Ministry for Atomic Energy of Russian Federation

ALEXANDROV SCIENTIFIC RESEARCH TECHNOLOGICAL INSTITUTE

Investigation of Corium Melt Interaction With NPP Reactor Vessel Steel (METCOR) Phase 2

Project 833.2

WORK PLAN

Sosnovy Bor

2002

I. Summary Project Information

1. Project Title

Investigation of Corium Melt Interaction With NPP Reactor Vessel Steel (METCOR).

2. Project Manager

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3. Participating Institutions

3.1 Leading Institution

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3.2 Other Participating Institution None

4. Foreign Collaborators/Partners

4.1. Collaborators

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4.2. Partners None

5. Project Duration

36 months

6. Project Location and Equipment

Institution	Location, Facilities and Equipment
Aleksandrov Research Institute of Technologies (NITI)	**Location address:** Building 11 (r.405,406), 12 of LSK «Radon» in Sosnovy Bor, Leningrad Region, Russia. **Equipment:** RASPLAV-2 and RASPLAV-3 experimental installations - to produce different kinds of corium melts (e.g. suboxidised and oxidised), and investigate its interaction with plant materials (It comprises HF generator, induction furnaces, protection and auxiliary technological systems), and data acquisition system. Devices and facilities for physical & chemistry analysis (mass-spectrometer, X-ray diffractometers and spectrometers, chromatograph, etc.**).** Computer systems and office equipment.

II. Specific Information

1. Introduction and Overview

The ultimate goal of the proposed project is the nuclear reactor safety enhancement in case of a severe accident involving the core degradation. The subject addressed by the project is the in-depth study of physico-chemical processes taking place during core melt interaction with reactor vessel steel.

At present two severe accident management solutions are foreseen both for operating and future NPPs.

1. Medium capacity reactors (VVER-640, VVER-440 NPP «Loviisa», AP600, SBWR) have external water cooling systems in order to retain corium melt inside the vessel.
2. Reactors without external vessel cooling systems are provided with a core catcher, which confines and cools the ex-vessel corium that has melted through the reactor vessel.

The analysis of both accident management options requires availability of quantitative characteristics of the melt-steel interaction, including data on physico-chemical processes involved.

In the case of uncooled vessels the data are necessary for the estimation of pre-failure period (strain growth) and identification of a likely location and size of failure.

In terms of the cooled vessel concept these characteristics are necessary for the estimation of vessel retaining capability.

Studies in the framework of ISTC Project No 833-99 have been started in NITI on April 1, 1999, in order to experimentally determine currently unavailable qualitative and quantitative characteristics of core melt - vessel steel interaction. Both thermo-hydrodynamic and physico-chemical processes will be considered in the study.

Due to considerable reductions of the Project budget by ISTC (contract No 833-99 provided funding only for the 1st Project phase, and a decision about the 2nd phase was taken by the Steering Board on August 6, 2002) the scope of 1st phase investigations was considerably reduced as compared to the original Project Proposal.

In the 1st phase of ISTC № 833-99, which was completed December 30, 2000 the corium-steel interaction characteristics were determined. Uranium-bearing corium had a composition, which was chosen jointly with collaborators: 56,0 w% UO_2 + 25,0 w% ZrO_2 + 19w%FeO_x. A vessel steel specimen was positioned horizontally under the molten pool. Thermo-hydrodynamic and physico-chemical processes taking place simultaneously were investigated.

The following parameters were varied for the study:

- corium melt temperature;
- steel specimen temperature at the interaction front;
- above-melt atmosphere, in the 1st phase the atmosphere was either inert or air;

Additionally, the 1st Project phase included experimental examination of free convection in the melt pool (without interaction with steel specimen) and its dependency on:

- melt pool depth;
- melt superheating degree.

These experiments were required for the validation of computer codes, which model the melt pool thermo-hydrodynamics.

By now all planned 1st phase studies uranium-bearing corium interaction with vessel steel specimens have been completed.

The following conclusions have been drawn:

- The system oxygen potential, which depends on the above-melt atmosphere and metallic Zr content in the melt, plays a key role in the process of corrosion of steel by the melt.
- Characteristics of oxide crust on the metal surface are of great impact on the melt-steel interaction process.
- Oxide crust properties – chemical composition, thickness, structure, thermo-physical and mechanical characteristics mainly depend on the following factors:
  - melt composition;
  - temperature on the metal surface;
  - heat flux through the crust;

- crust structure and formation conditions.

