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|  | PROJECT PROPOSAL | # |

## I. Summary Project Information

### 1. Project Title and Taxonomy

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| --- | --- | --- | --- |
| **Full title:** | **V**VER **E**xperiments on **R**elease due to **O**ver-heating: **N**ormal**I**zation and **K**nowledge **A**ugmentation VERONIKA | | |
| **Short title:** | VERONIKA Project | | |
| **Technology area:** | | Nuclear safety and assurance systems (FIR-NSS) | |
| **Category of technology development:** | | | Applied research |

### 2. Руководитель проекта

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Name:** | | | | | | Alexander V. Goryachev | | | | | |
| **Title:** | |  | | | | | **Должность:** | | | | Group leader |
| **Street address:** | | | | |  | | | | | | |
| **City:** | Dimitrovgrad-10 | | | | | | **City:** | | | Dimitrovgrad-10 | |
| **ZIP:** | | 433510 | | | | | **ZIP:** | | 433510 | | |
| **Tel.:** | | | (84235) 6-56-74 | | | | **Tel.:** | (84235) 6-57-64 | | | |
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### 3. Participating Institutions

#### 3.1. Leading Institution

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Short reference:** | | | | | | SSC RIAR | | | | | | | |
| **Full name:** | | | | | | Federal State Unitary Enterprise "State Scientific Centre Research Institute of Atomic Reactors | | | | | | | |
| **Дом, улица:** | | | | |  | | | | | | | | |
| **City:** | Dimitrovgrad-10 | | | | | | | **Region:** | | | | Uljanovsk | |
| **ZIP:** | | 433510 | | | | | | **Country** | | | Russia | | |
| **Name of Signature Authority:** | | | | | | | | | Alexander V.Bychkov | | | | |
| **Title:** | | Dr. | | | | | | **Position:** | | | | | Director of SSC RIAR |
| **Tel.:** | | | (84235) 3-52-80 | | | | | **Fax:** | | (84235) 3-56-48 | | | |
| **E-mail:** | | | | adm@niiar.ru | | | | | | | | | |
| **Governmental Agency:** | | | | | | | Federal Atomic Energy Agency | | | | | | |

#### 3.2. Other Participating Institutions

#### Participant Institution 1

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Short reference:** | | | | | IBRAE | | | | | | |
| **Full name:** | | | Nuclear Safety Institute of Russian Academy of Science | | | | | | | | |
| **Street address:** | | | | B. Tulskaya Street, 52 | | | | | | | |
| **City:** | Moscow | | | | | | | **Region:** | |  | |
| **ZIP:** | 115191 | | | | | | | **Country:** | | | Russia |
| **Name of Signature Authority:** | | | | | | | Leonid A. Bolshov | | | | |
| **Title:** | Dr., Professor | | | | | | | **Position:** | | Director | |
| **Tel.:** | (495) 952-24-21 | | | | | | | **Fax:** | (495) 958-00-40 | | |
| **E-mail:** | | bolshov@ibrae.ac.ru | | | | | | | | | |
| **Governmental Agency:** | | | | | | Russian Academy of Science | | | | | |
| **Sub-manager:** | | | | Mikhail S. Veshchunov | | | | | | | |
| **Title:** | Dr., Professor | | | | | | | **Position:** | | Head of laboratory | |
| **Tel.:** | (495) 955-22-18 | | | | | | | **Fax:** | (495) 958-00-40 | | |
| **E-mail:** | | vms@ibrae.ac.ru | | | | | | | | | |

### 4. Foreign Collaborators/Partners

#### 4.1. Collaborators

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Institution:** | | | | IRSN: Institut de Radioprotection et de Surete Nucleaire | | | | | | |
| **Street address:** | | | | | B.P.3 | | | | | |
| **City:** | SAINT PAUL-LEZ-DURANCE Cedex France | | | | | **Region/State:** | | | |  |
| **ZIP:** | F-13115 | | | | | **Country:** | | | France | |
| **Person:** | | | Roland.Dubourg | | | | | | | |
| **Title:** | | Dr | | | | **Position:** | | Research engineer | | |
| **Tel.:** | 33 4 42 19 95 02 | | | | | **Fax:** | 33 4 42 19 95 02 | | | |
| **E-mail:** | | | [roland.dubourg@irsn.fr](mailto:roland.dubourg@irsn.fr) | | | | | | | |

