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# Experimental facilities of the WWR-K reactor

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**Abstract**

The WWR-K reactor is a multipurpose research reactor located in Almaty, Kazakhstan. Originally commissioned in 1967, it has undergone several modifications, including seismic safety improvements and a transition to low-enriched fuel, which doubled the thermal neutron flux in the reactor core. Currently, the WWR-K reactor supports a wide range of experimental and applied research activities, including nuclear fuel and structural materials testing, neutron radiography and tomography, neutron reflectometry, and neutron activation analysis. This paper provides an overview of the key experimental facilities available at the WWR-K reactor, including the critical facility, gas-vacuum loop facility, neutron tomography and radiography facility, neutron reflectometry, neutron diffraction, and instrumental neutron activation analysis systems. Each facility is described in terms of its technical parameters, capabilities, and applications in nuclear research, material science, and industrial testing. The reactor's unique combination of neutron sources and experimental setups enables advanced studies in nuclear physics, radiation materials science, and applied engineering.

# Introduction

The WWR-K reactor is a multipurpose research reactor of a tank type with a beryllium reflector, light-water moderator and coolant [1-3]. The design power of the reactor is 10 MW. The height of the core is 600 mm, the diameter is up to 720 mm. The core has forced cooling and a dual-circuit cooling system. The reactor was first put into operation in 1967. The reactor operated without accidents until 1988. In the period 1988 to 1998, work was carried out to improve the seismic safety of the reactor and ensure its safe operation in conditions of increased seismicity. In 1998, the operation of the WWR-K reactor was restarted with an authorized capacity of 6 MW.

Since 2003, a feasibility study has been carried out on the reactor for low-enriched fuel while maintaining cost-effectiveness and experimental capabilities. As a result, a new WWR-KN fuel assembly was proposed on its basis — a compact core that improves the reactor characteristics. In early 2016, successful physical and power starts of the WWR-K reactor on low-enriched fuel were carried out [4-5]. As a result of the conversion, the thermal neutron flux in the center of the core doubled, which became possible due to an increase in the uranium concentration in the fuel elements from 1.2 g/cm3 to 3 g/cm3, the development of thin-walled fuel elements placed in the previous dimensions of the fuel assembly, a decrease in the radial size of the core to obtain the required reactor power, and the facility of side beryllium reflectors. At the same time, several safety-critical systems were modernized, such as the control and measuring system, the actuators of the control rods, the pumps of the emergency spraying and cooling system, the power supply of the emergency cooling system, the radiation monitoring system, etc.

Today, the main current tasks of the WWR-K reactor are: testing of fuel and structural materials of fourth-generation reactors, testing of materials for thermonuclear reactors, production of radioisotopes for medicine and industry. In addition, the reactor is equipped with facilities that expand its experimental capabilities. In particular, there are facilities for neutron activation analysis, neutron radiography and tomography, neutron reflectometry. At the same time, in accordance with the WWR-K reactor development strategy, work is constantly underway to design and commission new facilities, and a neutron diffraction facility is currently being created. The number of experimental facility is growing, the range of tasks and studies using neutron methods is expanding, and this follows the global trend of neutron centers such as ILL [6], BNC [7], NIST [8], FRM [9].This article presents data on experimental scientific facilities including operating on the beams of the WWR-K reactor.

# 1 Critical facility

The critical facility is designed for neutron-physical studies of nuclear reactors of various configurations and all kinds of experimental devices installed in the core [10]. The critical facility consists of a critical assembly, control panel and other infrastructure. According to the IAEA classification, the critical facility is a zero-power reactor. The critical assembly of the critical facility allows simulating the core of various water-cooled research reactors, in particular the core of the WWR-K reactor. The critical facility is used to conduct studies in terms of justifying the safety of research reactors of this type. Various reactor methods are tested, neutron-physical characteristics of experimental devices are studied, calculation codes are verified, and the safety of nuclear-hazardous experiments conducted on the WWR-K reactor is justified.

