RESULTS OF OLD AND PROGRAM OF NEW EXPERIMENTS ON THE SMALL-SIZED FAST MULTIPLYING SYSTEMS WITH HEU / LEU FUEL

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ABSTRACT

Benchmark criticality experiments on small-sized fast multiplying systems were performed using the “Giacint” critical facility of the Joint Institute for Power and Nuclear Research – Sosny of the National Academy of Sciences of Belarus. The critical assemblies’ cores comprised fuel assemblies with 19 HEU fuel rods. Three types of fuel assemblies with different contents of fuel rods were used. The side radial reflector comprises an inner layer of Be, and an outer layer of stainless steel. The top and bottom axial reflectors are stainless steel. The analysis of the experimental results obtained from these benchmark experiments by developing detailed calculation models and performing simulations for the different experiments is presented. The “Giacint” and “Kristal” critical facilities are being prepared for benchmark criticality experiments on multiplying systems, simulating physical features of the cores with LEU fuel to be uses at fast reactors with gaseous and liquid-metal coolants. The critical assemblies represent uniform hexagonal lattices of fuel assemblies, each of which consists of 7 fuel rods and have no cladding. Three types of fuel assemblies with different matrix material (air, aluminum and lead) were investigated. The side radial, top and bottom reflectors are Be (internal layer) and stainless steel (external layer). The description of the design and the composition of the critical assemblies and the results of calculation are presented.

1. Introduction

This paper presents the experimental and analytical parameters of criticality of the uranium-containing fast neutron multiplication systems with a core based on fuel assemblies with 36% and 90% U-235 fuel rods. The experiments were performed at the “Giacint” critical facility. The experimental results were analyzed in order to estimate whether they can be used as benchmark criticality data.
It is planned to use the “Giacint” and “Kristal” critical facilities to carry experiments at critical assemblies on fast neutrons, simulating physical features of the cores of fast reactors, cooled by gas and liquid-metal coolants. This paper describes the design and the composition of the critical assemblies, the results of calculation of K_{eff}, and the program of experiments at the critical assemblies.

2. The results of old experiments on the small-sized fast critical assemblies with HEU fuel at the critical facility “Giacint”

The fast critical assembly represents a lattice (35.7 mm pitch) of fuel cassettes with fuel rods based on metal uranium and uranium dioxide, 90% and 36% enrichment by U-235, respectively, with a beryllium-steel reflector. The critical assembly includes the core, the side reflector, the top and bottom axial reflectors and the control and protection system (CPS) rods.
The core of critical assembly, comprising fuel cassettes, is surrounded by several rows of beryllium and steel reflector units. These elements of the critical assembly are placed on the stainless-steel support grid. Neutron detectors are attached to special poles around the critical assembly.
The support grid of the critical assembly is placed on the frame and represents a stainless-steel

cylinder, 950 mm in diameter and 40 mm in thickness. The support grid has 18.2 mm diameter holes drilled in the hexagonal lattice with the 35.7 pitch; the holes receive the shanks of the fuel assemblies and the side reflector units.

The fuel cassette (Fig. 1) represents a cassette without a casing and comprises 19 fuel rods. There are two types the fuel cassettes: type 1 includes 16 fuel rods of type 2 and 3 fuel rods of type 1; type 2 includes 19 fuel rods of type 1 (Fig. 2). The fuel rods are arranged around the hexagonal grid with the 8 mm pitch and are fixed by means of the end parts. The fuel cassette dimensions are fit for a 34.8 mm wrench, with the cassette total length 1047 mm (the active part in 500 mm long, the top shank of the fuel rod is 60 mm, the top shank of the fuel rod is 60 mm, the top end parts of the assembly are 216 mm, and the bottom end parts of the cassette are 211 mm). All top and bottom end parts of the fuel cassette are made from stainless steel.

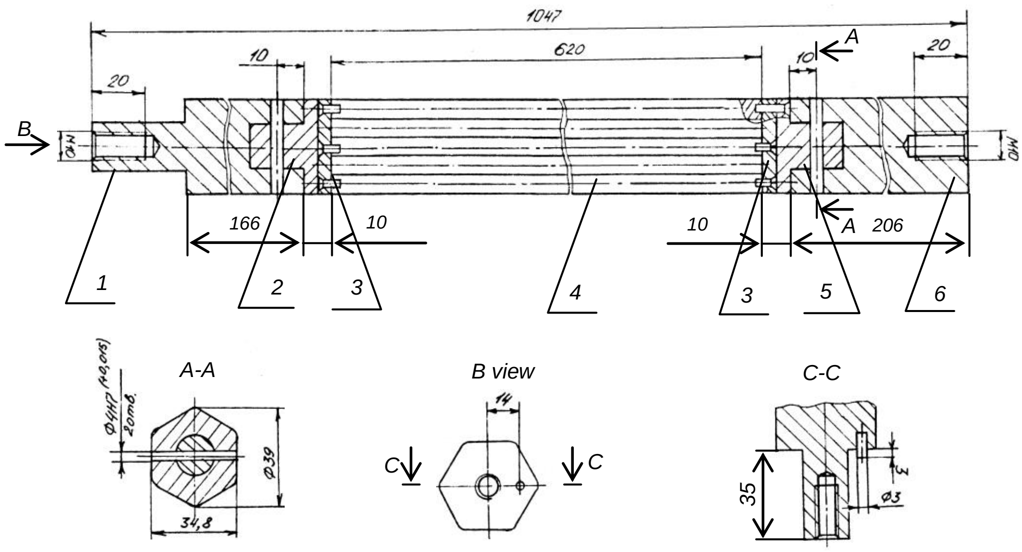


Fig 1. The fuel cassette:
1, 2 – bottom end parts, 3 – tube plate, 4 – fuel rods, 5, 6 – top end parts

