|  |  |  |
| --- | --- | --- |
|  | PROJECT PROPOSAL | # |

## I. Summary Project Information

### 1. Project Title and Taxonomy

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **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 investigation |

### 2. Project Manager

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Name:** | | Valeri P.Smirnov | | | | | | |
| **Title:** | Dr., Professor | | | | **Position:** | | Head of Fuel Research Department | |
| **Street address:** | | | |  | | | | |
| **City:** | Dimitrovgrad-10 | | | | **Region:** | | Uljanovsk | |
| **ZIP:** | 433510 | | | | **Country:** | | | Russia |
| **Tel.:** | (84235) 6-57-64 | | | | **Fax:** | (84235) 6-56-63 | | |
| **E-mail:** | | | jvv@niiar.ru | | | | | |

### 3. Participating Institutions

#### 3.1. Leading Institution

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Short reference:** | | | | | SSC RIAR | | | | | | |
| **Full name:** | | | State Scientific Centre Research Institute of Atomic Reactors | | | | | | | | |
| **Street address:** | | | |  | | | | | | | |
| **City:** | Dimitrovgrad-10 | | | | | | | **Region:** | | Uljanovsk | |
| **ZIP:** | 433510 | | | | | | | **Country:** | | | Russia |
| **Name of Signature Authority:** | | | | | | | Alexei F. Grachev | | | | |
| **Title:** | Dr., Professor | | | | | | | **Position:** | | Director of SSC RIAR | |
| **Tel.:** | (84235) 3-52-80 | | | | | | | **Fax:** | (84235) 3-56-48 | | |
| **E-mail:** | | adm@niiar.ru | | | | | | | | | |
| **Governmental Agency:** | | | | | | Ministry for Atomic Energy | | | | | |

#### 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

|  |  |
| --- | --- |
| **Institution** | **Location, Facilities and Equipment** |
| **Leading Institution**  **SSC RIAR** | Fuel Element Department. Hot cells and equipment of hot examination laboratory:  Test rig |

### 7. Financial Information

#### 7.1. Estimated Project Costs

|  |  |
| --- | --- |
| **Estimated total cost of the project (US $)** | 777400 |
| *Including:* |  |
| **Payments to Individual Participants** | 370000 |
| **Equipment** | 232600 |
| **Materials** | 37000 |
| **Other Direct Costs** (Sample pre-irradiation) | 100000 |
| **Travel** | 22800 |
| **Overhead** | 15000 |

#### 7.2. Funding Sources

|  |  |
| --- | --- |
| **Estimated total cost of the project (US $)** | 777400 |
| *Financial Sources:* |  |
| **Requested from the ISTC** | 777400 |
| **Other financial source 1** | - |
| **Other financial source 2** | - |
| *Non-Financial Sources:* |  |
| **Non-financial source 1** | - |
| **Non-financial source 2** | - |

|  |  |  |
| --- | --- | --- |
|  | PROJECT PROPOSAL | # |

## II. Detailed Project Information

### 1. Introduction and Overview

One of the major nuclear reactor safety basic aspects is a computer modelling of radioactive fission products (FP) release from the fuel in conditions of steady-state operation, design and severe accidents. Development and improvement of numerical codes is an iterative process in which the cycle «obtaining of experimental data − physical models development − computer modelling» repeats. It provides an improved representation of mechanisms and more exact quantitative prediction of FP release. New experimental results and the physical models developed in any scientific centre are integrated into a total sum of knowledge of the investigated phenomenon that allows revealing new problem aspects for other researchers.

Extension of the burn-up of the light water reactors (LWR) fuel is commercially in progress either for Russian (VVER) or for Western (PWR) types of reactors. The aim is to reduce the amount of total processing turnover within the nuclear fuel cycle and to improve the costs of fuel fabrication, intermediate storage, transport and reprocessing. One of the key issues for this technological step is to understand and ultimately control the fuel micro-structural changes (defects accumulation, swelling, restructuring, etc.) and FP release.