The specific features of the critical facility include the design of the support grid, which allows assembling the core with an asymmetric configuration, the ability to install displacers, which allow organizing experimental channels with a diameter of 63 to 320 mm. The second feature of the critical facility is the design of the control rod channels. They use small-sized servo drives as actuators, which are mounted directly on the channel. This allows, if necessary, to install the channel in almost any cell of the core grid. The critical assembly is located in special box. The box is separated from the laboratory rooms by two cast-iron doors, each 100 mm thick. An emergency exit is organized from the working platform, which allows evacuation of personnel to a safe place, in the event of an accident, bypassing direct contact with the core.

The box contains the critical assembly tank, the core with the instrumentation and control system channels, experimental channels, ionization chambers and an emergency water drain valve. A valve for filling the critical assembly with water from the reactor reserve tank is installed on the working platform of the tank in Figure 1.

Figure 1: Core of the critical assembly.

The permitted thermal power of the critical assembly, determined by biological protection, is 100 W. The moderator is demineralized water. The side reflector is demineralized water or beryllium. The upper and lower reflectors are water. The critical assembly has six reactivity compensating rods, three emergency rods and one power support rod. All rods have independent drives for the rods movement mechanism. The rods are connected to the drive through an electromagnetic gripper.

When the gripper is de-energized, the rods are introduced into the core under its own weight. Monitoring of the neutron flux density and emergency protection for this parameter are carried out via three independent instrumentations. Monitoring and emergency protection for the rate of increase in neutron flux density are also carried out via three independent instrumentations. The moderator temperature is determined by the temperature of the room (box) where the critical assembly is located. At a maximum power of 100 W, the thermal neutron flux density in the central positions of the core can reach 4.0x109 $n/cm^2 * s$ in Figure 2.

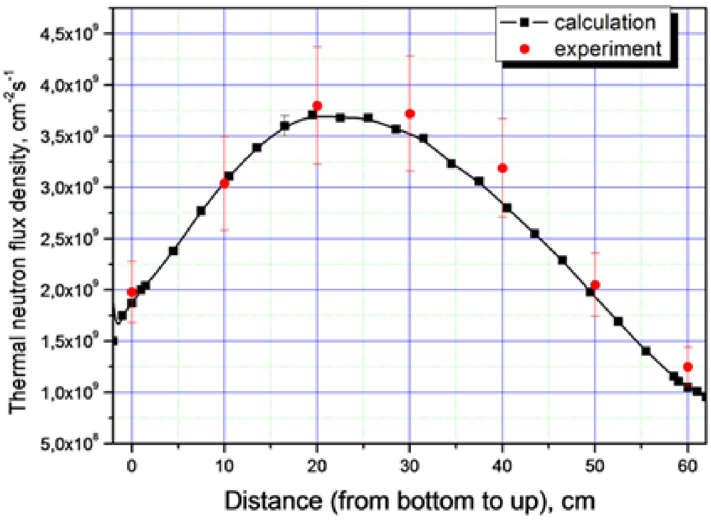


Figure 2: Axial distribution of the thermal neutron flux density in core center.

Over the past 10 years, various experiments have been performed at the critical facility to support the development of nuclear and radiation technologies, among which the following works can be highlighted:

- Experimental testing of an irradiation device designed to equalize the axial distribution of the neutron flux density in the irradiation channel during neutron-transmutation doping of silicon [11].
- Determining the efficiency of the developed irradiation capsule for radiation coloring of semi-precious stones in the WWR-K reactor [12].
- Experimental testing of an irradiation device increasing the production of molybdenum-99 in the WWR-K reactor [13].

In light of the development of nuclear energy in the Republic of Kazakhstan, the critical facility can play an important role in training personnel for the nuclear industry, since it is a good tool for understanding the basics of reactor physics. Practical classes at the critical facility, as well as experimental work for students' diploma projects, can be introduced into the educational programs of universities involved in training personnel for the nuclear industry.