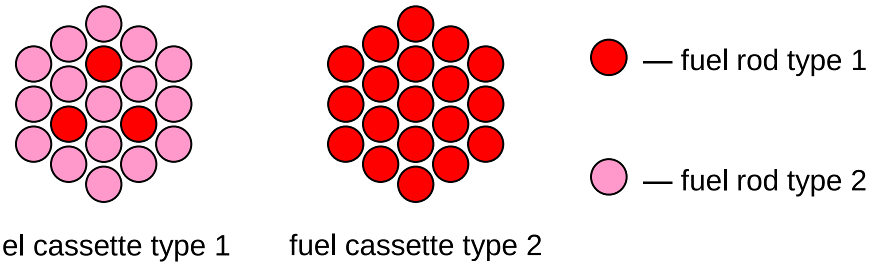


Fig 2. Layout of fuel rods in the fuel assemblies type 1 and 2

The type 1 fuel rod (Fig. 3) comprises a fuel core, a cladding and end parts. The fuel rod cladding is from stainless steel with the outer diameter 7 mm and the wall 0.2 mm thick. The fuel core comprises tablets, 6.4 mm in diameter and 5 mm in height, made from metal uranium 18.9 g/cm^3. The U-235 enrichment is 90%. The total core height is 500 mm. The U-235 weight in the fuel rod is 259.8 g. The top shank of the fuel rod is made from stainless steel with the 60 mm length and 6.6 mm diameter. The bottom end part of the fuel rod comprises the bottom shank 10 mm long and 6.6 mm in diameter and the bushing 50 mm long with the 6.6 mm diameter. The fuel rod is sealed, with the total length 620 mm.

The type 2 fuel rod (Fig. 3) has the same design structure as type 1 fuel rod, but with a different fuel core, comprising tablets with the 6.4 mm diameter and the 4-7 mm height, made from uranium dioxide 9.8 g/cm^3. The enrichment by U-235 is 36%. The total fuel core height is 500 mm. The 90% U-235 weight in the fuel rods is 49.1 g.

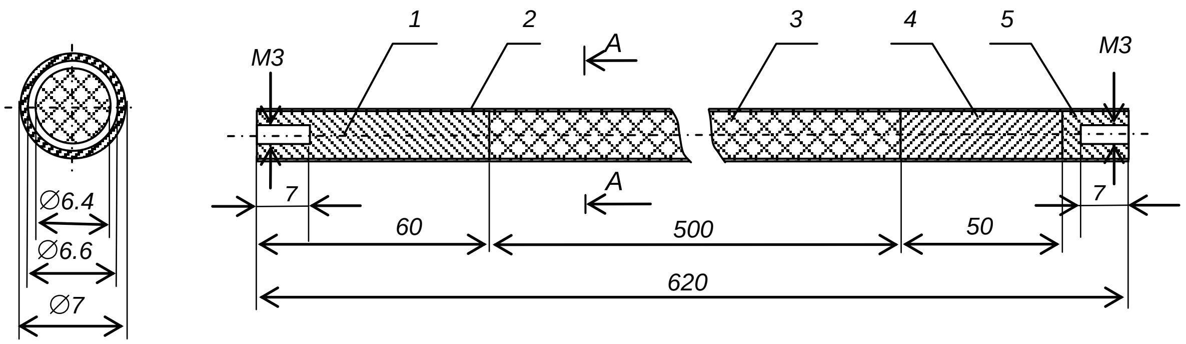


Fig 3. Fuel rod type 1 (type 2):
1 – upper end part; 2 – cladding; 3 – fuel core; 4, 5 – lower end part

The side reflector of the critical assembly is represented by several rows of beryllium and stainless steel reflector units. The bottom axial reflector of the critical assembly comprises bottom plugs of the fuel rods, bottom end parts of the fuel assembly and the support plate. The top axial reflector of the critical assembly comprises top end parts of the fuel rods and top end parts of the fuel assembly.
The beryllium reflector unit represents a hexagonal prism beryllium prism for the 34.8 mm wrench, 972 mm long. The bottom part of the unit bears a stainless steel shank, representing a seating surface when loaded into the critical assembly. The top part of the unit bears a stainless steel head for the 34.8 mm wrench, 40 mm long. The total length of the beryllium reflector unit is 1047 mm. The steel reflector unit is made from stainless steel, representing a hexagonal prism for the 34.8 mm wrench, 1047 mm long. The bottom part of the unit bears a shank, representing a seating surface when the critical assembly is installed on the support plate.
Figures 4 and 5 represent the loading charts of the fast critical assemblies. The core and reflector compositions of the fast critical assemblies are presented in Tab. 1.

