### **1. Project Title: №5243**

**Interaction Studies of Improved VVER Structural Materials at Severe Accident Conditions**

### **1.1 Key Words**

Water-cooled water-moderated reactor, core, accident, melting temperature, melt, structure, phase composition, viscosity, fluidity.

### **2. Project Management**

2.1 Project Manager

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### **3. Introduction and Overview**

What is the objective of the project?

The objective of the project is to obtain data:

- on interaction parameters of the materials used in upgraded designs of core components of water-cooled water-moderated reactors during simulation of severe accidents;

- on temperature parameters of melt formation, first and foremost of structural materials and of fuel and absorber rod components;

- identifying phase composition of the generated melts in solid state;

- identifying physical characteristics of viscosity and fluidity of the generated melts from materials used in standard and upgraded designs of VVER components.

What is the essence of the problem?

In terms of current safety level, water-cooled water-moderated reactors do not rule out a probability of severe beyond design-basis accidents, coincident with meltdown of fuel and core structural materials. To prevent environmental impact in the aftermath of accidents, modern reactor designs provide for melt traps. To substantiate reliable melt retention, there were carried out a number of experiments in melting resident reactor core materials and their interaction with the non-recoverable materials used in the traps.

Today, however, there are a number of problems requiring solution.

Firstly, it is necessary to develop means of managing beyond design-basis accidents. To this end it is necessary to have a relatively accurate scenario of the beginning and behavior of severe accidents. Since the main effect of accidents is destruction of the core, in order to develop the accident scenario that would include stages of core structural components' destruction, melt formation, and melt movement in time, it is necessary to know:

- behavior of core components, fuel rods, absorber rods, and fuel assemblies as structures in accident conditions;

- processes, kinetics and parameters of interaction of all materials used in structural components with the environment and with each other in conditions coincident with melt formation;

- melt parameters, especially viscosity, fluidity, and chemical activity during interaction with other solid state materials.

Secondly, to design reliable and efficient melt traps, it is necessary to obtain data on melt parameters as a function of qualitative and quantitative composition of materials used in actual reactor core structures which are continuously upgraded.

Thirdly. After severe accidents and melt transition to solid state, it is necessary to develop measures for handling these materials. As it is obvious that for some time all the materials in the reactor hall will be flooded with water, it will be necessary to carry out experiments on interaction of these actual materials with water. For this purpose it is necessary to know melt parameters in solid state versus conditions of their transition from a liquid to a solid state. This primarily includes element and phase composition of the melt material affecting corrosion resistance and other properties.

What do others do?

The analysis of the existing publications has shown that in the past 15-20 years there has been a worldwide focus on simulation of and research into processes occurring during severe accidents; several experimental programs have been completed.

Experimental research into various stages of NPP severe accidents was carried out by Argonne National Laboratory (USA), Joint Research Center of the European Commission, Kurchatov Institute (Russia), and research centers in Italy and Japan. Examples of such activities are provided below.

Investigation into interaction of core melt with the reactor vessel, where along with the main core components, such as U, Zr, and O, there are structural materials (iron), fission products, and control rod materials (boron carbide), within the framework of the international programs RASPLAV and MASCA involving 16 countries under the auspices of OECD. The investigation results of core melt (corium) behavior consisting of UO2– ZrO2–Zr demonstrated that when poured into the corium, molten stainless steel extracted zirconium and uranium from the corium and turned out to have a higher density that the corium melt. It demonstrated penetration of molten reactor materials (Zr – stainless steel) at 1800°C through relatively large core fragments (sized 8-10 mm). Viscosity, density and temperature of liquidus were measured for the range of compositions in the U-Zr-O system. It was established that U-Zr-O phase diagrams calculated using the GEMINI software at 2600°С predict existence of two immiscible liquids in a rather broad range of corium compositions. Conductivity, heat conductivity, phase transition temperatures, viscosity and "flow" temperature were measured for the range of compositions in the U-Zr-Fe system.

Argonne National Laboratory under the international Advanced Containment Experiment Program carried out research into interaction of the core melt with concrete. The main objectives of these experiments were to investigate thermal hydraulic and chemical processes during melt-concrete interaction and to expand the database on release of low-volatile fission products for further use in development and validation of computer codes which describe melt-concrete interaction and fission product release.

