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Definition of Thermophysical Parameters of the IVG.1M Reactor Core with LEU Fuel

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At present, as part of the international program aimed at reducing fuel enrichment in research reactors, the National Nuclear Center of the Republic of Kazakhstan has successfully completed the conversion project for the IVG.1M research reactor. The conversion of the reactor is necessary to contribute to the global efforts of reducing the use of highly enriched uranium fuel, which has the potential for nuclear weapons proliferation. During the conversion, the reactor core was equipped with water-cooled technological channels with innovative metallic fuel using fiber technology. During a series of power startups, the initial experimental data were obtained. The paper examines the thermophysical characteristics of the reactor core before and after the conversion by using both experimental data and computer simulation methods.

The objective of these studies was to investigate the thermophysical effects resulting from the conversion of the IVG.1M reactor to low enrichment fuel, and to determine the thermophysical operating conditions of the converted core.

Introduction

Most research reactors in the world were built in the middle of the 20th century using highly enriched uranium fuel (HEU), which contains up to 90% U-235. HEU fuel enables the development of compact cores with high neutron fluxes, offering versatility in various applications. However, its current usage is considered unsafe due to the potential for nuclear weapons proliferation. In 2010, the National Nuclear Center of the Republic of Kazakhstan initiated the conversion of the IVG.1M research reactor to low-enriched uranium fuel (LEU) as part of the international program aimed at reducing fuel enrichment in research reactors. [1].

The IVG1.M reactor was developed in the late 1980s as an adaptation of the IVG.1 gas-cooled reactor. It involved the incorporation of water-cooled technological channels (WCTC-HEU) and enhancements to the water supply system for reactor and channels cooling. The fuel rods in the WCTC-HEU were consisted of uranium-zirconium alloy with a uranium content ranging from 2% to 4% by weight, enriched to 90% for the U-235 isotope. The reactor successfully operated until 2020 [2].

The IVG.1M research reactor is a heterogeneous thermal nuclear reactor with a light water coolant and moderator, and a beryllium neutron reflector.

The reactor is cooled by a forced circulation system using a single-loop scheme without any heat exchange equipment. The cooling loop incorporates a drain tank with a volume of

1500 m3, which serves as a thermal accumulator. In accordance with its design, the water system includes the main cooling loop and the reactor's emergency cooling system.

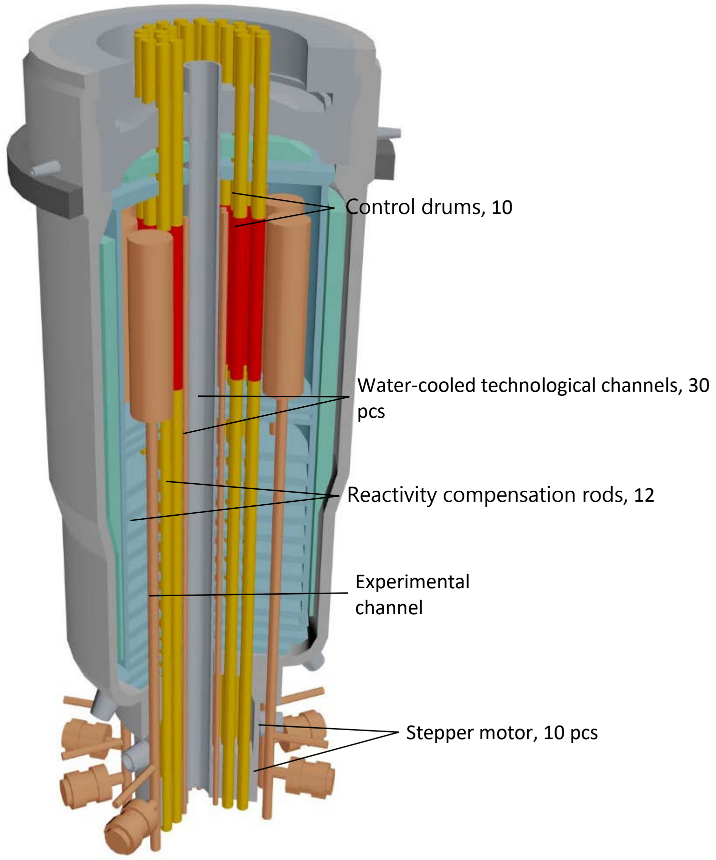

Figure 1. Scheme of the IVG.1M reactor.

