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# Development of Critical-Mass Measurement Techniques at RFNC-VNIITF

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**Abstract**—The experience of RFNC-VNIITF for the period since 1970 in the field of critical mass measurements is generalized and systematized. The specific features of setting up the benchmark-type critical mass experiments at the RFNC-VNIITF FKBN (FKBN-M, FKBN-2) bench for critical assemblies are considered. A brief description of a number of critical experiments performed at different time at the FKBN bench with spherical and cylindrical assemblies of uranium and plutonium metals is given. The issues of necessity and ways of preserving the primary experimental information for critical assemblies are discussed.

**Keywords:** critical assembly, uranium metal, plutonium metal, reflector, Monte Carlo method, effective multiplication factor, nuclear data libraries

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## INTRODUCTION

From the time of the establishment of the institute and up to the present time, critical mass measurements have been an important trend of experimental research in the Department of Experimental Physics of RFNC-VNIITF. The first bench for critical mass measurements at RFNC-VNIITF—the physical fast-neutron boiler (FKBN)—was put into operation in March 1958. According to the principle of operation, this bench was largely similar to its prototype—the bench for critical assemblies (FKBN) from Arzamas-16 (RFNC-VNIIEF), created in 1955. The FKBN was developed by a team headed by L.B. Poretsky under the direct supervision of the physical sector head V.Yu. Gavrilov. The FKBN is a remotely controlled mechanical bench and is designed for the slow approach of two parts of the investigated multiplying system (MS), containing a fissile material, to a critical state.

In the first years after the FKBN commissioning, the experimental research at the bench was carried out mainly with mockups of nuclear charges or their fragments and was aimed at improving the accuracy of calculations of nuclear weapon characteristics. A large amount of work was also associated with the experimental substantiation of nuclear safety in the course of work on the development and testing of nuclear weapons.

Later, in connection with the development of computer technology, the need arose for accurate critical experiments of the benchmark type. The simple geometry and well-known composition of the assemblies make it possible to isolate in the calculations the error caused by the inaccuracy of the libraries of nuclear physics constants used in the calculations.

In 1974, a team under the leadership of an employee of the theoretical department A.P. Vasiliev began work on improving the library of BAS neutron constants used in calculations by the Monte Carlo method [1]. In the course of this work, the BAS library was tested using experimental data published by that time. The comparison of calculations for various integral experiments with experimental results made it possible to identify the reactions and intervals of the neutron spectrum for which the correction of neutron data was required. Since the published experimental data were insufficient or incomplete, a special program of experimental research was developed at the institute, which included measurements of the neutron spectra of leakage from spherical samples of fissile and structural materials on a 14 MeV neutron generator, as well as carrying out the critical mass measurements at the FKBN critical test bench with systems of different composition and geometry.

The technology of assembling critical systems that existed at that time did not provide the required measurement accuracy: the use of a massive rotary table for assembling the upper part of the multiplying system (MS) (the bench appearance is shown in Fig. 1) created difficulties in taking into account its contribution to the reactivity of the studied MS and did not

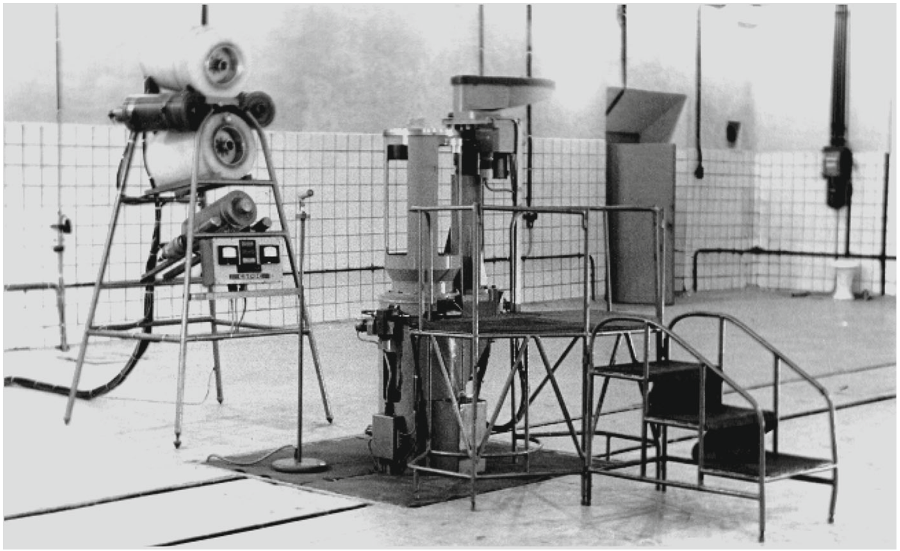

**Fig. 1.** FKBN-M bench with a rotary table.

allow centering the upper part of the MS relative to the lower part at the required accuracy.

