ABSTRACT

For the degree of a Doctor of Philosophy (PhD)
in specialty 6D072300 – "Technical Physics"

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Topic: "Development of a reactor method for obtaining corium and investigation of its structural-phase state and mechanical properties"

The research detailed in the thesis of V.K. Tskhe is committed to devising a method for obtaining corium under the scenario simulated conditions of a severe accident in a fast-neutron nuclear reactor and to investigating the properties and characteristics of the solidified melt of the reactor core structural and fuel materials. The outcomes attained from resolving the thesis objectives will enhance the precision of reactor experiments in obtaining corium, and significantly augment the sparse experimental data vital for advancing technologies for the extraction of solidified melt from damaged reactors.

Relevance of the research subject

Nuclear power plant accidents and the resulting radiation hazards currently pose a pressing issue for the entire scientific community. This is evidenced by severe, well-publicized accidents at nuclear facilities like "Three Mile Island", "Chernobyl", and "Fukushima-1".

In addition to preventive measures aimed at upholding and enhancing nuclear and radiological safety during the operation of existing nuclear facilities, the challenges associated with mitigating the aftermath of severe, beyond-design-basis accidents have proven highly significant and pertinent. Presently, research and efforts focused on mitigating the effects of past accidents persist, implemented through large-scale projects that aim to formulate strategies for the decommissioning of damaged reactor installations and minimizing its radiological impact on the environment.

From a scientific perspective, direct physical simulation of processes and phenomena, which allows for the acquisition of experimental data to address pressing issues related to the examination of processes at various stages of nuclear reactor accidents, as well as the investigation of properties and characteristics of the ensuing alloys and compounds, is currently the most effective and relevant approach.

Experimental studies, aimed at simulating severe accident scenarios, are conducted under the auspices of international organizations such as the OECD and IAEA, across numerous research centers worldwide. However, most scientific investigations utilize experimental installations and rigs with an external heat supply (for example, induction heating) and the application of a corium simulator based on materials such as aluminum oxide, basalts, silicate-containing materials, and less commonly, uranium dioxide.

Prototype corium possesses chemical and rheological properties that are akin to those of real corium. However, its main disadvantages include the absence of an autocatalytic heat source provided by self-sustaining radioactive decay, which can only be achieved in nuclear power installations. It is also necessary to highlight the difference in isotopic composition since a corium simulator based on uranium dioxide

often consists of natural or depleted compounds in place of real, enriched uranium dioxide.

When analyzing research results obtained using prototype corium, the constraints in adhering to certain similarity criteria with real corium become apparent, along with the inability to fully satisfy initial conditions of some experiments. As a result, the need for reactor tests to obtain model corium becomes extraordinarily high.

Discussing reactor research aimed at investigating processes accompanying severe accidents and the obtain of molten structural and fuel materials from the reactor core, it is essential to note the technical complexity of comprehensive testing. To investigate various corium properties, it requires the implementation of reactor experiments and the development of specialized devices within which the melt with the required component-element composition is formed. Therefore, research on the obtaining of model corium under neutron irradiation simulating severe accident conditions is unique and limited.

At the same time, there is currently a scarcity of reference data on the structural-phase states and mechanical properties of corium. It is only known that the mechanical properties of corium change significantly over the time. However, monitoring these changes under working conditions (in reactor and sub-reactor premises) is extremely difficult due to high radiation levels and its physical inaccessibility. Hence, research aimed at studying the structure, phase composition, and mechanical properties of corium and its temporal dynamics requires the development of obtain methods and new experiments. The most representative and reliable of these are in-pile (reactor) tests under neutron irradiation in nuclear reactors. The model corium obtained using these methods, considering the totality of its properties, will be most similar to real corium.

As a result of the analysis conducted, it becomes evident that the information about the structural and phase states, as well as mechanical properties of model corium, is not quite exhaustive and simultaneously requires new scientific explorations.

The apparent need for new research in this direction and the lack of methodologies for obtaining model corium under reactor conditions limit the use of the IGR research reactor in studying severe accidents and exclude the participation of the RSE NNC RK in forming an international bank of experimental data on the properties and characteristics of corium.

In this regard, it becomes crucial to develop the experience of previous in-pile experiments simulating severe accidents towards designing a specialized methodology for conducting experiments on the IGR research reactor to obtain model corium for studying its properties and characteristics. Also, this would enhance the application range and attractiveness of the IGR research reactor for specialists dealing with nuclear reactor safety issues.

