|  |  |  |
| --- | --- | --- |
| ISTC Project No. 2936 | | |
| Modelling of Reactor Core Behaviour under Severe Accident Conditions. Melt formation, relocation and evolution of molten pool | | |
| Final Project Activity Report | | |
| on the work performed from 01.08.2004 to 31.07.2007 | | |
| Nuclear Safety Institute of Russian Academy of Science (IBRAE) | | |
| **Moscow, 115191, B. Tulskaya, 52** | | |
| Project Manager | Mikhail S. Veshchunov Dr., Professor | 31.07.2007 |
|  |  | Signature / Date |

# Objectives of the Project, Scope of Work and Technical Approach

Processes of reactor core degradation represent the most significant factor of severe accident development since they provide the initial conditions for ex-vessel phenomena and determine the fission product and hydrogen source term. The investigation of in-vessel melt behaviour is of paramount importance with respect to reactor materials oxidation kinetics, possible reflooding of the core and reactor pressure vessel failure analysis.

The general objective of the project is to perform the detailed analysis of the available and new experimental data, to update, improve and verify the developed models and to prepare them for benchmarking of simplified models and for implementation in the existing system codes. Thus the project contributes to the reactor core degradation modelling.

# Summary of Technical Progress

## Current Technical Status

|  |  |  |  |
| --- | --- | --- | --- |
| Task  Subtask | Start  (quarter) | End  (quarter) | Status / Comments |
| Task 1. 1.1. | 2 | 8 | Task is completely fulfilled. |
| Task 2. 2.1. | 10 | 12 | Task is completely fulfilled. |
| Task 3. 3.1. | 6 | 12 | Task is completely fulfilled. |
| Task 4. 4.1. | 12 | 12 | Task is completely fulfilled. |
| Task 5. 5.1. | 10 | 12 | Task is completely fulfilled. |
| Task 6. 6.1. | 1 | 10 | Task is completely fulfilled. |
| Task 7. 7.1. | 5 | 12 | Task is completely fulfilled. |
| Task 8 8.1. | 5 | 12 | Task is completely fulfilled. |

## Tasks of the work plan

|  |
| --- |
| Task 1.: *Modelling of melt formation and onset of melt relocation*Subtask 1.1.: Improvement and implementation in the SVECHA code of the models for dissolution of ZrO2 and UO2 by molten Zircaloy, U-Zr-O melt oxidation and release from the cladding breach. Performance of verification calculations. |

#### State / Situation at the beginning of the project duration

There were no models for dissolution of ZrO2 and UO2 by molten Zircaloy and for U-Zr-O melt oxidation and release from the cladding breach, in the SVECHA code. The model for cladding oxide shell breachin, developed by participants of the project, had to be improved and implemented into the code.

#### Fulfilled work

The melt dissolution/oxidation model was extended to non-equilibrium conditions of severe accidents, on the base of the new crucible tests data from FZK collaborators. On the base of newly developed models, new numerical modules were developed and implemented in the SVECHA code with tight coupling of these modules with other SVECHA modules describing heat exchange, cladding oxidation and thermo-mechanical deformation.

#### Results by the end of the project duration

The model for dissolution of ZrO2 and UO2 by molten Zircaloy and U-Zr-O melt oxidation was extended to non-equilibrium conditions and validated against FZK crucible tests data. The modified SVECHA code was applied to interpretation of corium melt behaviour in the in-pile tests Phebus FP, in cooperation with collaborators from JRC, IRSN and CEA.

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Palagin Alexander Viktorovich | 1 | 206 |
| Sarkissov Аshot Аrakelovich | 1 | 80 |
| Boldyrev Andrey Victorovich | 2 | 80 |
| Shestak Valery Evgenyevich | 2 | 80 |
| Shpinkova Larisa Gennadyevna | 2 | 50 |
| Medved Yuri Ivanovich | 2 | 70 |
| Polyakov Aleksey Igorevich | 3 | 30 |
| Karyukina Tatyana Valentinovna | 3 | 20 |
| Egorova Nadezhda Leonidovna | 3 | 20 |

|  |
| --- |
| Task 2.: *Modelling of candling process*Subtask 2.1.: Development and implementation in the SVECHA code of the model for the candling process. Performance of verification calculations. |

#### State / Situation at the beginning of the project duration

There was no model for the candling process in the SVECHA code.

