2O level in the reactor tank can be twice reduced, to 0.1 mm.

The RB research reactor still operates as a critical system with a fission power range of 10 mW to 50 W. It rarely operates at higher power levels of up to 10 kW, and then only briefly. The total generated fission energy in fuel elements (for all three types of uranium fuel) over the reactor's 50 years history, including the energy released in the reactivity accident in October 1958 [11], is estimated at approximately 18 kWh, *i. e.*, the fuel burn-up deemed as insignificant and, consequently, not included in our calculations.

The isotopic "purity" of the RB reactor's heavy water is measured at the Chemical Laboratory of the Vinča Institute at least once a year. The major "impurity" in the heavy water is ordinary water (H_2O, absorbed from air humidity). Other impurities are negligible, which was confirmed by gamma-ray spectroscopy analyses [12] done for several samples of the heavy water taken over the years of operation of the RB reactor.

The temperature of the heavy water in the reactor's 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 RB reactor operates at low power, the temperatures of the fuel layer and cladding are equal to the temperature of the heavy water.

A few vertical experimental channels and/or horizontal experimental channels, made from low purity aluminum of various diameters and length, could be placed at several, predetermined by the lattice grid construction, positions in the core. The reactor tank, aluminum cladding of natural uranium metal fuel rods and the fuel support plates of the lattice grid, were made of low purity aluminum made in former Yugoslavia (known as the YuAl or LpAl).

Clean or mixed cores could be arranged in (usually square) heavy water lattices with different pitches. During the 50 years of operation of the RB nuclear reactor at the Vinča Institute, over 600 different RB reactor cores were designed, using all three types of fuel assemblies, including very complex and non-homogeneous RB reactor cores with coupled fast-thermal regions.

Following recent, worldwide, security demands for HEU to LEU fuel conversion in research nuclear reactors and the plan for the decommissioning of the Vinča RA research reactor, all fresh HEU TVR-S fuel elements have been shipped from the Vinča Institute back to their country of origin (the Russian Federation) in 2002 [13, 14].

DESCRIPTION OF THE RB CORE 39/1978 AND 3-D MODEL

The mixed RB 39/1978 core was designed of 31 natural uranium metal rods positioned in a lattice with a square pitch of 8 2 cm and 78 9 low enriched uranium metal TVR-S fuel slugs placed in square pitches of 8 cm and 8 2 cm. Such a complex composition and shape of the RB reactor core 39/1978 were chosen and conceived as a core that would supply a maximum thermal neutron current to the external neutron converter (ENC). The ENC itself was constructed within an aluminum box (size 112.0 cm 111.6 cm 7.8 cm), outside the RB core. The ENC box contains 561 HEU fuel elements (arranged in air) in two horizontal rows (shifted for the fuel slug radius) and 9 or 10 vertical rows (shifted for a half of the fuel slug height). Details of the ENC are described elsewhere [15, 16].

The ENC is designed to convert the thermal neutron flux escaping the RB reactor core to a fast one, with an almost fission spectrum at the ENC output, after transmitting a screen designed as a sheet of cadmium, 1 mm thick. A part of the ENC construction is shown in fig. 3, with a single line representing the 3 mm thick back aluminum plate (facing the RB reactor 39/1978 core at the shortest distance, that of 10 cm) used for assembling the ENC box. This is a strong neutron-coupled thermal (RB core) – fast (ENC) spectra system. The ENC itself, due to its construction and composition, is a deeply sub-critical system. Fast fissions in HEU fuel elements of the ENC have no significant influence on the criticality of the RB reactor core. They mainly influence the precise (manually) maintained critical level of heavy water, with the weak ex-
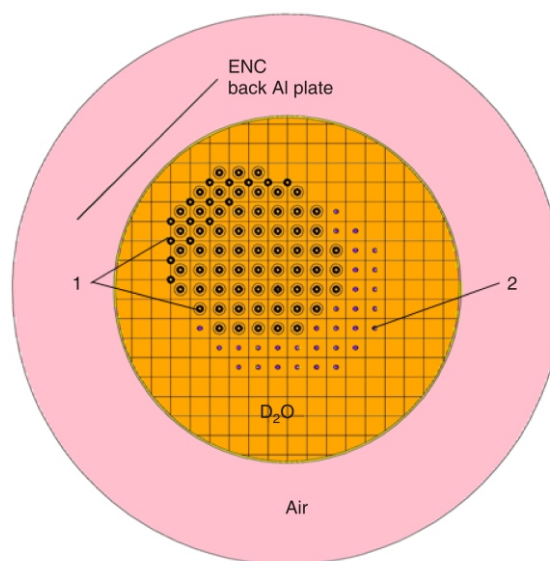

