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Realization of the Full-Core Conversion Program for the WWR-M Research Reactor in Ukraine

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ABSTRACT

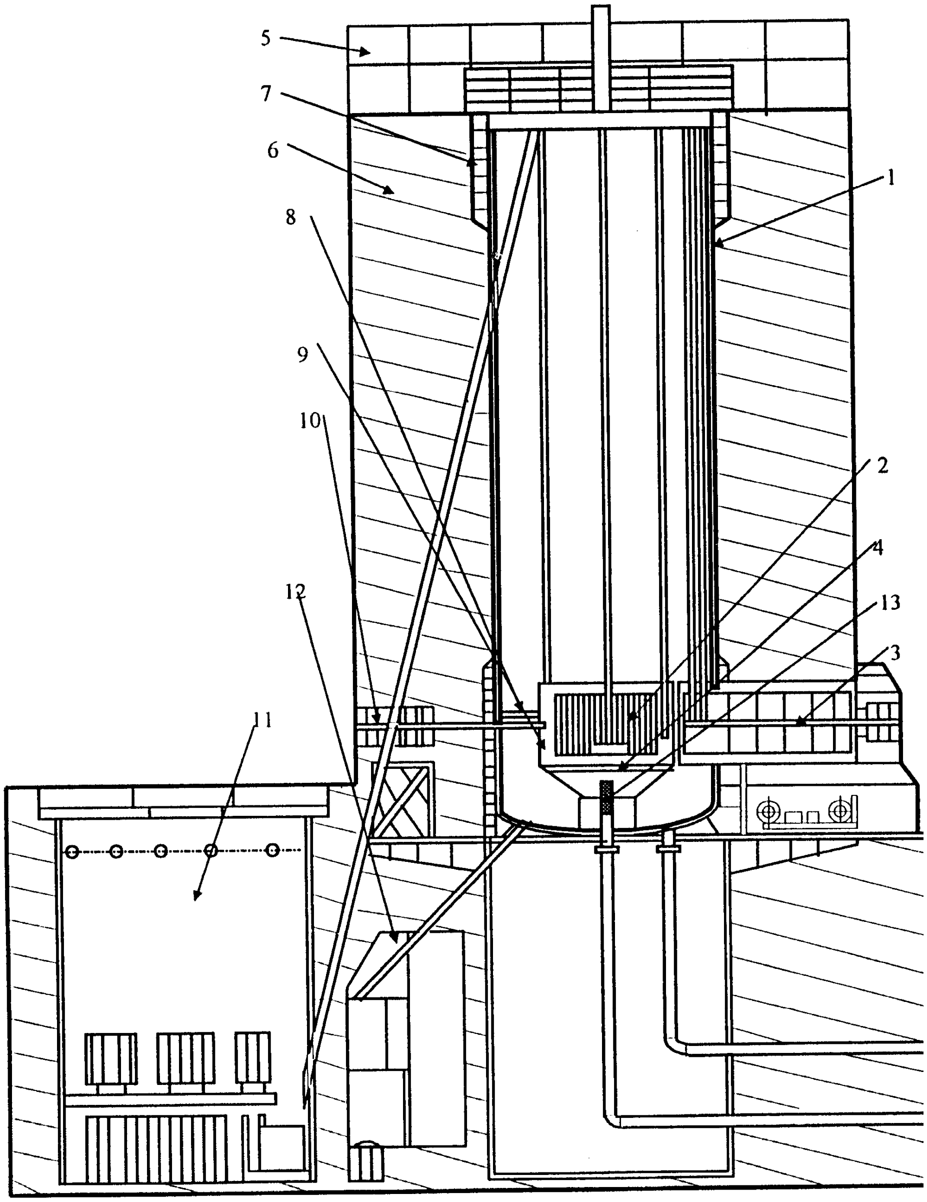
The full-core conversion program for the WWR-M research reactor in Ukraine was realized at the beginning of 2011 when sufficient amount of fresh LEU fuel was obtained. Because of essential decrease of the number of fuel assemblies in the core, a lot of old irradiated beryllium blocks with unknown He-3 poisoning had to be loaded. To provide safety of the core loading, 15 aluminum blocks were loaded for the nonce to decrease excess reactivity. Moreover, neutron flux was being monitored all the time during the core loading to estimate subcriticality and worth of the control and safety rods. When criticality was reached, excess reactivity and He-3 poisoning were estimated. Since excess reactivity was small because of high He-3 poisoning, the temporary aluminum blocks were replaced by beryllium ones. Then worth of the rods and excess reactivity were measured. By using comparative reactivity measurements, beryllium blocks with highest poisoning were detected and moved far away from the fuel to diminish their influence on the neutronics and thermal-hydraulics parameters of the core. Since such beryllium shuffling changed the worth of the rods and excess reactivity essentially, they were measured again. This measurement was in good agreement with calculation, so safety analysis was validated for the new LEU core.