Currently the development of new codes and improvement of existing ones, in order to predict high burnup fuel degradation and FP release under severe accident conditions, is an important problem related to LWR safety problem. The solution of this problem assumes realization of an extensive program including significant number of experiments and FP release modelling, since the severe accidents conditions are characterized by extended ranges of possible external parameters variation (temperature, oxygen potential of the gas environment, pressure, fuel micro-structure), that in turn causes complexity and variety of the processes defining fuel degradation and FP release.

The amount of necessary experimental and modelling works for VVER fuel may be optimized taking into account the current level of PWR fuel FP release modelling based on experimental programs HI-VI (ORNL), VERCORS (CEA), VEGA (JAERI) as well as the experimental database and fuel performance codes for VVER fuel, available in Russia at the moment. A necessary condition is confirmation of validity of the existing PWR fuel databanks to the VVER fuel under severe accident conditions.

On the other hand, the previous experimental programs revealed necessity of mechanistic modelling improvement for high burn up fuel. The main reason for this problem is connected with accurate representation of fuel microstructure evolution during long-term operation in power reactors and under transient and accident conditions. Such very analytical data on FP behaviour and fuel micro-structure were not available from previous tests, since they were not clearly devoted to code development but rather to source term evaluation. That is why a new analytical program connected to previous experiments is required, in order to propose improved modelling. The analytical character of the data needed for code development implies that the program must include many tests with many characterisations.

Thus the main point of the new project is to have at the end of project a new code able to give reliable results for all burn ups of the UO2 fuel. This code could be further validated against new experiments, for example, the foreseen European program VERDON. In this sense the VERONIKA project and future source term experiments would not be opposite but rather complementary to each other.

Also, the new code can be used as “benchmark” for the simplified modelling included in reactor codes (European ASTEC or Russian RATEG/SVECHA).

Therefore, the objective of the proposed Project is to obtain very analytical experimental data on fission products behaviour and release from highly irradiated VVER fuel as well as fuel micro-structure evolution, and to use these results for the development (and validation) of the numerical codes describing fuel behaviour and fission products release under severe accident conditions. Its realization will allow solution of the following problems:

* To receive a new very analytical experimental data on FP release and behaviour under the insufficiently investigated conditions for PWR and VVER fuel;
* To improve existing physical models, to develop and validate the codes predicting FP release under severe accident conditions basing on the existing and newly obtained data for VVER fuel;
* Basing on results of the new experiments, to obtain the data missing for FP release modelling and code development;
* To compare FP release from high burnup VVER and PWR fuel, to reveal the effects connected with peculiarity in manufacturing techniques and in operational characteristics.

These objectives are reflected in the Project title 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, have an experience of cooperation in the experimental research and modelling of FP release from VVER fuel in accident conditions. By the present moment some series of tests on examination of fission product release from spent VVER fuel at elevated temperatures in inert, air and steam environments were carried out by RIAR. Results of these tests were used by IBRAE for validation of the detailed mechanistic code MFPR, which was worked out during the last 10 years in close collaboration with IRSN (Cadarache, France), for the modelling of fission products release from fuel in various operating conditions (normal operation, transient, accident) of PWR and VVER nuclear reactors.

Performance of these works is the necessary precondition for experimental and theoretical modelling of FP behaviour in the fuel under severe accident conditions. On the one hand, these works have provided better understanding of physical processes and development of advanced models for VVER fuel behaviour at elevated temperatures in the inert environment. On the other hand, some inconsistencies were revealed (high burn up, for example) which made necessary a new analytical program for accurate accounting of fuel micro-structure.