### 5. Project Duration

36 months

### 6. Project Location and Equipment

|  |  |
| --- | --- |
| **Организация** | **Местоположение, установки и оборудование** |
| **Leading Institution**  **SSC RIAR** | Russia, 433510, Ulyanovsk region, Dimitrovgrad-10.  All main equipment and auxiliaries will be placed in the RIAR buildings and installations.  Work will be fulfilled in the building 170 rooms: 312б б.к., 316 б.к., 208 б.к., hot cell 044 ; building 118 rooms: .53/7a, 53/5, 53/6, 66, 207, 208, 223, 304, 305, 311, 312, 319; building 117 rooms : 233, 108а, building 103.  The existing equipment which will be used at Project realisation:  test reactors МIR.М1 and RBТ-10/2, the reloading equipment, a dismantable irradiation facility, hot cell ГК-2 (building 170);  hot cells, the in-hot cell equipment, devices for definition of the exposition dose of samples, milling machine for irradiated items and samples cut, grinding-polishing machines, installations for the remote cutting and polishing, remote microhardness meter ПМТ-6 and metalurgical microscopes МИМ-15 (building 118, hot cells К-1, К-2, К-3, К-4, К-5, К-7, ВК-24, ВК-26, ВК-27, ВК-42);  scanning electron microscope Philips XL 30ESEM-TMT;  electron probe microanalyzer MAR-4;  heavy boxes 1-6 (room108а, building 117);  The equipment to be modernized or purchased for the Project performance:  a metallurgical microscope; the equipment for the sample preparation for metallographic and SEM examinations;   spectrometers, measuring, registering, and dosimeter devices;  The computers and copy technique. |
| **Participant Institution IBRAE** | The computers and copy technique |

### 7. Общие трудозатраты по проекту

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| --- | --- |
| Общее количество участников | 67 |
| Количество «оружейных» специалистов | 32 |
| Общие трудозатраты (в человеко-днях) | 18400 |
| Общие трудозатраты «оружейных» специалистов (в человеко-днях) | 11500 |

### 8. Financial Information

#### 8.1. Estimated Project Costs

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| --- | --- |
| **Estimated total cost of the project (US $)** | 960000 |
| *Including:* |  |
| **Payments to Individual Participants** | 570 000 |
| **Equipment** | 295000 |
|  |  |
| **Materials** | 37 000 |
| **Other Direct Costs** | 20000 |
| **Travel** | 23000 |
| **Overhead** | 15 000 |

#### 8.2. Funding Sources

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| --- | --- |
| **Estimated total cost of the Project (US $)** | 960000 |
| *Financial Sources:* |  |
| **Requested from the ISTC** | 960000 |
| **Other financial source 1** | - |
| **Other financial source 2** | - |
| *Non-Financial Sources:* |  |
| **Non-financial source 1** | - |
| **Non-financial source 2** | - |

### 9. Short Project description

The necessary condition to increase the nuclear power plants safety it is a creation of reliable physical models and codes able to describe the behaviour of fission products (FP) in the uranium dioxide matrix and their release to the containment at high temperatures and a wide spectrum of environmental conditions (a various steam concentrations in presence of hydrogen formed as a result of a steam-zirconium reaction). Prediction of the fission products release at core beyond-design basis accident case is necessary for the radiation risk assessment and development of adequate measures to prevent the FP leak to the containment. Taking into account a variety of the possible beyond-design-basis accident conditions with heavy fuel damage the decision of this problem is possible only on the basis of model-based analysis.

One of the most reliable codes to solve this problem it is a MFPR code developed in IBRAE. The physical models included in the MFPR code allow describing all set of the FP release processes including diffusion of FP atoms in the crystal lattice, formation and migration of gas bubbles to the grain boundaries, their coalescence, formation of open porosity and release from fuel. Mechanistic character of the models implemented in the code assumes necessity of verification against the test results of both separate mechanisms and integrated results of calculation.

The purpose of the offered project is the realization of the tests aimed at the acquisition of data necessary for the perfection of the MPFR code physical models describing behaviour FP in a crystal lattice and verification of the calculation results

The Project structure includes three interrelated tasks:

manufacturing of the installation for the FP release examination at temperatures up to 2300 °C in oxidizing and a reducing conditions;

realization of the tests using the uranium dioxide with high FP concentration;

improvement of the models implemented in MPFR code on the base of obtained results.

The experimental part of the Project includes tests on examination of the FP release from irradiated uranium dioxide in which the structure of the intragranular and intergranular pores was formed that will allow estimating the working capacity of code models considering matrix microstructural parameters by means of the comparison of experimental and calculated results.

