ABSTRACT
Of the thesis for Philosophy Doctor Degree (PhD)
in specialty 6D072300 – "Technical physics"
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Investigation of parameters of fuel elements in irradiating experiments in a pulsed graphite reactor

The thesis presents results of the development of new methodological approaches for preparing and conducting tests on the IGR pulsed graphite research reactor, providing an increase in the quality of prediction and implementation of the specified parameters of reactor irradiation devices testing to study the processes accompanying a severe accident of a nuclear reactor with core meltdown.

Relevance of the research subject

Today, there is a high demand in the world for experimental studies of the behavior of new types of reactor fuel in transient and accident operating modes. The most representative experimental data can be obtained under dynamic test conditions in research reactors. There are several research reactors in the world on which dynamic tests can be carried out; however, all of them provide an opportunity to study assemblies consisting of only a few fuel elements.

IGR reactor neutronic characteristics provide the opportunity to study fuel elements behavior in transient and accident operating modes on different types of reactors consisting of dozens of fuel elements, containing up to 8 kg of uranium dioxide. The methods developed and adapted to the experimental conditions applied to dynamic tests make it possible to provide a qualitative determination of the parameters of the tested fuel.

The main task of the experimental programs currently being implemented is to simulate the conditions of formation and provide controlled movement of the core melt, as well as to study related processes in order to develop recommendations for improving the safety of new generation power nuclear reactors. At the same time, the rate and complication of experiments on the IGR reactor are continuously increasing. On the part of the developers of new types of fuel, additional requirements are imposed on the detailing of the processes occurring at the stages of development of a severe accident with core melting, their calculated prediction and provision of conditions for the most accurate implementation of the specified parameters at all stages of the experiment, which is a rather difficult task for dynamic tests.

In particular, the task is to improve approaches ensuring a given energy release in fuel assemblies, which characterizes the conditions of its actual operation in a power reactor; full consideration of the factors leading to an increase in pressure in the cavities of the irradiation device ensuring the safety of the experiment; determination and establishment of a power diagram in the test object that provides a given sequence of events of the experiment.

Reconstruction of the volume energy release in an assembly that corresponds to the maximum energy release in the conditions of real operation in a power reactor is a specific requirement for conducting experiments in an IGR reactor with model fuel assemblies. This makes it possible to model in detail the processes occurring inside the fuel assembly during the development of an accident. In this regard, development and substantiation of approaches to the creation of the specified characteristics of the neutron field in the test object in terms of ensuring a given non-uniformity of energy release in fuel assemblies is an important task of methodological support for the IGR reactor tests.

In addition, when designing irradiation devices, a multiple margin of safety of load-bearing structures to the effect of internal loads is ensured, which is associated with the difficulty of accurately determining its numerical values. This safety margin is formed due to a significant increase in the force barriers of the irradiation devices. This leads to a decrease in the useful space for placing fuel elements and fuel assemblies in it, a decrease in the neutron flux reaching the fuel, and the resulting limitation of the possibility of ensuring the specified test conditions. In particular, previously during the IGR test preparation, the pressure increase due to the release of impurity gases from the molten nuclear fuel into the cavity of the irradiation device was not taken into account. The presence of impurity gases is due to the technology of manufacturing fuel pellets. Determining the volume of gas sold from pellets of tested fuel assemblies in modes with fuel melting is an important task, the solution of which will allow reaching a qualitatively new level of development of experimental devices.

Moreover, in preparation for conducting research in the IGR reactor with model fuel elements and fuel assemblies of power reactors, an important stage is to determine the power diagram planned for implementation in the test object. The diagram should correspond to the set goals and tasks of the test and provide a given sequence of events. It is formed on the basis of a complex of neutronic, thermohydraulic calculations and on the results of relevant experimental studies aimed at establishing a relationship between the energy parameters of the test object and the reactor.

Previously, during calculation of the test in the IGR reactor, the heat-mass exchange processes in the device containing the model fuel elements were considered from the point of view of providing a predetermined experimental program and preventing exceeding of parameters, which could affect the integrity of the device itself, and did not take into account the movement of liquids and gases.

The increase in the requirements for the test procedure of irradiation devices designed for a more detailed research of the processes accompanying all stages of a severe accident with core meltdown has necessitated the development of new approaches to the creation of computational models and a supporting mathematical apparatus.

All of the above facts determine the need to develop new methodological approaches that provide a further improvement in the quality of preparation and conduct of experiments in the IGR research reactor.

The aim of the research is to develop new methodological approaches to improve the quality of prediction and implementation of the specified test parameters of reactor irradiation devices for the research of processes accompanying a severe accident of a nuclear reactor with core meltdown.

To achieve this goal, the following tasks were solved:

1. To develop approaches providing specified axial and radial distribution in the model fuel elements and fuel assemblies;

2. To confirm by the results of computational and experimental research the possibility of providing a specified volume profile of energy release in fuel element and fuel assembly of an irradiation experimental device;

3. To develop a methodology for determining the content of impurity gases in ceramic nuclear fuel and the degree of their influence on the parameters of reactor experiments;

4. To test in a series of reactor experiments the developed methodology for determining the content of impurity gases in ceramic nuclear fuel, and to determine the content of impurity gases in the fuel of the irradiation device;

5. To develop a methodology for determining the power diagram in the test object, providing a given sequence of events in the experiment, based on detailed modeling of thermophysical processes in the irradiation device;

6. To implement the specified parameters with high accuracy in the reactor test of fuel element using the developed methodology for determining the power diagram in the test object.

Research methods:

- experiments in the IGR research reactor;
- computational modeling of thermophysical and neutron processes;
- post-reactor materials research of fuel elements.