For systems without reflectors or with thin (~1 cm) reflectors, a noticeable contribution that requires consideration was made to the MS reactivity by the structural elements of the bench: a support tube, to which the rotary table was attached, and a cup, in which the lower part of the MS was assembled.

For these reasons, in 1973, a decision was issued that allowed assembling a MS without a rotary table.

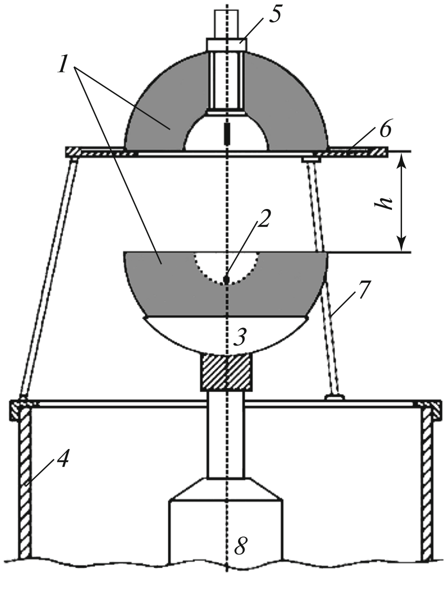

**Fig. 2.** Schematic of a spherical assembly on a duralumin support: (*1*) core, (*2*) neutron source, (*3*) copper cup, (*4*) support tube, (*5*) brace, (*6*) steel diaphragm, (*7*) duralumin support, (*8*) movable rod.

For the assembly of compact, lightweight systems, an openwork rack made of duralumin was developed (Fig. 2), which hardly contributes to the reactivity of the assembled MS. With this bench, using the adjusting screws on it, it is possible to ensure the centering of the upper MS block relative to the lower block and the parallelism of the planes of the upper and lower blocks of the MS with an accuracy of ~0.1 mm. The use of an openwork rack for assembly also allows the contribution to reactivity from the support tube to be reduced.

One of the problems was the difficulty of accounting for the MS contribution to the reactivity, first of all, the MS without a reflector of neutrons reflected from walls of the room in which the critical test bench was located. For the purpose of reducing the influence of reflected neutrons on the measurement results, during the FKBN modernization in 1969–1970, accompanied by the bench transfer to another work site, the dimensions of the experimental hall (18 × 12 × 8 m), in the center of which the mechanical bench was located, were significantly increased. The walls, floor, and ceiling of the hall were covered with a layer of boron-containing concrete (the content of natural boron in concrete was at least 3%, and the layer thickness was 10 cm).

In 1974, to carry out critical mass measurements at the FKBN critical test bench, there were two kits of spherical assemblies made of highly enriched uranium and plutonium metals in the $\delta$ phase, which consisted of a set of hemispherical shells. Initially, when assembling a MS, the systems were divided into two approximately equal blocks. The upper MS block was assembled on a thin diaphragm 2 mm thick. An analysis of the results of critical experiments with the uranium assembly showed that, in describing the experimental system in the calculations, it was most difficult to take

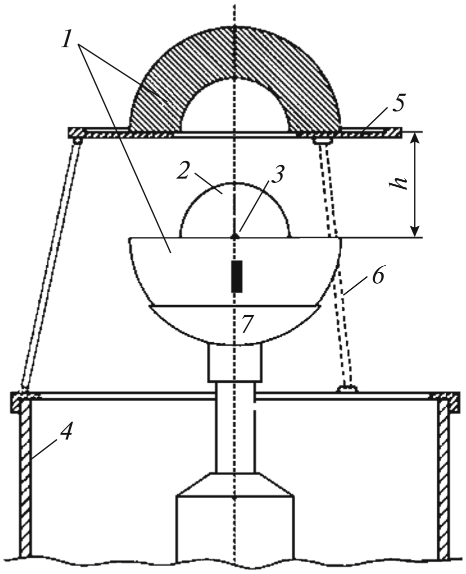

**Fig. 3.** Schematic of a spherical assembly made of uranium with a reflector made of polyethylene with asymmetric MS division: (*1*) reflector, (*2*) core, (*3*) neutron source, (*4*) support tube, (*5*) steel diaphragm, (*6*) duralumin support, (*7*) copper cup.

into account the crescent-shaped gaps between hemispherical details in the upper MS block, which arose owing to deflection of the diaphragm. Disregarding the crescent-shaped gaps in the calculations, according to estimates, led to an error of $\delta K_{\text{eff}} \approx 0.1\%$. Because of this, during the subsequent assemblies, if the conditions for ensuring the safety of work permitted, the preference was given to the option of asymmetric division of the assembled MS (Fig. 3), where a part of the fissile material (FM) was moved from the upper MS block to the lower one. In this case, the upper MS block was assembled on a ring diaphragm.

