
Experimental studies of Power distribution in LEU-fuel of the IVG.1M reactor

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Abstract

For the past ten years, the IVG.1M research reactor has been converted from HEU fuel to LEU fuel. Currently, the final stages of conversion (physical and energy start-ups of reactor) are being carried out. One of the tasks of physical start-up was to conduct physical studies of power distribution by radius and height of water-cooled technological channels. Studies were carried out using the activation gamma-spectrometric method based on correspondence between energy release and measured gamma-radiation activity of fission-products or activation products. Study object was activation of indicators from copper wire and fuel element fragments placed in physical mock-up of technological channels with LEU fuel. ENREDI program, based on polynomial interpolation and approximation methods, was used to determine the detailed (in each fuel elements) relative power distribution by radial cross section of fuel assembly. During these experimental studies, relative power distribution over the height and radial cross section of technological channels of each rows, power peaking factors and value of absolute power were obtained. These studies will make it possible to evaluate changes in power profile in the IVG.1M reactor fuel after reducing of the enrichment, and also to check the accuracy of neutronic simulation.

Keywords**:** reactor, power distribution, low-enriched uranium fuel, physical mock-up, gamma spectrometry

1.- INTRODUCTION

As a result of the conversion of the IVG.1M research reactor to low-enriched uranium (LEU) fuel, the fuel composition has changed, which, according to the simulation results [Zhanbolatov *et al.*, 2022; Irkimbekov *et al.*, 2019; Gnyrya *et al.*, 2019], should retain the initial value of the thermal neutron flux density and increase the excess reactivity.

To reduce enrichment, it was necessary to increase the uranium content (^{235}U and ^{238}U) in the fuel by about 5.5 times. This made it impossible to use the same fuel element fabrication technologies used for to high-enriched uranium (HEU) fuel. Therefore, it was decided to use a microheterogeneous U-Zr quasi-alloy [Zaitsev 2017] as the core of the LEU fuel element, while retaining the original drill-like geometry of the HEU fuel element. Thus, the core of an LEU fuel element (see Figure 1) is a zirconium matrix with metallic uranium filaments placed in it, distributed along the axis of the fuel element [Polunin *et al.*, 2019; Irkimbekov *et al.*, 2022].

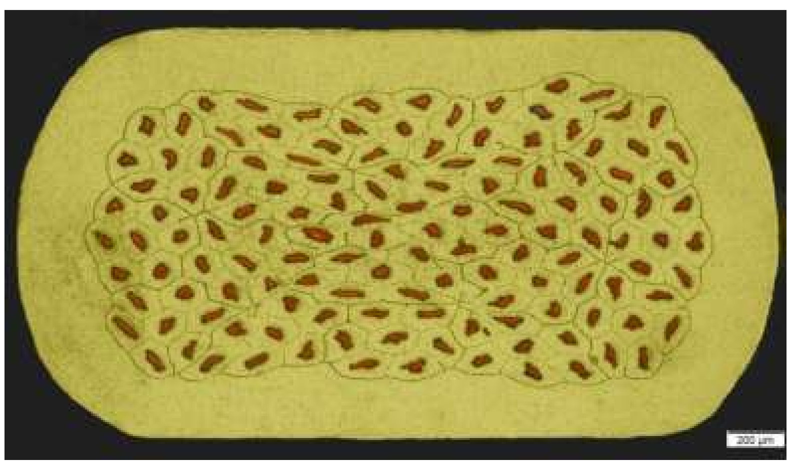


Figure 1.- Cross-section of the LEU fuel element.

Experimental evaluation and confirmation of new characteristics of the reactor with low enrichment fuel is currently underway during the physical and energy startups of the reactor.

Of particular interest is the power distribution in the fuel assemblies and reactor core, since this parameter determines the fuel efficiency and the allowable thermal power of the reactor.