When the reactor operates at a nominal power level of up to 10 MW, three 4MSK-10 pumps are utilized. The pumps are started before the power rises to the nominal level. During nominal operation, water is drawn from the drain tank and supplied to the distribution manifold by the three pumps. From there, the water follows four separate paths to provide cooling to the loop channel, a reactor head, a side reflector and the central channel with the core. Subsequently, the water is drained from the reactor through drain pipes and collected into the drain tank.

The reactor core is comprised of 30 WCTC with fuel assemblies (FA). WCTC are located in three rows: the first and second rows consist of 12 channels with 800 mm height, while the third row consists of 18 channels with FA height of 600 mm.

The designed thermal power of the IVG.1M research reactor, including the power of the fuel assemblies being tested in the reactor, is 60 MW. However, due to the incomplete implementation of the reactor cooling system modernization as outlined in the IVG.1M modernization project, the nominal power of the reactor is limited to 10 MW, which is achieved during the power startup phase.

During the conversion of the reactor from HEU to LEU, the aim was not only to preserve, but also improve the operational characteristics of the reactor core. Through computational and theoretical analysis, an optimal arrangement of the core was chosen without making changes to the design of the core elements, but only modifying the composition of the fuel assemblies. The LEU fuel elements are unique and consist of a composition of zirconium alloy E110 with uranium filaments distributed uniformly over the cross section and a zirconium shell. The enrichment level of U-235 is 19.75%. Figure 2 shows the LEU fuel rod cross-section, and Figure 3 shows a general view of the set of rods.

Figure 2. LEU fuel rod cross section.

Figure 3. General view of the fuel assembly.

At the beginning of 2023, work on the conversion of the reactor core was completed in full, the reactor was put into operation, and a series of power start-ups were also carried out. The data obtained in a series of start-ups using modern computational methods make it possible to determine the thermophysical characteristics of the conversion core.

Research methodology

During a standard power start-up, thermotechnical parameters are measured and recorded, enabling the determination of the thermophysical characteristics of the IVG.1M reactor core with LEU fuel.

To calculate the power generated in each channel during the experiments, the water flow rates in each of the WCTC-LEU, along with the water temperature at the core inlet and the water temperature at the outlet of each channel, were taken into account.

The power released in one WCTC-LEU was determined using the following formula [3]:

$$N_i = \left[Q_i \cdot Cp \cdot (T_{out} - T_{in})\right] / 1000000, \tag{1}$$

where N_i – power, allocated in the i-th channel, MW;
Q_i – water flow through the i-th channel, kg/s;
C_p – specific heat capacity of water at average temperature in the channel, J/(kg·°C);
T_{in} – reactor inlet water temperature, °C;

T_{out} – outlet water temperature WCTC-LEU, °C.

Since the registration data do not allow determining the temperature distribution of water and structural elements along the length of the fuel assemblies, computer simulation methods are used for this purpose. The calculation model used in the study is shown in Figure 4. The ANSYS Fluent software package was used for the calculation [4].

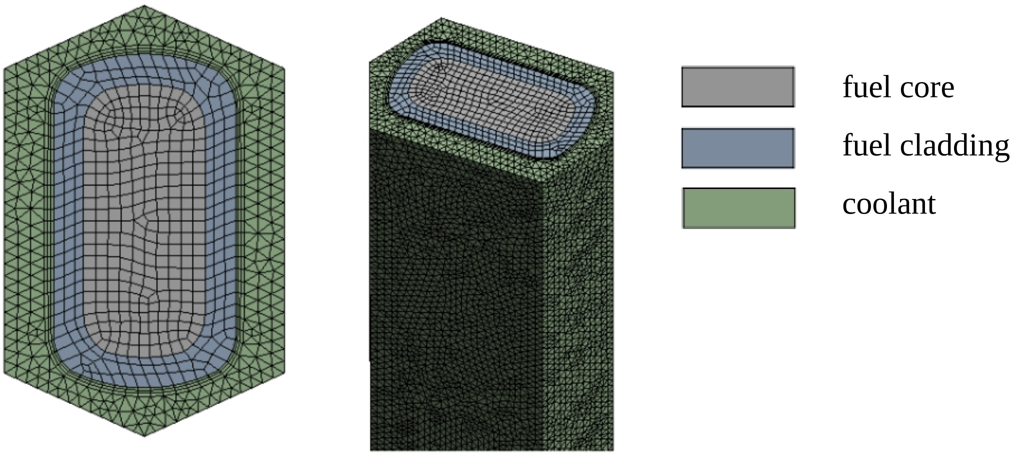

Figure 4. Calculation model.