CORA facility at the FZK research center (Germany) studied thermal and physical-chemical processes in a sample fuel assembly of the VVER-1000 type in conditions simulating a severe accident with the fuel assembly components melt and investigated the effects of the accident parameters on deterioration of the boron-carbide Rod Control Cluster Assembly.

A large share of studies focused on UO2 fuel melt interaction with additives of structural materials and non-recoverable trap materials. Some studies focused on investigation of melt parameters versus quantitative combinations of materials which participate in interaction at the beginning and in the course of severe accidents.

What do you intend to do?

Currently, activities are underway to extend the operation life and reliability of reactor cores through application of new materials and structural improvements. Knowledge of how the use of new materials and structures will affect core melt formation during beyond design-basis accidents is a sine qua not of activities to increase NPP safety in general.

Knowledge of melt fluidity parameters versus phase composition allows predicting accident development scenarios and staging more detailed experiments on interaction of melts with non-recoverable trap materials to predict their integrity as a function of interaction intensity with the melt, melt mixing, and various stratifications as a function of melt phase state.

The project objectives:

Based on the analysis of the data available in the literature to identify a probable scenario for heavy accident development at NPP.

To upgrade and prepare process equipment and instrumentation for carrying out research.

To upgrade design and manufacturing of sample fuel and absorber rods for research.

To develop methodologies to conduct experiments and study the structure and composition of power reactor core materials before and after their interaction (in the solid state and after melting).

To study the effects of fuel and absorber rod structural features (close contact, presence of oxides on the surface) on the nature of the beginning of their materials' interaction and interaction of first and second types of melts. To obtain data on the temperature parameters of the beginning of melt formation as a function of material state.

To obtain melts of standard VVER fuel and absorber rods, namely combination of UO2 with the alloy Zr1%Nb (E110) and stainless steel Ch18N10T with boron carbide.

To study processes of melt formation for new combinations of absorber materials B4C, Dy2O3•TiO2;Hf and interaction of these components with the melt of fuel materials.

To identify phase composition of melts thus formed.

To identify melt viscosity and fluidity parameters depending on their phase composition.

What is new?

The project provides for a possibility to obtain data on interaction of new combinations of materials, mainly UO2 + Gd2O3; Ch18N10T + B4C + (Dy2O3•TiO2); Zr + B4C +Hf and interaction of these components with the melt of UO2 + Zr fuel materials. The study will cover phase composition of the generated melts, determine their viscosity and fluidity, and investigate the effects of changes in the melt phase compositions on their fluidity, which will allow to more accurate describe the kinetics of VVER core material melt formation and spread during beyond design-basis accidents.

Who are you?

The project involves 33 specialists, including 2 Full Doctors of Physics and Mathematics, 7 Ph.D.s (Candidates of Science) in Physics and Mathematics, 3 staff scientists and 13 engineers who come from .4. research divisions of the institute.

NSC Kharkiv Institute of Physics and Technology (KIPT) is a research center in Ukraine with extensive experience, available infrastructure and licenses for working with α–active materials. Founded in 1928, NSC KIPT is a lead organization in Ukraine in the sphere of nuclear power industry. Research in this area ranges from development of radiation-resistant materials and fuel for nuclear reactors to solving problems of processing and compacting highly-active radioactive waste.

**Krasnorutskyy, Volodymyr**, Ph.D. (Candidate of Science) in Physics and Mathematics, NFC STE NSC KIPT Director, senior staff scientist. He is a well-known expert in physical material science and development of materials for nuclear technologies. Author and co-author of over 400 research publications. In the Project he will be in charge of scientific and administrative management of all research activities.

**Gann, Volodymyr**, Doctor of Physics and Mathematics. He is a well-known expert in physical material science. In the Project he will participate in determining melt fluidity as a function of quantitative ratio of materials and their temperature.

