ABSTRACT

of the thesis for the degree of "Doctor of Philosophy" (Ph.D.)
in the specialty "6D060500 - Nuclear physics"

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Study of neutron-physical characteristics of the core of the WWR-K research reactor with a side beryllium reflector

The dissertation work is devoted to the theoretical and experimental study of the neutron-physical characteristics of the research reactor WWR-K with a side beryllium reflector. The change in the neutron-physical characteristics of the WWR-K reactor is shown with the gradual replacement of the neutron water reflector with beryllium.

The relevance of the topic. Undoubtedly, the role of research reactors in the modern world is great, they are widely used in science and technology. For example, testing of structural materials and fuel for nuclear and thermonuclear reactors, production of medical and industrial radioisotopes, neutron transmutation doping of silicon, radiation staining of semiprecious stones, neutron activation analysis, nuclear medicine, education and training. However, the research reactor is a nuclear installation with a potential nuclear and radiation hazard, therefore, the scientific community faces an important task, not only for wide application, but also, first of all, to ensure its safe operation.

According to the specific requirements of the IAEA Code of Conduct on the Safety of Research Reactors, the organization operating the research reactor must ensure its safety at all stages of the life cycle. The gradual replacement of the neutron water reflector with beryllium belongs to the stage of modernization of the core. Such modernization will reduce neutron leakage from the side surface of the core and improve its critical characteristics, which will undoubtedly affect the neutron-physical characteristics of the reactor. In addition, loading beryllium into the reactor core is a nuclear-hazardous operation, which requires forecasting changes in the neutron-physical characteristics of the reactor to ensure its safety. The modern development of calculation methods and programs allows for sufficiently detailed and accurate calculations, which makes them one of the main scientific research methods. Especially, it is possible to note numerical modelling methods based on the Monte Carlo method, which allow for precision calculations.

The relevance of this work is to obtain new calculated and experimental data on the change in the neutron-physical characteristics of the reactor core of the WWR-K with low-enriched fuel with the gradual replacement of the neutron water reflector with beryllium, which are necessary for the analysis and justification of the safe operation of the reactor.

The purpose of this thesis is to determine the effect of the gradual completion of the lateral beryllium reflector on the neutron-physical characteristics of the core of the research reactor WWR-K.

The objectives of the study. To achieve the goals, the following tasks were set:

– development a computational model of the WWR-K reactor and to determine the main neutron-physical characteristics of the WWR-K reactor;

– investigation the dynamics of changes in the main characteristics of the WWR-K reactor, such as the kinetic parameters of the core, the efficiency of the operating organs of the control and protection system, reactivity, temperature reactivity coefficients and neutron flux density during the gradual replacement of the water neutron reflector with beryllium;

– investigation of the effect of uranium burnout in fuel and the accumulation of poison nuclei in a beryllium reflector on the neutron flux density in the irradiation channels of the WWR-K reactor.

– conduction of the experimental studies of the main neutron-physical characteristics of the WWR-K reactor and compare the results obtained with the calculated data.

The object of the study is the core of the WWR-K research reactor with low-enriched fuel and a side beryllium reflector.

The subject of the study is the neutron-physical characteristics of the core of the WWR-K reactor with low-enriched fuel and a side beryllium reflector.

Research methods. Neutron-physical characteristics were studied using the following methods: numerical Monte Carlo method - for mathematical modeling of the research reactor WWR-K and determination of its neutron-physical characteristics; activation foil method - for experimental measurement of neutron flux density in the irradiation channels of the reactor WWR-K; calculation of reactor reactivity using a point model. Experimental modeling of the core of the reactor WWR-K on a critical stand.

Scientific novelty.

1. The calculated and experimental dependence of the influence of the beryllium neutron reflector on the neutron-physical characteristics of the core of the reactor WWR-K with low-enriched fuel is obtained.

2. Calculated data on the accumulation of poisoner nuclei in a beryllium reflector and their effect on the neutron-physical characteristics of the core of the WWR-K reactor were obtained.

3. A computational model of the WWR-K reactor with a heterogeneous description of the core elements and a lateral beryllium neutron reflector has been developed, the reliability of which has been confirmed by the results of benchmark experiments and real experimental work on the WWR-K reactor.

Theoretical and practical significance of the study.

The theoretical significance of the study is to establish the dependence of changes in the neutron-physical characteristics of a light-water reactor with the gradual replacement of a water neutron reflector with a beryllium one.

The practical significance of the study is as follows:

1. Calculated data on fuel burnout in the fuel assembly and the reactivity reserve of the core were used to select the optimal algorithm for fuel assembly overloads in order to create the necessary working reactivity reserve.