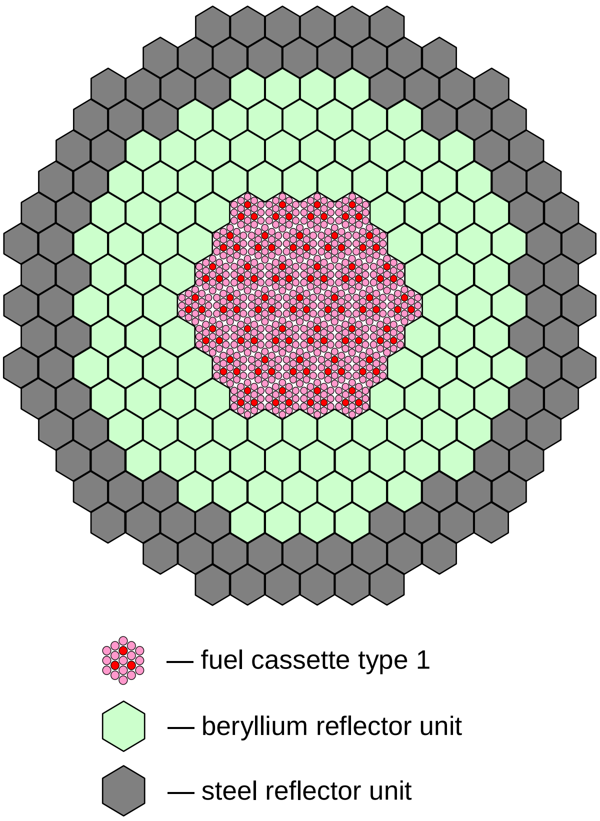


Fig 4. Loading chart of the critical assembly type 1

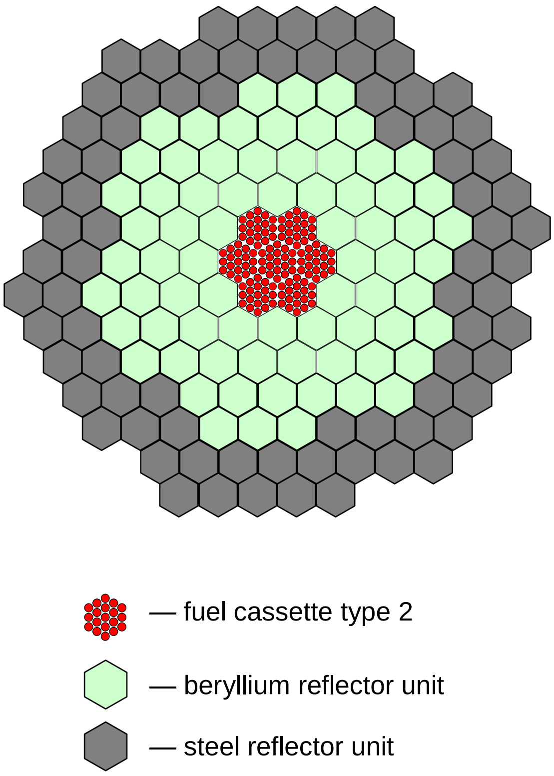


Fig 5. Loading chart of the critical assembly type 2

The critical assembly	The fuel cassette, pcs		Beryllium reflector unit, pcs	Steel reflector unit, pcs
	type 1	type 2		
Type 1	19	—	189	99
Type 2	—	7	72	78

Tab 1. The core and reflector compositions of the fast critical assemblies

The neutron physical characteristics of the critical assembly are measured by the experimental unit “Reactivity Meter”, using the inverted solution of reactor kinetic equation. In order to exclude spatial effects of reactivity, the measurements were made using three ionization chambers, arranged at every 120° behind the side reflector of the critical assembly.
For estimating the results of the critical experiments, we calculated the effective neutron multiplication coefficient K_{eff} of the fast critical assemblies. The calculations were made by the Monte Carlo method using the MCNP-4C [1] and MCU-PD [2] computation codes. The experimental data and the calculation results are presented in Tab. 2.

The critical assembly	Reactivity margin measurement result *, β_{eff}	K_{eff} calculation result		β_{eff} calculation result
		MCNP-4C	MCU-PD	MCU-PD
Type 1	0,20 ± 0,02	1,0018 ±0,0005	1,0024 ±0,0012	0,00750
Type 2	0,60 ± 0,02	1,00310 ±0,00022	1,00130 ±0,00050	0,007227

* – the total error of experimental results for the given confidence probability 0,68.

Tab 2. The experimental data and the calculation results of the fast critical assemblies

3. The program of new experiments on the small-sized fast-thermal and fast-fast multiplying systems with LEU / HEU fuel at the critical facility “Giacint”

Currently, experiments on the criticality of assemblies simulating some physical features of the core of fast gas-cooled reactors have been prepared. For these purposes, the critical assemblies were developed at the “Giacint” critical facility. These critical assemblies represent a uniform hexagonal lattice (35.7 mm pitch) of fuel cassettes without cladding: the central area is based on cassettes with 7 fuel rods with UZrCN (19,75% U-235), the peripheral area (thermal and fast) is based on cassettes with 19 fuel rods with metallic U (90% U-235), UO_2 (36% U-235) and natural U; and the moderator is Be and the reflector is Be (the internal layer) and stainless steel (the external layer).
The core of critical assembly, comprising fuel cassettes, is surrounded by several rows of beryllium and steel reflector units. These elements of the critical assembly are placed on the stainless-steel support grid. The neutron detectors are attached on special poles around the critical assemblies.
The support grid of the critical assembly is placed on the frame and represents a stainless-steel cylinder, 950 mm in diameter and 40 mm in thickness. The support grid has 18.2 mm diameter holes drilled in the hexagonal lattice with the 35.7 pitch; the holes receive the shanks of the fuel cassettes and the side reflector units.
There are five types the fuel cassettes without a casing: type 1 includes 19 fuel rods (16 fuel rods of type 2 and 3 fuel rods of type 1); type 3 includes 18 fuel rods (13 fuel rods of type 2 and 5 fuel rods of type 3); type 4 includes 19 fuel rods (12 fuel rods of type 2, 4 fuel rods of type 1

and 3 fuel rods of type 4); type 5 includes 7 fuel rods of type 5; and type 6 includes 7 fuel rods of type 6. The fuel cassettes of type 1, type 3, type 4 and type 5 are presented in Figure 1, and the layout of fuel rods in these fuel cassettes is presented in Figure 6. The fuel rods of type 1 and type 2 are described above and shown in Figure 3.