During the thermophysical calculation, the following boundary conditions were set:

- a symmetry condition is imposed on the side faces of the model;
- for the coolant flow conditions, the flow velocity at the inlet (velocity inlet) and the flow exit (outflow) are used;
- the pressure in the cooling path is assumed to be 1 MPa;
- to account for the uneven energy release along the height of the fuel assembly, a text file with a profile was used to specify the energy release distribution.

The calculated thermophysical model was verified according to the results of experiments, the deviation between the calculated and experimental data is no more than 4°C. For the calculation, the properties of materials are taken from the reference literature [5, 6] and defined as a functional dependence on temperature. The energy release values used in the calculation were taken from the neutron-physical calculation.

During the reactor physical start-up in 2022, experiments were carried out to determine the energy release distribution in fuel assemblies of the 1st, 2nd and 3rd row of WCTC using physical mock-up [7].

Results

From October 2022 to February 2023, a series of nine power start-ups were conducted on the reactor with power ranging from 0.1 to 10 MW. The thermal engineering values obtained during the start-ups were used to determine the thermophysical characteristics of the reactor. The maximum nominal power level achieved during the power start-ups of the IVG.1M reactor was 10.22 MW.

The main parameters of the reactor cooling system obtained during the implementation of power start-ups are presented in table 1.

Table 1. Values of the main parameters of the reactor cooling system

Parameter name	Minimum value	Maximum value
Thermal power of stationary reactor modes, MW	0.01	10.22
Water consumption in the loop channel, kg/s	0.94	1.27
Water consumption through the lid, kg/s	4.7	6.9
Water consumption through the side reflector, kg/s	18.2	20.1
Total water consumption through WCTC kg/s	57.1	59.7
Water consumption at the drain from thermal screens, kg/s	0.55	0.62
Water pressure in the pressure manifold, MPa	1.07	1.12
Water pressure at the outlet from the reactor, MPa	0.91	0.97
Water temperature at the reactor inlet, °C	16.6	26.9
Water temperature under the reactor cover, °C	16.7	32.0
Water temperature at the outlet of the reactor, °C	19.6	68.4

The figure 5 illustrates a diagram of a typical power start-up, where two levels of stationary power of 6 and 10 MW were implemented. In addition, the diagram provides information regarding the water temperature at the core’s inlet and outlet, as well as the total water flow through the WCTC-LEU.

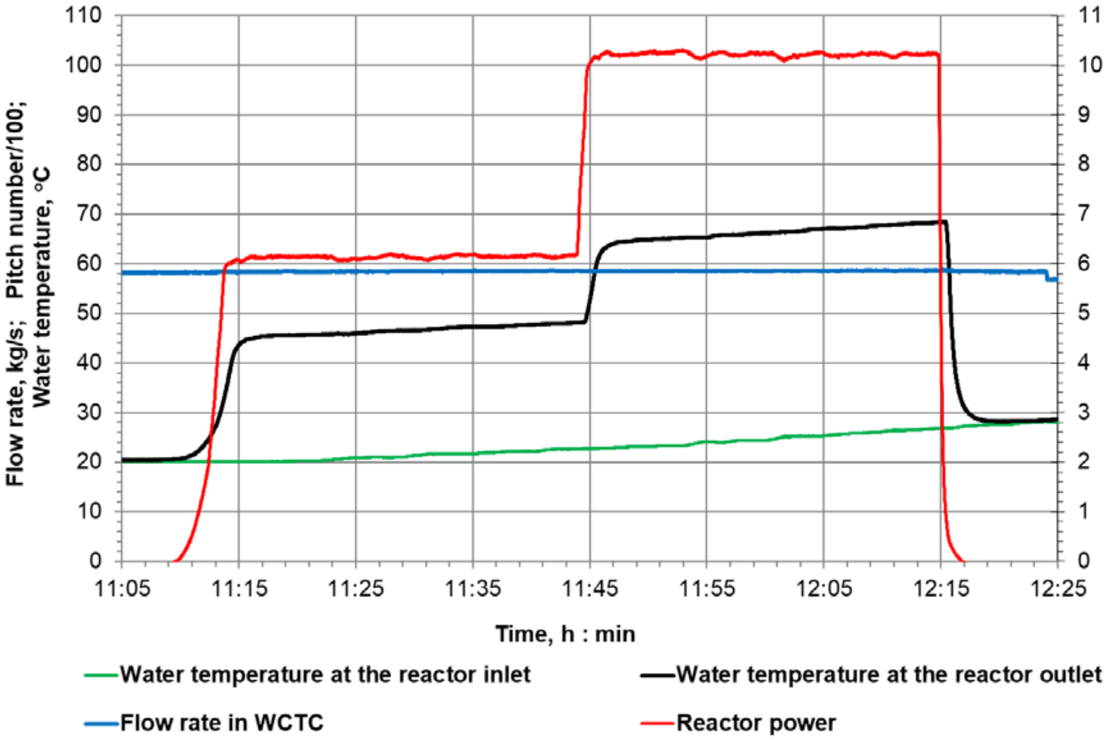

Figure 5. Reactor start-up diagram.

