ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD)
in the specialty 8D05302 – «Technical Physics»

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Experimental simulation of interaction between model corium of light water nuclear reactor and Al2O3 - sacrificial material with fluidized lead layer of core catcher

General overview of the work

The dissertation work is devoted to the study of the interaction of the model corium of a light–water nuclear reactor with a candidate sacrificial material – Al2O3 and a lead layer of a core catcher in the conditions of modeling the processes of a severe accident, as well as the study of the structural and phase state of corium obtained as a result of the high-temperature interaction.

Relevance of the research topic

As it knows, thirty-one countries in the world currently receive energy from nuclear power plants. Kazakhstan is also considering the possibility of building a III+ reactor. In this regard, improving the safety of nuclear power plants (NPP) is one of the relevance and priority tasks. The entire world community is busy solving this problem after several major accidents. It is clear that a severe accident can occur even with a very low probability based on the experience of operating nuclear power plants. There are many scenarios for the development of a severe accident. One of which is the interaction of the reactor core melt with the reactor vessel with further melting and leakage into the core catcher.

The main purpose of core catcher is to localize the processes of decay heat of corium and prevent it from falling outside the core catcher. The core catcher is a steel vessel with blocks of sacrificial materials installed in it. The vessel is surrounded by thermal insulation layers cooled by a partitioned circular pool with boiling water. The main difference between all crucible core catcher lies in the design and composition of the sacrificial material.

Sacrificial materials as the main element of the crucible core catcher which used for:

- reducing the temperature of the high-temperature corium melt;
- reducing the density of the oxide part of corium to carry out gravitational inversion with its metal part in order to reduce the release of explosive hydrogen during steam-metal reactions and ensure safe water supply to the surface of corium.

The selection of sacrificial materials for the core catcher of nuclear power plants is one of the most important tasks determining the development of their passive safety systems. To date, many different tests and studies have been conducted in this area, which have allowed us to make an approach and understanding of which materials are suitable to use in core catcher for effective and reliable localization of corium in the event of its escape from the reactor vessel during a severe meltdown accident.

At the same time, it becomes obvious that the efficiency of heat removal, the rate of dissolution of SM in corium, as well as the cost of manufacturing SM is one of the key factors in ensuring effective localization.

The purpose of this dissertation is experimental modeling the interaction of corium with sacrificial material based on aluminum oxide (Al_2O_3) with a lead layer in the conditions of modeling a severe accident with core melting and to study the structural and phase state of corium after interaction.

The following **tasks** were solved to achieve this goal:

1. To analyze the processes occurring during the interaction of light-water reactor corium with sacrificial materials in a core catcher and to develop a methodology for experimental modeling of their interaction;
2. To perform experimental modeling of the interaction of corium with sacrificial material in the conditions of simulation of decay heat in corium;
3. To study the macro- and microstructure, elemental and phase compositions of corium after interaction with sacrificial material based on aluminum oxide (Al_2O_3) and lead layer.

Key provisions for defense:

1. Computer modeling of the interaction of corium with sacrificial material based on aluminum oxide and lead layer of the core catcher of a light-water reactor showed that the use of a lead layer provides heat removal of 0.45 MW from corium due to thermal energy expended on the phase transition of the fluidized bed material to a vapor state;
2. The specific energy release in the graphite block is 2.02 kW/kg, which corresponds to the required power value in the corium melt of 0.41 kW/kg to maximize the approximation of the process of simulating decay heat to the real one during induction heating;
3. The microstructure of the solidified corium after interaction with the sacrificial material is represented by a solid solution consisting of two phases with different types of crystal lattice. In the areas of "dark" dense corium and the transition region of the interaction of corium with ceramic material, the phase of this solid solution crystallized in a tetragonal modification of the lattice of the spatial group P42/nmc, while in the area of "light" porous corium with the same composition, the phase is in a cubic modification of the lattice of the spatial group Fm3m.

The scientific novelty of the work lies in the fact that it:

- the use of a lead layer as a component for the sacrificial material of a melt trap in a light-water reactor has been justified by computer modeling for the first time;
- a method for calibrating the parameters of an induction heating system has been developed and approved to increase heating efficiency for simulating decay heat in corium;
- experimental studies have been conducted and the features of the interaction of nuclear reactor corium with sacrificial aluminum oxide (Al_2O_3) with a lead layer

have been identified in the simulation of a severe accident with core meltdown for the first time.