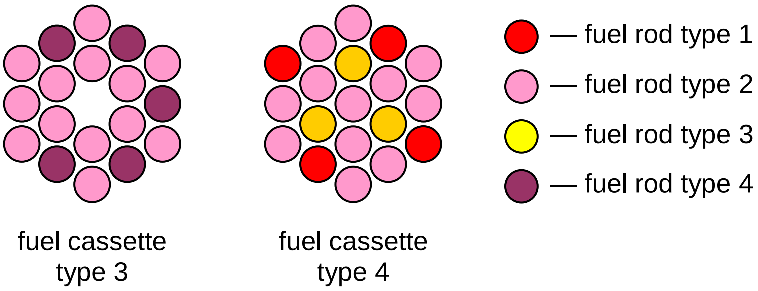


Fig 6. Layout of fuel rods in the fuel cassettes type 3 and 4

The fuel rod of type 3 (Fig. 7) represents a stainless steel tube, 7 mm in diameter, 0.35 mm wall, and 600 mm length, filled with U(36%)O2 to the 500 mm height; with top stainless steel caps 60 mm long length. The total length of the fuel rod is 620 mm.

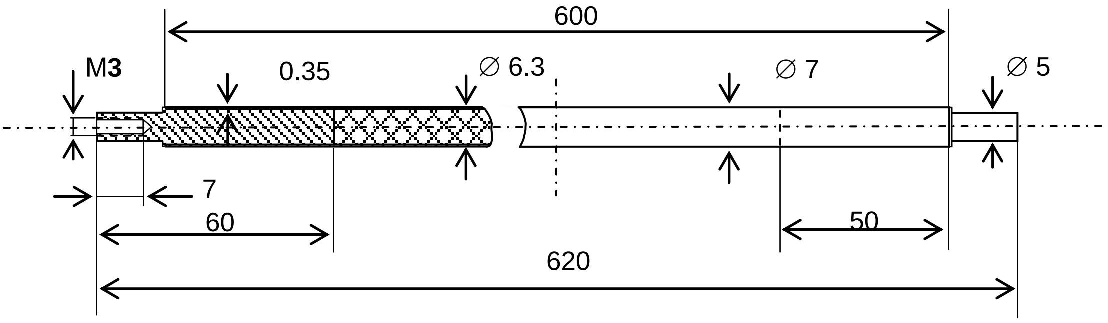
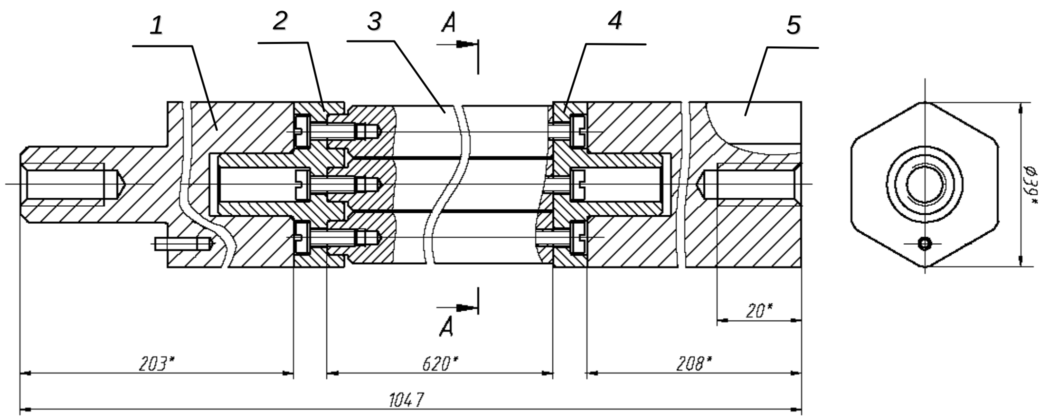