In the frames of the Project it is planned to carry out the examinations of the FP release from VVER fuel with burn up of about 60 MWd/kgU in steam, steam-hydrogen and hydrogen environments at temperatures up to 2300°С characteristic for severe accidents. In contrast to the previous RIAR tests, it will be investigated the behaviour of the representative set of fission products (85Kr, 133Xe, 131I, 137Cs, 134Cs, 106Ru, 103Ru, 144Ce, 99Mo, 140Ba, 95Zr, 125Sb, etc.), that will be provided by pre-irradiation of the fuel samples in the RIAR research reactors before the tests.

**VERONIKA Project includes the following parts:**

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

In this Part the experimental rig will be manufactured, experiments on radioactive fission products release from highly irradiated VVER fuel during annealing in oxidizing and reducing gas environments and post-test examinations of tested fuel samples will be carried out. Two types of fuel samples will be used: single fuel pellets (pellet fragments) without cladding and segments of fuel rods (fuel pellets in genuine 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 behaviour under conditions of severe accidents without fuel melting.**

The received experimental results will allow developing theoretical models of fission products and irradiated VVER fuel behaviour in conditions of heavy accident and lead to improvement and/or adaptation of codes and the physical models developed for PWR fuel with reference to VVER.

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 of nuclear safety by manufacture of energy and provides solution of national and international problems.

High cost and man-power of experimental researches in the field of nuclear safety lead to necessity of a wide international co-operation. Such collaboration is currently developed and coordinated in the framework of the European SARNET program (6th Framework Programme of EC).

### 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 processing of experimental results, development of physical models and validation of numerical codes will be carried out.

#### Task 1

|  |  |  |
| --- | --- | --- |
| **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- SSC RIAR  2- IBRAE |
| Description of deliverables | | |
| 1 | Test program | |

#### Task 2

|  |  |  |
| --- | --- | --- |
| **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

|  |  |  |
| --- | --- | --- |
| **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

|  |  |  |
| --- | --- | --- |
| 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

|  |  |  |
| --- | --- | --- |
| 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

|  |  |  |
| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| **Processing, analysis and modelling of 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 | Intermediate 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. Technical Approach and Methodology

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

In the earlier RIAR tests on investigation of the FP release from VVER fuel in conditions characteristic for severe accidents, the test rig located inside the hot cell was used. The rig has provided the following test parameters [1-3]:

* The inert gas environment, temperature up to 2800°С;
* The air environment, temperature up to 1200°С;
* The steam-argon environment, temperature up to 1200°С.

During experiments the activity of radioactive gaseous and volatile fission products was measured by means of gamma-spectrometer:

* Volatile fission products - on the filter or in the fuel sample;
* Gaseous fission products - in the carrier-gas flow.

The fragments of irradiated fuel pellets with total weight up to 5 g and segments of the fuel rod (irradiated fuel in a genuine cladding) of 12 and 20 mm length were used as the test samples.

Tests in the inert environment have been carried out for the fuel with burnups from 15.8 to 64.0 MWd/kg U. In these tests the kinetic and temperature dependences of krypton and caesium release as well as the data on influence of fuel-clad interaction on the FP release were obtained in the temperature range from 1000 to 1700°С.

In the air environment the fuel samples with burnup of 36.8 and 0.02 MWd/kg U were tested. In those tests the data on influence of temperature and burnup on microstructure and FP release were obtained. Before the tests fuel has been pre-irradiated in the research reactor that has allowed investigation of the short-lived fission products release (iodine and ruthenium).

In the steam-argon environment the tests of VVER fuel with burnup of 51.7 and 55.2 МWd/kgU were carried out. During the tests the caesium and krypton release as well as the hydrogen formed due to fuel and cladding oxidation were measured. An important objective of these tests was determination of the fuel oxygen factor changed during oxidation in steam. The technique has been developed for determination of the oxygen factor of the tested fuel by execution of auxiliary tests on reduction of samples in the argon-hydrogen environment up to the stoichiometric state. The oxygen factor was calculated from measured amount of hydrogen spent for reduction of fuel up to the stoichiometric UO2.