Figure 3. Horizontal cross-section of a 3-D model of the RB 39/1978 core surrounded by air (1 = LEU fuel assemblies; 2 = natural U rods)

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ternal neutron source. Fission processes, produced by the RB core's leaking neutrons in HEU fuel elements in the ENC box, create an isotropic volume fast fission neutron source. Some newborn neutrons in the ENC may interact, or not, with the ENC material (aluminum and HEU fuel) and may go to the RB reactor core, as well.

The RB 39/1978 core was designed with a thin (2.4 cm thick) top axial heavy water reflector to the enriched uranium fuel assemblies in the RB reactor's core and without experimental channels.

The molar concentration of heavy water, at the time of the core's design (in 1977 and 1978), was determined at 99.40 0.02% of D_2O, the remainder to 100%, is H_2O. The critical height of the heavy water in the RB reactor's core 39/1978 was experimentally determined as 103.65 0.01 cm at a temperature of heavy water at 21.0 0.2 °C. The horizontal cross-section of the 3-D (simplified) model of the RB reactor core 39/1978, surrounded by air, used, *e. g.*, in the MCNP code [17], is shown in fig. 3.

This RB mixed core is being proposed to the ICSBEP as a possible U-D_2O criticality benchmark, due its complex irregular lattice, almost impossible to simulate with computer codes that require axial symmetry or regular lattice. Geometric data and the composition of materials, including all known material impurities and evaluated uncertainties, determined in [5], have been used. These data were then applied in the development of the new, 3-D simplified model of the RB reactor core 39/1978, based on the TVR-S fuel slug model, taken from [5], and shown in fig. 4. Parts of uranium fuel elements, suspended in air above the critical level of heavy water in the reactor's tank, have been neglected in this 3-D simplified model of the RB reactor core.

CALCULATION, RESULTS AND DISCUSSION

Initial calculations

Initial calculations of the RB 39/1978 core were done using the diffusion 20GRAND reactor lattice computer code in a few neutron energy groups and two dimensions: X-Y or R-Z, in 1977. These calculations were done under the 48-bit SCOPE operating system (OS), on the Control Data Co. CDC 3600 mainframe computer. The two neutron energy group data for the RB reactor cells were generated at Vinča Institute (then known as the "Boris Kidrič" Institute of Nuclear Sciences). The well known K7-THERMOS computer code [18] was used in the thermal energy range of neutrons in order to obtain neutron cross-sections and the diffusion constant for the condensed, single, thermal energy neutron group. Computer code MULTI [19], developed in the "Boris Kidrič" Institute for RB reac-
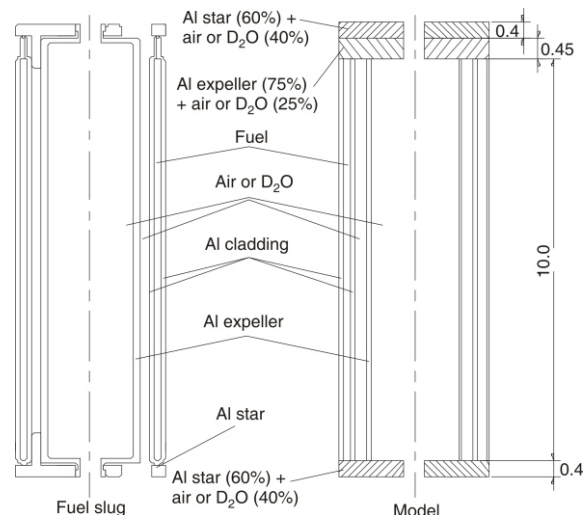

Figure 4. **Vertical cross-section of the TVR-S fuel slug and the 3-D model [5]**

tor cell calculations in epithermal, intermediate, and fast energy range of neutrons, using the Soviet/Russian ABBN/BNAB 28-group neutron cross-section data library [20] was applied, too. This computer code is used to create cross-sections and the diffusion constant for the single fast neutron group, condensing obtained neutron interaction data for 24 highest neutron energy groups. These calculations are done for RB reactor fuel cells with natural uranium metal rods and enriched uranium assemblies in heavy water and heavy water cells.