For the acquisition of data necessary for verification of the code diffusion models the tested samples will be subjected to an additional short-term irradiation at a low temperature. The purpose of an additional irradiation consists in accumulation of low concentration of short-lived FPs in solid solution in the uranium dioxide matrix. Experimental definition of their release kinetics will allow the verification of all the set of code models from diffusion of separate atoms to their release through a network of porosity both formed as a result of the base irradiation and developing as a result of heating up to temperatures, characteristic for the beyond-design basis accident. Planned tests in oxidizing and reducing environments have for an object to define the influence of fuel stehiometry on the model-based diffusion processes

Owing to essential influence of structure modifications (formation of the open and closed porosity, and inclusions influencing moving of gas bubbles) on a FP release the extensive program of post-test examination of uranium dioxide structure is planned in the experimental part of the work. A main objective of examinations is the careful definition of morphology of porosity, as a key parameter influencing a FP release and predicted by code (verification of results of calculation). The estimation of the inclusions structure and morphology formed in the uranium dioxide matrix at high-temperature heating, also will allow the verification of code diffusion models.

The variation of parameters (temperature, environment) of the planned tests having character of parametrical tests, does not cover a possible range of the beyond-design-basis accident conditions which generally are not well known, but the obtained data will allow improving the code physical models and to raise the reliability of code predictions. In view of high complexity, laboriousness and duration of each test, the matrix of tests in the range parameters of interest is divided in two parts. During the offered Project the first part consisting of ten tests will be executed. Realization of the second part supposed as possible continuation of examinations within the framework of the subsequent Project in dependence and taking into account the results to be obtained at realization of the first part.

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|  | PROJECT PROPOSAL | # |

## II. Detailed Project Information

### 1. Introduction and Overview

Now within the framework of nuclear power plants safety validation one of actual problems is code development for the FP release under the conditions of a beyond-design basis accident. Solution of this problem assumes carrying out of the considerable number of tests on examination of FP release and computational modelling. It is connected with the fact that beyond-design-basis accident conditions are characterized by considerable ranges of possible change of external parameters (temperature, an oxygen potential of the gas environment, pressure), that in turn causes complexity and variety of the processes causing the FP release. At the moment the coordination of examinations is in progress within the framework of European SARNET program (6th Framework). The optimization of the volume of necessary experimental and modelling works is possible, if at code development consider the reached level of the FP release modelling, based on experimental programs: HI-VI (ORNL), VERCORS (CEA), VEGA (JAERI), and also experimental data and the software products which are available in Russia at the moment. The purpose of this Project consists in obtaining of the experimental data, development and improvement on the basis of the obtained data of the physical models, development and verification of MPFR code

Considering problems to be solved the Project is named VERONIKA (**V**VER **E**xperiments on **R**elease due to **O**ver-heating: **N**ormal**I**zation and **K**nowledge **A**ugmentation).

Developers and executors of the project, RIAR and IBRAE the Russian Academy of Sciences, have the cooperation experience in the experimental research and modelling of the FP release under the accident conditions. In RIAR to the present time several series of tests on FP release examination are realized at heating up in inert, air and steam environments. Results of these tests were used by IBRAE for development of the detailed mechanistic MFPR code, which is developed throughout last 10 years together with IRSN (Cadarache, France) for modelling of the FP release from uranium dioxide under the accident conditions.

Realization of these works is the necessary precondition for computational modelling of FP behaviour under the severe accident conditions. On the one hand, they have provided development of physical representations and models of the FP release at elevated temperatures in the inert environment. On the other hand - the accumulation of necessary methodical experience for carrying out of tests in more demanding conditions typical for the severe accidents.

Within the framework of the Project it is planned to carry out the examinations of the FP release from uranium dioxide with burnup of 60 MW d/kg U in steam, steam-hydrogen and air environments at temperatures from 1400 to 2300°С, those are in the range of temperatures and gas environments, typical for a severe accident. Unlike earlier RIAR tests, it will be investigated the behaviour of the representative set of fission products, including short-lived isotopes (85Kr, 133Xe, 131I, 137Cs, 134Cs, 106Ru, 103Ru, 144Ce, 99Mo, 140Ba, 95Zr, 125Sb, etc.), that will be provided by preliminary short-term irradiation of the fuel samples in the RIAR test reactors before the tests.

**VERONIKA Project includes the following parts:**

**Part A. VVER FUEL-FPR: Experimental study of the fuel behavior and fission products release at temperatures and gas environments, typical for severe accidents.**

At this stage the experimental rig will be manufactured, the tests on examination of radio-activ fission products release from uranium dioxide with a high burnup at heating in oxidizing and reducing gas environments, and also post-test examinations of samples will be done. Two types of samples will be used: a pellet (fragments) without a cladding and a pellet in a cladding.

