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| ISTC Project No. 2936 |
| Modelling of Reactor Core Behaviour under Severe Accident Conditions. Melt formation, relocation and evolution of molten pool |
| Final Project Technical Report |
| on the work performed from August 1, 2004 to July 31, 2007 |
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# Brief description of the work plan: objective, expected results, technical approach

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.

# Method, Experiments, Theory etc.

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.

# Results

### 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.

* 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.
* 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.

### 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.

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

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

**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.

* The physical model and numerical module on melt relocation in the form of massive blockage (slug) were developed.

#### 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.

**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.

* 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.
* 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.

**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.

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

### Task 6: *Development of a three-dimensional code and adaptation to the LIVE project*

Subtask 6.1: The adaptation of the three-dimensional CONV code (within Boussinesq approximation) for the LIVE project conditions. Development and implementation in the CONV code of the thermal-hydraulic model with a variable density (without Boussinesq approximation)

#### The previously developed three-dimensional CONV code was intended for simulation of three-dimensional flows in the Boussinesq approximation on Cartesian grids with a local refinement near domain with singularities of flows.

#### The model for calculation of flows with a variable density without Boussinesq approximation was developed and implemented in CONV code. The necessary modification of numerical algorithm to fast solving of pressure correction equation with usage algebraic solver on the basis of Fast Fourier Transformation (with variable properties) was carried out. Comparison with Boussinesq model on such parameters as 3d heat flux distribution on cooled boundary and possible crust formation depending on the power density and the external cooling was conducted.

#### On the base of the carried out numerical researches and adaptation of previously developed software, more perfect version of a code permitting of calculation of three-dimensional flows with variable properties, appropriate to real corium properties or prototypes was obtained.

### Task 7: *Theoretical analysis and code validation*

Subtask 7.1: The numeric-theoretical analysis of the flows in a boundary layer adjacent to cooled boundaries. Validation of the developed flow models using experimental data, including experiments with a heat generating fluid such as LIVE, COPO, SIMECO …

#### The numerical simulation of natural convection and heat flux distribution was supplemented by the theoretical analysis of major phenomena such as boundary layers formation, with the analysis of energy balance in heat-generating fluids. Theoretical dependences were compared with the results of calculations, namely for such processes as: free convection in a heat-generating fluid for cylindrical geometry; convective heat exchange for a heat-generating fluid in an upper of enclosure. In all cases a good coincidence was obtained between analytic and numerical results.

#### Heat generating fluids exhibit temperature stratification depending upon boundary conditions at the top (isothermal or adiabatic). Corresponding theoretical assessments for the heat transfer and their dependence upon dimensionless parameters such as Rayleigh number were compared with numerical results and in this case a good coincidence was observed.

#### Matrix of validation for developed models was created, including as results of the theoretical analysis and experimental data (BALI, COPO and SIMECO) for convection of a heat-generating fluid. The preliminary numerical simulation of circular heat used in experimental facility LIVE was carried out by means of CONV code which was validated and adapted to conditions of project.

### Task 8: *Thermal-hydraulic model with accounting for the crust formation*

Subtask 8.1: Development of models and code for numerical simulation of flows at high Rayleigh numbers under conditions of crust formation on a cooled surface. Testing of the developed models and modules on experimental data with crust formation using, for example RASPLAV tests

#### Model for numerical simulation of melt flows simultaneously with heat transfer in the reactor case and crust formation at high Rayleigh numbers was developed and implemented in code. For the modeling of turbulence implemented algebraic turbulent models and direct numerical simulation were used. A computing technique of modeling of turbulence was validated on results of problems with lid-driven flows and flow in tube. In all cases the good coincidence of numerical results to the reference data is marked.

#### On the basis of the modified CONV version the simulation of molten-salt tests obtained on RASPLAV facility was carried out. The obtained results demonstrate, that the developed approach predicts correctly the absolute values of crust thickness.

# Conclusion

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

# References

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

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| Attachment 1: | List of published papers and reports with abstracts |
| Attachment 2: | List of presentations at conferences and meetings with abstracts |
| Attachment 3: | Information on patents and copy rights (List and describe patents and copyrights which were obtained or may be obtained as a result of the project) |