#### Fulfilled work

The physical model and numerical module on melt relocation in the form of drops and rivulets were developed and implemented in the SVECHA code.

#### Results by the end of the project duration

#### The new numerical module was implemented in the code as a subroutine of the massive blockage (slug) relocation model (see Task 3).

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Sarkissov Аshot Аrakelovich | 1 | 80 |
| Kalantarov Valentin Evgraphovich | 1 | 60 |
| Evstratov Еvgeny Vyacheslavovich | 1 | 80 |
| Boldyrev Andrey Victorovich | 2 | 80 |
| Shestak Valery Evgenyevich | 2 | 80 |
| Shpinkova Larisa Gennadyevna | 2 | 80 |
| Medved Yuri Ivanovich | 2 | 70 |
| Polyakov Aleksey Igorevich | 3 | 30 |
| Karyukina Tatyana Valentinovna | 3 | 20 |
| Egorova Nadezhda Leonidovna | 3 | 20 |

|  |
| --- |
| **Task 3.:** ***Modelling of slug relocation***  **Subtask 3.1.:** Development and implementation in the SVECHA code of the model for the slug relocation. Performance of verification calculations. |

#### State / Situation at the beginning of the project duration

There was no model for the slug relocation in the SVECHA code.

#### Fulfilled work

The physical model and numerical module on melt relocation in the form of drops and rivulets were developed.

#### Results by the end of the project duration

#### The new numerical module was implemented in the SVECHA code. Tight coupling of this module with other SVECHA modules describing candling, heat exchange, cladding oxidation, thermo-mechanical deformation was organised. The initial and boundary conditions for the model are self-consistently calculated by the SVECHA code.

#### 

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Palagin Alexander Viktorovich | 1 | 32 |
| Sarkissov Аshot Аrakelovich | 1 | 80 |
| Kalantarov Valentin Evgraphovich | 1 | 60 |
| Evstratov Еvgeny Vyacheslavovich | 1 | 80 |
| Bolshov Leonid Аlexandrovich | 1 | 33 |
| Boldyrev Andrey Victorovich | 2 | 80 |
| Shestak Valery Evgenyevich | 2 | 80 |
| Shpinkova Larisa Gennadyevna | 2 | 64 |
| Tarasov Vladimir Ivanovich | 2 | 60 |
| Medved Yuri Ivanovich | 2 | 70 |
| Polyakov Aleksey Igorevich | 3 | 30 |
| Karyukina Tatyana Valentinovna | 3 | 40 |
| Egorova Nadezhda Leonidovna | 3 | 20 |

|  |
| --- |
| **Task 4.:** ***SVECHA/MELT code verification***  Subtask 4.1.: Verification of the newly developed SVECHA/MELT code against available experimental data. Preparation of the newly developed modules for the implementation in the system codes such as ICARE/CATHARE, MELCOR, or ASTEC. |

#### State / Situation at the beginning of the project duration

SVECHA/QUENCH which was a progenitor code for the new SVECHA/MELT code, had no models for physico-chemical interactions of melt during its relocation.

#### Fulfilled work

The developed SVECHA/MELT code includes all the models developed in Tasks 1-3 and describes a complicated process of molten corium relocation under severe accident conditions at NPP.

#### Results by the end of the project duration

#### The code SVECHA/MELT was validated against integral bundle tests CORA-WWER performed by collaborators from FZK. The new modules for melt relocation and physico-chemical interactions are prepared for implementation in the system codes such as ICARE/CATHARE, MELCOR, or ASTEC.