**Kuznyetsova, Tamara**, deputy head of NSC KIPT division, develops and ensures physical protection and accounting of nuclear materials at every stage of their handling and use, immediately responsible for storage of nuclear materials and implementation of access procedures to the nuclear facility and to the nuclear materials. In the Project she will participate in development and implementation of measures on physical protection and accounting of nuclear materials at every stage of their handling and use.

**Grytsyna, Viktor**, NSC KIPT staff scientist. He is an expert in development of structural and fuel materials. His most noteworthy accomplishments consist in development of methods of thermo-mechanical treatment of uranium and zirconium alloys which significantly reduce their deformation under irradiation (STCU Project 349) and research into substantiation of operation life and reliability of fuel for various types of reactors. Author and co-author of over 30 research publications. In the Project he will participate in determining melt fluidity as a function of quantitative ratio of materials and their temperature.

**Tatarinov, Volodymyr**, Ph.D. (Candidate of Science) in Technical Sciences, NSC KIPT staff scientist. He is an expert in design and development of structural and fuel materials, methods, and processes of nuclear fuel and fuel rod manufacturing. His most noteworthy accomplishments consist in development of fuel materials and means of obtaining permanent joints in nuclear fuel rod and fuel assembly designs. Author and co-author of over 50 research publications. In the Project he will participate in management of activities.

**Danilov, Anatoliy**, NSC KIPT staff scientist. He is an expert in design and development of microspherical fuel materials, methods, and processes of nuclear fuel and fuel rod manufacturing for various purpose reactors. His most noteworthy accomplishments consist in development of dispersive nuclear materials and methods of obtaining microspheres from uranium compounds with protective coating and of powder mixes with specified grain-size and chemical composition. Author and co-author of over 60 research publications. In the Project he will participate in the upgrading of the available equipment and melt preparation.

**Yevseyev, Volodymyr**, NSC KIPT process engineer, 1st category. He is an expert in design and development of microspherical fuel materials, methods, and processes of manufacturing fuel from uranium powder materials for fuel rods of various purpose reactors. His most noteworthy accomplishments consist in development of methods to obtain powder mixes of specified grain-size and chemical composition. Author and co-author of over 20 research publications. In the Project he will participate in the upgrading of the available melting equipment.

**Dolgyi, Valeriy**, NSC KIPT process engineer, 1st category. He is an expert in design and development of vacuum technologies. His most noteworthy accomplishments consist in development of methods to spray heat-resistant materials. In this project he will participate in the upgrading of the available uranium melting equipment and development of methods, instructions and support documents during preparation, adjustment, and commissioning of the facilities for determination of viscosity and fluidity.

**Slabospytska, Olena**, Ph.D. (Candidate of Science) in Technical Sciences, NSC KIPT staff scientist. She is an expert in chemistry and metallography. Her most noteworthy accomplishments lie in the area of process flows for manufacturing fuel with additions of burnable absorber and research into the structure of compounds produced by interaction of fuel with structural materials and engineering structures. Author and co-author of over 20 scientific publications and reports at conferences. In the Project she will study the interaction of fuel components versus conditions of their production.

**Korneyeva, Vira**, Ph.D. (Candidate of Science) in Biological Sciences, NSC KIPT staff scientist. She is an expert in radiation hygiene. Her most noteworthy accomplishments consist in development of measures and guideline documents on radiation safety for operation with sources of ionizing radiation. Author and co-author of over 20 research publications. In the project she will participate in preparation of documents on radiation safety and development of guideline materials for conducting research.

**Kushtym, Yana**, NSC KIPT research engineer, 2nd category, post-graduate student. She is an expert in metallography. Her most noteworthy accomplishments lie in the area of process flows for manufacturing fuel with additions of burnable absorber and research into the structure of compounds produced by interaction of fuel with structural materials and engineering structures. In the Project she will study the structure of materials during melt formation.

**Svichkar, Natalia**, NSC KIPT analytical chemist. She is an expert in chemistry of fuel materials. In the Project she will study the chemical composition of produced melts.

**Gulko, Volodymyr**, research engineer, 2nd category. Search and procurement of the required equipment. Analysis of the materials' state by x-ray structural analysis.