## 2 Gas-vacuum loop facility (GVLF)

The gas-vacuum loop facility (GVLF) is designed to support reactor studies and long-term life tests of products, devices, and samples located in the reactor core in Figure 3. The facility includes: a system for providing vacuum and maintaining it during long-term reactor experiments; tanks for collecting and storing radioactive gases emitted from the object under study, means for evacuating them into the atmosphere upon reaching a certain level of radioactivity; analysis of samples of radioactive gases emitted from the object under study; collection, processing, and storage of thermal and electrical characteristics of the object under study; a device for metered supply of gas or a mixture of gases and retention of the required amount of gas in the test object; temperature control of the object under study located in the reactor core; a dosimetric control system [14-16].

The control system and instrumentation of the gas-vacuum loop facility are designed for operational monitoring and control of the following functions: monitoring of thermal, electrical and thermodynamic characteristics (temperature, current, voltage, pressure) via a PC and control and measuring devices; power supply system; dosimetric monitoring system; public address system; video monitoring system; control circuit for valves, gates, pumps.


Figure 3: Photo of a gas-vacuum loop facility

The GVLF plays an important role in conducting complex in-reactor experiments on the WWR-K reactor. Radiation tests of fuel and structural materials of the HTGR have been and are being conducted using the GVLF. These works are being carried out by order of the Japan Atomic Energy Agency and with the financial support of the ISTC. The GVLF allows testing HTGR materials under their operating conditions such as an inert environment and high temperature. Reactor tests of

TRISO fuel and graphite-containing materials have been performed, which made it possible to determine their reliability and service life [17].

# 3 Neutron tomography TITAN facility

The TITAN facility (Transmission Imaging with ThermAl Neutrons) is a modern neutron system for neutron radiography and tomography, located on the No. 1 horizontal channel of the WWR-K research reactor. TITAN was commissioned in 2019 and is designed for non-destructive investigations of the internal structure of various objects [18-22]. The diagram of the main components of the TITAN facility is shown in the Figure 4.

The TITAN setup consists of several key components: sapphire filters to remove fast neutrons from the beam; an aperture system to collimate the neutron beam and improve image quality; a vacuum tube to minimize neutron losses due to scattering in the air; a rotating table system is used to conduct tomographic experiments; a detector system to register neutron projections; biological protection. The detector system operates on the basis of a scintillation screen and a video camera: neutrons are converted into photons or visible light by a scintillator (6LiF/ZnS:Ag); then the photons reflect off a two-mirror optical system and enter a CCD camera. As a result of these processes, a neutron image of the sample under study is created.

The spatial resolution of neutron radiography systems depends on the characteristic parameter L/D, which is determined by the ratio of the distance L between the entrance aperture of the collimator system and the position of the investigated sample to the diameter D of the collimator's entrance aperture. For TITAN, the distance L is 7 m, and the diameter D of the entrance aperture is 2 cm, which corresponds to L/D = 350. The characteristic L/D parameter can be adjusted from 75 to 1400. Neutron-to-photon conversion is achieved using a 6LiF/ZnS (Ag) scintillator screen with a thickness of 0.1 mm, manufactured by RC TRITEC Ltd (Switzerland). Photon detection is performed using a CCD chip HAMAMATSU S12101. The CCD matrix of photoelements has dimensions of 24.5 mm $\times$ 24.5 mm with a resolution of $2048 \times 2048$ pixels. The field-of-view (FOV) of radiographic images ranges from $50 \times 50\text{mm}^2$ to $200 \times 200\text{mm}^2$. Tomography experiments are conducted using a rotate table, which provides a minimum rotation angle of 0.02° and features a remote control system. The high neutron flux at the sample position enables short exposure times, with image acquisition times as low as 10 seconds per frame. TITAN facility conduct neutron research on archaeological artifacts, allowing their internal structure to be studied without destruction. These studies include the analysis of ancient metal objects, ceramics and other cultural heritage artifacts, the identification of hidden details, restoration interventions and the composition of historical finds. In addition, the research is aimed at detecting pores and cracks in structural materials, measuring the kinetics of moisture penetration into the structure of concrete materials, as well as methodological work to improve the temporal and spatial resolution of the TITAN facility [23-25].