In a spherical uranium assembly without a reflector, the crescent-shaped gaps in the upper MS block were eliminated by using an aluminum alloy brace (Fig. 2).

In the period from 1973 to 1980, at the FKBN-M critical test bench, about 100 spherical critical systems of the benchmark type were assembled with cores of highly enriched uranium and plutonium metals in the δ phase, including combined cores with different ratios of uranium and plutonium, without a reflector and with reflectors made of beryllium, beryllium oxide, steel, depleted uranium, aluminum, copper, polyethylene, boron-containing polyethylene, as well as with combined reflectors made of beryllium, beryllium oxide, steel, depleted uranium in combination with polyethylene.

Critical mass experiments at RFNC-VNIITF were further developed in the transition to the cylindrical geometry of measurements.

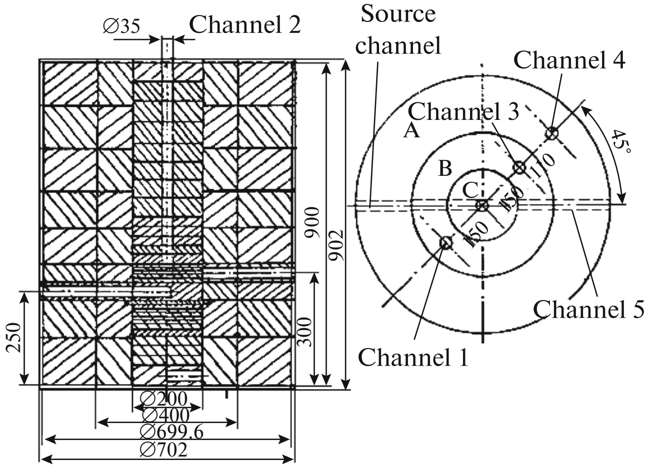

**Fig. 4.** Dismountable experimental blanket model (ROMB): A, B, and C are the outer, middle and central regions; 1, 3, and 4 indicate through channels; channel 2 has a depth of 625 mm.

In the early 1980s, the possibility of the institute's participation in the project of creating a thermonuclear reactor was considered. One of the areas of this work could have been the neutronic calculations of the blanket of a hybrid thermonuclear reactor using the KLAN and PRISMA programs developed at the institute [2].

In 1981, on the initiative of E.N. Avrorin, A.P. Vasiliev, L.B. Poretsky, and I.S. Pogrebov, for research aimed at correcting the constants of interaction between neutrons and matter at energies up to 14 MeV, an experimental blanket model of a hybrid thermonuclear reactor—demountable experimental blanket model (ROMB)—was developed and fabricated [3]. This model is a demountable cylinder of depleted uranium (Fig. 4) with a diameter of 70 cm, a height of 90 cm, a total mass of 6.5 tons with an average density of 18.75 g/cm$^3$, consisting of three independent regions: outer, middle, and central.

The ROMB assembly has horizontal and vertical experimental channels, a channel for the targetry of the 14 MeV neutron generator. The composition of the central region, the neutron spectrum formed in it, can vary within wide limits owing to the use of additional assembly kits made of various construction materials and polyethylene. The design of the ROMB assembly allows it to be used for experiments on the FKBN-2 critical test bench with systems that include fissile materials. For this purpose, the possibility is provided to divide the central area of the ROMB assembly into two parts: a fixed upper part and a movable lower one, which is attached to the piston rod of the critical test bench.

In the first series of experiments with the ROMB assembly, a large amount of measurements of distributions of the U-238, U-235, Np-237, and Pu-239 fis-

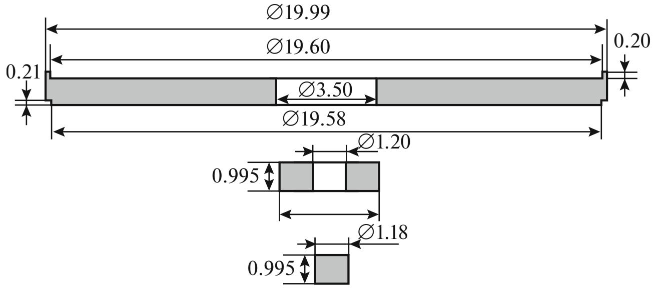

**Fig. 5.** The design and geometry of the ROMB assembly core disks.

sion reactions and also the $^{19}$F($n$, $2n$) and $^{56}$Fe($n$, $p$) reactions with a 14-MeV source over the assembly was performed. The experimental data were compared with the calculations.