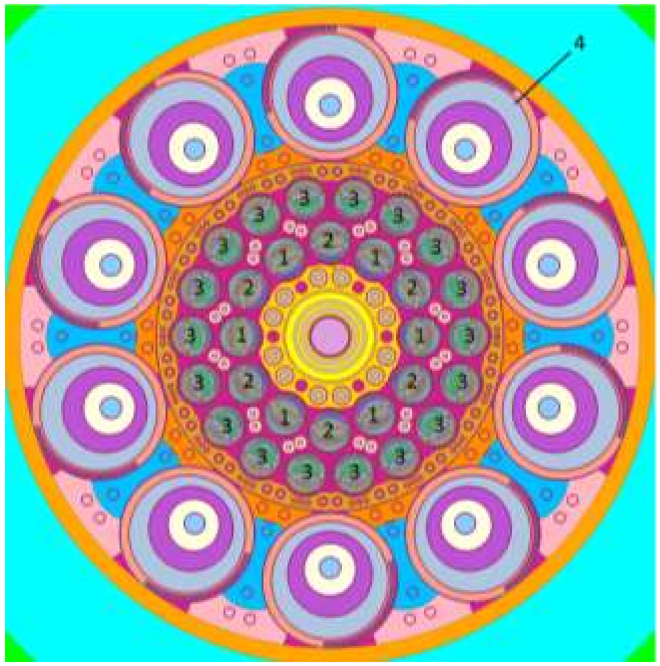
The **purpose** of this work was to experimentally determine the power fields in the LEU fuel of the IVG.1M reactor during the physical start-up using the activation gamma spectrometric method.

The results of the study will confirm the expected power distribution for the IVG.1M reactor after conversion [Irkimbekov *et al*., 2019, Prozorova *et al*., 2013] and complete the comparative analysis of the power profile between HEU and LEU fuel conducted in [Sabitova *et al*., 2022].

2.- MATERIALS AND METHODS

2.1.- IVG.1M reactor

The IVG.1M research reactor is a heterogeneous thermal reactor with a light water coolant and moderator. Beryllium is used as a neutron reflector. The reactor core consists of 30 water-cooled technological channels (WCTC), each containing a fuel assembly. The WCTCs are placed in the reactor core in three rows according to the diagram in Figure 2.



1,2,3 – WCTC's rows; 4 – control drums

Figure 2.- IVG.1M reactor core.

2.2.- Research method

At the physical startup of the reactor, the main methodological tool for determining the power distribution was the activation of fuel/activation detectors, followed by measurement of the gamma radiation activity of the fission/activation products accumulated in them [Giot *et al.*, 2017].

Due to the symmetry of the core, it is sufficient to investigate one WCTC from each row of the core, replacing it with a physical mock-up. Each physical mock-up of a WCTC's fuel assembly (see Figure 3) was equipped with a copper wire indicator to study the axial power distribution and with measuring fuel elements to study the radial power distribution.

Measuring fuel elements (46 pieces) are fragments of fuel elements 100 mm long, located in the measuring section of the physical mock-up in the manner of a lattice with a certain step.

The measuring section is located at the level of 300-400 mm from the bottom end of the physical mock-up and corresponds to the level of the core center.

1 – the measuring section of 100 mm height; 2 – measuring fuel elements (marked with color);
3 – activation indicator (800 or 600 mm high, depending on WCTC's row)

Figure 3.- Contents of the physical mock-up of the fuel assembly of WCTC.

The measuring fuel elements were pre-calibrated for the content of ^{235}U. The calibration was performed by the relative method based on measurements of the natural gamma activity of fuel elements in the range from 80 to 300 keV. Based on the calibration results, fuel element fragments with the minimum deviation from the average value of ^{235}U content for each profiling zone were selected to equip the physical mock-ups.

Table 1 shows the average content of ^{235}U in the fragments of fuel elements of the physical mock-ups of WCTCs of rows 1, 2, and 3.

Table 1.- Content of ^{235}U in fragments of fuel elements of physical mock-ups.