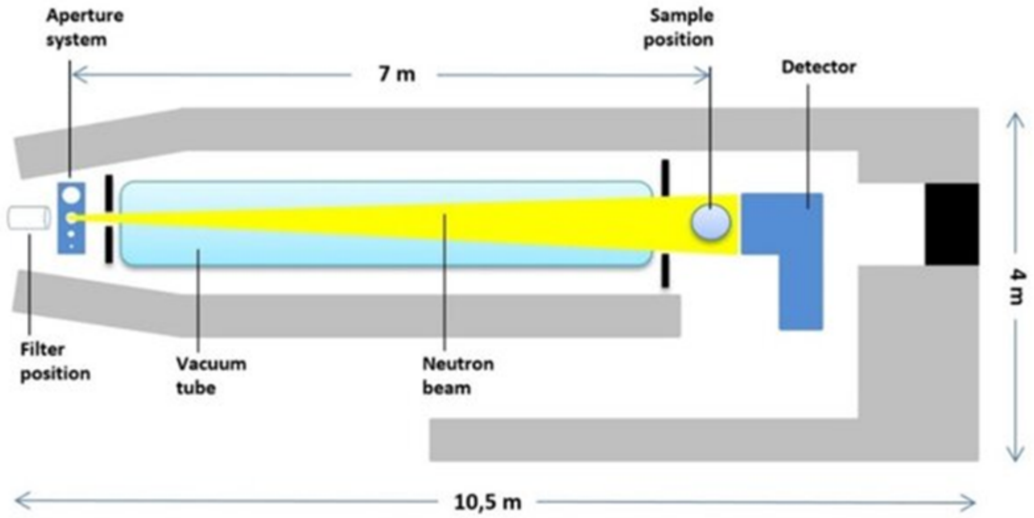


Figure 4: Layout of the TITAN neutron radiography and tomography facility

# 4 Neutron radiography AGAVA facility

The AGAVA setup is operating on the horizontal channel No. 2 of the WWR-K reactor. It is designed to conduct a neutron radiographic experiment for radiation materials, especially for the power generating assembly, parts and units of the fuel assembly.

Neutron radiography as one of the methods of non-destructive testing of material characteristics is similar to radiographic testing methods using other types of ionizing radiation, such as gamma or X-ray radiation. With regard to the fuel assembly, gamma or X-ray radiation is not very effective due to their low resolution, since the fuel assembly contains materials with close specific densities that overlap (shield) each other.

Since the mass absorption coefficient of thermal neutrons of various refractory metals used in Power Generating Assemblies (W, Mo, Nb, Re and their alloys) has an abrupt nature, neutron radiography can effectively separate and determine the change in the geometry of each individual material. The basic diagram of the setup is shown in Figure 5. The setup consists of two collimators (1 and 3). Collimator 1 is a sleeve with outer and axial diameters of 100 and 12 mm, respectively, and a length of 400 mm, filled with paraffin, boron carbide and cast iron shot, which is inserted into the gate of the horizontal channel using a threaded connection. The neutron beam is transported from the horizontal channel to the radiographic chamber 5 in collimator 3, which is a channel 3 m long and with a variable rectangular cross-section of $100 \times 100$ mm and $200 \times 200$ mm at the input and output, respectively, which is mounted in a block filled with paraffin and boron carbide. The second collimator ensures collimation of the neutron beam with an angular divergence of $d/L = 0.003$. The maximum density of the slow neutron flux in the control zone is $4 \times 10^8$ n cm$^{-2}$sec$^{-1}$ .