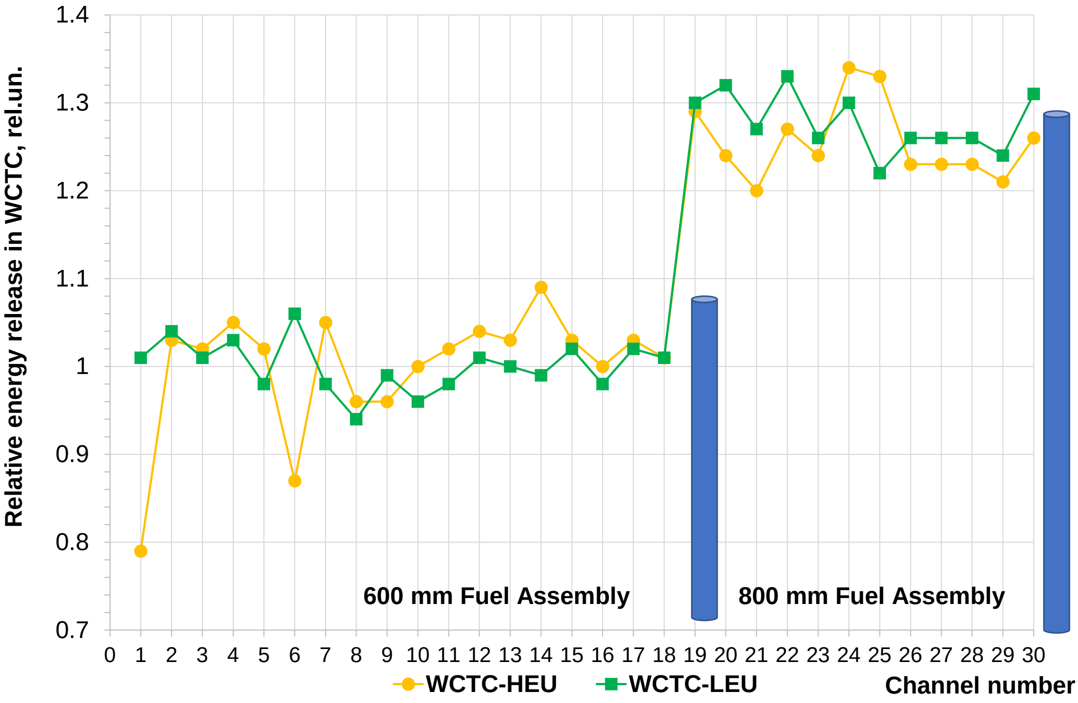

Figure 6. Distribution of relative energy release in the channels of the reactor core.