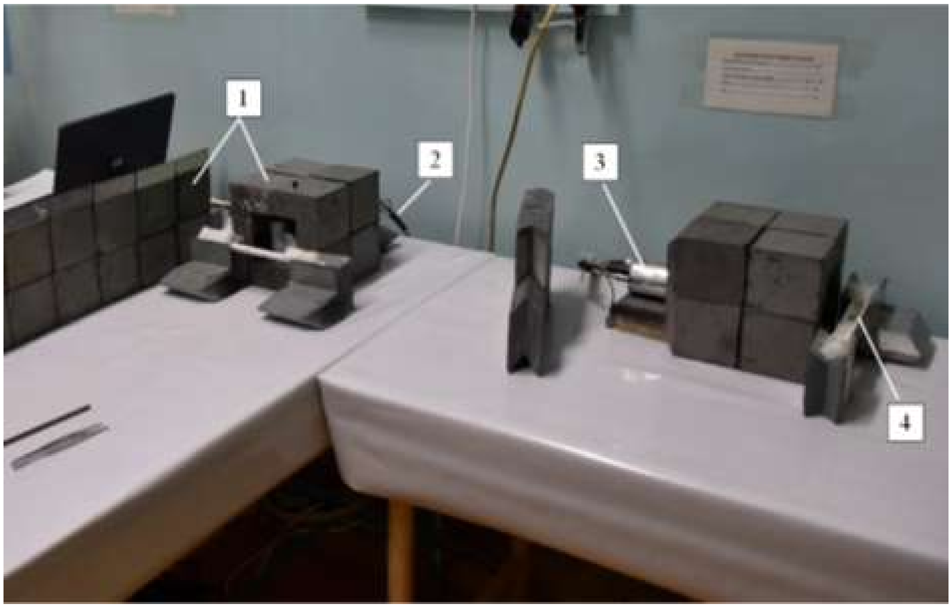
WCTC's row	**Mass of ^{235}U in the fuel element fragment [g]**	
	Central profiling zone	Peripheral profiling zone
1	0.06101	0.05005
2	0.06080	0.04974
3	0.06957	0.06078

2.3.- Measuring equipment

Two scintillation gamma spectrometers with NaJ(Tl) crystals were used for gamma-spectrometric measurements. The sensor of one of the spectrometers was used for a series of measurements, while the other sensor served for parallel measurements of only one sample, chosen as a monitor of the decline in activity of the samples over time. To attenuate the background radiation, the gamma spectrometer sensors were placed in a lead shielding (see Figure 4). To measure the absolute number of fissions in the measuring fuel elements, a semiconductor detector GC1518 was used.

2.4.- Measurement and processing of results

Gamma-spectrometric measurements were carried out after irradiation of physical mock-ups on reactor startups with a power of 400 W and duration of 1000 s each. Table 2 shows the measurement conditions that were constant in the studies of all three physical mock-ups.



1 – lead shielding; 2 – sensor for samples measurement;
3 – sensor for monitor measurement; 4 – sample holder

Figure 4.- Measuring installation.

Table 2.- Measurement conditions.

Measurement object	**Copper indicator (sections of 20 mm)**	**Measuring fuel element**
Registration	total absorption peak of the ^{64}Cu at 511 keV	sum of pulses in the range of 0.2 to 2.0 MeV
Distance from the sensor to the sample	50 mm	100 mm
Exposure time	150 s	100 s
Monitor	central section	central measuring fuel element

The relative value of power in the i-th segment of the copper indicator was determined based on the measurement of the induced gamma radiation intensity by the formula (1):

$$q_i = \frac{I_i}{I_m}, \tag{1}$$

where I_i – gamma radiation intensity of the i-th segment of the copper indicator minus the background value, imp/s;

I_m – gamma radiation intensity of the monitor minus the background value, imp/s.

The ENREDI program [Sabitova et al., 2022] was used to determine the relative power distribution along the fuel assembly cross-section. The program based on the methods of approximation and interpolation allows to obtain power values in all 468 fuel elements by using results of gamma-radiation intensity measurements in the measuring fuel elements. For this purpose, the relative value of power in the i-th measuring fuel element was normalized to the relative content of ^{235}U in it.