To reduce the $\gamma$-radiation of the reactor, a lead filter 2 was installed in the path of the neutron beam. Subsequently, in order to further increase the efficiency of the facility, the lead filter was replaced with a bismuth filter with transverse dimensions of $100 \times 100$ mm and a thickness of 80 mm. This replacement of filters reduced

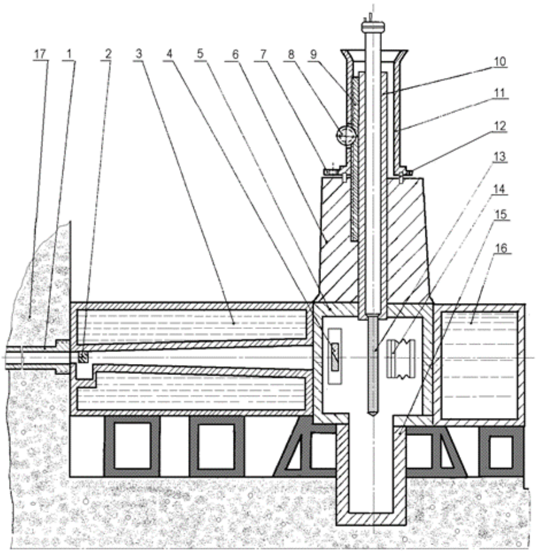


Figure 5: Schematic diagram of the neutron radiography setup:
1 - sleeve of the horizontal channel of the reactor; 2 - bismuth filter; 3 - collimator; 4 - framing diaphragm; 5 – radiographic chamber; 6 – cast iron shield; 7 – rotation electric drive; 8 – vertical movement electric drive; 9 – rack; 10 – sleeve; 11 – upper container; 12 – bearing; 13 – product under study; 14 – filming device; 15 – lower container; 16 – trap (water with added boric acid); 17 – reactor biological shielding.

$\gamma$-radiation by an order of magnitude while simultaneously increasing the neutron flux by approximately 2.5 times compared to the original material. In front of the loop channel 13, a framing diaphragm 4 is installed in the radiographic chamber 5. The loop channel is attached to a movable sleeve 10, which moves in the vertical plane using a rack 9 and an electric drive 8. Rotation of the PC around its own axis is performed on bearings 12 using an electric drive 7 together with the upper container 11. A filming device 14 with a photo cassette and a corresponding detector is installed behind the PC.

As a detector, converter screens are used that can be activated by neutrons, made of dysprosium, indium or gadolinium foils with a thickness of 100, 300 and 100 $\mu$m, respectively. For operation, dysprosium and indium foil are glued to a rigid aluminum plate, and gadolinium foil is glued to a substrate made of polyvinyl butyral film. A neutron image of the controlled object is obtained on X-ray film of the FT-31 or RT-5 type. The best image quality can be obtained on a converter screen made of 100 $\mu$m gold foil. However, the practical application of gold screens is greatly complicated by organizational issues.

The use of neutron radiography in the loop test program allows us to estimate the rate of swelling of the fuel composition of the EGS cores and changes in the geometry of the emitter cladding, record the amount of fuel material removed from the core, determine the shape of the central gas cavity formed as a result of fuel mass transfer processes, short circuits of elements, breaks in electrical circuits, cracks in materials, etc.