1. Introduction

The WWR-M reactor in Kiev (Ukraine) is a light-water cooled and moderated research reactor with beryllium reflector. Its maximal power is 10 MW. Replaced HEU fuel assemblies are WWR-M2 (36%). LEU replacement fuel assemblies are LEU WWR-M2 (19.75%), which have been tested successfully in the WWR-M reactor in Gatchina, Russia by irradiation to over 75% burnup [1]. The reactor and fuel assembly parameters and designs are shown in Fig.1-3 and Table 1 [1-3].

Study confirming feasibility of converting the WWR-M research reactor in Ukraine to the use of LEU fuel was completed in 2002 [4]. Safety analysis to qualify LEU WWR-M2 fuel assemblies for conversion was performed in 2004-2005 [5-6]. Safety of fresh and depleted LEU fuel storage was analyzed also [6]. The models applied for calculations were validated against measured data, which include critical experiment results for fresh fuel assemblies and measured neutronic distributions in a real WWR-M reactor core [6]. Safety documentation for LEU conversion of the WWR-M reactor was approved officially by the Nuclear Regulatory Committee of Ukraine in 2005.

In accordance with the program of pilot usage of LEU fuel approved by the Ukrainian Regulatory Committee in 2008, most burned HEU fuel assemblies of the WWR-M reactor were successively replaced by fresh LEU fuel. However, such the conversion progressed very slowly. Thus, the new full-core conversion program with simultaneous replacement of all remaining HEU fuel by fresh LEU fuel was developed in 2010 [7].



1 – Reactor Vessel
2 – Reactor Core
3 – Thermal Column
4 – Supporting Plate
5 – Cover
6 – Shield
7 – Cast Iron
8 – Grid for Water Flow Alignment
9 – Beryllium Reflector
10 – A Beam Tube
11 – Spent Fuel Storage
12 – Hot Cell
13 – Filter