The executor of the Project Part A: RIAR, the co-executor: IBRAE

**Part B. MFPR: Improvement of models and codes for description of fission products and highly irradiated VVER fuel behavior under the conditions of severe accidents without fuel melting.**

The experimental results to be received will allow developing the theoretical models of the FP release from uranium dioxide under the conditions of a severe accident and improvement and adaptation of codes and the physical models developed for foreign installations, with reference to the Russian ones.

The executor of the Project Part B: IBRAE, the co-executor: RIAR.

### 2. Expected Results and Their Application

The main results of investigation will be development of experimental database and improvement of the codes describing the fission products release from irradiated VVER fuel under conditions of severe accidents.

The obtained results will allow estimation of the possible consequences of accident, determination of measures on their reduction and developing the advanced safety criteria.

### 3. Meeting ISTC Goals and Objectives

The Project gives an opportunity for the scientists and engineers connected with the military developments to reorient their ability to peace activity.

Work under the Project in cooperation with foreign collaborators provides integration of Russian scientists in the international scientific community.

The Project represents applied research in the peace purposes, directed to increase the nuclear safety of energy generation and provides solution of national and international problems.

### 4. Scope of Activities

The Project consists of two Parts. Within the framework of the first Part the test rig will be manufactured and tests with irradiated fuel samples will be carried out. In the second Part the processing of experimental results, development of physical models and validation of numerical codes will be carried out.

#### Task 1

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| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| **Test plan development**  In this stage basing on pre-test MFPR calculation the test parameters and conditions, volume and structure of post-test examinations including amount of necessary complimentary experiments should be defined. | | 1- RIAR  2- IBRAE |
| Description of deliverables | | |
| 1 | Test program | |

#### Task 2

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| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| Manufacturing of the test rig  This stage includes the necessary equipment purchase, equipment arrangement, test rig adjustment and putting into operation. | | 1- SSC RIAR |
| Description of deliverables | | |
| 1 | Report | |

#### Task 3

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| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| **Test execution**   * Preparation and certification of fuel samples, including pre-irradiation for accumulation of short-lived fission products; * Carrying out of 10 tests in accordance with the test program. | | 1- SSC RIAR |
| Description of deliverables | | |
| 1 | Intermediate report | |

#### Task 4

|  |  |  |
| --- | --- | --- |
| Task description and main milestones | | Participating Institutions |
| **Post-test examinations**  The work includes the examination of the tested fuel samples to obtain of the following characteristics:   * Fuel microstructure; * Fuel oxidation (experiments in steam environment); * The local content and radial distribution of FP, U, Pu; * Content of metal inclusions in the fuel. | | 1- SSC RIAR |
| Description of deliverables | | |
| 1 | Intermediate report | |

#### Task 5

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| --- | --- | --- |
| Task description and main milestones | | Participating Institutions |
| **The analysis of test results**   * Obtained experimental data processing, development of the experimental database for models and codes. | | 1- SSC RIAR  2- IBRAE |
| Description of deliverables | | |
| 1 | Final report | |

#### Task 6

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| --- | --- | --- |
| Task description and main milestones | | Participating Institutions |
| **Preparation and adaptation of models and codes**   * Simulation using the MFPR code of an initial state of irradiated fuel and comparison of calculated micro-structural characteristics of fuel with results of measurement; * Adaptation of MFPR code to conditions of new experiments, in view of complex physical and chemical conditions of the gas environment; * Preparation of new input files for the code application to the test conditions. | | 1- IBRAE |
| **Description of deliverables** | | |
| 1 | Intermediate report | |

#### Task 7

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| **Task description and main milestones** | | **Participating Institutions** |
| **Processing, analysis and modelling of the experiments**   * Simulation of new experiments with the base version of the MFPR code and comparison with experimental results on various fission products release, microstructure, swelling and extend of fuel oxidation (hyper-stoichiometry); * Revealing the reasons of divergence of calculation results with experimental data and formulation of requirements for improvement of existing and development of new models; * Correction of conditions of the subsequent tests. | | 1- IBRAE |
| **Description of deliverables** | | |
| 1 | Intermediate report | |

#### Task 8

|  |  |  |
| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| **Development and improvement of theoretical models**  The work to be carried out on the basis of requirements formulated in **Task 7** | | 1- IBRAE |
| **Description of deliverables** | | |
| 1 | Intermediate report | |