Fig 7. Fuel rod type 3

The fuel rod type 4 (Fig. 3) has the same structure as type 1 fuel rod, but fuel core made from natural metal uranium 18.9 g/cm^3.
The fuel cassette type 5 (type 6) is unclad and comprises 7 fuel rods of type 5 (7 fuel rods of type 6) and end pieces. The designed model of the fuel cassette is presented in Figure 8. The fuel rods are placed in a cassette with a 12,6 mm pitch over the hexagonal grid and fixed by means of the end pieces. The turn-key size of the design model of the cassette is 34.8 mm, the total length of the design model of the cassette is 1047 mm (including the core length 500 mm, the upper end piece of the fuel rods 60 mm, the lower end piece of the fuel rods 60 mm, the upper end piece of the cassette 216 mm, the lower end piece of the cassette 176 mm, and the tail-piece of the cassette 35 mm). All upper and lower end pieces of the cassettes are made from stainless steel.
The fuel rod type 5 (type 6) comprises a fuel core, cladding, and end pieces (Fig 9). The fuel rod cladding has the outer diameter 12 mm and the wall thickness 0.6 mm. The fuel rod comprises tablets, 10.75 mm in diameter and 14.7 mm in height, from uranium-zirconium carbonitride $U_{0,9}Zr_{0,1}C_{0,5}N_{0,5}$. The enrichment by U-235 was 19.75%. The gaps between the fuel rod cladding tablets and the fuel rod cladding contain He under ~0,11 MPa. The total core height is 500 mm. The total length of the fuel rod is 620 mm. The material of the fuel rod clad and end pieces (plugs) is stainless steel (fuel rod type 5) or alloy NbZr-1 (fuel rod type 6).
The side reflector of the critical assemblies is several rows of the beryllium and stainless steel reflector units. These reflector units are described in the previous part of this paper.



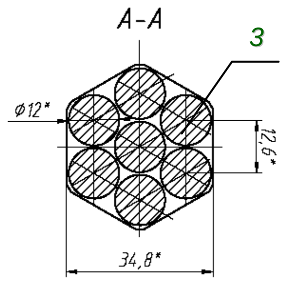


Fig 8. Fuel cassette type 5 (type 6):
1 — bottom nozzle;
2 — bottom tube plate;
3 — fuel rod type 5 (type 6);
4 — top tube plate;
5 — top nozzle

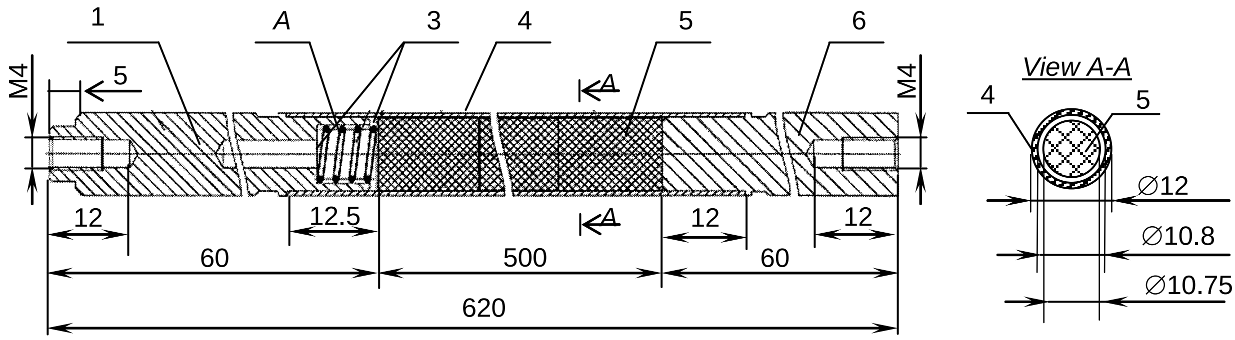


Fig 9. Fuel rod type 5 (type 6):
1 – lower plug; 2 – spring; 3 – gaskets; 4 – cladding; 5 – fuel core; 6 – upper plug

The experiments are to be performed research on two critical assemblies. The core and reflector compositions of these critical assemblies are presented in Tab. 3. The calculation results of K_{eff} made by the Monte Carlo method using the MCNP-4C [1] and MCU-PD [2] computation codes are presented in Tab. 4. Figures 10 and 11 represent the loading charts of the two-region fast-thermal and fast-fast critical assemblies.

The critical assembly	The fuel cassette, pcs					Beryllium moderator and reflector unit, pcs	Steel reflector unit, pcs
	type 1	type 3	type 4	type 5	type 6		
Type 3	36	—	—	24	7	162	123
Type 4	—	30	30	24	7	162	114

Tab 3. The core and reflector compositions of the fast-thermal and fast-fast critical assemblies

The critical assembly	K_{eff} calculation result		β_{eff} calculation result
	MCNP-4C	MCU-PD	MCU-PD
Type 3	1,00458 ± 0,00013	1,00520 ± 0,00038	0,007444
Type 4	1,00297 ± 0,00012	1,00026 ± 0,00041	0,007483

Tab 4. The calculation results of the fast-thermal and fast-fast critical assemblies