### **4. Expected Results**

Upon work completion, the following will be accomplished:

- there will be studied the effects of fuel and absorber rod structural peculiarities on the nature of the beginning of interaction of UO2 + Zr; Ch18N10T + B4C; there will be obtained data on temperature parameters of the beginning of melt formation depending on the material state;

- there will be studied the processes of melt formation for new combinations of materials, mainly Ch18N10T+Dy2TiO5; Ch18N10T + B4C + (Dy2O3•TiO2); Zr + B4C + Hf, and interaction of these components with the melt of UO2 + Zr + Gd2O3 fuel materials.

- there will be studied the composition of forming melts;

- there will be obtained melts of VVER core materials, identified the effects of melting parameters (temperature, environment, time) on characteristics of the obtained materials, and determined parameters of melt viscosity and fluidity as a function of phase composition.

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| Deliverables | Due date  (by the end of Month \_\_) | To be submitted to (person, address) |
| Analyze literature data on interaction of materials in the core during severe accidents with core meltdown. Prepare categorized materials for conducting experiments | 1- 6 |  |
| Prepare model items from the researched structural elements. Obtain data on temperature parameters of the beginning of melt formation. Identify structural and phase composition of the mix | 1-18 |  |
| Determine the effects of structural peculiarities (close contact, availability of oxide on the surface) on the nature of the beginning of interaction of fuel and absorber rod materials. Study the structural state peculiarities of structural elements. | 7-21 |  |
| Determine melt viscosity and fluidity parameters as a function of phase composition. Compare the results of the structural and phase state of the melts after primary and secondary melting.  Analyze the results obtained | 10-24 |  |

### **5. Scope of Activities**

Overview and analyze national and foreign (theoretical and experimental) research and practice related to behavior of nuclear fuel in conditions simulating various development stages of design-basis and beyond design-basis accidents.

Upgrade and prepare process equipment and facilities for carrying out research. Select and prepare materials for experimental research.

Develop design and processes to manufacture sample fuel and absorber rods for research.

Develop experiment methodology.

Develop methodologies to study structure and composition of power reactors' core materials before and after their interaction.

Study and analyze physical-chemical interaction processes of the following materials: UO2, Gd2O3, alloy Zr1%Nb (E110), Ch18N10T, boron carbide, hafnium, dysprosium titanate.

Determine viscosity and fluidity of melts as a function of their phase composition.

Study behavior of molten fuel in various conditions and during its interaction with structural and construction materials. Carry out experiments to identify the effects of the environment (vacuum, atmosphere) and temperature modes on the parameters of the interacting products.

Study the melts obtained using the following methods: metallographic, x-ray structural analysis.

Study the phase composition of the formed melts and research the effects of changes in the phase composition of melts on melt fluidity.

Summarize and analyze the results obtained, compare the obtained data and proposed theoretical assumptions with the literature data and published results.

### **6. Technical Approach and Methodology**

National Science Center "Kharkiv Institute of Physics and Technology" has a license (AB No. 112916) to carry out activities with ionizing radiation sources. A Certificate by the Sanitary and Epidemiological Station of the Specialized Medical and Sanitary Division of the Ministry of Health of Ukraine dated Aug. 29 confirmed readiness of the workstations for Category 2 activities with open radioactive materials as of Sept. 3, 2007.

Implementation of the project will employ experimental research equipment to obtain melts of fuel and structural materials, and to study their phase composition, viscosity and fluidity. Methodologies for investigating material viscosity using plane-parallel plates and fluidity by pressing the melt through a calibrated aperture will be updated; there will be developed methodologies of lava-like fuel-containing mass fluidity by rotating a rod in the melt. Methodologies of metallographic research and of material chemical state analysis will be elaborated.

### **7. Project Location and Facilities**

The work will be performed at the site of the National Science Center "Kharkiv Institute of Physics and Technology" (NSC KIPT). NSC KIPT has the following equipment available:

a mixing installation;

a melting installation VUM-1;

laboratory scales;

exhaust hood;

a press for hot pressing;

a grinding machine;

metallographic microscopes MIM-10 and MIM-8;

a microhardness tester MPT-3;

an x-ray structural analysis installation DRON 3M;

a decontamination room, a ventilation system, and a radioactive drain for Category 2 activities.