#### Task 9

|  |  |  |
| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| **Implementation of the models in the MFPR code and code validation**   * Implementation of the new models (developed in **Task 8**) in the MFPR code; * Simulation of experiments by the improved version of the MFPR code, revealing and analysis of differences with results of the base code version (obtained in **Task 6**); * Application of the new code version to simulation of the VERCORS-type experiments carried out earlier with PWR fuel samples under similar experimental conditions. | | 1- IBRAE |
| **Description of deliverables** | | |
| 1 | Final report | |

#### Task 10

|  |  |  |
| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| **Comparison of experimental results and calculations**   * Comparison of calculation results obtained using the improved version of the MFPR code (obtained in **Task 9**) with experimental data on various fission products release, fuel microstructure, fuel swelling and oxidation (obtained in **Task 4**); * Formulation of the basic conclusions from the analysis of highly irradiated fuel behaviour under severe accident conditions. | | 1- IBRAE  2- SSC RIAR |
| **Description of deliverables** | | |
| 1 | Final report | |

### 5. Role of Foreign Collaborators/Partners

IRSN takes part in development of the test matrix and the procedure of the tests execution, in the analysis of the results and comparison of VVER and PWR fuel behaviour. IRSN integrates the results of experiments and/or the models developed within the frames of the Project, into IRSN computer codes (ASTEC code and mechanistic code MFPR).

### 6. The technical approach and methodology

The purpose of tests consists in obtaining of the experimental data on a FP release, including short-lived isotopes, uranium dioxide microstructural change at temperatures and gas environments typical for severe accident, for the subsequent development of models and code verification.

Samples of uranium dioxide for testings are selected with burnup of 60 МWd/kgU. It is supposed use of the samples of two kinds:

 the fuel rod fragments with genuine cladding

bare pellet without a cladding.

Sample preparation procedure includes the following main stages:

* manufacturing and certification of the irradiation capsule with samples;
* irradiation of the irradiation capsule in the RIAR test reactor for accumulation of short-lived fission products;

certification of the irradiated capsule;

samples withdrawal from the irradiated capsule.

Tests will be carried out on the basis of experience of similar works carried out in RIAR earlier [1-4].

It supposed to realize the tests on the experimental rig which basic diagramme is presented in figure 1.

The following test modes are assumed:

the maximal temperature of 2300 °С

the gas environment: argon - hydrogen, argon - steam, air

the heating in the inert environment up to temperature of 600°С

the heating from 600 to 1400 °C at a rate of ~ 5°С/s

the holding at temperature of 1400°С during time defined by a test program

 the heating to a target temperature (1700 or 2300°C) at a rate of ~1°С/s

the holding at the reached temperature during time defined by a test program

 heating switch-off and cooling the sample with the heating module.



Figure 1Test rig

The parametres to be controlled during the test:

 sample temperature

 pressure at the inlet of the heating module channel

 gas mixture flow rate

 steam flow rate.

The parametres to be measured during the test:

* activity 85Kr and 133Xe at the outlet
* activity FP in the fuel sample
* activity FP in the main filter
* hydrogen content in the outlet flow.

Post-test examinations will include:

Quantitative metallography of the tested samples with definition of the following parametres: grain size; intergranular porosity; intragranular porosity.

EPMA and scanning electron microscopy for definition of a local content and radial distribution of FP, U, Pu, element structure of metal inclusions in samples after tests in the reducing gas environment.

Following results will be presented:

the fractional release of fission products as function of temperature and time

the hydrogen release in the gas environment at uranium dioxide oxidation in the steam environment as function of time

characteristics of the microstructure of the tested samples (grain size, porosity)

post-test element structure of the phases and inclusions.

The test matrix includes 10 tests with samples in the form of the pellet fragment with the genuine cladding without end caps and in the form of the pellet without a cladding. The gas environments are: steam - argon mixture, hydrogen - argon mixture, air (see table 6.1.).

Table 6.1. – Test matrix

|  |  |  |  |
| --- | --- | --- | --- |
| **Test #** | **Sumple** | **Gas environment** | **Test temperature (°C)** |
| 1 | Bare pellet | H2O/Ar | 1700 |
| 2 | Bare pellet | H2/Ar | 1700 |
| 3 | Bare pellet | H2O/Ar | 1400 |
| 4 | Bare pellet | H2O/Ar | 2300 |
| 5 | Bare pellet | H2/Ar | 1400 |
| 6 | Bare pellet | H2/Ar | 2300 |
| 7 | Bare pellet | Air/Ar | 1400 |
| 8 | Bare pellet | Воздух /Ar | 1700 |
| 9 | Pellet in the cladding | H2O/Ar | 1700 |
| 10 | Pellet in the cladding | Air/Ar | 1700 |