- Under conditions of air above melt, metal surface temperature of 700-1000 °C and heat fluxes between 0.3 and 0.9 MW/m^2, the steel specimen corrosion rate is low.
- When the temperature on the specimen surface exceeds 1050 °C the melt-specimen interaction process becomes unstable, this is manifested in the acceleration of specimen temperature growth.
- Steel surface temperatures have oscillatory dynamics near this range of instability, though the average level of power in the melt remains unchanged.

The results of 1st phase experimental studies were discussed with collaborators at the meeting in St. Petersburg, 19-20 April, 2001. The discussions were summarized in the Minutes confirming that the completed studies were in full compliance with the Work plan.

The Second Project phase is proposed to investigate high-temperature corium - vessel steel interaction taking into account the latest MASCA OECD project results which provide a new understanding of the conditions of the core melt/ reactor steel interaction which is a key aspect of in-vessel melt retention. In particular, the new results have shown that the steel melt extracts a significant amount of uranium and zirconium from highly suboxidized core melt and, due to the density differences, metal & oxide layer inversion of a stratified molten pool takes place. Therefore, the METCOR phase 2 project proposal is revised to take into consideration these new and important phenomena and to incorporate a new methodology for experimental study of suboxidized core melt interaction with a prototype structure of vessel steel with external cooling.

In the revised METCOR-2 test matrix, tests with suboxidized core melt in inert atmosphere and oxidized core melt in steam atmosphere will be carried out. These correspond to the initial and late phases of in-vessel melt retention respectively.

A new experimental procedure is proposed, in which the study of melt-induced steel corrosion will include the additional metal introduction from the top and measurements of the bottom steel plate corrosion (Test 2). This will be followed by the interaction test with steel melting.

Test series 1 will be carried out with a single phase, suboxidized U/Zr/O melt. Test series 2 will be carried out with a 2-phase metallic/oxidic U/Zr/Fe/O melt; both under argon atmosphere. The vessel steel/melt interaction corresponds to the early phase in-vessel retention. These investigations will answer important questions related to the early phase of an in-vessel melt retention concept, in case of failure of water supply.

Test series 3 will be carried out with a fully oxidic U/Zr/O and U/Zr/Fe/O melts under steam atmosphere and will follow vessel steel/melt interaction during the late phase of in-vessel retention scenario, when water is added to the melt in the RPV.

In consideration of the additional preparation necessary for these test series' then 3 years is proposed for the execution of the project (1 year per series) compared to the originally expected 2 years duration. This will enable a better experimental evaluation and less conflict with other experimental programmes (e.g. CORPHAD). Nevertheless the budget requested for the second phase remains the same.

METCOR phase 2 upgraded experimental matrix

Test series №	Test series	Melt composition	Melt temperature, ºC	Above the melt atmosphere
1	Interaction of suboxidized/oxidized core melt (oxidic phase)with vessel steel	$UO_2/ZrO_2/Zr$ UO_2/ZrO_2	Up to 2600	Argon
2	Interaction of metal/oxide suboxidized core melt with vessel steel (oxidic+ metallic phases)	$UO_2/ZrO_2/Zr + Fe$	Up to 2600	Argon
3	Interaction of core melt with vessel steel in steam	$UO_{2+x}/ZrO_2/FeO_y$ UO_{2+x}/ZrO_2	Up to 2800	Steam

2. Expected Results and Their Application

The project belongs to the category of applied studies. The implementation of Project 1st and 2nd phases will produce the following output:

1. Qualitative and quantitative characteristics of corium melt interaction with steel obtained in plant-comparable conditions, and their dependency on:

– corium composition (including fractions of metallic Zr and steel);

– corium melt superheating;

– above-melt atmosphere

2. Mechanisms of corium – steel interaction.

3. Structural characteristics of corium and steel samples.

The complete experimental matrix of Phase 2 is given in Section 1.