# 5 Instrumental neutron activation analysis

Neutron activation analysis (NAA) has long and firmly established itself as a reliable means for solving many scientific and practical problems in various areas of production. The development of this method in Kazakhstan began in 1961 of the last century after the establishment of the Laboratory of Activation Analysis of the Department of Applied Nuclear Physics at the Institute of Nuclear Physics (INP), currently the Laboratory of Nuclear-Physical Methods of Analysis (LNPA) of the Center for Comprehensive Environmental Research (CER). The need for the NAA method was determined by the first President of the Academy of Sciences of the Kazakh SSR, Academician K.I. Satpayev. He noted that the use of the NAA method in the development of the geological industry of Kazakhstan is of great importance: "Activation analysis should contribute to the most rational use of fossils with the most complete extraction of all the useful components contained in them." After the restart of the WWR-K nuclear reactor in 1998, the NAA method was restored. In 2012, a Pneumatic Transport System was manufactured for conducting NAA on short-lived radionuclides [26]. This system was installed on horizontal channel 3 of the WWR-K reactor with a thermal neutron flux density of $4 \times 10^{12}$ n cm$^{-2}$sec$^{-1}$ . The NAA setup is equipped with two coaxial semiconductor detectors, one of which is integrated with the PTS, and a planar detector, which allows for more detailed studies in the low-energy region of the induced activity spectra. The setup is equipped with an automatic sample changer controlled by specialized software in Figs. 6 and 7. The calculation of contents is performed by a relative method (using standard samples) using a special proprietary program [27].

Figure 6: Pneumatic transport system for NAA for short-lived isotopes

At present, a fleet of modern gamma-spectrometric equipment manufactured by Canberra and Ortec is successfully used to perform NAA of various objects based on the updated WWR-K reactor. Samples are irradiated in a vertical peripheral channel with a thermal neutron flux density of 8*1013 n cm-2 s-1. For the first time at the INP, a comparator NAA was developed and introduced into practice for performing analysis using the internal standard method, aimed at determining the elemental composition of various objects [28-32]. The NAA method is included in the scope of accreditation of the Center for Qualification and Evaluation of Radioactive Nuclei for compliance with the international standard ISO/IEC 17025-2019 "General requirements for the qualification of testing and calibration laboratories", accreditation certificate

KZA041DF6215F49D53. Since 2012, with the involvement of the NAA method, it has annually participated in interlaboratory comparative tests (proficiency tests) organized by WEPAL, IAEA and FNCA. Much attention is paid to expanding the areas of NAA application, in particular, in archaeological research [33]. Recently, within the framework of the Targeted Financing Program of the Ministry of Energy of the Republic of Kazakhstan, a method for determining the elemental composition of solid samples by the NAA method for short-lived radionuclides is being developed and prepared for certification for inclusion in the register of the State Scientific Inspectorate of the Republic of Kazakhstan [34-36in]. The use of this method provides a significant expansion of the list of elements to be determined and an increase in the sensitivity of determining individual elements.

Figure 7: Automated section for conducting NAA on medium- and long-lived isotopes

# 6 Neutron reflectometry facility

The ARMAN neutron reflectometer (Almaty Reflectometer on therMAl Neutrons) is a state-of-the-art facility designed to study the structure and properties of surfaces and interfaces on scales ranging from nanometers to submicrometers. The instrument is located on the 4th horizontal channel. Its geometry is designed for scattering in the horizontal plane with a vertically positioned sample. The main areas of research of this setup are studying the structure of thin films on a solid substrate and determining the neutron-optical density of layer materials. It operates in the monochromatic neutron beam mode. Below is a scheme with the main components of the facility in Figure 8.

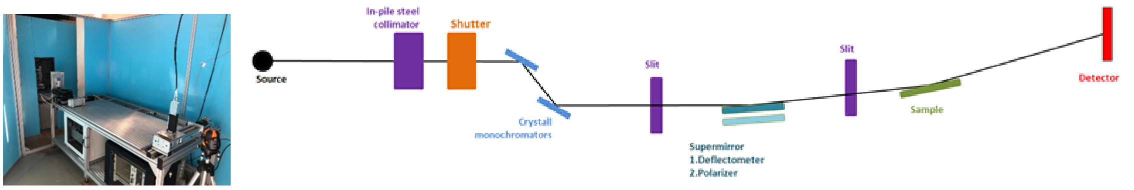


Figure 8: Scheme of the main components of the neutron reflectometry facility.