As the subsequent continuation of works within the framework of the separate Project the carrying out the second series of tests (Table 6.2) is considered

Table 6.2 the Matrix of the second series of tests

|  |  |  |  |
| --- | --- | --- | --- |
| **Test #** | **Sumple** | **Gas environment** | **Test temperature (°C)** |
| 11 | Pellet in the cladding | H2O/ H2 | 1400 |
| 12 | Pellet in the cladding | H2O/ H2 | 1700 |
| 13 | Pellet in the cladding | H2O/ H2 | To be defined |
| 14 | Pellet in the cladding | H2O/Ar | 1400 |
| 15 | Pellet in the cladding | H2O/Ar | To be defined |
| 16 | Pellet in the cladding | Air/Ar | 1400 |
| 17 | Pellet in the cladding | Пар/Air | 1400 or 1700 |
| 18 | Bare pellet | H2O/ H2 | 1400 |
| 19 | Bare pellet | H2O/ H2 | 1700 |

**Part B. MFPR: Improvement of models and codes for description of fission products and highly irradiated VVER fuel behaviour under conditions of severe accidents without fuel melting.**

The numerical MFPR code is developed during last 10 years in collaboration between IBRAE and IRSN for modelling of the fission products release from fuel in various accident conditions [4-7].

For today the code most completely (in comparison with analogues) and mechanistically describes behaviour and release of the fission products (both gas, and chemically active) from fuel rods at accidents with a heating up of highly irradiated uranium dioxide, including core melting. Release the following chemical elements is simulated by the code: Xe, Cs, Ce, I, Eu, Mo, Nd, Ru, Nb, Ba, Sb, Sr, Te, Zr, Xe, La. Diffusion and an release of chemically active fission products is described in the frames of a multi-phase multi-component chemical model with the limited nomenclature of compounds.

The code contains the models for calculation of gas, volatile and non-volatile FP accumulation in the grains, in the closed porosity and in the fuel rod gap, depending on initial structure of fuel (the grain size and density), power level and burnup of the fuel. Simultaneously with calculation of FP accumulation during fuel burnup the change of grain structure characteristics (growth of grains, additional sintering, growth of intragranular and intergranular bubbles, generation and growth of dislocations) is calculated self-consistently. Distributions of FP in the fuel rods are the input data for determination by the code of the fission products in case of accidents.

The code contains the models for calculation of FP release rate during the fuel heating up considering formation of the open porosity owing to growth of pores on grain boundaries. Simultaneously with calculation of FP release the code allows to describe increase in a fuel swelling and grain growth as well as experimentally observable change in size distribution of intragranular and intergranular bubbles.

The code contains the models for calculation of FP release rate during thermal annealing due to thermal diffusion and biased migration of atoms and gas bubbles directed to the grain boundaries in a vacancy field gradient. For high temperatures the code describes the increase in FP release rate due to the grain growth as well as the burst FP release due to sweeping of gas bubbles by the dislocations to the grain boundaries as a result of high-temperature dislocations annealing.

The model of uranium dioxide oxidation allows considering influence of such factors as oxidizing properties of gas-steam environments (partial pressure of oxygen), temperature of heating, duration of annealing and physical and chemical properties of FP, in particular, their ability to oxidation and formation of complex oxide compounds (so-called molibdates, zirconates and uranates).

The code is successfully verified and applied to the description of experiments with the irradiated fuel in conditions of a steady-state irradiation, high-temperature annealing, transient conditions, design basis accidents (LOCA) and severe accidents, in particular, for modelling of the VERCORS-type tests with fragments of a fuel rod in an oxidation-reduction atmosphere [8], RIAR tests on FP release during annealing at temperatures up to 2000°С, and also integral experiments Phebus FP [9]. Also this code was successfully applied for modelling of the in-pile experiments (for example, international HALDEN project) with the irradiated fuel in transient conditions.

The MFPR code is planned to be used at the first stage of the offered ISTC Project for pre-test calculations of new experiments for the determination of parameters and conditions of tests. Also the code will be used for the processing and analysis of results of new experiments. On the basis of the obtained experimental data the development and improvement of the code theoretical models on fission products release and high burnup VVER fuel behaviour in conditions of severe accident will be done. The developed and improved models will be implemented in the MFPR code which will be verified against the new experimental database and other new available data at the end or during the program.