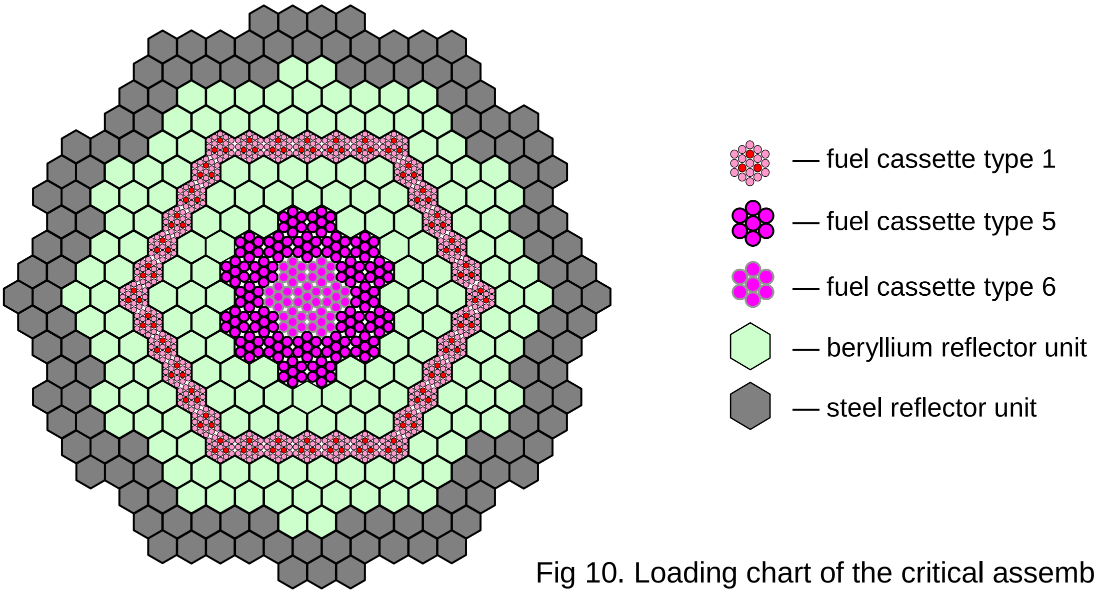


Fig 10. Loading chart of the critical assembly type 3 (fast-thermal)

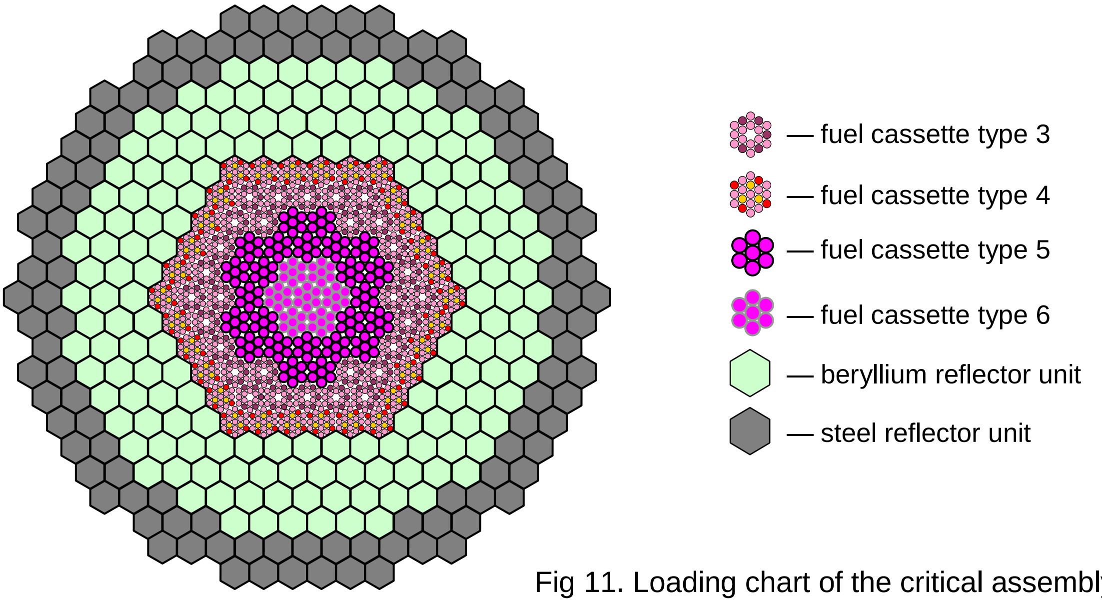


Fig 11. Loading chart of the critical assembly type 4 (fast-fast)

4. The program of new experiments on the small-sized fast multiplying systems with LEU fuel at the critical facilities “Giacint” and “Kristal”

The critical facilities “Giacint” and “Kristal” are used to prepare the experiments on the criticality of multiplying systems simulating physical features of the core of the future fast-neutron reactors with gaseous and liquid-metal coolants. Lattices of fuel cassettes in a matrix from air, aluminium and lead were investigated.
This fast critical assemblies represent a lattice (39 mm pitch) of fuel assemblies with fuel rods based on uranium-zirconium carbon nitride (19.75% enrichment by U-235) and with air or lead or aluminum as matrix materials, with a beryllium-steel reflector. The critical assemblies included a core, a side reflector, top and bottom axial reflectors and a control and protection system’s (CPS) rods.
The cores of critical assembly, comprising fuel assemblies, is surrounded by several rows of beryllium and steel reflector units. These elements of the critical assemblies are placed on the stainless-steel support grid. The neutron detectors are attached on special poles around the critical assemblies.
There are six types the fuel assemblies. The fuel cassette type 7 (type 8) with air as matrix materials is unclad and comprises 7 fuel rods of type 5 (7 fuel rods of type 6) and end pieces. The design model of the fuel cassette is presented in Figure 12. The fuel rods are placed in a cassette with a 14 mm pitch over the hexagonal grid and fixed by the end pieces. The turn-key size of the design model of the cassette is 38.5 mm; the total length of the design model of the cassette is 912 mm. All upper and lower end pieces of the cassettes are made from stainless steel.