Fig. 1. WWR-M reactor

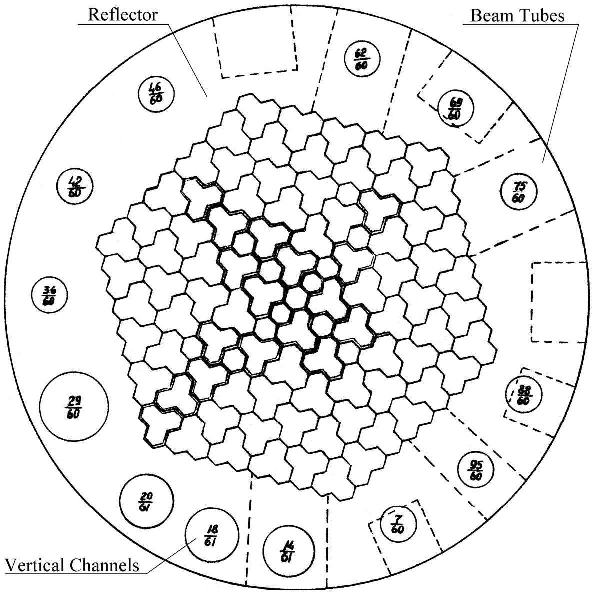


Fig. 2. Reactor core and beryllium reflector

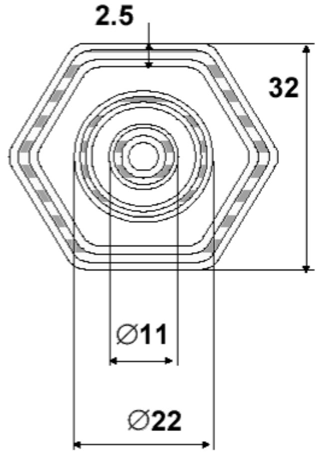


Fig.3. WWR-M2 fuel assembly

Table 1. Fuel assembly parameters

	HEU WWR-M2	LEU WWR-M2
Enrichment, %	36	19.75
Number of fuel elements	3	3
Mass of ^{235}U, g	37	41.7
Fuel meat composition	UO_2-Al 1.1 gU/cm^3	UO_2-Al 2.5 gU/cm^3
Length of fueled region, cm	50	50
Pitch/flat-to-flat, mm	35/32	35/32
Element/clad/meat, mm	2.5/0.76/0.98	2.5/0.78/0.94
Hydraulic resistance coefficient	4.35	4.35
Relative coolant velocities between fuel elements (starting from the center)	1.18;0.89;1.05;0.86	1.18;0.89;1.05;0.86

2. Safety analysis of the LEU core

The full-core conversion with simultaneous replacement of all remaining HEU fuel by fresh LEU fuel deteriorates performance of the reactor because of considerable decrease of the number of fuel assemblies in the core with accompanying rise of fuel expenditures and reduction of total reactor power. Moreover, for small size of the core, it is more difficult to enhance isotope production by increasing number of irradiation channels. Another disadvantage of such the core is very small difference in burnup of available fuel assemblies, resulting in inability to increase power density near irradiation channels by using shuffling of fuel assemblies with distinct burnups.

In order to maintain sufficient production of medical and industrial isotopes, the new LEU core pattern was optimized [7], as shown in Fig.4. Because of the safety and control rods peculiarity, their location in the WWR-M reactor core can not be changed. Thus, the center of the core had to be shifted toward the irradiation channels. Main calculated parameters of the old mixed and new LEU cores are shown in Table 2. For calculations, the MCNP code based on the Monte Carlo method was applied [8]. To determine He-3 poisoning of beryllium, the following equations were used:

$$\frac{dn_{Li}(t)}{dt} = R_{Be} - R_{Li}n_{Li}(t),$$

$$\frac{dn_T(t)}{dt} = R_{Li}n_{Li}(t) - \lambda_T n_T(t),$$

$$\frac{dn_{He}(t)}{dt} = -R_{He}n_{He}(t) + \lambda_T n_T(t),$$

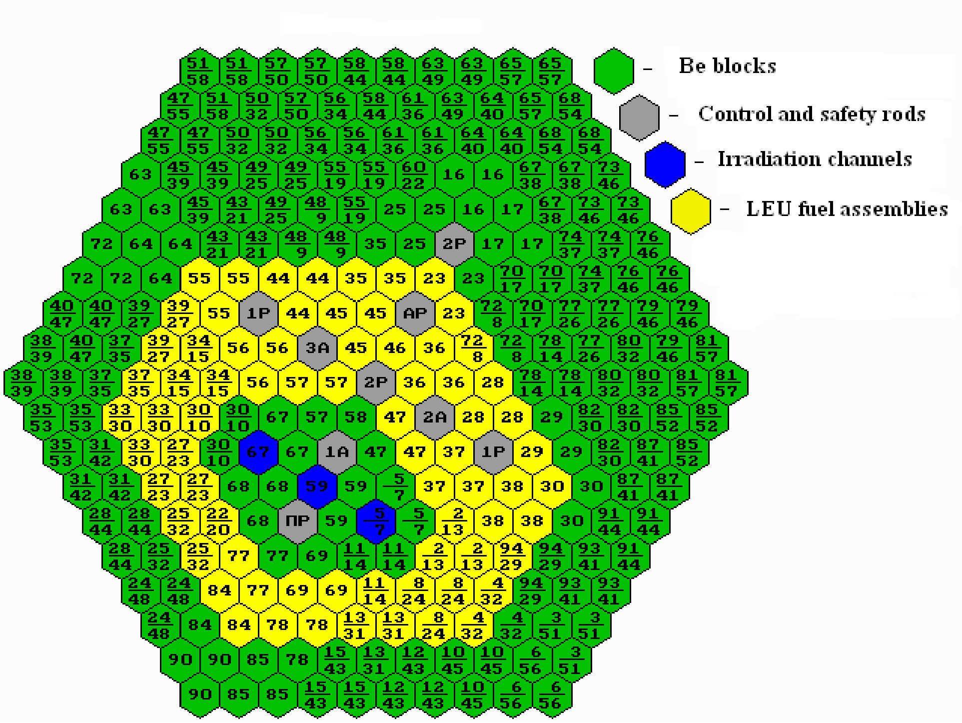


Fig.4. LEU core layout

Table 2. Main parameters of the old mixed and new LEU cores

		Mixed core	LEU core
Power, MW		10.0	7.0
Number and type of fuel assemblies		207 (HEU and LEU)	72 (LEU)
Average fuel burnup, %		30	0.5
Reactivity worth of control rods, $	1P	4.2	7.6
	2P	3.8	6.0
	ПР	2.6	3.9
	AP	0.5	0.7
Reactivity worth of safety rods, $	1A	2.5	4.6
	2A	2.0	4.3
	3A	2.5	4.6
Minimal sub-criticality when all control rods are fully in and all safety rods are fully out, %		2.5	7.3
Maximal reactivity due to loading a fuel assembly in a cell of the core, %		1.1	2.2
Power peaking factor		2.0	1.6
Maximal thermal flux, 10^{14} n/cm^2/s		1.2	1.3
Maximal specific activity of ^{99}Mo (without self-shielding), Ci/g ^{98}Mo		17.0	19.1

where $n_{Li}(t) \equiv \dfrac{N_{Li}(t)}{N_{Be}}$, $n_T(t) \equiv \dfrac{N_T(t)}{N_{Be}}$, $n_{He}(t) \equiv \dfrac{N_{He}(t)}{N_{Be}}$;

N_{Be}, N_{Li}, N_T and N_{He} are the nuclear densities of ^{9}Be, ^{6}Li, ^{3}H and ^{3}He, respectively;

R_{Be}, R_{Li} and R_{He} are the rates of ^{9}Be(n,α), ^{6}Li(n,α) and ^{3}He(n,γ) reactions, respectively;

λ_T is the tritium decay constant.

For $R_{Li} \neq \lambda_T$ and $R_{He} \neq \lambda_T$, solutions of this set of equations for $t \geq t_0$ are as follows:

$$n_{Li}(t) = n_{Li}(t_0)e^{-R_{Li}(t-t_0)} + \frac{R_{Be}}{R_{Li}}(1 - e^{-R_{Li}(t-t_0)}),$$

$$n_T(t) = (n_T(t_0) - \frac{R_{Li}}{\lambda_T - R_{Li}}(n_{Li}(t_0) - \frac{R_{Be}}{\lambda_T}))e^{-\lambda_T(t-t_0)} + \frac{R_{Li}}{\lambda_T - R_{Li}}(n_{Li}(t) - \frac{R_{Be}}{\lambda_T}),$$

$$n_{He}(t) = (n_{He}(t_0) - \frac{\lambda_T}{R_{He} - \lambda_T}(n_T(t_0) + \frac{R_{Li}}{R_{Li} - R_{He}}(n_{Li}(t_0) - \frac{R_{Be}}{R_{He}})))e^{-R_{He}(t-t_0)} +$$

$$+ \frac{\lambda_T}{R_{He} - \lambda_T}(n_T(t) + \frac{R_{Li}}{R_{Li} - R_{He}}(n_{Li}(t) - \frac{R_{Be}}{R_{He}}))$$