The dissertation presents the results of developing a reactor method for obtaining model corium, which includes a technique for calculating the IGR reactor's reactivity margin, and ampule irradiation device. The localized melt in the latter, according to its component-element composition, is similar to the melt of the reactor core on fast neutrons. In addition, the results of post-test materials research into its structural-phase states and mechanical properties significantly contribute to the existing experimental data base. This data is used both for forming the concept of corium extraction from damaged reactors and for mathematical modeling and verification of physical processes.

The purpose of the work

Develop a reactor method for melting the structural and fuel materials of the power reactor core and investigate its structural-phase state and mechanical properties.

To achieve the purpose of the work, the following tasks were solved:

- develop a design for an ampule irradiation device with a fuel assembly for conducting research on obtaining model corium in the central experimental channel of the IGR research reactor, based on previous experience conducting in-pile experiments to study severe accidents;
- based on the adaptation of known methods for selecting and justifying reactor experiment modes, perform neutron-physical and thermophysical calculations to justify the possibility of conducting an experiment to obtain corium under the conditions of simulating an accident situation;
- develop a methodology for determining the required reactivity margin of the IGR research reactor to implement the model corium obtaining experiment;
- choose a reference in-pile experiment that meets the conditions for forming corium of a given composition as a result of melting fuel and structural materials of the model fuel assembly;
- study the structural-phase state and microhardness of the model corium obtained in the reference experiment, confirming its conformity with generally accepted representations of corium.

The key provisions submitted for the defense of the thesis

1. Results of the neutron-physical and thermophysical calculations to justify the possibility of conducting an experiment to irradiate the fuel assembly located in the developed ampule irradiation device, under the conditions of reactor severe accident simulation.

The required power change diagram in the fuel assembly in the "Pulse" mode has been defined, which is capable of providing the specified specific energy release in the fuel ~2.8 kJ/g UO_2 and temperature ~3170°C.

2. Methodology for determining the required reactivity margin of the IGR reactor to implement a start-up in the "Pulse" mode.

The main dependencies between the parameters of the required power change diagram of the reactor, energy release in the reactor core, and the number of compensating rods, minimally sufficient for its implementation, have been established.

3. Characteristics of the structural-phase state and mechanical properties of the solidified model melt of structural and fuel materials of the nuclear reactor core.

The presence of inclusions in the form of uranium compounds (up to ~1.5 wt.% for U) in the body and at the grain boundaries of the metallic matrix does not significantly affect the microhardness (148÷152 HV0.2) of the model corium.

The scientific novelty of the work lies in the fact that for the **first time:**

– the experimental ampule irradiation device has been developed for testing fuel assemblies, ensuring the retention of the melt of structural and fuel materials within its protective barriers when simulating a severe reactor accident;

– the methodology for calculating the reactivity margin of the IGR reactor for the start-up in the "Pulse" mode has been developed and tested in a series of reactor experiments;

– new data have been obtained on the possibility of obtaining corium, which is a solidified melt of fuel and structural materials of a model fuel assembly, the properties of which depend on the percentage content of materials in the melt.

Research object

The method for obtaining model corium of structural and fuel materials of the nuclear reactor core under the in-pile conditions.

Subjects of research

The ampule irradiation device into the IGR reactor, the structure, the phase composition, and the mechanical properties of the model corium of the nuclear reactor core.

Research methods

Experiments to obtain model corium were carried out on the research impulse graphite reactor IGR. Calculation work (thermophysical and neutron-physical processes) for the selection and justification of the experiment safety was carried out using a set of modern calculation codes (ANSYS, MCNP). General scientific methods of metallographic research were used to analyze the macro- and microstructure, the phase composition of the model corium. The elemental composition of the samples was studied by the method of X-ray spectral microanalysis. The determination of the mechanical properties was carried out using a microhardness tester and a certified software product.

Practical relevance

The practical application of the method for obtaining model corium will ensure the quality of implementing the melting modes of materials during the reactor power change, guaranteeing the exclusion of the possibility of unauthorized increase in integral heat release in the reactor core and, therefore, in the ampule irradiation device.