2. The energy distribution of neutrons in the irradiation channels of the WWR-K reactor for each configuration of the core was used to plan scientific and applied work at the WWR-K reactor.

3. The obtained neutron-physical characteristics of the core were used to justify the operational limits and conditions of the WWR-K reactor during its safety analysis.

4. The results were applied to substantiate the safety of operation of the WWR-K reactor. Act on the implementation of the results of the dissertation No. 34-02/11 dated 27.01.2022.

The main provisions to be defended.

1. A full annular beryllium neutron reflector in the WWR-K reactor improves critical characteristics and reduces neutron leakage from the side surface of the core, in particular, the critical mass of uranium-235 decreases from 6258 g to 4335 g and the density of thermal neutron flux in peripheral irradiation channels increases almost twice.

2. For 952 effective days, the maximum accumulated atomic concentration of helium-3 and lithium-6 poison nuclei in the beryllium reflector of the WWR-K reactor was 9.14×10^{16} poisons/cm3 and 2.15×10^{18} poison/cm^3, respectively, which leads to a decrease in the reactivity margin by 0.4% Δk/k.

3. The maximum standard deviation of the neutron-physical characteristics of the WWR-K reactor with a full lateral beryllium neutron reflector obtained on the basis of the Monte Carlo solution of the neutron transfer equation from experimental data is 11%.

Personal contribution of the author. The author was directly involved in the development of a detailed computer model of the core of the WWR-K reactor in the MCNP6 environment, which allows, from campaign to campaign, to determine: (a) the nuclide composition of the fuel composition (uranium burnout, plutonium production, fission products formation) for each fuel assembly of the WWR-K reactor core, (b) the efficiency of the working bodies of the control system, (c) the neutron flux density in the energy intervals required for researchers, (d) energy release in each fuel assembly. The author was directly involved in experimental work at the WWR-K reactor and was engaged in processing the data obtained. He summarized the information received and performed a systematic analysis of the results of the study.

The reliability and validity of the results obtained are confirmed, first of all, by the current practice of operating the IR WWR-K using the results obtained by the applicant and publications in publications recommended by the Committee for Quality Assurance in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan and indexed by the international databases SCOPUS and Web of Science, as well as in the proceedings of international scientific conferences near and far abroad. Also, the reliability of the results obtained in the dissertation is ensured by the fact that the research was carried out using widely recognized theoretical and experimental methods and techniques, as well as using modern equipment that has passed metrological certification. The mathematical model of the WWR-K reactor used in the dissertation was confirmed by numerous experiments and many years of trouble-free experience in the operation of the WWR-K reactor. The results obtained do not contradict generally accepted concepts and principles.

Work approbation. The research results presented in this paper were reported and discussed at:

– International Conference of Students and Young Scientists "FARABI ALEMI" (April 9-12, 2018, Almaty, Kazakhstan).

– The 14th International Scientific and Practical Conference on Nuclear Energy "Safety, Efficiency, Resource", (October 1-6, 2018, Sevastopol, Russia).

– II International Scientific Forum "Nuclear Science and Technology" (June 24-27, 2019, Almaty, Kazakhstan).

– IX International Scientific and Practical Conference "Actual problems of the uranium industry" (November 7-9, 2019, Almaty, Kazakhstan).

Publications.

Based on the materials of the dissertation, 10 works were published (6 articles, 4 theses), 3 of which were published in journals recommended by the Committee for Control in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, 3 articles with a non-zero impact factor in journals indexed by Thomson Reuters and in Scopus.

The relationship of this work with research projects. The dissertation research was carried out within the framework of the scientific and technical program "Development of nuclear energy in the Republic of Kazakhstan" on the topic 01.04 "Conversion of the core of the reactor WWR-K to low-enrichment fuel" (2015-2017) and the scientific and technical program of the Ministry of Education and Science of the Republic of Kazakhstan No. BR05236400 "Applied scientific and technical research in the field of radiation materials science, analytical chemistry and nuclear safety on the basis of the WWR-K research reactor" on topic No. 2.1 "Investigation of experimental capabilities and conditions for ensuring nuclear safety of the WWR-K research reactor with low-enriched fuel and beryllium reflector" (2018-2020).

The volume and structure of the thesis. The dissertation is written on 113 pages of typewritten text and consists of an introduction, 3 sections, a conclusion and a list of sources used, contains 44 figures and 23 tables, 2 appendices. The list of sources used includes 87 titles.