To calculate the absolute reactor power value, the number of fissions in the central measuring fuel element of each physical mock-up was measured by the total absorption peak of the ^{140}La (E = 1596 keV). The absolute power was calculated using the formula:

$$P = \frac{1}{\gamma} \cdot \frac{N_f}{t_{irr}} \cdot k_{R1} \cdot k_{H1}, \tag{2}$$

where $\gamma = 3.2 \cdot 10^{10}$ fission/(W·s) – the constant corresponding to a fission rate of ^{235}U at a reactor power of 1 W;

N_f – number of fissions in the central measuring fuel element;

t_{irr} – effective irradiation time, which takes into account the time of achieving a steady-state reactor power level and the time of power drop during reactor shutdown;

K_{R1} – relative radial coefficient that equals the ratio of the power in the measuring section to the power in the central measuring fuel element;

K_{H1} – relative axial coefficient equal to the ratio of the power in the fuel assembly to the power in the measuring section of the physical mock-up.

3.- RESULTS AND DISCUSSION

Figure 4 shows the experimentally obtained axial power distribution of the fuel assemblies of three rows of WCTCs. The distributions are normalized to the average value of power in the fuel assemblies. The zero mark corresponds to the bottom end of the WCTC. For comparison, the power distribution curves for fuel assemblies with HEU fuel are added in Figure 4.

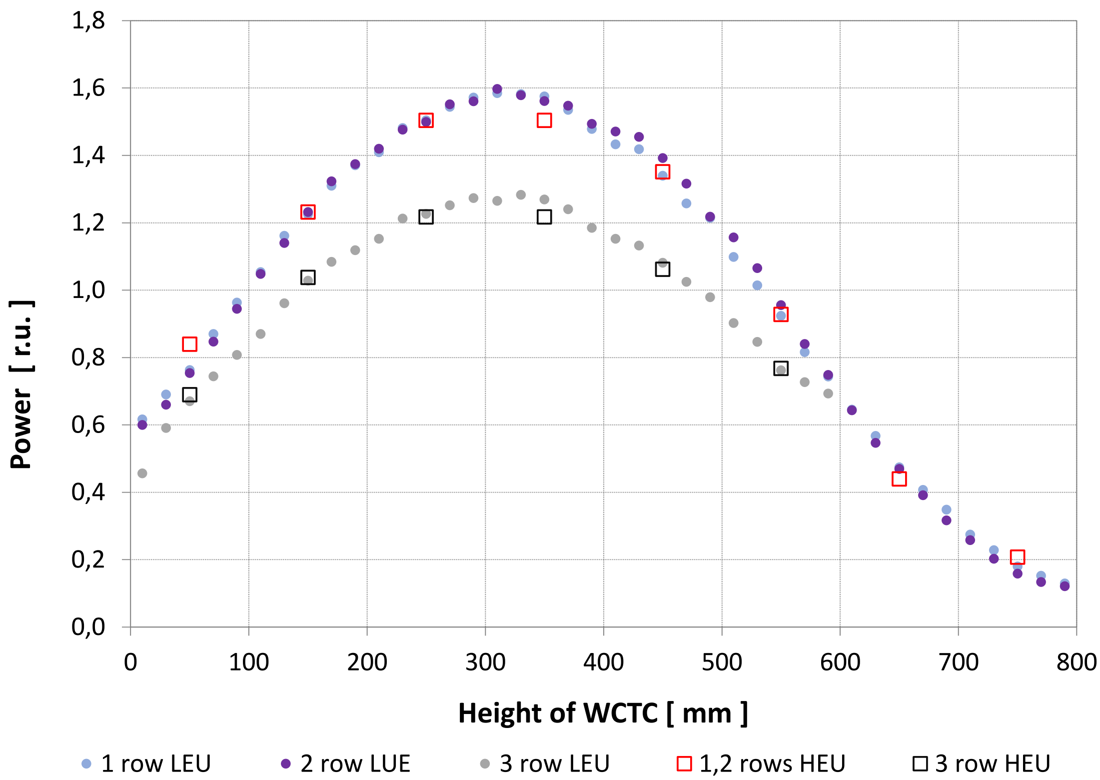


Figure 4.- Relative power distribution along the fuel assembly height.