The ampule irradiation device, protected by a certificate of invention, developed based on the experience of using experimental devices for reactor tests and research of the fuel assemblies under conditions simulating a severe accident of a nuclear power reactor, can be used to obtain samples of model corium suitable for further materials research.

The model corium obtained in the in-pile experiment, which includes fuel and structural materials that have undergone transformations in the process of melting and interaction due to internal heat release in the fuel, can be used in the development of technologies for extracting solidified melt from the damaged reactors.

Certificates of the dissertation work results implementation into preparation and conduction of start-up in the IGR reactor, into the educational process of the Faculty of Basic Engineering Study, as well as a patent for the invention “The device for the studying the destruction process of the lower base plate of the CPS control rod guide duct in the conditions of the nuclear reactor severe accident" were obtained.

Author's personal contribution

The author's personal contribution consists in setting and formulating the tasks of the study, analyzing literary data and patent search, developing an ampule irradiation device; conducting theoretical and calculation studies to justify the method for calculating reactivity margin to obtain stable pulses on the IGR reactor, preparing and conducting experimental and analytical works, as well as performing statistical processing of the obtained results. Electron microscopic and mechanical tests of model corium samples were conducted jointly with the staff of the materials testing department of the "IAE" branch of the RSE NNC RK.

The work implemented as part of the dissertation was carried out in close cooperation with scientists and specialists of the RSE "National Nuclear Center of the Republic of Kazakhstan". The analysis of the results obtained in the course of the dissertation research, as well as the formulation of the main conclusions on the dissertation work, which summarize the results of the study and the performed computational and experimental work, were carried out jointly with scientific consultants.

Relation of the topic with the research programs plans

The results presented in the work were obtained mainly with the financial support of the State Institution "Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan" in the framework of Contract No.305 dated 30.03.2018 on the theme "Properties and characteristics of the core melting materials of the nuclear reactor obtained at the IGR research reactor" (No. AP05133086).

The degree of validity and reliability of the results presented in the work is ensured by the correctness, accuracy and originality of the tasks set, the systematics of the calculation and experimental studies, including in-pile reactor experiments on the production of structural and fuel material melt of, as well as by application of classical methods in the part of material research. The main results of dissertation are published in list of publications recommended by the Committee for Quality Assurance in Science and Higher Education of the MOHEAS RK, for the publication of research findings, as well as in peer-reviewed foreign scientific journal included in the database of Scopus and Web of Science.

Approbation of the work results

The main results of the dissertation were reported and discussed at five international conferences:

1. XIV International Scientific and Practical Conference "The Future of Nuclear Energy" (Obninsk, Russia, November 29-30, 2018);
2. International Scientific and Technical Conference of Students and Postgraduates "Radio electronics, Electronics and Energy" (Moscow, Russia, March 14-15, 2019);
3. International Conference "Advanced manufacturing materials and research: new technologies and techniques AMM&R2021" (Ust-Kamenogorsk, Republic of Kazakhstan, February 19, 2021);

4. IX International Conference “Semipalatinsk Test Site: Legacy and Prospects for the Development of Scientific and Technical Potential” (Kurchatov, Republic of Kazakhstan, September 07-09, 2021);

5. All-Russian Scientific Conference "Achievements of Science and Technology - DNiT-2021" (Krasnoyarsk, Russia, December 10-11, 2021).

Moreover, the main results of dissertation work were reported and discussed at scientific seminars of the Technical Physics Department of D. Serikbayev East Kazakhstan Technical University, at Scientific and Technical Councils of the IAE branch of the “National Nuclear Center of the Republic of Kazakhstan”, at online seminars of PhD students at the National Research Tomsk Polytechnic University (Tomsk, Russia).

Publication

According the results of the research set out in the dissertation, 12 printed works have been published, including:

- 2 articles in scientific publications of the Republic of Kazakhstan, recommended by the Committee for Quality Assurance in Science and Higher Education of the MOHEAS RK;
- 3 in a journal included in the number of international information resources and indexed in the Web of Science Core Collection (Clarivate Analytics) and Scopus databases;
- 6 articles and abstracts in collections of the international conference’s materials;
- 1 patent for invention.

Structure and volume of thesis

The work consists of an introduction, five chapters, a conclusion, and a list of used sources. It is outlined on 116 pages, contains 73 figures, 12 tables, a list of used sources consisting of 134 items and 3 appendixes.