**References**

1. I.A.Kungurtsev, V.A.Zhitelev, V.V.Chesanov etc, "Study of the Inert Gas Release and Structural Changes of the VVER Spent Fuel at Heating above the Operating Temperature." Transactions of the sixth Russian Conference on Reactor Material Science, Dimitrovgrad, 2000, Vol. 2, Part 3, pp. 30 ‑ 45.
2. I.A.Kungurtsev, V.V.Chesanov, I.V.Kuzmin and L.N.Stupina, "Some Regularities of High-Temperature Oxidation and Hydrogen Saturation of Spent VVER Fuel Rod Claddings." Transactions of the sixth Russian Conference on Reactor Material Science, Dimitrovgrad, 2000, Vol. 2, Part.1, p.p. 285 ‑ 302.
3. Investigation of fission products release and structural changes of VVER spent fuel in inert and oxidizing environment. I.A. Kungurtsev, V.P. Smirnov, V.V.Chesanov etc, Proceedings of Technical Committee meeting held in Dimitrovgrad, 9-13 October 1995, p.79, IAEA
4. Экспериментальный стенд для исследования поведения материалов отработавших твэлов в условиях, характерных для аварийных ситуаций. И.В Кузьмин, И.А. Кунгурцев, В.В Чесанов, Сборник трудов НИИАР, 2000 г.
5. M.S. Veshchunov, V.D. Ozrin, V.E. Shestak, V.I. Tarasov, R. Dubourg, G. Nicaise, “Development of the mechanistic code MFPR for modelling fission products release from irradiated UO2 fuel”, Eng.& Des., v. 236, 2006.
6. M.S. Veshchunov, V.D. Ozrin, V.E. Shestak, V.I. Tarasov, R. Dubourg, G. Nicaise, “Modelling of Defect Structure Evolution in Irradiated UO2 Fuel in the MFPR Code”, Proceedings of the 2004 International Meeting on LWR Fuel Performance Orlando, Florida, September 19-22, 2004, Paper 1085.
7. M.S. Veshchunov, A.V. Berdyshev, V.D. Ozrin, V.E. Shestak, V.I. Tarasov, “Development of mechanistic code MFPR for modelling fission product release from irradiated UO2 fuel. Part1: Development and validation of new models,” – Proc. Internat. Conference “TopFuel 2003: Nuclear Fuel for Today and Tomorrow. Experience and Outlook”, March 16 to 19, 2003, Würzburg, Germany, INFORUM GmbH 2003
8. R. Dubourg, G. Nicaise, “Development of mechanistic code MFPR for modeling fission product release from irradiated UO2 fuel. Part2: Application to integral tests VERCORS 4/5 and PHEBUS FPT0/1,” Proc. Internat. Conference “TopFuel 2003: Nuclear Fuel for Today and Tomorrow. Experience and Outlook”, Würzburg, Germany (March 16 to 19, 2003).
9. M.S. Veshchunovand R. Dubourg, “Numerical simulation of fission product release under accidental conditions with the MFPR code”, EUROSAFE 2004, Berlin, November 8-9, 2004.
10. R. Dubourg, H. Manenc, G. Nicaise, M. Barrachin “FP release in the first two PHEBUS tests FPT0 and FPT1” Nucl. Eng. Des. 235 (2005) 2183–2208.

### 7. Technical Schedule

|  | **Quarter 1** | **Quarter 2** | **Quarter 3** | **Quarter 4** | Quarter 5 | **Quarter 6** | **Quarter 7** | **Quarter 8** | **Quarter 9** | **Quarter 10** | **Quarter 11** | **Quarter 12** | **Person\* days** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Task 1  Test plan development** | Test program |  |  |  |  |  |  |  |  |  |  |  |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 2 Manufacturing of the test rig** |  |  |  | Report |  |  |  |  |  |  |  |  |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 3  Test execution** |  |  |  |  |  |  |  | Intermediate report |  |  | Intermediate report |  |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 4  Post-test examinations** |  |  |  |  |  |  |  |  | Topical meeting |  |  | Intermediate report |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 5  The analysis of test results** |  |  |  |  |  |  |  |  | Topical meeting |  |  | Final report |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 6  Preparation and adaptation of models and codes** |  |  |  |  | Intermediate report |  |  |  |  |  |  |  |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 7  Processing, analysis and modelling of experiments** |  |  |  |  |  |  |  | Intermediate report |  |  |  |  |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 8  Development and improvement of theoretical models** |  |  |  |  |  |  |  |  | Intermediate report |  |  |  |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 9 Implementation of the models in the MFPR code and code validation** |  |  |  |  |  |  |  |  |  |  | Intermediate report |  |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Task 10 Comparison of experimental results and calculations** |  |  |  |  |  |  |  |  |  |  |  | Final report |  |
| **Person\*days** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **TOTAL** |  |  |  |  |  |  |  |  |  |  |  |  |  |