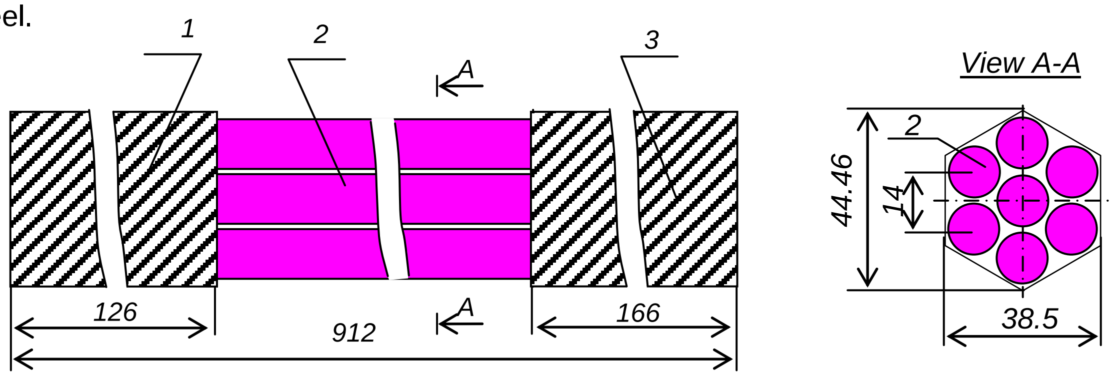


Fig 12. The design model of fuel cassette type 7 (type 8):
1 – lower end piece; 2 – design model of fuel rod type 5 (type 6); 3 – upper end piece

The fuel cassette type 9 (type 10) with lead as matrix materials is unclad and comprises 7 fuel rods of type 5 (7 fuel rods of type 6) and end pieces (Fig. 13). The fuel rods are placed in a cassette with a 14 mm pitch over the hexagonal grid and fixed by the end pieces. The lower end piece of the cassette comprises a shank (stainless steel), a lead end piece and the lower tube plate (stainless steel); the upper end piece of the cassette comprises the upper tube plate (stainless steel),the lead end piece and the head (stainless steel). The turn-key size of the design model of the cassette is 38.5 mm; the total length of the design model of the cassette is 912 mm.

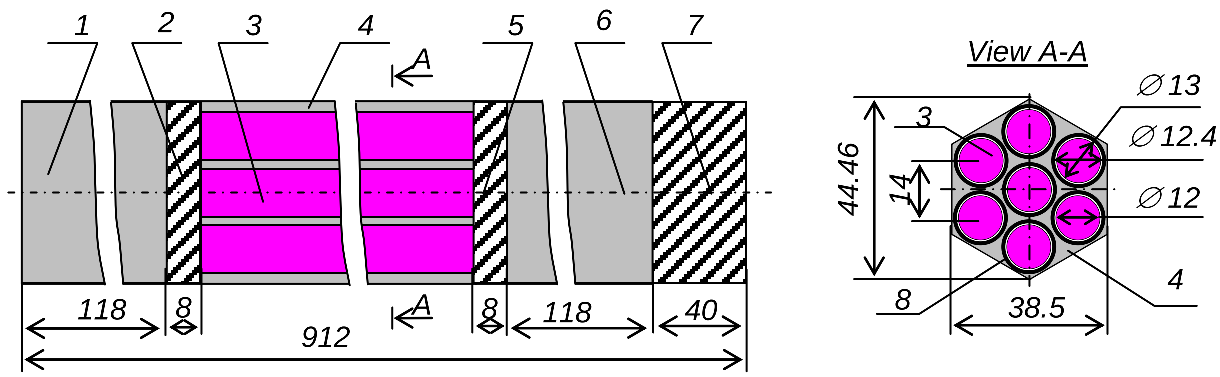


Fig 13. The design model of fuel cassette type 9 (type 10):
1 – lower lead end piece; 2 – lower tube plate; 3 – fuel rods type 5 (type 6); 4 – lead matrix;
5 – upper tube plate; 6 – upper lead end piece; 7 – head; 8 – casing tube

The fuel cassette type 11 (type 12) with aluminum as matrix materials is unclad and comprises 7 fuel rods of type 5 (7 fuel rods of type 6) and end pieces (Fig 14). The fuel rods are placed in a cassette with a 14 mm pitch over the hexagonal grid and fixed by the end pieces. The turn-key size of the design model of the cassette is 38.5 mm; the total length of the design model of the cassette is 912 mm. All upper and lower end pieces of the cassettes are made from stainless steel.

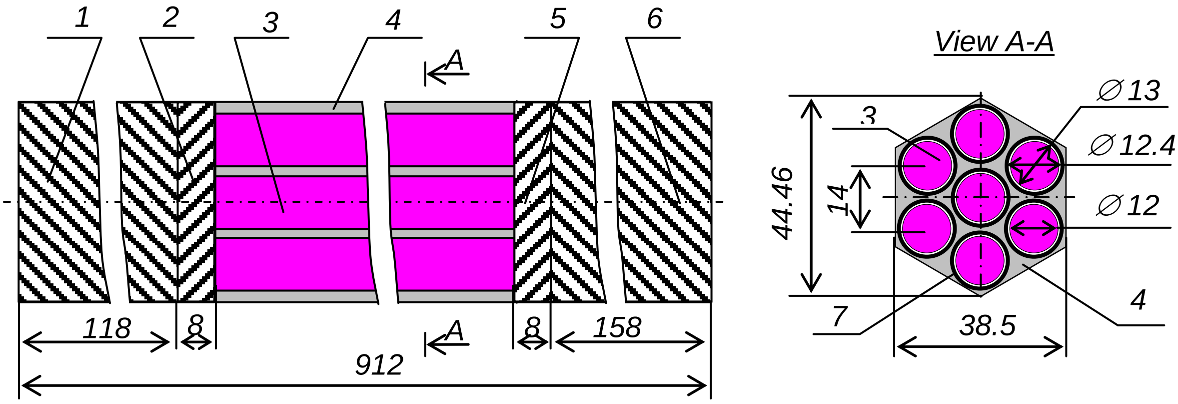


Fig 14. The design model of fuel cassette type 11 (type 12):
1 – lower steel end piece; 2 – lower tube plate; 3 – fuel rods type 5 (type 6); 4 – aluminum matrix; 5 – upper tube plate; 6 – upper steel end piece; 7 – casing tube