The above described experience and technical approach will be realized for the new experimental rig preparation and new tests performance in the proposed Project.

OBJECTIVES OF THE TESTS

Elaboration of experimental data on fission products release, including short-lived isotopes, and microstructure of high burnup VVER fuel under conditions characteristic for severe accidents, development of physical models and verification of numerical codes.

TASK OF THE TESTS

Determination of the fission products release from highly irradiated fuel at temperatures and gas environments typical for severe accidents.

Determination of fission products behaviour and evolution of fuel micro-structure by means of micro-analyses at different levels of temperature.

Determination of hydrogen generation during fuel oxidation.

TEST SAMPLES

Samples from spent VVER fuel rod with burnup of about 60 MWd/kgU (samples with a lower burn up can be additionally studied for comparison and better understanding of physical mechanisms). It is supposed to use the samples of two kinds:

* A segment of the fuel rod (pellet in the genuine cladding without end cups);
* A fuel pellet without cladding (fragments of fuel pellet).

Procedure of sample preparation includes the following basic stages:

* + Certification of the irradiated VVER fuel rod;
  + Manufacturing of refabricated fuel rods;
  + Short irradiation of the refabricated fuel rods in the research reactor for accumulation of short-lived fission products (at low power and low temperature);
  + Certification of the irradiated refabricated fuel rods;
  + Preparation of samples from the irradiated refabricated fuel rod.

TEST RIG

Tests are supposed to be carried out in the experimental rig which is schematically presented in the figure:



The maximal test temperature: 2400 °С.

The flowing gas environment: helium - hydrogen, steam or steam - hydrogen mixture.

TEST PROCEDURE

Heating in the inert environment up to temperature of 600°С.

Heating from 600 to 1400 °C at a rate of 5 K/s in steam.

Annealing at temperature of 1400°С in steam during the time period defined in the test program.

Heating up to the prescribed temperature (1700 or 2300°C) at a rate of about 1K/s .

Annealing at the reached temperature during the time period defined in the test program.

Sample cooling in the furnace.

PARAMETERS CONTROLLED DURING THE TEST

Sample temperature;

Pressure in the heating channel inlet;

The gas mixture flow rate;

The steam flow rate.

PARAMETERS TO BE MEASURED DURING THE TEST

85Kr and 133Xe activity in a flowing gas;

Fission products activity in the fuel sample;

Fission products activity in the basic filter;

Hydrogen concentration in the carrier-gas

POST-TEST EXAMINATIONS AND AUXILIARY TESTS

Optical metallography (pre- and post-test):

- Grain size;

- Porosity;

- Gas swelling.

EPMA and SEM: determination of the local concentration and radial distribution of the FP, U, Pu, element content of inclusions in the fuel.

Auxiliary tests on determination of the fuel oxygen factor of the samples tested in the steam environment.

Auxiliary tests on determination of the initial content of gaseous fission products in the fuel by means of dissolution of initial fuel samples in the acid and measurements of the gaseous fission products release (long half-life gas 85Kr inventory).

RESULTS TO BE OBTAINED

Fission products release as a function of time.

Hydrogen generation as a result of fuel oxidation in steam as a function of time.

Extend of fuel oxidation in steam.

Microstructure of the tested fuel samples.

FP distribution in the fuel on the base of EPMA dot mappings or line scans by EPMA.

Elemental content of inclusions.

TEST MATRIX

It is planned to carry out 20 tests which are offered to be broken into 2 independent Stages (Projects). This will provide an opportunity of the feedback that is necessary for long Projects. In this case the test matrix may be corrected for the second Stage depending on results of the first Stage as well as flexible cooperation with the other Projects may be provided.