In spite of the cylindrical geometry of the RB core, computer code 20GRAND is applied in the R-Z geometry mode with the requirement for core volume conservation. In order to find a critical level of heavy water in the RB 39/1958 complex core and satisfy the requirement for a regular lattice pitch of the computer code, two independent runs of the computer code are done. First, the 20GRAND computer code is run for the RB reactor core with LEU fuel assemblies arranged in a lattice pitch of 8 2 cm in the central part of the core only. From the code run for several assumed levels of heavy water, the critical heavy water is determined. In the second run, the computer code is run with the same fuel assemblies in the central part of the core, while the rest of the fuel assemblies and fuel rods (of the real core) are arranged in symmetrical rings around this central part of the core in the same lattice pitch. The 20GRAND computer code is also run for this artificial core for several assumed levels of heavy water and the critical heavy water is determined. In this manner, a rough estimation of the critical level of heavy water in the RB 39/1978 core has been obtained from two virtual RB simplified cores. It is determined as an average value, between two critical levels of heavy water, determined from both runs of the com-

puter code, as 105.0   8 cm. This value was, surprisingly, close to the experimentally measured heavy water critical level 103.65   0.01 cm at heavy water temperature of $T = 21$ °C for the RB39/1978 core (see tab. 1).

First MCNP calculations with a 3-D simplified model in 1998

The MCNP4B computer code [21] became available at the Vinča Institute after more than 20 years. This computer code was run for the RB 39/1978 3-D simplified model, using continuous neutron cross-sections data library based on the ENDF/B-VI.2 for the main isotopes. The data from older versions of the ENDF/B libraries, RMCCS (based on ENDF/B-V) and BMCCS (based on ENDF/B-IV) for isotopes (not available in ENDF/B-VI.2) for some impurities (Cu, Fe, Ni, Cr, Cd, and Ar) in materials, were used. Our calculations were done under a 16-bit Windows 98 OS on a PC 80386 processor machine. Neutron scattering at hydrogen atoms bounded in H_2O molecules and at deuterium atoms bounded in D_2O molecules in the neutron thermal energy range at temperature of 300 K is described by using corresponding $S(\alpha, \beta)$ laws given in the TMCCS library, available with the MCNP4B computer code.

In the representation of the 3-D simplified model of the RB 39/1978 core, the geometry of the system was modelled as close as possible to the real one. In the 3-D model, only minor approximations of the enriched uranium TVR-S fuel slug are introduced. The high purity aluminum "stars" and top parts of the fuel cladding and the "expeller" (known as the "ejector") are, separately, homogenised (using their volume fractions) with the surrounding parts of the heavy water or air (fig. 4). Corresponding volume fractions for the homogenisations of materials are determined by independent material-geometry measurements [5]. Neutron interactions with the RB reactor's supporting

platform (low purity aluminum), concrete walls, floor and ceiling of the RB reactor hall are neglected in the calculations, based on information data on neutron reflection [10]. Parts of the fuel assemblies surrounded by air (i. e., that lie above the critical level of the heavy water in the RB reactor tank) are also neglected in this 3-D geometry simplified model. The aluminum grid structure of the bottom of the RB reactor tank and the supporting plate for fuel elements is modelled as a low purity aluminum plate with thickness equivalent to 4.0 cm [5].

Sensitivity studies on the neutron effective multiplication factor of the system (k_{eff}) for various RB reactor clean cores of different uncertainties in geometry and material composition are done in evaluations presented in [5]. The values of the total combined uncertainty were shown to lie in the range of 0.51-0.68% k_{eff}. Sensitivity studies, carried out for the RB 39/1978 core, of various uncertainties in geometry and material composition, show that the value of the total combined uncertainty in k_{eff} is 0.44%.