The results of this programme can further be used for:

- refinement of numeric models describing corium melt - steel interaction processes;
- verification of computer codes modelling free convection processes in the melt pool particularly in terms of physico-chemical and thermal-hydraulics processes;
- calculation for and safety upgrading of operating and future reactors (PWR and BWR-types).

3. Meeting ISTC Goals and Objectives

The Project 2nd phase will be implemented during 36 months, about 36 persons will be employed, 21 of them were previously involved into the development of war technologies. In this respect the work is in full compliance with ISTC goals. The complete work programme will be carried out by NITI of RF Ministry for Atomic Energy with participation of invited experts from other institutions.

The proposed project will:

- help specialists, previously engaged in the development of defence technologies, to reorient to non-military research;
- support applied studies targeted at solving society-relevant problems, in particular in the field of environmental protection, power generation and nuclear safety;

- promote the integration of Russian scientists into the world scientific community and support the research potential of Russia;
- facilitate the transition to the market economy oriented towards demands of the society.

3. Scope of Activities

The approved experimental matrix foresees 5 tasks (Table of Section 1). All tasks are aimed at the implementation of the overall Project objective: getting experimental data on the interaction kinetics of molten corium and vessel steel with varied oxygen potential in the system, corium composition (oxidic, metal-oxidic), melt superheating and overlying atmosphere.

Task 1 Experimental setup preparation and adjustment. Adaptation of methodologies. Finalization of experimental matrix.

Task 2 Interaction of suboxidized/oxidized molten corium (oxidic phase) with vessel steel.

Task 3 Interaction of suboxidized metal-oxidic molten corium (oxidic + metallic phases) with vessel steel.

Task 4 Interaction of molten oxidic corium with vessel steel at overlying steam atmosphere.

Task 5 Integrated analysis of completed tests, experimental series and all experimental and numeric studies.

Tasks 2, 3 and 4 are divided into experimental stages, i.e. primary analysis, physico-chemical posttest analysis, pre- and posttest calculations and integrated analysis of results.

Task 1

Task description and main milestones	Participating Institutions
For experimental series of Tasks 2, 3, 4 “Rasplav-2” and “Rasplav-3” test facilities are prepared and adjusted; experimental sections are manufactured; experimental procedure is specified, methodologies for specimen measurements and analyses are refined. Major stages: 1.1. Preparation of the installation, techniques and experimental procedures for performing a test series in conformity with Task 2. 1.2. Preparation of the installation, techniques and experimental procedures for performing a test series in conformity with Task 3. 1.3. Preparation of the installation, techniques and experimental procedures for performing a test series in conformity with Task 4.	NITI

Description of deliverables	
1	Technical briefs in quarterly reports
2	The description of techniques

Task 2

Task description and main milestones	Participating Institutions
Interaction study of molten suboxidized corium $UO_2/ZrO_2/Zr$ and vessel steel in argon at varied temperatures of steel specimen top and different mass fraction of metallic Zr corresponding to C100 and C30 compositions. Main milestones: 2.1 Performance and primary analysis of experimental series with composition C100 2.2 Physico-chemical posttest analysis of samples and specimens 2.3 Performance and primary analysis of experimental series with composition C30 2.4 Physico-chemical posttest analysis of samples and specimens	NITI

Description of deliverables	
1	Protocol of experiments
2	Tables with outcomes of the physico-chemical analyses
3	Charts and histograms

Task 3

Task description and main milestones	Participating Institutions
Interaction study of molten suboxidized corium $UO_2/ZrO_2/Zr$ (C30) and vessel steel in argon at steel degradation in the molten pool followed by the dynamic thermal impact of composition Fe/U/Zr at the cooled steel specimen. Main milestones: 3.1 Performance and primary analysis of experiments with steel mass fraction 10%. 3.2 Physico-chemical posttest analysis of samples and specimens 3.3 Performance and primary analysis of experiments with steel mass fraction 20% 2.4 Physico-chemical posttest analysis of samples and specimens	NITI

Description of deliverables	
1	Protocol of experiments
2	Tables with outcomes of the physico-chemical analyses
3	Charts and histograms