After the completion of this work, the experiments with the ROMB assembly as with a blanket model of a hybrid thermonuclear reactor did not receive a continuation, while the main direction of experimental research with the ROMB assembly became running of critical experiments.

The transition to cylindrical geometry allowed expanding significantly the types of systems assembled at the FKBN critical test bench. It became possible to assemble heterogeneous systems, the structure of which could be changed during experiments using the already existing assembly units. By combining fissile and structural materials with a moderator of various thicknesses, it is possible to change the average neutron energy in the core, increasing in the process the fraction of neutrons in the range of intermediate energies, where the resonance structure of neutron cross sections is manifested. The cylindrical geometry of assemblies makes it possible to assemble systems consisting of repeating cellular structures, which cannot be done in spherical geometry. It is much easier and cheaper to manufacture cylindrical parts than kits of hemispherical parts, especially in the case of difficult-to-machine and expensive materials. In essence, the ROMB assembly, being two-dimensional, occupies an intermediate position between spherical (one-dimensional) assemblies and BFS-type systems [4], which allow modeling three-dimensional structures. Thus, in the ROMB assembly, it was possible to combine the simplicity inherent in spherical one-dimensional structures with the rich capabilities inherent in complex systems of the BFS type.

At present, the ROMB assembly includes a set of geometrically compatible parts in the form of (i) outer zone rings (with outer diameter of 70 cm and inner diameter of 40 cm) made of depleted uranium and polyethylene; (ii) middle zone rings (with outer diameter of 40 cm and inner diameter of 20 cm) made of depleted uranium, lead, steel, polyethylene, and boron-containing polyethylene; (iii) the central zone disks with a diameter of 20 cm made of depleted uranium, highly enriched uranium, lead, polyethylene, boron-containing polyethylene, beryllium, beryllium oxide, aluminum, titanium, iron, copper, molybdenum, nickel, niobium, tungsten; and (iv) the disks made of plutonium with a diameter of 12 cm. The total mass of U-235 is approximately twice the critical mass of a cylinder 20 cm in diameter, which makes it possible to assemble the critical systems using significant dilution of fissile materials with non-fissile materials.

Since 1984, about 500 cylindrical critical systems of various compositions have been assembled at the FKBN critical test bench. For most of the systems, computational models were composed and $K_{\text{eff}}$ was calculated. The calculation results were used to certify the PRIZMA-D program as applied to the calculations of nuclear safety parameters. Some of the experiments were carried out to solve specific applied problems. More detailed information about experiments at the FKBN critical test bench is given in [5] and in the book edited by A.V. Lukin [6].

Below a brief description of some experiments carried out at different times at the FKBN critical test bench is presented, which give an idea of the nature of the performed research.

## 1. MEASUREMENT OF CRITICAL PARAMETERS OF A CYLINDRICAL ASSEMBLY OF HIGHLY ENRICHED URANIUM WITHOUT A REFLECTOR

Experiments with a cylindrical assembly of highly enriched uranium without a reflector were carried out at the FKBN critical test bench in 1984 immediately after the manufacture of a cylindrical core (ROMB core) consisting of 20 disks made of highly enriched uranium metal. The configuration and geometrical dimensions of disks with plugs are shown in Fig. 5.

The fixation of the disks in the assembly is carried out using beads and grooves on the edges of the disks. To ensure the joining of the planes of adjacent disks, the height of the beads is 0.1 mm less than the depth of the grooves.

When preparing the experiment, the task was set to minimize the impact of the used equipment on the reactivity of the assembly. Therefore, for fastening the upper fixed block of the assembled MS, an openwork rack made of duralumin was used, which was applied previously for assembling spherical MSs, while for fixing the lower MS block, a dished rack made of steel with a thickness of 2 mm was used. Measurements have shown that the contribution from this rack to the critical gap is significant and amounts to ~2 mm. In this regard, for fixing the lower MS block, it was proposed to use a conical frame (Fig. 6) made of duralumin, the contribution from which to the critical gap for an assembly without a reflector is about 0.2 mm; this is comparable to the accuracy of measuring the critical gap.