Pyrolytic graphite crystals are used to produce a monochromatic neutron beam. Due to their structure, they can reflect neutrons of a certain wavelength. They also have low absorption, which makes them effective when working with neutrons. The use of two crystals located at the same angles allows you to maintain the parallelism of the beam relative to the original one. The reflected beam from graphite crystals, in addition to neutrons with the fundamental wavelength, reflects high harmonics ( $\lambda/2$ , $\lambda/3$ , $\lambda$ /4...). Filtering of the fundamental wavelength of the beam from these harmonics is performed using a neutron deflector based on a Ni/Ti supermirror. A supermirror with a controlled critical reflection angle can effectively deflect and filter out unwanted wavelengths, leaving only the fundamental beam. The incident neutron beam is formed by a collimation system consisting of 2 slits located along the beam. This geometry allows for good collimation and reduced beam divergence. The beam size is 1x50 mm2. Neutron registration is performed with a helium-3 gas counter. The registration efficiency of such a counter is 80% at a pressure of 15 atm in Table 2. The setup software, written in the Python programming language, allow to control all the modules of the setup and configure the experimental mode.

| | |
|---|---|
| The beam channel | channel No. 4 - diameter of 100 mm |
| The scattering plane | Horizontal |
| Sample plane | Vertical |
| Double monochromator | Graphite PG (002), wavelength $\lambda = 1.8 - 3$ A |
| . | +(removal filter $\lambda/2$, $\lambda/3$) |
| The size of the neutron beam | 1x50 mm2 |
| The detector | Neutron detector He-3 (efficiency 80%) |
| The collimation | 1-3 mrad |
| Sample positioning | Rotation and lateral movement |
| Potential expansion | Polarizer, spin-flipper, PSD |

Table 1: Parameters of the neutron reflectometry facility.

# 7 Neutron difraction

At present, within the framework of the development of scientific and experimental instruments of the WWR-K research reactor, a tool for the neutron powder diffraction method is being created. This method is one of the popular methods for determining the phase structure of materials and is based on the scattering of neutrons by atomic lattices. As a complementary method to X-ray diffraction, neutron diffraction allows studying the arrangement of atoms in crystals. However, it has a number of advantages over X-ray diffraction such as: sensitivity to light elements, lack of charge, sensitivity to magnetic moments. Today, this method is successfully used in various fields of material science, condensed matter physics, chemistry and biology to solve problems such as the study of crystal structures and analysis of magnetic materials, the study of polymers and liquids, as well as the study of deformations and residual stresses.

The optimal combination of the neutron beam of channel 5 at the WWR-K research reactor, the focusing unit of monochromators, and the unique multidetector system of the diffractometer under development will allow obtaining high-quality data on the crystalline and magnetic structure of compounds. Neutron structural studies will allow identifying the structural mechanisms of formation of various functional states: ferroelectric, magnetic, spin, etc., in complex functional materials, the conditions for the formation of a particular physical phenomenon or effect. The conceptual model of the main units of the new diffractometer is shown in Figure 9.

