ABSTRACT
of the dissertation for the degree of Doctor of Philosophy (PhD)
in the specialty 8D05302 – «Technical Physics»
Toleubekov Kuanyshbek Orazbekovich
Interaction of the melt of the materials of the core of a light-water nuclear reactor with metal-coolers in the conditions of the ex-vessel stage of development of a severe accident

General overview of the work

The dissertation work presents the results of studies conducted on the possibility of using the effect of boiling metals to cool corium in a core catcher of a light-water reactor in the event of a severe accident with core meltdown at a nuclear power plant.

Relevance of the research topic

The history of nuclear energy shows that in the event of a loss of cooling of the reactor core during a severe accident at a nuclear power plant, it melts to form a melt of structural materials known as corium. The reactor vessel collapses and corium exits into the sub-reactor space with the further development of the accident.

The consequences of such accidents can be significant radioactive pollution of the environment. At the same time, the causes of such deviations, which lead to the development of an emergency situation at a nuclear power plant, may be not only the human factor or imperfection of the NPP design, but also natural disasters, leading to failure of various equipment.

Thus, today, not only issues related to the safe operation of nuclear power plants and the prevention of emergencies are relevant, but also reducing the consequences of severe accidents in case of their occurrence. In this regard, with the accumulation of knowledge about the development of severe accidents, as well as the significant weakening of the most dangerous consequences of its occurrence, additional technical means of managing a severe accident were adopted to ensure the preservation of the tightness of the nuclear power plant's containment.

One way to manage the final stage of a severe accident with core meltdown is the concept of ex-vessel corium retention and cooling in a core catcher. The most technically developed and widely used in practice among the well-known core catchers of light-water nuclear reactors is the core catcher of the crucible type of the WWER reactor. Such a core catcher has been installed at all nuclear power plants with WWER reactors since the construction of the Tianwan NPP in China.

The concept of corium cooling in core catcher of the WWER reactor is to dilute it with sacrificial materials, heat removal through water-cooled vessel of the core catcher and supply water to the corium surface. Dilution of corium is used to cool it and reduce the density of its oxide part located in the lower area of the core catcher. This is necessary for the implementation of the so-called process of gravitational inversion of corium layers in order to prevent steam-metal reactions, reduce volumetric energy release in corium and increase the heat exchange surface with vessel of the core catcher. Cooling water is supplied to the surface of the corium after the ascent of its oxide part.

The operability of the ex-vessel corium retention and cooling in a core catcher is confirmed on the basis of a complex of computational and experimental work, however, there is currently a demand for various studies aimed at further improving the efficiency and safety of their operation.

It can be noticed that when corium is localizing in the core catcher, there is a time interval when the cooling of the corium surface is not organized. In this regard, to increase the efficiency of localization of corium in the core catcher, it is possible to organize cooling of its surface before the water enters the core catcher to carry out continuous heat removal from the corium.

One of the most promising ways to organize such cooling is to use the effect of boiling metals. The choice of metals is primarily due to their thermophysical properties. The idea is based on using the effect of boiling metals on the surface of corium in a similar way to cooling with water. Thus, it was advisable to conduct computational, analytical and experimental studies in order to understand all aspects of such interaction.

The purpose of this dissertation is to study the interaction of the corium of a light-water reactor with metal-coolers under conditions of modeling a severe accident with core meltdown to confirm the possibility of their use as coolers.

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

1. To analyze the physical-chemical properties of known metals with followed by a computational and analytical justification for using the boiling effect of metals to cool the surface of corium in a core catcher;

2. To develop a method for conducting experiments to study the interaction of metals with corium in the conditions of modeling the processes of a severe accident at the VCG-135 test bench;

3. To study the features of the interaction of metal-coolers with corium under conditions of discharge of solid metal fragments into the melt and the impact of metals on the structural and phase state of corium after experiments.

Key provisions for defense

1. Thermal calculations of the boiling effect of metal-coolers for the organization of continuous heat removal from the surface of corium.

Modeling has shown rapid melting of a metal-coolers (zinc, antimony and manganese) due to intensive heat exchange when they are discharged to the surface of corium. The time of complete melting is determined by the melting point of a specific metal-cooler: zinc (~ 1.6 s), antimony (~ 3.4 s) manganese (~ 5.5 s). In this process, zinc boils completely, while the boiling of antimony is partial (in some areas of the calculation model, the temperature of antimony is below the boiling point of T_{boil} = 1908 K). Manganese does not reach the boiling point, establishing thermal equilibrium with corium with an average temperature of ~ 1750 K.

2. The developed and approved method of conducting experiments under conditions of discharging the studied metal-coolers into a crucible with a corium melt at the VCG-135 test bench.