The MCNP4B computer code is run in the KCODE mode, with an initial neutron source chosen for each fuel element in the core (KSRC option), for 4000 neutron histories in each of the 800 active cycles, after the initial 200 cycles. The number of active neutron cycles and neutron histories are selected so as to obtain an average effective neutron multiplication factor, with a statistical standard error of 1 σ less than 1%, an acceptable uncertainty for criticality benchmarks. The uncertainty of 1% in the k_{eff} is accepted by ICEBEP [5], since it is assumed that, in case a simplified model of a reactor core is used by a computer code, it should result in a criticality parameter (k_{eff}) that is within 1% of the measured criticality parameter of a real reactor core. This experimental value for k_{eff} is supposed to be corrected for experimental uncertainties, e. g. temperature and other uncertainties, including the bias for physical values like neutron reflections from the walls. For this reason, all Monte Carlo based computer codes are run for a selected number of neu-

Table 1. Criticality results for RB 39/1978 core

Year	OS/hardware	Code version/neutron library	Neutron histories/active cycles	k_{eff} 1 or critical height H_c	
1977	48-bit SCOPE/CDC 3600	20 GRAND/Vinča 2 group	–	$H_c = 105$ 8 cm for $k_{eff} = 1$	
1998	16-bit Windows 98/PC 80386	MCNP4B2/endfb60 and tmccs	4000/800	0.99309	0.00042
2011	Windows 7 Home Premium 64-bit/laptop four i7-processor Toshiba A660	MCNP5.1.2/endfb60 and tmccs	5000/1000	0.99335	0.00032
		MCNP5.1.2/endfb66 and sab2002	5000/1000	0.99775	0.00032
		MCNP5.1.2/jeff3.1.1 and jeff3.1_TSL	5000/1000	1.00120	0.00032
		KENO V.a/44 group in SCALE 4.4a with ENC, MCNP data	5000/2000	0.98843	0.00022
		KENO V.a/44 group in SCALE 4.4a [5] with ENC	5000/2000	0.99694	0.00023
		KENO V.a/44 group in SCALE 4.4a [5] without ENC	5000/2000	0.99287	0.00022
Experiment		$H_c = 103.65$ 0.01 cm at $T = 21$ °C			

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tron histories and number of neutron generations (active cycles), given in tab. 1, in order to achieve the statistical standard error (1 σ) near 0.1%, *i. e.* ten times better than the required uncertainty in benchmark criticality calculations.

All materials used in the 3-D simplified model are assumed at a temperature of 293 K, except for the heavy water atom densities, determined at a temperature of 21 °C. The neutron effective multiplication factor of the system (k_{eff}) is determined by running the MCNP4B computer code with associated neutron cross-section data libraries from 1998, as 0.99309

0.00042 for the experimentally determined critical level of heavy water (tab. 1).

Criticality calculations with the MCNP5 and KENO V.a codes for the 3-D simplified model in 2011

The new 5.1.2 version of the MCNP computer code [17] has also offered a more recently evaluated neutron library (ENDF/B-VI, realise 6), as well as a newly updated thermal neutron scattering library. SAB2002 is based on $S(\alpha, \beta)$ laws for neutron scattering of hydrogen atoms bounded in H$_2$O molecules and deuterium atoms bounded in D$_2$O molecules in the thermal energy range at temperature of 300 K. These criticality calculations were done on a four Intel i7-processor Toshiba Satellite laptop A660, with a 64-bit Windows 7 Home Premium OS.

The MCNP5.1.2 computer code is run in the KCODE mode, with an initial neutron source originating from fuel elements in the core (KSRC option), for 5000 neutron histories in each of the 1000 active cycles, after the initial 200 cycles. The effective neutron multiplication factor of the 3-D simplified model of the system (k_{eff}) is determined as 0.99775   0.00032 for the experimentally determined critical level of heavy water (tab. 1).

The MCNP5.1.2 computer code is also run using the same OS/hardware configuration, but with a newly evaluated neutron library JEFF3.1.1 [22], based on the ENDF/B-VII realise 0, and thermal (neutron) scattering library (TSL) of JEFF3.1 (labelled in tab. 1 as jeff3.1_TSL). This TSL is based on $S(\alpha, \beta)$ laws for neutron scattering of hydrogen atoms bounded in H$_2$O molecules and deuterium atoms bounded in D$_2$O molecules in the thermal energy range at temperature of 293 K.

The MCNP5.1.2 computer code is run in the KCODE mode and the same initial neutron source originating in each of the fuel element of the core (KSRC option), for 5000 neutron histories in each of the 1000 active cycles, after the initial 200 cycles. The neutron effective multiplication factor of the system is determined as 1.00120   0.00032 for the experimentally determined critical level of heavy water (tab. 1).