The test matrix includes 10 tests with samples in the form of fuel rod segment (Т1), and 10 tests with samples in the form of a fuel pellet without a cladding (Т2). The gas environments: steam, steam-hydrogen mixture of two different hydrogen contents, helium-hydrogen mixture.

|  |  |  |  |
| --- | --- | --- | --- |
| Environment | **Test temperature, °С** | | |
| **1400** | **1700** | **2300** |
| H2O | Т1, Т2 | - | Т1, Т2 |
| (H2O/H2)1 | Т1, Т2 | Т1, Т2 | Т1, Т2 |
| (H2O/H2)2 | Т1, Т2 | - | Т1, Т2 |
| H2/He | Т1, Т2 | Т1, Т2 | Т1, Т2 |

The test matrix contains 3 series of tests aimed at:

1. Examination of influence of gas environment (H2O, (H2O/H2)1, (H2O/H2)2, H2/He) on FP release from bare fuel and fuel in the cladding at temperatures of 1400 and 2300°С.
2. Examination of FP release dependence on temperature (1400, 1700 and 2300°С) from bare fuel and fuel in the cladding at the same (H2O/H2)1 environment.
3. Examination of influence of fuel - cladding interaction on FP release in the reducing gas environment at temperatures of 1400, 1700 and 2300°С.

Combination of these series in one matrix allows reducing number of experiments.

The estimated time necessary for performance of all experiments is 5,5 years, total cost - 1100 000 $.

In the framework of the presented Project it is planned to carry out 10 experiments under the following program:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| # | Sample type | Environment | Test temperature,°С | Post-test examination | | |
| Metallography | EPMA, SEM | Determination of oxygen factor |
| 1 | Fuel rod segment | Н2 /Не | 1400 | + | + | - |
| 2 | Fuel rod segment | Н2 /Не | 1700 | + | + | - |
| 3 | Fuel rod segment | Н2 /Не | 2300 | + | + | - |
| 4 | Bare fuel | Н2 /Не | 1400 | + | + | - |
| 5 | Bare fuel | Н2 /Не | 1700 | + | + | - |
| 6 | Bare fuel | Н2 /Не | 2300 | + | + | - |
| 7 | Fuel rod segment | Н2 О | 1400 | + | - | + |
| 8 | Fuel rod segment | Н2 О | 2300 | + | - | + |
| 9 | Bare fuel | Н2 О | 1400 | + | - | + |
| 10 | Bare fuel | Н2 О | 2300 | + | - | + |
| 11 | Reference sample of initial irradiated fuel | | | + | + | - |

**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 conditions (normal operation, transient, accident) of PWR and VVER nuclear reactors [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 infringement of normal operation and at accidents with a heating up of uranium dioxide, including core fusion. 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 a fission products release at infringement of normal operation and 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.

**Literature**:

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. 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.
5. 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.
6. 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
7. 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).
8. 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.
9. 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** | 777400 |
| **Leading Institution SSC RIAR** | 661200 |
| **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 |  |  |  | 270000 |
| **Participant Institution 1** IBRAE |  |  |  | 100000 |
| ***Subtotal:*** | | | | **370000** |

#### 9.1.2. Equipment

|  |  |  |
| --- | --- | --- |
| **Institution** | **Equipment description** | **Cost (US $)** |
| **Leading Institution** SSC RIAR |  | 230100 |
| **Participant Institution 1** IBRAE |  | 2500 |
| ***Subtotal:*** | | **232600** |

#### 9.1.3. Materials

|  |  |  |
| --- | --- | --- |
| **Institution** | **Materials description** | **Cost (US $)** |
| **Leading Institution** SSC RIAR |  | 37000 |
| **Participant Institution 1** IBRAE |  | 0 |
| ***Subtotal:*** | | **37000** |

#### 9.1.4. Other Direct Costs

|  |  |  |
| --- | --- | --- |
| **Institution** | **Direct costs description** | **Cost (US $)** |
| **Leading Institution** SSC RIAR | Sample pre-irradiation | 100000 |
| **Participant Institution 1** IBRAE |  | 0 |
| ***Subtotal:*** | | **100000** |

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

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

#### 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** |  | 777400 |
| 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.