In general, the axial power distribution curves for HEU and LEU fuel are very close. Since the power distribution coincides with the distribution of thermal neutron flux density, the lower power in the third row of WCTC-HEU and WCTC-LEU (Figure 4) is associated with greater thermal neutron leakage in the periphery zone of the core (zero-order Bessel function law of the first kind).

A more detailed study of the power for LEU fuel shows that the power values drop insignificantly at fuel assembly heights of 390 to 430 mm for each row of WCTCs, which is caused by the presence of a steel lattice in the core construction, which absorbs part of the thermal neutron flux.

The axial power peaking factor is 1.60 for first and second rows of the core, and approximately 1.27 for the third row.

The relative power distribution over the fuel assembly cross section is shown in Figure 5 on the example of the fuel assembly of the physical mock-up of the first row WCTC. Consider the two most representative sections of the fuel assemblies, denoted as "1" and "2" in Figure 5. The arrows indicate the direction from the center of the core denoted as "CC".

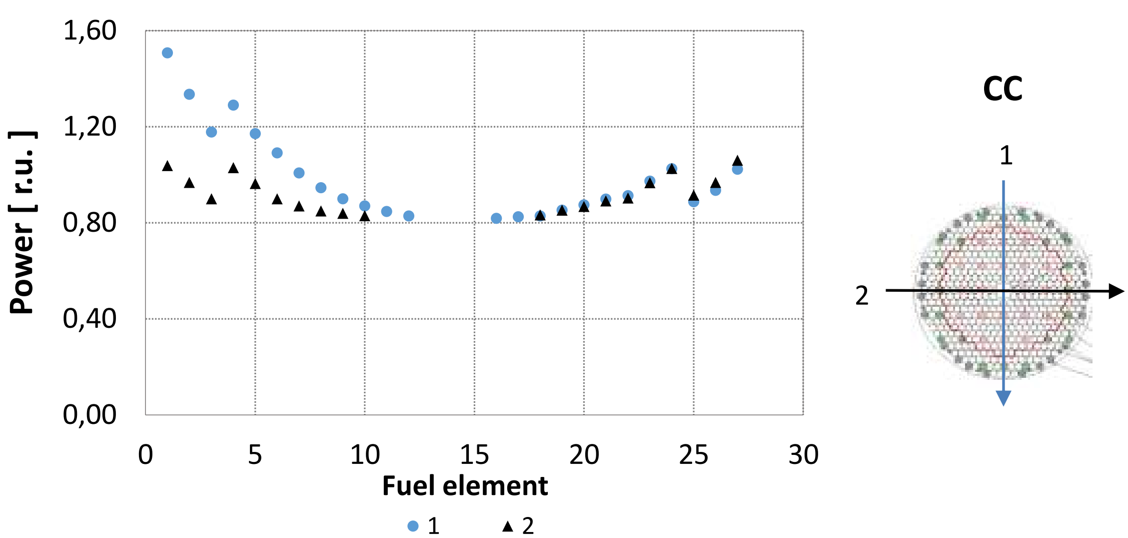


Figure 5.- Relative radial power distribution of the fuel assembly of the first row of WCTC

The power distribution curve 1 differs from the curve 2 in the higher relative power values in the region of fuel elements №1-12, which can also be explained by zero-order Bessel function law of the first kind. Differences in power values between fuel elements №3-4 and №24-25 characterize the change in profiling zones.