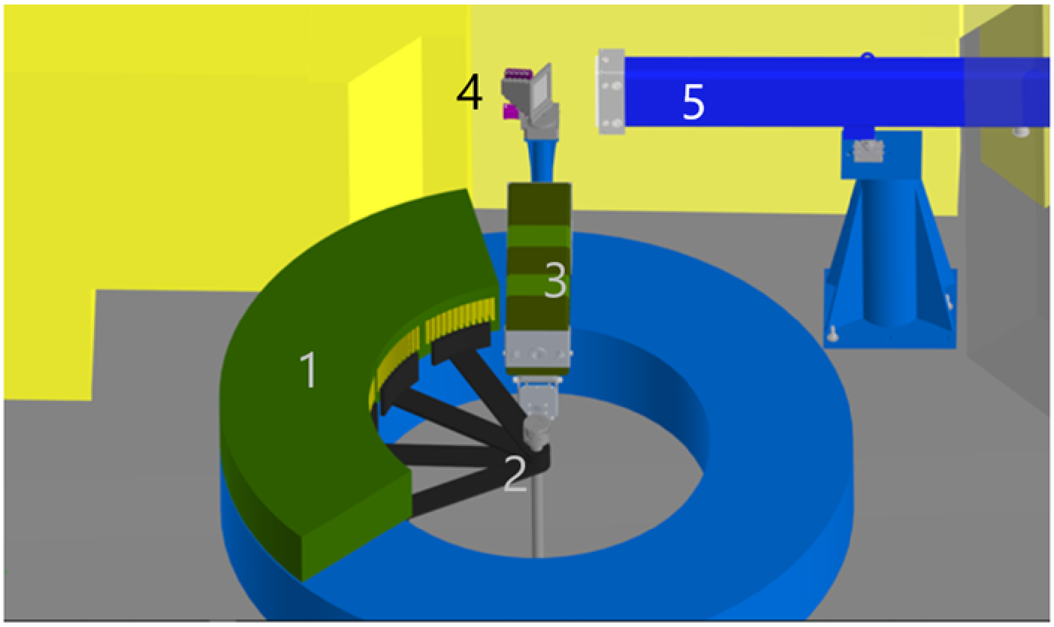


Figure 9: Conceptual model of the new diffractometer at the WWR-K reactor. 1-multidetector system, 2-sample mounting module, 3-collimator system, 4-focusing monochromator unit with germanium single crystals, 5-neutron guide section for extracting the neutron beam from the beam exit from the gate.

The new setup will be created on channel 5 of the WWR-K reactor. Beam monochromatization will be performed using a germanium crystal with a reflection plane of 511, the angle of the incident and scattering beam from the crystal is 90 degrees. The divergence of the incident beam will be adjusted by a Soller collimator. The distance between the crystal and the sample will be 2 m, while the detector is located at a distance of 1 m from the sample. The detector system is assembled from 32 helium-3 gas counters and is compactly located on a rotating table. Radial collimators are inserted in front of each counter to reduce the background and improve the quality of the diffractogram.The expected parameters are shown in Table 2.

The optimal combination of the neutron beam of channel 5 of the WWR-K research reactor, the focusing unit of the monochromators and the unique multi-detector system of the diffractometer under development will allow obtaining high-quality data on the crystalline and magnetic structure of compounds. The new diffractometer should provide the possibility of routine study of wide classes of materials with normal neutron scattering lengths and average values of the magnetic moment at room temperatures with good resolution. The corresponding configuration makes the parameters of this diffractometer comparable with the most modern specialized devices in other leading neutron scattering centers [37-38].

# Conclusion

The WWR-K reactor serves as a vital platform for nuclear research and applied science, offering diverse experimental capabilities that support fundamental and

| | |
|---|---|
| Thermal neutron flux (n/cm2/s) | 1*107 |
| Distance: source - Monochromator<br>Monochromator-Sample<br>Sample-Detector | 5.0 m<br>2.0 m<br>1.0 m |
| Wavelength | 0.9-1.54A |
| Resolution | 0.001-0.01 |
| Volume of sample, mm | 100 |
| Experiment time | 1-5 h. |

Table 2: Expected specifications of the new diffractometer

applied studies in neutron physics, material science, and nuclear engineering. The reactor's transition to low-enriched fuel has significantly enhanced its neutron flux, allowing for more precise and efficient experiments. The experimental infrastructure, including neutron radiography and tomography, neutron activation analysis, neutron diffraction, and neutron reflectometry, provides researchers with state-of-the-art tools for studying nuclear materials, investigating historical artifacts, and improving industrial processes. Future developments, such as the planned neutron powder diffraction facility, will further expand the reactor's research potential. The continuous modernization of the WWR-K reactor and its experimental facilities underscores its importance in advancing nuclear science and technology both in Kazakhstan and internationally.

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