The key provisions submitted for the defense of the thesis

1. The energy release in fuel assemblies during the tests in the IGR reactor corresponds to the operational value when operating in a fast neutron nuclear power reactor providing specified non-uniformity at the radial (K_r=1.05±0.02) and axial (K_z=1.08±0.02) direction.

2. The developed and tested methodology for determining the content of impurity gases in ceramic nuclear fuel allows us to establish their contribution to the total gas formation during experimental modeling of a severe accident of a nuclear reactor with core melting.

3. The computational and experimental diagram of changes in power with integral energy release E=1,56 kJ/gUO_2 in the developed irradiation device provides the implementation of a given sequence of events corresponding to the development of a severe accident in a fast neutron nuclear power reactor.

The scientific novelty of research is that for the first time it presents as follows:

- approaches providing a specified volume distribution of energy release in fuel elements and fuel assemblies during tests in a research nuclear reactor are formulated, substantiated and experimentally tested. The possibility of providing a specified volume energy release in the fuel assembly (K_r =1.05±0.02; K_z =1.08±0.02) corresponding to the real one during operation in a fast neutron power reactor has been confirmed by calculation and experiment;

- a method for determining the amount of impurity gases released from fuel during its melting has been developed and tested in a series of reactor experiments. The actual values of the amount of impurity gases realized during the melting of non-irradiated ceramic nuclear fuel under the conditions of a research nuclear reactor have been established;

- a method for calculating a specified power in a test object based on detailed computational modeling of thermophysical processes in an irradiation device has been developed and tested in a reactor experiment. It is established that the integral energy release E=1.56 kJ/gUO_2 at a stationary power N=14 kW under the conditions of a reactor irradiation device provides a correct reproduction of the sequence and consequences of the processes accompanying the development of a severe accident with the melting of the core of the fast neutron nuclear reactor.

Practical relevance.

The proposed methodological approaches to predicting and providing the reactor tests specified parameters of fuel elements allow: to improve the procedure for preparing reactor experiments, to expand the methodological base for preparing and conducting tests of the reactor fuel in the IGR pulsed research reactor, to improve the quality of predicting and implementing the specified parameters of fuel tests. All this makes it possible to expand the range of experimental programs in support of the safe development of nuclear energy.

The proposed methodologies and approaches have already been successfully applied in conducting IGR reactor experiments and can be used in the preparation and implementation of experimental programs related to reactor fuel testing at other research reactors.

The acts on the implementation of the thesis results in the procedure for preparing experiments in the IGR reactor, in the educational process of the Basic Engineering Training Faculty, as well as a "Testing device for fuel elements in the experimental channel of a research reactor" patent for invention were obtained.

Author's personal contribution

The author's personal contribution consists of setting and formulation of research objectives, conducting an analytical review of literature data and computational studies, forming approaches which provide a specified volume distribution of energy release in tested fuel elements and fuel assemblies, developing a methodology for determining the content of impurity gases in ceramic nuclear fuel, performing computational justification of experimental device designs and their test modes, performing calculations, developing technical, program-methodological and reporting documentation used in conducting reactor experiments.

The entire research activity was mplemented in close cooperation with leading scientists and specialists of the Republican State Enterprise "National Nuclear Center of the Republic of Kazakhstan" (RSE NNC RK). The analysis of the obtained results during the thesis research, as well as the formulation of the main conclusions on the thesis, which summarizes the results of the study and the conducted computational and experimental works, were carried out jointly with scientific consultants.

How the topic relates to plans of the research programs

The results presented in this thesis were obtained within the framework of the scientific and technical program implemented under the program-targeted financing, "Development of nuclear energy in the Republic of Kazakhstan" for 2018-2020 (State registration No. 0118RK01131) on the theme "Research of processes occurred during a severe accident in a fast neutron reactor core; grant funding project "Development of tools for simulating the dynamics of the neutron field of an pulsed research nuclear reactor" for 2021-2023 (AP09058353).

The degree of validity and reliability of the results obtained in the work is ensured by the correctness and consistency of the computational and experimental studies, including a set of methodological reactor experiments to substantiate the proposed methods, using well-tested general scientific research methods. The main results of the thesis were published 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 for the publication of the results of scientific activities, as well as in peer-reviewed foreign scientific journals included in the Scopus and Web of Science databases.

Testing of the research results

The key provisions and results of the thesis are presented at five international conferences: the VIII International conference "Semipalatinsk Test Site: Legacy and Prospects for Scientific-Technical Potential Development", Kurchatov, September 11-13, 2018; XIV International Scientific and Practical Conference "The Future of Nuclear Energy – AtomFuture", 2018 (Obninsk: November 29-30, 2018); XXV International Scientific and Technical Conference of students and postgraduates "Radioelectronics, Electrical engineering and Power Engineering"; The X International Scientific and Practical Conference "Physical and technical problems in Science, Industry and Medicine. Russian and international experience in personnel training"; IX International Conference "Semipalatinsk Test Site: Legacy and Prospects for Scientific-Technical Potential Development", Kurchatov September 07-09, 2021.

In addition, the main results of the thesis were reported and discussed at scientific seminars of the Technical Physics Department, D. Serikbayev East Kazakhstan Technical University, at meetings of the Scientific and Technical Council of the RSE NNC RK, as well as at online workshops of PhD students at the National Research Tomsk Polytechnic University (Tomsk, Russia).

Publications

According to the research results presented in the thesis, 9 efforts were published, 6 of which - in peer-reviewed scientific publications recommended by the Committee for the Control of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan; 2 - in journals indexed in the Scopus database (1 is indexed in the Web of Science); 1 patent for invention was received.

Structure and volume of thesis

The paper consists of introduction, three chapters, conclusion and list of references. It is presented on 144 pages, contains 82 figures, 9 tables and a list of references of 130 items.