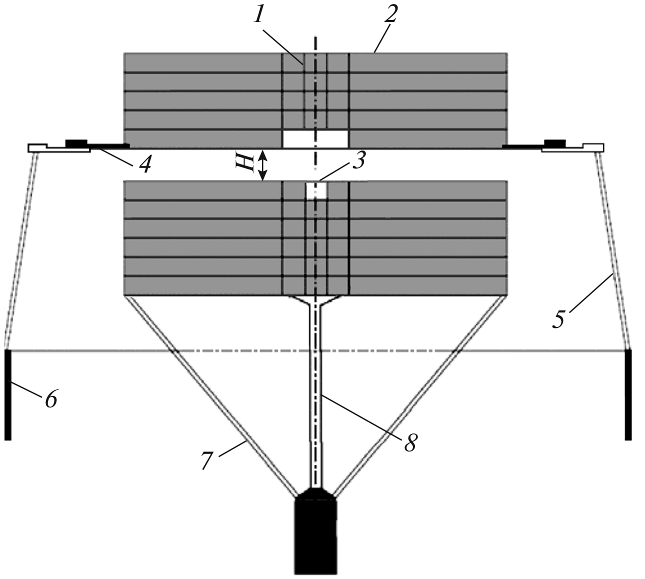

**Fig. 6.** Cylindrical assembly made of uranium without a reflector (the lower part of the assembly is mounted on a conical frame made of duralumin): (*1*) plugs, (*2*) disks, (*3*) neutron source, (*4*) steel diaphragm, (*5*) duralumin rack, (*6*) support tube, (*7*) conical duralumin frame, (*8*) rod.

The assembly design made it possible to almost completely eliminate the contribution to reactivity from the diaphragm on which the upper block of the assembly is attached. In this case, the deflection of the diaphragm under load when assembling the upper MS block does not affect the accuracy of the critical gap measurement, since the critical gap is measured directly between the adjacent disks of the upper and lower blocks of the MS.

This critical assembly, after being evaluated by experts, has been included in the International Handbook of Evaluated Criticality Safety Benchmark Experiments [7] under identification number HEU-MET-FAST-015. The manual contains detailed data on the geometry and composition of the assembly, its critical parameters, and the design model of the assembly.

## 2. CRITICAL MASS EXPERIMENTS TO ESTIMATE THE CONSTANT ERROR IN CALCULATING THE CRITICALITY OF LATTICES FROM CONTAINERS WITH FM [8]

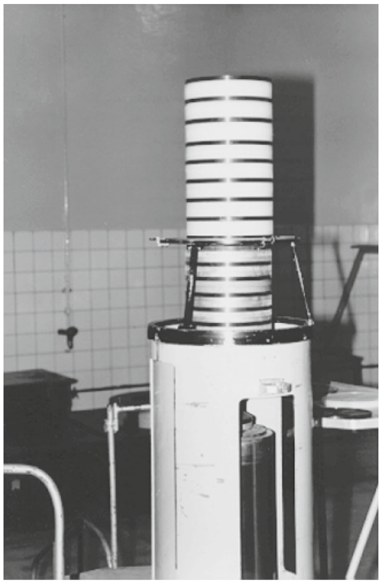

**Fig. 7.** Critical assembly including cells that simulate the structure of the container with FM.

The BAS system of neutron constants currently used in nuclear safety rationale calculations has been tested by comparing the calculated and experimental $K_{\mathrm{eff}}$ values for a large number of single critical assemblies containing metal FMs with various neutron absorbers and reflectors. However, single assemblies do not fully reflect the specific features of neutron propagation in infinite systems of interacting assemblies, to which the lattices from shielding containers pertain.

To estimate the constant error of calculating $K_{\mathrm{eff}}$ of an infinite lattice of typical shielding containers, the experiments were carried out with cylindrical systems consisting of identical cells (Fig. 7) which simulated a structure of the container with FM.

The cell with a diameter of 20 cm included disks of uranium and plutonium metals, which form an integral part of the ROMB assembly, with layers of cadmium, polyethylene, and iron at the ends of the disks. The parameters of the cells were selected in such a way that the critical state was reached with the number of cells of 10–20.

As a result of the experiments, it has been shown that, for all assemblies, the constant error of the $K_{\mathrm{eff}}$ calculation has a sign that is unfavorable from the viewpoint of nuclear safety. An estimate of the constant error in calculating $K_{\mathrm{eff}}$ of three-dimensional lattices from typical shielding containers with metal FMs which was made at the time of the experiments (1990) on the basis of the experimental data obtained gives the value $\delta K_{\mathrm{eff}} \sim 0.015$.