The object of the study is a material obtained as a result of high-temperature interaction of corium with sacrificial ceramic material based on aluminum oxide (Al_2O_3) with a lead layer.

The subject of the study is methodological approaches to ensuring the qualitative conduct of the experiment and the impact of candidate sacrificial material on the structural and phase state of the model corium as a result of high-temperature interaction in the conditions of modeling a severe accident.

Research Methods

Various research methods were used to achieve the set goal and tasks of this dissertation, including both physical and computer modeling, as well as methods for studying the structure and composition of materials.

The use of the selected methods is based on the use of ANSYS software, the «Lava-B» experimental facility and equipment for conducting materials science research.

Computer modeling consisted of a series of numerical experiments to study the interaction of sacrificial material with corium and the choice of a method for simulating decay heat in it, as well as the development of thermophysical models of the experimental section (melt trap).

Experimental modeling of the interaction of corium with sacrificial ceramic material based on aluminum oxide (Al_2O_3) with a lead layer under conditions of modeling a severe accident with core meltdown was carried out at the «Lava-B» experimental facility.

The use of modern materials science methods for the study of materials obtained as a result of experimental modeling of the interaction of sacrificial material with corium made it possible to conduct a comprehensive analysis of the studied interaction.

The practical significance of the work lies in the fact that:

- the developed thermophysical models of the experimental section of the «Lava-B» facility can be used to analyze future experiments on experimental modeling of a severe accident with core meltdown;
- the developed method of calibration of an induction heater to simulate decay heat in corium can be applied in any technological facilities using an induction heater to increase the efficiency of its use;
- the obtained results of materials science studies of the interaction of corium with sacrificial ceramic material based on aluminum oxide (Al_2O_3) with a lead layer under conditions of modeling a severe accident with core meltdown can be used to improve core catcher and develop new sacrificial materials in order to increase the reliability of passive safety systems of nuclear power plants.

The author's personal contribution consists in the formulation of the tasks of the dissertation research, conducting an analytical review of literary data, conducting computational, experimental, materials science research and analysis of the results obtained.

The author was directly involved in the formation of methodological approaches to ensuring high-quality research, conducting an experiment at the «Lava-B» facility and subsequent materials science studies.

All work was carried out in close cooperation with leading scientists and specialists of the branch of the "Institute of Atomic Energy" RSE NNC RK. The analysis of the results obtained during 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 conducted computational, experimental and post-experimental work, were carried out jointly with scientific consultants.

Relation of work with research programs

The results presented in this dissertation work were obtained in the framework of the scientific and technical program "Development of nuclear energy in the Republic of Kazakhstan" for 2021-2023 (BR09158470) of the Ministry of Energy of the Republic of Kazakhstan.

The reliability and validity of the obtained results are ensured by the correctness and consistency of the conducted analytical and computational experimental studies. The main results were obtained using direct, well-approved experimental research methods.

The main results of the dissertation research have been published in journals recommended by the Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan for the publication of scientific results, in peer-reviewed foreign scientific journals included in the Scopus and Web of Science databases, as well as collections of proceedings of international and domestic scientific conferences.

Approbation of the results of the dissertation work

18 printed works have been published according to the results of the research presented in the dissertation. These include 6 publications in journals indexed in Scopus and Web of Science, 1 publication in other scientific journal, 1 patent for a utility model from RSE NIIP, as well as 10 contributions to proceedings of international conferences.

The main results of the dissertation work were reported and discussed at scientific seminars of the Department of Technical Physics and Thermal Power Engineering of the Non-profit joint-stock company “Shakarim University of the Semey city”, at meetings of the Scientific and Technical Council of the RSE NNC RK and the “Institute of Atomic Energy” branch, as well as at PhD seminars of doctoral students of regional universities.

The structure and scope of the dissertation

The dissertation work consists of an introduction, five chapters, a conclusion and a list of references. The dissertation is presented on 118 pages, contains 66 figures, 12 tables and a list of references with 125 sources.