Because of considerable increase of reactivity due to loading a fuel assembly into the core and reactivity worth of control rods, the following potential accidents were analyzed for the new LEU core: incidental falling of a fuel assembly in a cell of the core and spontaneous withdrawal of a control rod group because of malfunction of electronic equipment. To provide safety of the reactor, some limiting conditions for operation were revised. In particular, maximum allowed effective multiplication factor when all control rods are fully in and all safety rods are fully out was decreased from 0.988 to 0.977, and maximum allowed power of the reactor was decreased from 10 MW to 7 MW. The safety analysis confirmed that with the revised limiting conditions for operation, such the events with accompanying one additional equipment malfunction and one error of personnel could not lead to damage of fuel elements and release of radioactivity exceeding allowed level.

3. Loading of the LEU core

Because of decrease of the number of fuel assemblies in the core from 210 to 72, a lot of beryllium blocks had to be loaded. Most of these blocks were not used more than 40 years and information of their irradiation history was not available. Thus, excess reactivity for the new LEU core was difficult to calculate accurately because of unknown He-3 poisoning. To provide safety of the new core loading, conservative approach was used. Irradiated beryllium blocks with unknown He-3 poisoning were assumed to be fresh, and 15 aluminum blocks were loaded for the nonce instead of beryllium to decrease excess reactivity, as shown in Fig.5. Moreover, neutron flux was being monitored all the time during the core loading to estimate subcriticality and worth of the control and safety rods.