## 3. STUDIES OF THE CRITICALITY ANOMALIES OF URANIUM ASSEMBLIES WITH Be–$CH_2$ AND BeO–$CH_2$ COMPOSITE REFLECTORS

Studies of the critical parameters of systems containing fissile materials showed that, in a number of cases, at first glance, paradoxical effects are observed, which are called criticality anomalies. For example, in [9], it was shown that a sphere of highly enriched ura-

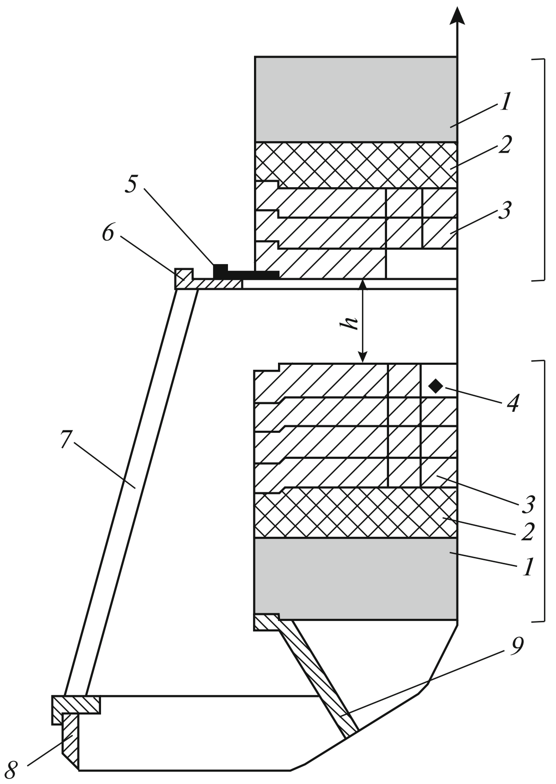

**Fig. 8.** Schematic of a critical assembly made of uranium with a two-layer reflector made of polyethylene and Be or BeO: (*1*) Be (BeO), (*2*) polyethylene, (*3*) uranium disks, (*4*) neutron source, (*5*) diaphragm, (*6*) duralumin ring, (*7*) rack, (*8*) support tube, (*9*) conical frame.

nium hydride with a composite reflector made of nickel and natural uranium has a critical mass that is less than with each of these reflectors of the same thickness separately. In 1995, Yu. I. Chernukhin found by calculation that a similar effect can also be observed for systems of highly enriched uranium metal with a two-layer reflector made of polyethylene and beryllium.

This effect was experimentally confirmed in 2003. By that time, kits of reflectors made of Be and BeO had been manufactured, which were compatible in geometry with the details of the ROMB assembly. Ten cylindrical critical uranium assemblies (Fig. 8), at the ends of which there were two-layer reflectors of a fixed thickness (15 cm) made of polyethylene and Be or BeO, were investigated during the experiments.

In these assemblies, the polyethylene layer was adjacent to the FM, while the side reflector was absent. All studied MSs had the same core. In the course of the experiments, the dependence of the critical gap on the thickness of the polyethylene interlayer between the upper and lower blocks (UB and LB) of the assemblies was measured. The measurement results are shown in Fig. 9.

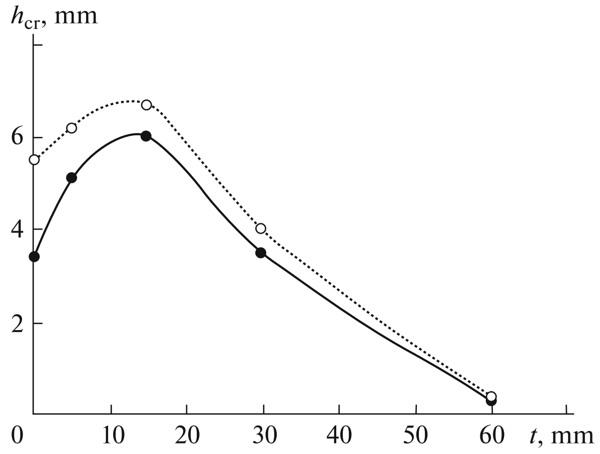

**Fig. 9.** Critical gap as a function of the thickness of polyethylene interlayer in a two-layer reflector: Be–$CH_2$ (solid circle), BeO–$CH_2$ (open circle).

As can be seen from Fig. 9, the experimental results confirmed the presence of criticality anomalies for assemblies of this type. In this case, it is shown that a reflector made of BeO is more efficient than that of Be, and the maximum contribution of the composite reflector Be–$CH_2$ or BeO–$CH_2$ to the reactivity of the assembly is achieved at a polyethylene thickness of 1–1.5 cm.

## 4. CRITICAL EXPERIMENTS WITH URANIUM ASSEMBLIES CONTAINING VANADIUM, MOLYBDENUM, TUNGSTEN

Carrying out critical experiments for the purpose of meeting the needs for nuclear data, as well as for testing nuclear safety (NS) calculations, is one of the possible trends of international scientific and technical cooperation. Earlier, the RFNC-VNIITF under ISTC project no. 3110 performed a large volume of critical benchmark experiments, including critical experiments with cylindrical assemblies made of highly enriched uranium metal containing vanadium, molybdenum, and tungsten. The interest in these materials is associated with their widespread use in the composition of alloys in the nuclear reactor industry.