The relative radial power distribution of the fuel assembly for the physical mock-ups of first, second and third rows of the core is shown in Figure 6. The arrows indicate the direction from the center of the core denoted as "CC". In general, the power distribution curves for all rows of channels are similar to each other. It is possible that the difference in values in the fuel assembly of the third row is due to the rotation of the physical mock-up of this row during its loading into the physical channel before the irradiation experiment. This is evidenced by the slope of the curve, which differs from the slope of the curves of the first and second rows.

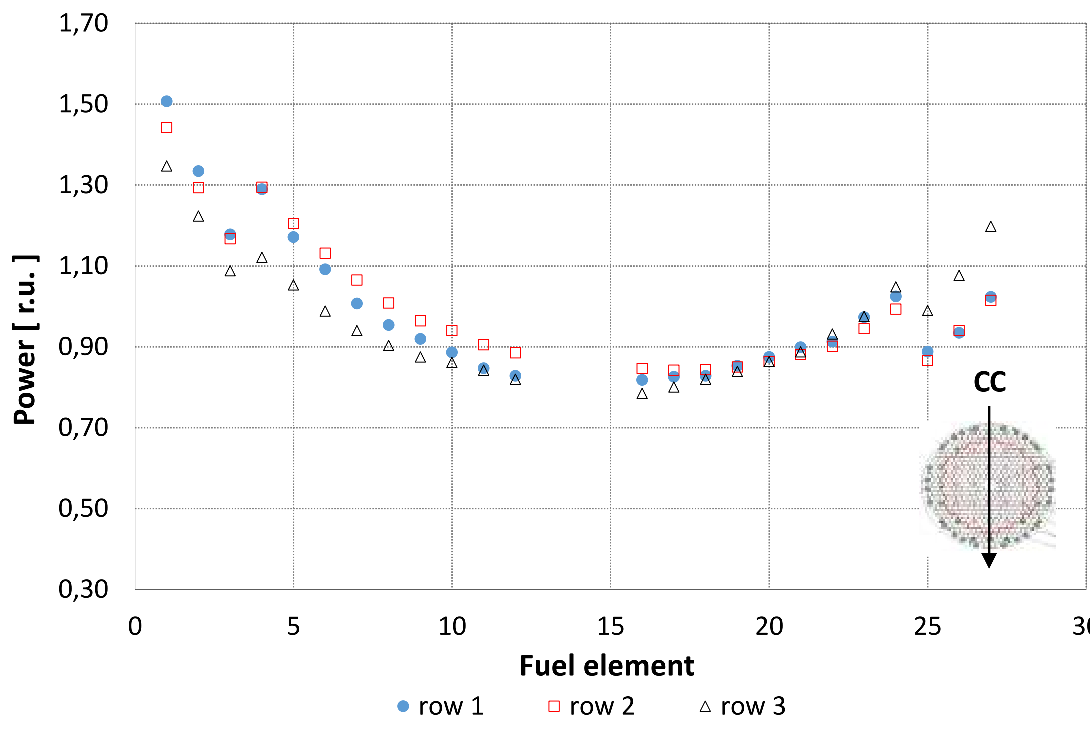


Figure 6.- Relative radial power distribution of the fuel assembly of 1, 2 and 3 rows of WCTC

The radial peaking factor is 1.52 for the first row of WCTC, 1.55 for the second row, and 1.37 for the third row.

Figure 7 shows a comparison of the relative radial power distribution for LEU and HEU fuel by the example of fuel assemblies of the physical mock-up of the third-row WCTC. The arrows indicate the direction from the center of the core denoted as "CC".

In the figure 7, it can be seen that at the periphery of the fuel assemblies the power for LEU fuel is higher than for HEU due to the increased amount of ^{235}U. Also the increased amount of ^{235}U explains the steeper slope of the curve for LEU fuel due to the enhanced internal block effect.