The side reflector of the critical assemblies is several rows of the beryllium and stainless steel reflector units. The beryllium reflector unit represents a hexagonal beryllium prism with turn-key size 38.5 mm and the length 872 mm. To the bottom of the unit is attached to the shank. The head (stainless steel) with the turn-key size 38.5 mm and the length 40 mm is fixed to the upper part of the unit. The total length of the unit is 947 mm, and the shank length is 35 mm. The steel reflector unit represents a hexagonal prism from stainless steel with the turn-key size 38.5 mm. To the bottom of the unit is attached to the shank. The total length of the unit is 947 mm, 35 mm shank length.
The experiments are to be performed on three fast critical assemblies. The core and reflector compositions of these critical assemblies are presented in Tab. 5. The calculation results of K_{eff} made by the Monte Carlo method using the MCNP-4C [1] and MCU-PD [2] computation codes are presented in Tab. 6. Figure 15 represent the loading chart of the fast critical assemblies.

The critical assembly	The fuel cassette, pcs						Beryllium reflector unit, pcs	Steel reflector unit, pcs
	type 7	type 8	type 9	type 10	type 11	type 12		
Type 5	210	7	—	—	—	—	504	306
Type 6	—	—	210	7	—	—	504	306
Type 7	—	—	—	—	210	7	504	306

Tab 5. The core and reflector compositions of the fast critical assemblies

The critical assembly	K_{eff} calculation result		β_{eff} calculation result
	MCNP-4C	MCU-PD	MCU-PD
Type 5	1,00494 ± 0,00021	1,00993 ± 0,00030	0,007408
Type 6	1,01672 ± 0,00021	1,01244 ± 0,00027	0,007362
Type 7	1,01412 ± 0,00020	1,01619 ± 0,00037	0,007367

Tab 6. The calculation results of the fast critical assemblies

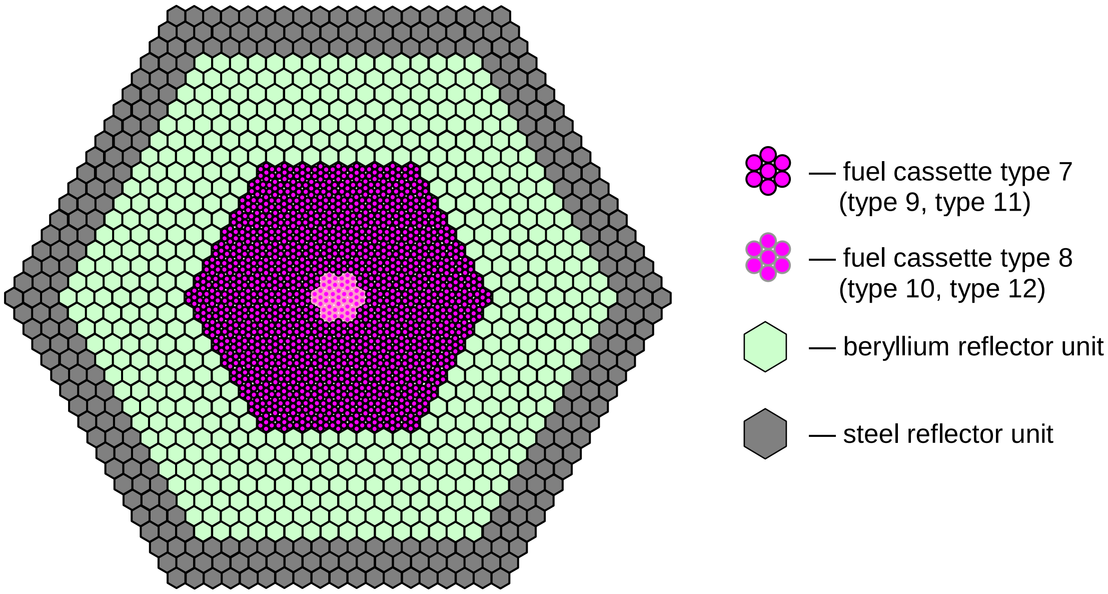


Fig 15. Loading chart of the critical assembly type 5 (type 6, type 7)

5. Conclusions

Analysis of the experimental data (including data on the composition and sizes of the critical assembly components) and of the calculated K_{eff} on small-sized fast critical assemblies with HEU fuel allows a conclusion that the results of criticality experiments obtained on this assemblies can be used as benchmark data.
It is planned to use the “Giacint” and “Kristal” critical facilities to carry experiments at critical assemblies on fast neutrons, simulating physical features of the cores of fast reactors, cooled by gas and liquid-metal coolants.

6. References

[1] MCNP – A General Monte Carlo N-Particle Transport Code, Version 4C, Ed. J. F. Briesmeister, Report LNL, LA-13709-M, 2000.
[2] Application Description and User’s Manual for MCU-PD program, Report NRC "KURCHATOV INSTITUTE", №36-10/30-11, 2011.