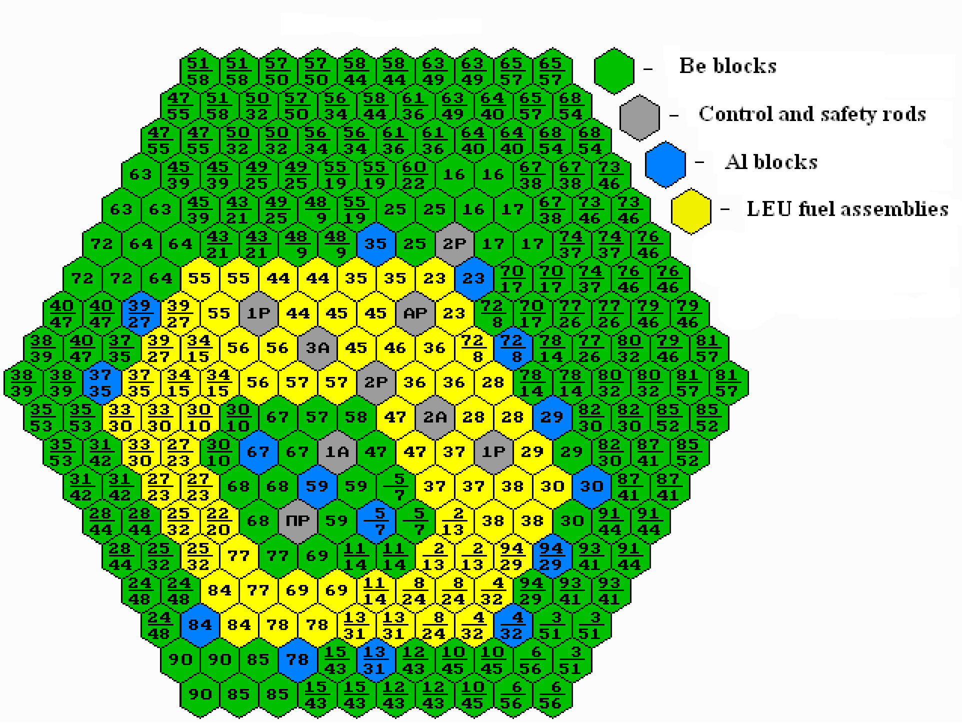


Fig.5. LEU core with temporary aluminum blocks

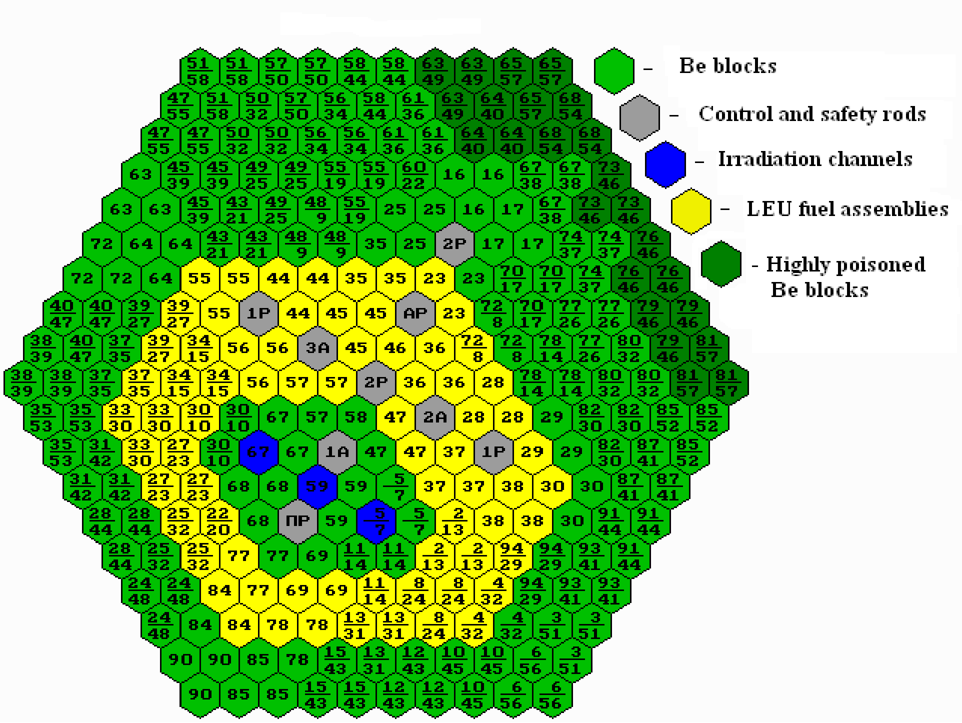


Fig.6. LEU core with 24 highly poisoned beryllium blocks at the periphery

When criticality was reached, He-3 poisoning of beryllium blocks with unknown irradiation history was estimated. It was about $7. Since excess reactivity was small because of high He-3 poisoning, the temporary aluminum blocks were replaced by beryllium ones. Due to this replacement, increase of excess reactivity was $3.6. Then, by using comparative reactivity measurements, beryllium blocks with highest poisoning were detected and moved far away from the fuel to diminish their influence on the neutronics and thermal-hydraulics parameters of the core, as shown in Fig.6. Due to such beryllium shuffling, increase of excess reactivity was $1.5 and He-3 poisoning of beryllium blocks with unknown irradiation history became about $5.5.

Then worth of the rods was measured. As shown in Table 3 and Fig.7-9, it was in good agreement with calculation.

Table 3. Reactivity worth of the control and safety rods, $

	Calculation	Measurement
1P	7.55	7.71
2P	5.95	6.15
ПР	3.88	3.97
AP	0.70	0.73
1A	4.61	4.9
2A	4.26	4.0
3A	4.57	4.9