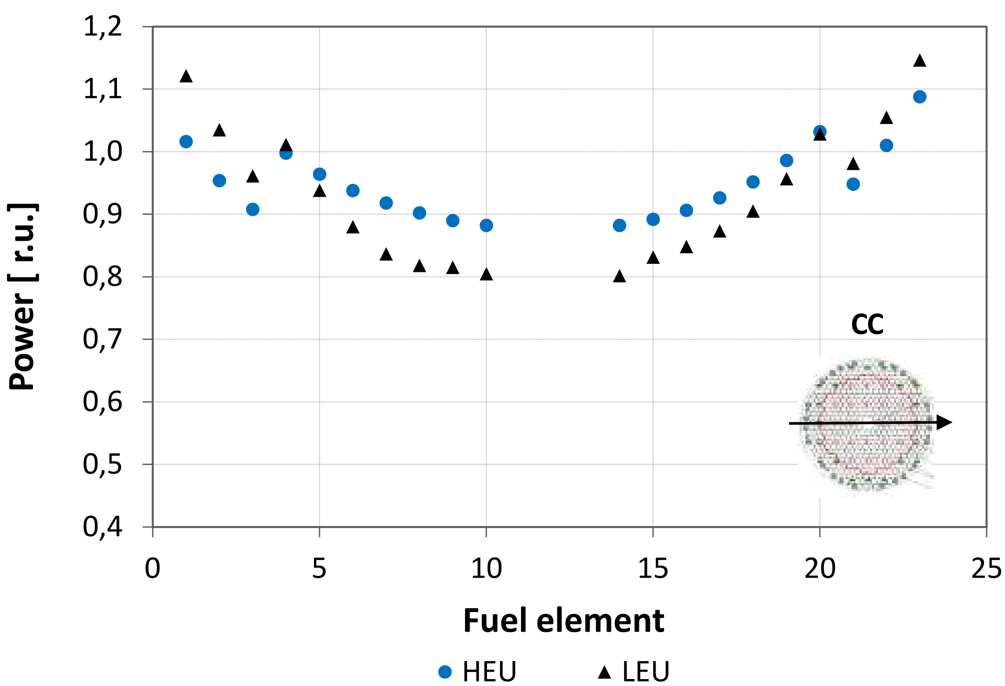


Figure 7.- Comparison of the radial power profile in fuel assemblies with LEU and HEU fuel

According to the results of measuring the number of fissions in central measuring fuel element (MFE), the absolute values of power of the physical mock-ups were obtained, which are presented in the Table 3.

Table 3.- The results of determining the absolute power of the physical mock-ups of the WCTC.

Row of WCTC	The number of fissions in MFE [fissions]	Power [W]
1	$1.89 \cdot 10^{11}$	15.6
2	$1.84 \cdot 10^{11}$	15.0
3	$1.57 \cdot 10^{11}$	12.4

The relative power distributions by rows of WCTCs compared to HEU fuel are shown below in Table 4. All values are normalized by the power value of the channel of the third row.

Table 4.- Comparison of relative power distribution by rows of WCTCs

Row of WCTC	Power [r.u.]	
	HEU-fuel	LEU-fuel
1	1.25	1.26
2	1.18	1.21
3	1.00	1.00

In general, the power distribution in the reactor core before and after conversion remained almost unchanged. At the level of the fuel assembly, in the radial section, one can note a decrease in power near the center of the fuel assembly due to an enhanced internal block effect caused by an increase in the fuel not only of ^{238}U, but also of ^{235}U.

5.- CONCLUSIONS

The paper presents the results of experimental studies of power distribution in the IVG.1M research reactor fuel using the activation gamma spectrometric method and physical mock-ups of the WCTCs. The methodology and conditions of research are described. The axial and radial power peaking factors for the fuel assembly of each row of the core were obtained.

A comparative analysis of the power distributions of LEU and HEU fuel was carried out, which showed insignificant changes. At the level of microdistributions, the lower power in the center of the fuel assembly is caused by the increased absorption of thermal neutrons by the fuel (internal block effect).

The experimental data obtained will make it possible to estimate the allowable thermal power of the channels of each row of the core and will be useful for the purposes of calibrating the measurement channels of the reactor control system, as well as checking the reliability of the neutron-physical modeling.

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