The production of a corium melt at the VCG-135 test bench is conducted by induction heating of the prepared charge in a graphite crucible. After obtaining the required corium temperature of ~ 2250 ° C, the studied metal-cooler is discharged into the corium melt from a special device by opening the flap using an electromagnetic drive. The temperature of the metal-cooler at the time of its discharge reaches ~ 400 °C.

3. The impact of metal-cooler on the structural and phase composition of corium during high-temperature interaction.

The interaction of zinc with the corium melt at a temperature of ~ 2250 ° C leads to intense boiling of the metal-cooler and complete evaporation from the crucible. No more than 20% of total mass of antimony boils during interaction with corium, while the rest of mass interacts with corium to form a phase composition based on a number of solid solutions of uranium-zirconium type $(Zr,U)O_{2-x}$, as well as a small number of phases belonging to α-zirconium stabilized by oxygen, and the phase Zr-Sb-O connections. Manganese does not reach the boiling point and makes changes in the composition of corium, while forming a large number of solid solutions of uranium-zirconium type, zirconium-manganese and oxygen compounds (Zr-Mn-O, Zr_2Mn, Zr_3O), and interaction with the melting volume material is also observed.

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

- It was proposed to use metal boiling to cool the surface of the corium melt to organize continuous heat removal during the entire period of corium localization in the core catcher for the first time. Requirements have been formulated and metals that can be used to cool corium in a core catcher have been identified;

- The method for testing materials with a low melting point relative to the temperature of existence of a corium melt has been developed and approved in a series of experiments;

- The impact of the studied metals on the structural and phase state of corium has been established as a result of experiments conducted under conditions of modeling a severe accident with core meltdown.

The object of the study is candidate metals that can be used to cool corium in a core catcher.

The subject of the study is methodological approaches to ensuring high-quality experiments and the impact of the studied metals on the structural and phase state of 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 VCG-135 test bench and a fleet of equipment for conducting materials science research.

The computer modeling was a series of numerical experiments to study the interaction of metals with corium in a severe accident. In addition, computer modeling was used to justification the operability of the developed method for conducting experiments on the discharge of metal fragments into liquid corium during the simulation of a severe accident at the VCG-135 test bench.

The use of modern materials science methods for studying materials obtained as a result of physical modeling of the interaction of metals with corium made it possible to conduct a comprehensive analysis of the studied interaction and make appropriate conclusions.

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

- The developed method of physical modeling ensures timely contact of the metal-cooler with corium and allows to study the processes occurring in a severe accident with simulation of the proposed method of cooling the melt.

The proposed method of conducting an experiment on the VCG-135 high-temperature test bench can be used to solve similar problems on similar experimental installations.

- The experimental data obtained on the interaction of low-melting metals with corium in a severe accident can be used by specialists in the field of atomic energy in the development of accident localization systems for promising reactor installations.

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 research and analyzing the results obtained.

All work was carried out 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 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 and 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 grant financing project of the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan on the topic " Development and research of a method for the corium cooling in the core catcher of NPP in a severe accident " for 2022-2024 (AP14870512).

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

The main provisions and results of the dissertation work were presented at 9 international and domestic scientific conferences:

1. IV International Scientific Forum «Nuclear Science and Technology» (Almaty, Republic of Kazakhstan, September 26-30, 2022);
2. International Scientific and Practical Conference «Ualievsky Readings-2022» on the topic «Current problems of science and education under conditions of modern challenges», (Ust-Kamenogorsk, Republic of Kazakhstan, September 16-17, 2022);
3. International Scientific Conference «Abdildin readings: actual problems of modern physics» (Almaty, Republic of Kazakhstan, April 12-15, 2018);
4. XX International Conference of students, graduate students and young scientists «Prospects of fundamental sciences development» (Tomsk, Russian Federation, April 25–28, 2023);
5. XX International Conference "Semipalatinsk test site: legacy and prospects for the development of scientific and technical potential" (Kurchatov, Republic of Kazakhstan, September 12-14, 2023);
6. International Conference "Fundamental and Applied Problems of Modern Physics" (Tashkent, the Republic of Uzbekistan, October 19-21, 2023);
7. International Scientific and Practical Conference "Current state and prospects of development of the nuclear industry in the Republic of Kazakhstan" (Almaty, Republic of Kazakhstan, November 27-28, 2023);
8. IX International Congress on Energy Fluxes and Radiation Effects (Tomsk, the Russian Federation, September 15-21, 2024);
9. XXIII research and development contest conference among young scientists and specialists of RSE NNC RK (Kurchatov, Republic of Kazakhstan, October 16 - 18, 2024).

Also, 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.

Publications

12 printed works have been published according to the results of the research presented in the dissertation. These include 1 publication in a peer-reviewed scientific journal recommended by the Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, 3 publications in journals indexed in Scopus and Web of Science, 7 contributions to proceedings of international conferences, as well as 1 patent for an invention from RSE NIIP.

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 106 pages, contains 53 figures, 12 tables and a list of references with 145 sources.