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Sarkissov Аshot Аrakelovich | 1 | 100 |
| Kalantarov Valentin Evgraphovich | 1 | 60 |
| Evstratov Еvgeny Vyacheslavovich | 1 | 80 |
| Aroutyunian Rafael Varnazovich | 1 | 60 |
| Boldyrev Andrey Victorovich | 2 | 113 |
| Shestak Valery Evgenyevich | 2 | 80 |
| Medved Yuri Ivanovich | 2 | 70 |
| Tarasov Vladimir Ivanovich | 2 | 60 |
| Polyakov Aleksey Igorevich | 3 | 30 |
| Karyukina Tatyana Valentinovna | 3 | 50 |
| Egorova Nadezhda Leonidovna | 3 | 20 |

|  |
| --- |
| **Task 5.:** ***Modelling of U-Zr-O mixture behaviour***  Subtask 5.1.: Analytical support for the ITU tests on irradiated and MOX fuel dissolution by molten Zr and U-Zr-O melting points determination. |

#### State / Situation at the beginning of the project duration

The previously developed models for fuel dissolution by molten Zr were based on the tests with fresh (unirradiated) UO2. Furthermore, the ternary U-Zr-O phase diagram is an important issue in modelling dissolution tests.

#### Fulfilled work

Analysis of the new ITU tests on irradiated and MOX fuel dissolution by molten Zr and U-Zr-O melting points determination was carried.

#### Results by the end of the project duration

On the base of the tests analysis, correction of the fuel dissolution model for irradiated and MOX fuel was implemented. The ternary U-Zr-O phase diagram which is a part of the melt physico-chemical interactions model is improved using the new tests data on U-Zr-O melting points determination.

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Kalantarov Valentin Evgraphovich | 1 | 24 |
| Evstratov Еvgeny Vyacheslavovich | 1 | 20 |
| Boldyrev Andrey Victorovich | 2 | 80 |
| Shestak Valery Evgenyevich | 2 | 112 |
| Kuzmicheva Ekaterina Dmitryevna | 2 | 100 |
| Polyakov Aleksey Igorevich | 3 | 30 |
| Karyukina Tatyana Valentinovna | 3 | 39 |
| Egorova Nadezhda Leonidovna | 3 | 20 |

|  |
| --- |
| **Task 6.:**  Subtask 5.1.: |

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Aksenova Anna Evgenyevna | 1 | 120 |
| Pervichko Valery Alekseevich | 1 | 110 |
| Kalantarov Valentin Evgraphovich | 1 | 60 |
| Evstratov Еvgeny Vyacheslavovich | 1 | 80 |
| Aroutyunian Rafael Varnazovich | 1 | 100 |
| Kondratenko Petr Sergeevich | 1 | 15 |
| Kuzmicheva Ekaterina Dmitryevna | 2 | 110 |
| Shpinkova Larisa Gennadyevna | 2 | 50 |
| Tarasov Vladimir Ivanovich | 2 | 60 |
| Polyakov Aleksey Igorevich | 3 | 38 |
| Karyukina Tatyana Valentinovna | 3 | 20 |
| Egorova Nadezhda Leonidovna | 3 | 20 |

|  |
| --- |
| **Task 7.:**  Subtask 7.1.: |

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Aksenova Anna Evgenyevna | 1 | 110 |
| Pervichko Valery Alekseevich | 1 | 110 |
| Bolshov Leonid Аlexandrovich | 1 | 33 |
| Aroutyunian Rafael Varnazovich | 1 | 90 |
| Kondratenko Petr Sergeevich | 1 | 16 |
| Kuzmicheva Ekaterina Dmitryevna | 2 | 110 |
| Tarasov Vladimir Ivanovich | 2 | 23 |
| Medved Yuri Ivanovich | 2 | 70 |
| Polyakov Aleksey Igorevich | 3 | 40 |
| Karyukina Tatyana Valentinovna | 3 | 20 |
| Egorova Nadezhda Leonidovna | 3 | 20 |

|  |
| --- |
| **Task 8.:**  Subtask 8.1.: |

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Aksenova Anna Evgenyevna | 1 | 120 |
| Pervichko Valery Alekseevich | 1 | 110 |
| Aroutyunian Rafael Varnazovich | 1 | 90 |
| Kondratenko Petr Sergeevich | 1 | 15 |
| Kuzmicheva Ekaterina Dmitryevna | 2 | 120 |
| Polyakov Aleksey Igorevich | 3 | 40 |
| Karyukina Tatyana Valentinovna | 3 | 20 |
| Egorova Nadezhda Leonidovna | 3 | 16 |

|  |
| --- |
| Task 0.: Project Management |

#### Fulfilled work

Coordination of the Project works in accordance with the time schedule and scientific management of the works have been carried out.