The simplified model of the RB 39/1978 core in 3-D geometry, together with the 3-D model of the ENC, is used in additional calculations done by the KENO V.a [23] computer code, based on the Monte Carlo method from the SCALE package, version 4.4a [24]. The horizontal cross-section of the 3-D simplified model for the RB 39/1978 core with the ENC, at a height of 40 cm, generated by the KENO V.a computer code, is shown in fig. 5. These KENO V.a computer code calculations have also been run at four Intel i7-processor Toshiba Satellite laptop A660, with a 64-bit Windows 7 Home Premium OS.
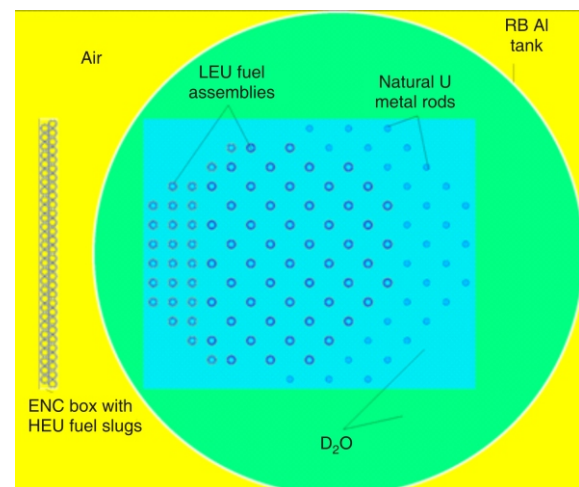

Figure 5. Horizontal cross-section of the 3-D model of RB 39/1978 core with ENC in KENO V.a code

The standard broad-structure 44-group SCALE 4.4a neutron cross-section library [25] for natural occurring materials (based on ENDF/B-V) has been modified. Neutron cross-sections generated by using the multi-region option of the CSAS2 module [26] in the SCALE package ignore lattice geometry effects. Because of this, KENO V.a computer code calculations are based on the VEGAKENO [27] computer module. The VEGAKENO module is used for computing neutron effective cross-sections of a pseudo moderator in equivalent homogeneous media, representing the heterogeneous problem and NITAWL computer code [28] treatment of nuclide cross-section resonance self-shielding in the said homogeneous media. This computation approach was already applied and explained in LEU-MET-THERM-002 [5]. As it is already mentioned, all materials used in the 3-D simplified model are assumed at a temperature of 293 K, except heavy water atom densities that are determined at a temperature of 21 °C.

The KENO V.a computer code is run for 5000 neutrons in each of the 2000 generations. The neutron effective multiplication factor of the system is deter-

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mined as 0.99694 0.00023 (see tab. 1) for the experimentally determined critical level of heavy water 103.65 0.01 cm at temperature $T = 21$ °C. It was shown that the neutron effective multiplication factor is weakly dependent on a (reasonable) selection of the neutron number (from 1000 to 5000) in each generation and the number of generation (from 650 to 2000) in KENO V.a computer code.

In addition to mentioned neutron group cross-section corrections, done by NITAWL and VEGOKENO computer codes, are important in precise criticality benchmark calculations, where all possible uncertainties and errors have to be minimised or avoided. The KENO V.a computer code is also run without these corrections, *e. g.* with the SCALE original 44 group neutron cross-sections and nuclide compositions of materials from the MCNP code. These KENO V.a calculations are done for the same number neutron generations (2000) and neutrons per each generation (5000), at determined critical heavy water level and temperature. The value of the neutron effective multiplication factor is obtained as 0.98842 0.00022. The achieved result (also presented in tab. 1) is not acceptable in benchmark criticality evaluations, because it is outside the 1% of experimental k_{eff}.

The KENO V.a computer code is also run, with the same OS/hardware and under the same conditions for the number of neutrons and number of generations, without the ENC modelled, *i. e.*, for the RB 39/1978 core alone, at a critical level of heavy water and temperature of 21 °C. The neutron effective multiplication factor of the system is determined as 0.99287 0.00022 (see tab. 1). It can, thus, be concluded that the contribution of the ENC to the criticality of the completely coupled system is, as mentioned above, very small: $0.00407 = \Delta k_{eff}$, *i. e.*, 0.41 0.03% k_{eff}.

Overview and discussion

The Vinča Institute has had various and numerous experiences with the MCNP5 computer code and SCALE package in complex research reactor systems, *e. g.* [29]. It can be concluded that these criticality results, summarized in tab. 1, obtained by MCNP5 and KENO V.a computer codes for the RB 39/1978 core, confirm that the proposed 3-D simplified model of the RB 39/1978 core can be selected as a new criticality benchmark. All geometric and material data of the core are known, with satisfactory uncertainty and computation results obtained by two independent criticality computer codes, based on the Monte Carlo method, in acceptable agreement with the reported experimental result (<1% k_{eff}). Sensitivity studies to various uncertainties in geometry and material composition for the RB 39/1978 core show that the value of the total combined uncertainty in k_{eff} is 0.44%, which is, again, acceptable according to the ICSBEP.