To carry out the experiments, kits of disks made of metallic vanadium, molybdenum, and tungsten, geometrically compatible with the details of the ROMB assembly, were manufactured. In the course of experiments at the FKBN critical test bench, cylindrical critical systems with cores of metallic highly enriched uranium, typical of such experiments, were assembled:

– cylindrical assemblies with reflectors at their ends, up to 20 cm thick;

– heterogeneous cylindrical assemblies with dilution of uranium with vanadium, molybdenum, and tungsten;

– heterogeneous cylindrical assemblies with a side reflector made of depleted uranium and a moderator in the core made of polyethylene, Be, and BeO;

– heterogeneous cylindrical assemblies with a side reflector made of polyethylene and a moderator in the core made of polyethylene.

All studied critical systems were evaluated by experts and were included in the International Handbook of Evaluated Criticality Safety Benchmark Experiments [7].

Figure 10 shows a scheme of the HEU-MET-MIXED-016 assembly as an example.

## 5. CRITICAL ASSEMBLY OF HIGHLY ENRICHED URANIUM METAL WITH ONE-SIDED POLYETHYLENE REFLECTOR WITH SIMULATION OF A LARGE-DIAMETER CORE

The purpose of this work, carried out under the ISTC project no. 3110, was to clarify the results of critical experiments with a cylindrical assembly made of uranium metal with a reflector made of polyethylene carried out in one of the laboratories. Since the uranium disks in these experiments had a larger diameter, for their simulation, the geometry of measurements with the core in the form of a layer of three stacks of disks of the ROMB kit was proposed (Fig. 11). In this case, a polyethylene reflector with a diameter of ~1 m and a thickness of 15 cm was mounted from above on height-adjustable supports. The critical state of the system was achieved by lifting the lower block made of uranium, assembled on the movable piston of the FKBN bench. The assembly design made it possible to adjust the gap between the core and the reflector during the experiments. On the basis of the results of the experiments, an assembly benchmark model was built.

## 6. CRITICAL EXPERIMENTS OF BENCHMARK TYPE FOR TESTING CALCULATIONS OF NEUTRONIC CHARACTERISTICS OF REACTORS WITH LEAD COOLANT

When discussing in 1990 possible areas of cooperation with specialists from NIKIET, where at that time the development of a fast reactor with a lead coolant BRS satisfying modern requirements of safety was conducted [10], the proposal of RFNC-VNIITF to conduct critical benchmark experiments with the ROMB assembly in addition to experiments at the BFS-61 bench with a critical assembly simulating a fast reactor with a lead coolant was supported, as well as a proposal to RFNC-VNIITF of neutronic calculations of the characteristics of the BFS-61 critical assembly.

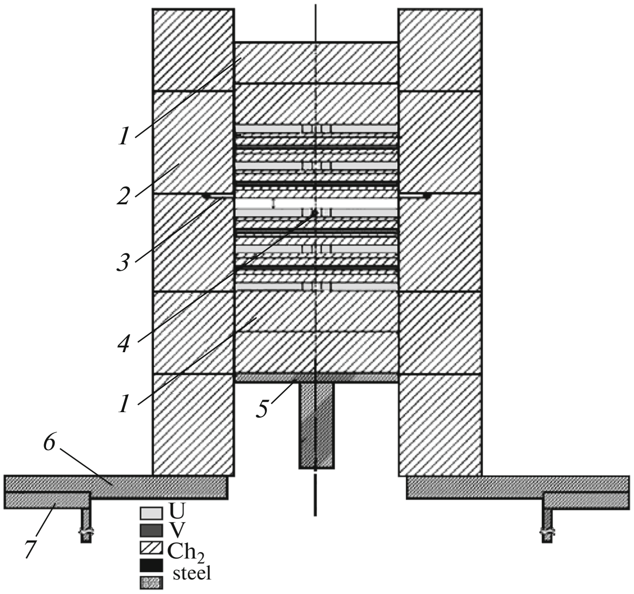

**Fig. 10.** Scheme of a heterogeneous assembly made of uranium, vanadium, and polyethylene with a side reflector made of polyethylene: (*1*) end reflectors, (*2*) side reflector, (*3*) diaphragm, (*4*) neutron source, (*5*) dished rack, (*6*) plate, (*7*) support tube.