#### Personnel Commitments

|  |  |  |
| --- | --- | --- |
| Name | Category | Days |
| Veshchunov Mikhail Sergeevich | 1 | 434 |
| Chudanov Vladimir Vasilyevich | 1 | 352 |
|  |  |  |

# Summary of Personnel Commitments

|  |  |  |  |
| --- | --- | --- | --- |
|  | Number of persons | Total days | Total grants, USD |
| Category I | 11 | 3100 | 100798.00 |
| Category II | 6 | 2102 | 61856.00 |
| Category III | 3 | 653.7 | 13074.00 |
| Category IV |  |  |  |
| Total | 20 | 5855.7 | 175728.00 |

# Presentation of project results

|  |  |
| --- | --- |
| see Attachment 1. | List of published papers and reports without abstracts |
| see Attachment 2. | List of presentations at conferences and meetings without abstracts |
| see Attachment 3. | Information on patents and copy rights |

# Co-operation with foreign collaborators

#### exchange of scientific material (information, computer codes and data, samples)

* JRC/ITU (Karlsruhe) has presented test data on irradiated and MOX fuel dissolution by molten Zr and U-Zr-O melting points determination, in order to improve the melt physico-chemical interactions model;
* FZK(Karlsruhe) presented test data from bundle tests CORA and QUENCH with core melting. Data on melt formation (in the upper bundle part), oxidation, interaction with fuel and downward relocation were presented for analysis;
* FZK(Karlsruhe) presented test data from the project LIVE (Late In-Vessel phase Experiments) concerning 3-d distribution of heat fluxes to the walls and crust formation on a cooled surface of reactor vessel;
* IRSN and ITU presented data form in-pile reactor tests Phebus FPT0 and 1 for analysis and modelling with the SVECHA code of corium melt behaviour.

#### signature of protocols (with short description)

#### research carried out jointly

* Analysis of presented experimental data;
* Development of the model for corium melt oxidation in steam (ITU, FZK);
* Verification of new models and SVECHA/MELT (ITU, FZK).

#### trips to/from foreign collaborators

#### Participation in ISTC CEG/SAM meetings (2 times per year) and presentation of current status of the performed work

#### workshops, topical meetings organized by the project team

#### ISTC Project #2936 Topical Meeting (Moscow, July 2006)

#### ISTC Project #2936 Topical Meeting (Podolsk, July 2007)

#### joint attendance to international conferences

#### 10th QUENCH International Workshop (Karlsruhe, October 2004)

#### 11th QUENCH International Workshop (Karlsruhe, October 2005)

#### 12th QUENCH International Workshop (Karlsruhe, October 2006)

#### 24th Meeting of the Phébus FP Bundle Interpretation Circle (Bergen, April, 2005)

#### 26th Meeting of the Phébus FP Bundle Interpretation Circle (Alkmaar, April, 2006)

#### 28th Meeting of the Phébus FP Bundle Interpretation Circle (Alkmaar,, March, 2007)

# Co-operation with CIS sub-contractors

#### Communication and organization of project implementation

#### workshops, topical meetings organized by the project team

#### signature of protocols (with short description)

# Procurement

|  |  |  |
| --- | --- | --- |
| Work plan No. | Name | Status |
|  |  |  |
|  |  |  |
|  |  |  |

# Conclusion, Problems, Suggestions

#### How the project results will be implemented in the future work

* The models and codes developed within the Project will be implemented in the Russian severe accident code SOCRAT and will be prepared for implementation in the European system codes such as ICARE/CATHARE, MELCOR, or ASTEC.

#### Perspectives of future developments of the research/technology developed

* The new codes SVECHA/MELT and CONV will be further developed for analysis of new experiments modelling accidents with core degradation at NPP

#### Potential commercial application of project results

* The above mentioned system codes in which the new models will be implemented, are commercial products are widely used for safety analysis of operating NPP and design of new ones.

|  |  |
| --- | --- |
| Attachment 1: | List of published papers and reports |
| Attachment 2: | List of presentations at conferences and meetings |
| Attachment 3: | Information on patents and copy rights |
| Attachment 4: | Technology Implementation Plan |