CONCLUSIONS

The mixed multipart RB 39/1078 core is presented in all details unnecessary to create a 3-D geometry material simplified model for criticality calculations carried out by using recent versions of the MCNP5 and KENO V.a computer codes. All information on experimentally determined criticality for this RB core is available in RB reactor logbooks, internal reports and related published papers and has been evaluated in the generation of the benchmark simplified model. Using this 3-D model, new criticality calculations with the MCNP and KENOV.a computer codes with different neutron data libraries, available at the Vinča Institute, have been done. The results of these calculations were compared to the ones obtained earlier with the 20GRAND diffusion computer code and the experimental value of the critical level of heavy water. Information on these new calculations has been presented here and satisfactory results confirmed.

The results of these calculations are based on our newly developed 3-D simplified model of fuel slugs, fuel assemblies, fuel rods and the entire RB assembly. In the case of the KENO V.a computer code, verification is also done for additional options that include 3-D geometry model of the ENC. Results confirm that the selected RB 39/1978 core may be chosen as a new U-D$_2$O criticality benchmark, to be used for the validation of reactor design computer codes and nuclear data libraries.

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Милан П. ПЕШИЋ

ПРЕДЛОГ ЗА НОВИ U-D₂O РЕФЕРЕНТНИ СИСТЕМ НА КРИТИЧНОСТ: РБ РЕАКТОРСКО ЈЕЗГРО 39/1978

Експериментални реактор РБ пројектован је 1958. године као критични систем са горивом од природног уранијум метала у тешкој води. То је био први нуклеарни фисиони критични систем у Институту за нуклеарне науке "Борис Кидрич" (сада "Винча") у бившој Југославији. Прво реакторско језгро, без рефлектора и биолошке заштите зрачења, формирано је у алуминијумском суду, постављеном на растојању од око 4 m од било које површине у хали реактора, да би се постигла што мања рефлексија умаклих неутрона назад у језгро. Гориво од 2% обогаћеног уранијум метала и 80% обогаћеног уранијум-диоксида (диспергованог у алуминијуму), у облику познатом као слаг ("slug"), набављено је у СССР-у 1960-те и 1976-те године, респективно. Такозвана "чиста" језгра реактора РБ, формирана од горивних елемената само истог типа, као и "мешана" језгра, у којима се користи гориво различитих типова, могу се формирати у решеткама квадратног корака, од 7 cm до 24 cm у тешкој води. Језгра обично имају и радијални рефлектор од тешке воде различите дебљине.

Четири сета чистог језгра (укупно 44 конфигурације) су прихваћени као референтни системи (бенчмарци) на критичност и укључени у OECD пројект за Међународни приручник евалуираних критичних бенчмарк експеримената (ICSBEP) до 2006. године. Мешано језгро реактора РБ 39/1978 пројектовано је и формирано од 31 горивних шипки од природног уранијум метала распоређених у решетку корака 8 2 cm у тешкој води и од 78 ниско обогаћених горивних елемената од уранијум метала (сваки са по 9 слагова) распоређених у решетку корака 8 cm и 8 2 cm у тешкој води. Овакво језгро реактора РБ, састављено из више делова, предложено је пројекту ICSBEP као могући нови U-D₂O референтни систем на критичност. Због своје комплексне конфигурације, која је формирана у нерегуларној решетки, изабрано језгро је скоро немогуће симулирати у рачунарским кодовима који захтевају аксијалну симетрију или регуларну решетку у језгру. Овакво језгро је зато један могући, изазован, референтни систем.

Резултати, добијени прорачунима на критичност урађеним са новим верзијама рачунарских кодова MCNP5 и KEVO V.a и са различитим библиотекама за неутронске пресеке, потврђују да се предложено сложено језгро РБ 39/1978 реактора РБ може прихватити као нови U-D₂O референтни систем на критичност за потврђивање исправности рачунарских програма за дизајн реактора и верификацију библиотека неутронских попречних пресека.

Кључне речи: РБ критични систем, тешка вода, референтни систем на критичности