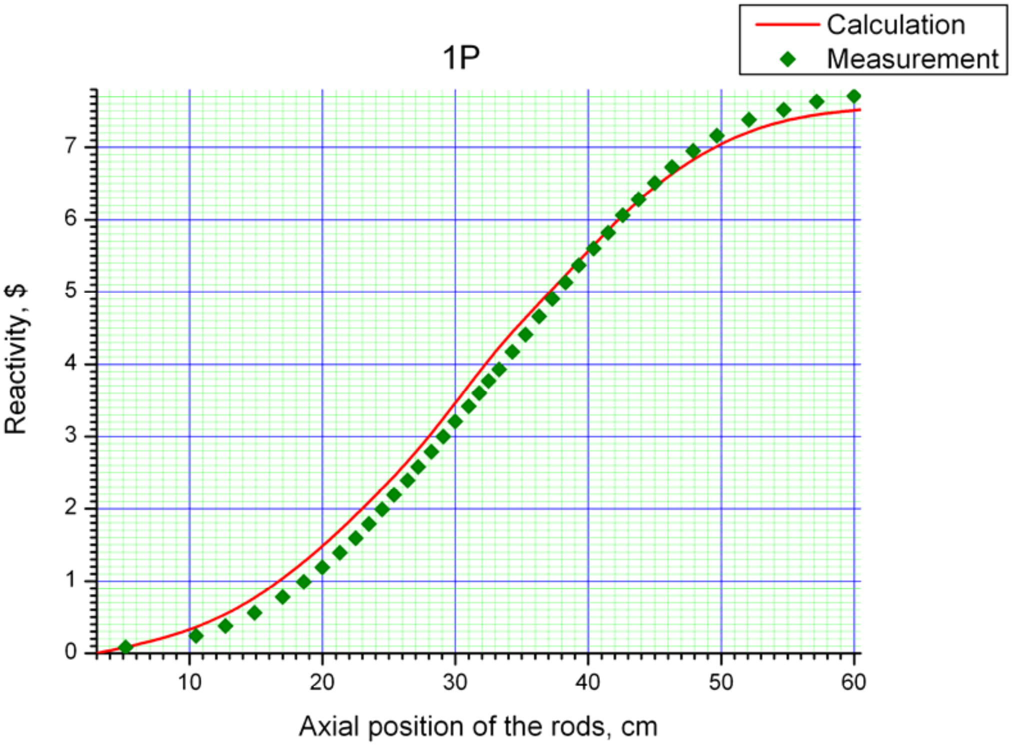


Fig.7. Reactivity worth of the 1P rods

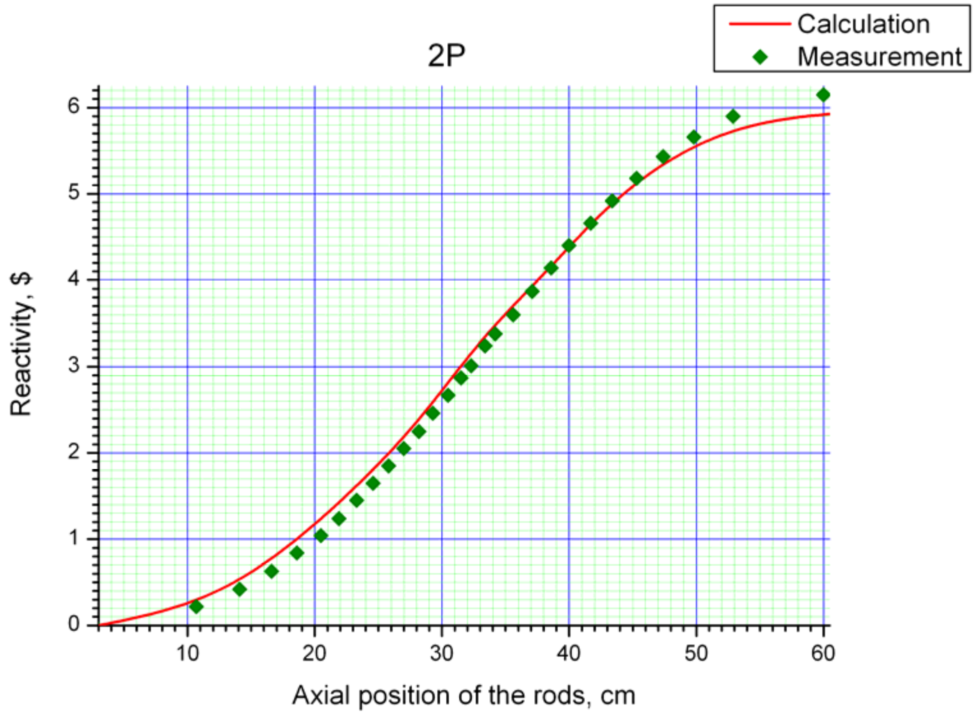


Fig.8. Reactivity worth of the 2P rods

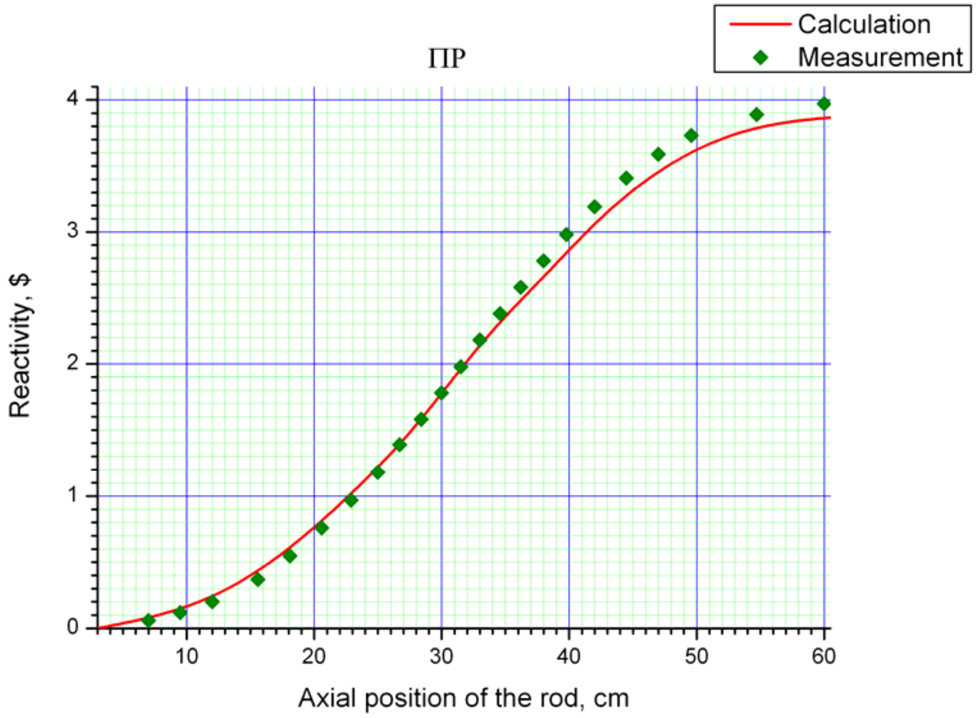


Fig.9. Reactivity worth of the ПР rod

4. Conclusions

The full-core conversion program has been realized for the WWR-M research reactor in Ukraine. To provide safety of the reactor, some limiting conditions for operation were revised. In particular, maximum allowed effective multiplication factor when all control rods are fully in and all safety rods are fully out was decreased from 0.988 to 0.977, and maximum allowed power of the reactor was decreased from 10 MW to 7 MW.

Because of essential decrease of the number of fuel assemblies in the core, a lot of old irradiated beryllium blocks with unknown He-3 poisoning had to be loaded. To provide safety of the core loading, 15 aluminum blocks were loaded for the nonce to decrease excess reactivity. Moreover, neutron flux was being monitored all the time during the core loading to estimate subcriticality and worth of the control and safety rods.

When criticality was reached, excess reactivity and He-3 poisoning were estimated. Since excess reactivity was small because of high He-3 poisoning, the temporary aluminum blocks were replaced by beryllium ones. Then worth of the rods and excess reactivity were measured. By using comparative reactivity measurements, beryllium blocks with highest poisoning were detected and moved far away from the fuel to diminish their influence on the neutronics and thermal-hydraulics parameters of the core. Since such beryllium shuffling changed the worth of the rods and excess reactivity essentially, they were measured again. This measurement was in good agreement with calculation, so safety analysis was validated for the new LEU core.

At this moment, the power of the reactor is 7 MW, while the number of fuel assemblies in the core is 85. With fuel burnup, the number of fuel assemblies in the core will be increased and the reactor power will reach 10 MW.

5. References

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