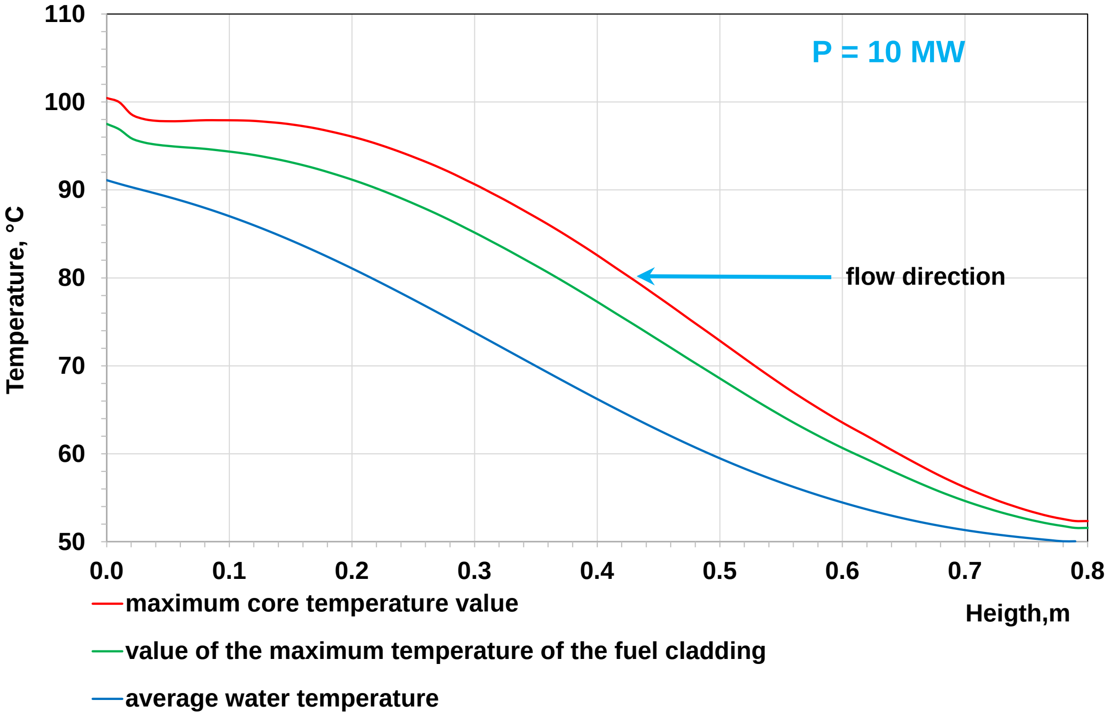

Figure 7. Temperature distribution along the height of WCTC-LEU.

Based on the average thermal power values of WCTC-LEU obtained during a series of start-ups, the relative energy release distribution in the channels was determined. The relative energy release was obtained by normalizing the power value of each WCTC-LEU to the arithmetic mean power value of the channels located in the third row of the reactor core. Figure 6 shows a distribution diagram of the relative energy release in 30 WCTC. For comparison, the diagram also includes the relative energy release values obtained from the results of the reactor start-ups in 2017, when the core was equipped with WCTC-HEU.

Figure 7 shows the calculated temperature distribution along the fuel assembly height for the first row of WCTC, obtained through computer simulation at a reactor power of 10 MW. The water temperature at the inlet to the reactor is assumed to be 50°C, which corresponds to the maximum allowable temperature of the coolant at the inlet to the cooling path according to the passport data of WCTC-LEU.

Figure 8 presents the obtained distribution of energy release along the fuel assembly height in comparison with preliminary neutron-physical calculations performed using MCNP5 and a full-scale model of the IVG.1M reactor with LEU fuel [4].The energy release of the fuel assembly in the third WCTC row is lower compared to the other, due to its shorter length and further position from the reactor core center.