### 9. Financial Information

### 9.1. Estimated Project Costs (US $)

|  |  |
| --- | --- |
| **Estimated total cost of the project** | 800000 |
| **Leading Institution SSC RIAR** | 683800 |
| **Participant Institution 1 IBRAE** | 116200 |

#### 9.1.1. Payments to Individual Participants (US $)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Institution** | **Category I** | **Category II** | **Supporting personnel** | **Total** |
| **Leading Institution** SSC RIAR |  |  |  | 290000 |
| **Participant Institution 1** IBRAE |  |  |  | 100000 |
| ***Subtotal:*** | | | | **390000** |

#### 9.1.2. Equipment

|  |  |  |
| --- | --- | --- |
| **Institution** | **Equipment description** | **Cost (US $)** |
| **Leading Institution** SSC RIAR | * Installation of induction heating * System of the evaporation and mixture control * Pyrometer М780 * Detectors on the basis of superpure Ge with a preamplifier, the power supply, 40 КэВ-10МэВ * Gamma spectrometer of 16 channels, 130000 imp/s, a software package * Computers * Gas mass spectrometer * Flowmeters and regulators of the gas flow * Pressure transducers and pressure regulators * Gas fitting * Cardboards for control and data acquisition system | 292500 |
| **Participant Institution 1** IBRAE | Computers  Copying technics | 2500 |
| ***Subtotal:*** | | **295000** |

#### 9.1.3. Materials

|  |  |  |
| --- | --- | --- |
| **Institution** | **Materials description** | **Cost (US $)** |
| **Leading Institution** SSC RIAR | * thermocouples * high-temperature ceramics * tungsten tubes | 37000 |
| **Participant Institution 1** IBRAE |  | 0 |
| ***Subtotal:*** | | **37000** |

#### 9.1.4. Other Direct Costs

|  |  |  |
| --- | --- | --- |
| **Institution** | **Direct costs description** | **Cost (US $)** |
| **Leading Institution** SSC RIAR |  | 18000 |
| **Participant Institution 1** IBRAE |  | 2000 |
| ***Subtotal:*** | | **20000** |

#### 9.1.5. Travel costs (US $)

|  |  |  |  |
| --- | --- | --- | --- |
| **Institution** | **CIS travel** | **International travel** | **Total** |
| **Leading Institution** SSC RIAR |  | 11400 | 11500 |
| **Participant Institution 1** IBRAE |  | 11400 | 11500 |
| ***Subtotals:*** |  | 22800 | 23000 |

#### 9.1.6. Overhead (US $)

|  |  |  |
| --- | --- | --- |
| **Institution** |  | **Amount** |
| **Leading Institution** SSC RIAR |  | 12700 |
| **Participant Institution 1** IBRAE |  | 2300 |
| ***Subtotal:*** | | 15000 |

### 9.2. Funding Sources

|  |  |
| --- | --- |
| **Estimated total cost of the project (US $)** | 777400 |

#### 9.2.1. Financial Sources

|  |  |  |
| --- | --- | --- |
| **Financial Source** | **Written confirmation (Y/N)** | **Amount**  **(US $)** |
| **Requested from the ISTC** |  | 960000 |
| Other financial source 1 |  | - |

#### 9.2.2. Non-Financial Sources

|  |  |  |  |
| --- | --- | --- | --- |
| **Source** | **Short description of contribution** | **Written confirmation (Y/N)** | **Estimated**  **amount**  **(US $)** |
|  |  |  |  |
|  |  |  |  |

#### 9.2.3. Submitted for Funding to Program beside the ISTC

### 10. Intellectual Property Statement

The rights for intellectual property that are generated during the course of the project will be regulated by the laws of the Russian Federationand by the procedures, which have been developed by the ISTC.

The general conditions on Intellectual Property Rights as described in the Model Project Agreement will be observed.

### 11. Monitoring and Auditing Statement

In accordance with Article VIII of the ISTC Agreement, project recipients will give to the Center and to each Party which wholly or partly finances a project the right of access to carry out on-site monitoring and audit of all activities of the project. Project agreements will specify the portions of facilities, equipment, documentation, information, data systems, materials, supplies, personnel, and services which will concern the project and therefore will be made accessible for monitoring and audit. Project recipients shall have the right to protect those portions of facilities that are not related to the project.