For the experiments, an additional kit of rings and disks of lead was fabricated, which followed the shape of the rings of the middle region and the disks of the central region of the ROMB assembly. In the process of preparing the experiments, preliminary calculations of possible variants of critical assemblies were carried out for the purpose of selecting systems for which the spectrum of neutrons in the assembly approaches the spectrum of neutrons in the core of the reactor with a lead coolant. It was assumed that, for the selected critical systems, measurements of the spatial distributions in the core of the numbers of fissions and spectral indices, measurements of the contributions of relatively small samples to the reactivity in "difference" experiments, and measurements of neutron spectra using the existing method of activation indicators would be carried out.

In the first series of experiments to test the lead neutron constants, five critical uranium assemblies were mounted: an assembly with a 20-cm-thick lead reflector at the ends; a heterogeneous assembly in which the uranium layers alternated with layers of lead 1.3 cm thick; three assembly options with a side reflector made of lead with varying degrees of dilution of uranium with lead. On the basis of the results of the experiments, the benchmark models were constructed and comparative calculations were carried out. All these assemblies are currently included in the interna-

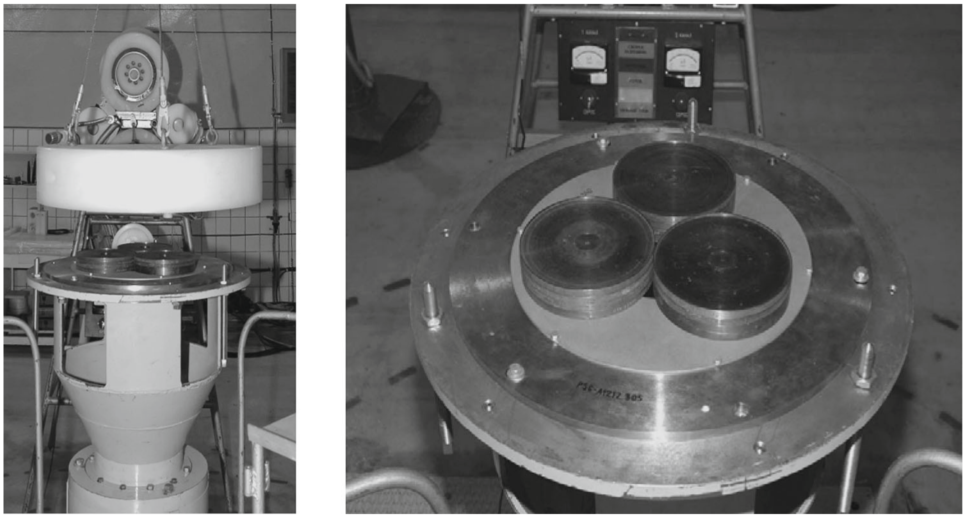

**Fig. 11.** Critical uranium assembly with one-way polyethylene reflector with simulation of a large-diameter core.

tional handbook [7]. Unfortunately, owing to lack of funding, the continuation of the work did not follow.

## 7. CRITICAL MASS BENCHMARK EXPERIMENTS WITH CYLINDRICAL SYSTEMS MADE OF URANIUM, PLUTONIUM, AND POLYETHYLENE AT THE FKBN BENCH FOR TESTING NEUTRONIC CALCULATIONS OF THE CHARACTERISTICS OF VVER-TYPE REACTORS

In 1999, in the context of works carried out with the support of the ISTC under project no. 116-96, the task was set to create a methodically closed algorithm for verifying the nuclear databases used in calculating the neutronic characteristics of VVER-type reactors according to the results of benchmark-type experiments.

A part of the project was to carry out a large number of experiments with the ROMB assembly. Six series of experiments were carried out with side reflectors of depleted uranium and polyethylene. In this case, the composition of the central region was varied both in the composition of fissile materials (uranium, plutonium, and their combination) and in the degree of dilution of fissile materials with polyethylene. Depending on this, the neutron spectrum in the assembly changed. A total of 65 critical systems were examined. For eight critical systems, in six series of experiments, the numbers of reactions were measured with sets of activation and fission detectors (36 detectors). According to the results of measurements, the spectral composition of the neutron fluence was estimated. At the moment, in [11], only general data on the nature of experiments carried out are given. The exact data on the composition of assemblies and the benchmark models of assemblies were not transmitted to the ISTC.

## ON THE ISSUE OF PRESERVATION OF DATA OF CRITICAL EXPERIMENTS

To date, at RFNC-VNIITF and RFNC-VNIIEF, a large amount of critical mass measurements with assemblies of different configuration and composition have been performed. The experimental data obtained are unique and, in the author's opinion, should be preserved. A possible way to save the data of critical experiments is the creation of an industry-specific reference manual on critical experiments, which is similar in structure to the handbook [7]. In creating this reference manual, it is important to preserve the system of expert assessments of the materials included in the reference manual, thereby ensuring that the most reliable and valid experimental data are inserted in the manual.

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