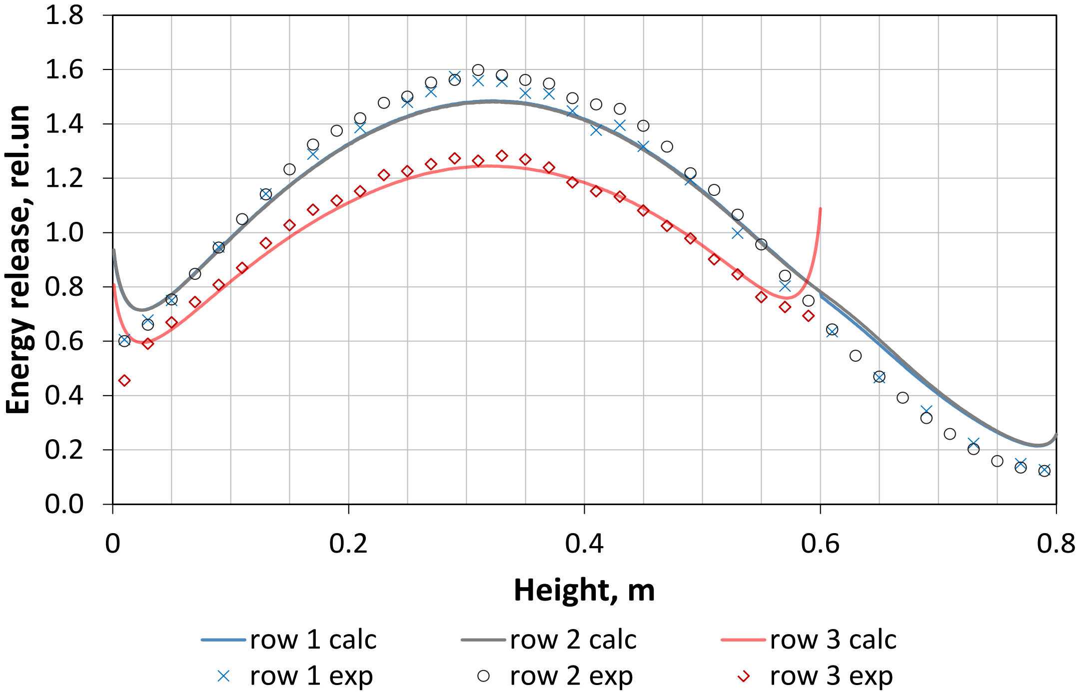

Figure 8. Distribution of energy release in fuel assemblies of each WCTC row according to the data of physical start-up and neutron-physical simulations.

The discussion of the results

During the power start-up stage of the IVG.1M research reactor, studies were conducted to determine the thermophysical effects resulting from the reactor conversion to LEU fuel, and the thermophysical operating conditions of the converted core were determined.

The thermophysical calculation model was verified according to experimental data, and the deviation between the calculated and experimental results was found to be within 4°C.

Based on the average values of the thermal power of WCTC-LEU obtained in a series of start-ups, the relative energy release distribution was determined. An analysis of the distribution of the relative energy release in the channels of the reactor core shows that after the conversion, the energy release in the third row channels became more uniform.

Based on the analysis of the energy release distribution curves obtained from the physical start-up and the neutronic calculations, it can be concluded that the difference between the calculated and experimental data for LEU fuel lies within the measurement error, which indicates the reliability of the neutronic calculation model.

The analysis of the thermophysical parameters of the coolant recorded during the power start-ups, as well as the data obtained through calculation methods, has confirmed that the thermotechnical parameters of the WCTC-LEU during the start-ups corresponded to the values expected for the normal operation of the reactor.

Conclusion

Based on the results of the study, it can be concluded that the conversion of the IVG.1M reactor to LEU fuel successfully preserved the key functional characteristics of the reactor core. The operability of the LEU reactor core was confirmed through a series of reactor power start-ups at the nominal power level as part of the power start-up program. Power start-up is the final stage before the reactor's operational phase, allowing for comprehensive system checks under standard conditions

Acknowledgments

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References

1. Irkimbekov R.A. , Gnyrya V.S., Prozorova I.V., Hanan, Nelson A., Garner, Patrick L., Stevens, John G. The IVG.1M Reactor Conversion: Current State and Prospects. European Research Reactor Conference 2022 Budapest, 6–10 June, 2022, pp 296-299, https://www.euronuclear.org/download/rrfm-2022-proceedings/.
2. E.G. Batyrbekov, V.S. Gnyrya, R.A. Irkimbekov, I.V. Prozorova, A.S. Azimkhanov, A.V. Timonov, Yu.A. Popov, I.K. Derbyshev, A.V. Vdovin, A.P. Maslov N.A. Hanan, P.L. Garner, J.G. Stevens, Physical Start-up of the IVG.1M Reactor with Low-Enriched Uranium Fuel. International Meeting on Reduced Enrichment for Research and Test Reactors RERTR Program, Nuclear Science and Engineering Division at Argonne, https://www.rertr.anl.gov/RERTR42/index.shtml.
3. Mikheev M.A., Mikheeva I.M., "Fundamentals of heat transfer", M.: Energy, 1977.
4. ANSYS release 2021 R2. Documentation for ANSYS Workbench: ANSYS Inc. – 2021.
5. Rivkin S.L., Aleksandrov A.A. Thermodynamic properties of water and water vapor: a handbook. M: Energoatomizdat, 1984, 84 p.
6. Thermophysical Properties of Materials for Nuclear Engineering: A Tutorial and Collection of Data / International Atomic Energy Agency – Vienna, 2008.
7. R.R. Sabitova, I.V. Prozorova, R.A. Irkimbekov, Yu.A. Popov, S.V. Bedenko, A.A. Prozorov, A.K. Mukhamediyev (2022), Methods to Study Power Density Distribution in the IVG.1M Research Reactor after Conversion, Applied Radiation and Isotopes, Vol. 185, 2022, 110259, https://doi.org/10.1016/j.apradiso.2022.110259.
8. Irkimbekov R.A., Zhagiparova L.K., Kotov V.M., Vurim A.D., Gnyrya V.S. (2019) Neutronics Model of the IVG.1M Reactor: Development and Critical-State Verification. Atomic Energy – Vol. 127.– Issue 2.– P. 69–76., https://doi.org/10.1007/s10512-019-

00587-1.