Task 4

Task description and main milestones	Participating Institutions
Interaction study of molten corium having compositions $UO_{2+x}/ZrO_2/FeO_y$ (corresponds to those used in the 1st METCOR phase) and UO_{2+x}/ZrO_2 with vessel steel in steam atrmosphere. Main milestones: 4.1 Performance and primary analysis of experiments with corium composition $UO_{2+x}/ZrO_2/FeO_y$ 4.2 Physico-chemical posttest analysis of samples and specimens 4.3 Performance and primary analysis of experiments with corium composition UO_{2+x}/ZrO_2 4.4 Physico-chemical posttest analysis of samples and specimens	NITI

	Description of deliverables
1	Protocol of experiments
2	Tables with outcomes of the physico-chemical analyses
3	Charts and histograms

Task 5

Task description and main milestones	Participating Institutions
Integrated analysis of completed tests including pre- and posttest calculations of power distribution in the test facility components, melt and experimental section; numeric evaluation of the tested specimen temperature condition; pre- and posttest electromagnetic calculations; physico-chemical analysis of samples and specimens. Main milestones: 5.1 Integrated analysis of Task 2. 5.2 Integrated analysis of Task 3. 5.3 Integrated analysis of Task 4. 5.4 Integrated analysis of the whole complex of experimental and numeric data including those of the 1st Project Phase	NITI

	Description of deliverables
1	Chapter in annual reports
2	Minutes of meetings with collaborators
3	Final report on the Project

Each year the annual progress report is issued, which is discussed at the meeting with collaborators. After completion of each intermediate stage an analytical brief is produced, which is sent to collaborators for express discussions. If jointly decided so, the experimental matrix can be amended.

Fig. 1 presents the relationship of tasks.

Interaction of tasks 1-5

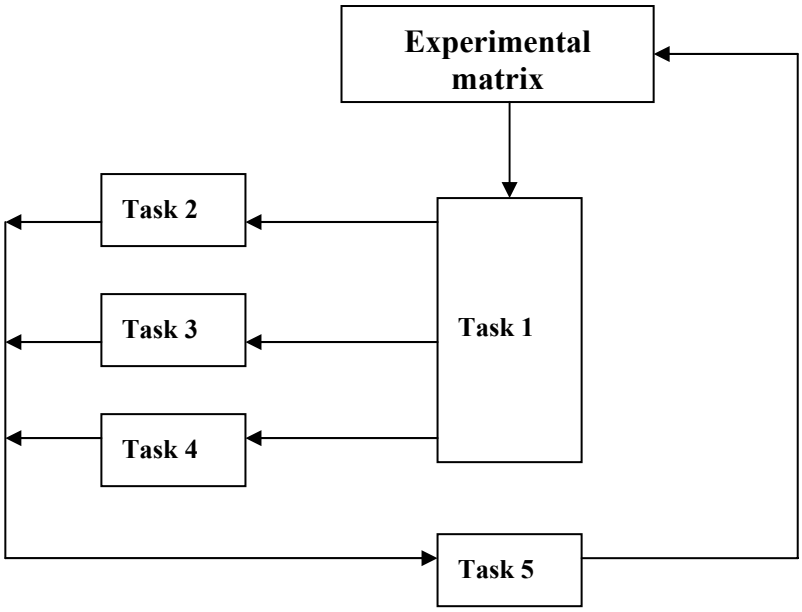

Fig. 1

5. Role of Foreign Collaborators/Partners

The following forms of co-operation with foreign collaborators are proposed in the Project framework:

- joint development and updates of experimental matrix
- continuous information exchange throughout the Project implementation;
- discussion of research and technical reports (progress, annual, final) in order to refine experimental methodologies, consider proposals for improving physico-chemistry models;
- cross-check of results produced during the Project implementation;
- joint symposiums and seminars;
- joint publications, papers and presentations at conferences.

6. Technical Approach and Methodology

Experimental studies of melt-steel interaction will be conducted on RASPLAV-2 facility, which has been successfully operated for 12 years and new RASPLAV-3 facility, which is an important experimental part of the MASCA-OECD project.

To produce corium melt in the installations the original technology of induction melting in a cold crucible (IMCC) is employed. The solid phase (lining crust) between the melt and crucible prevents crucible-melt mass transfer. At present RASPLAV-2 could be used to produce up to 10 kg of superheated oxidic corium melt in the inert or oxidising environment. RASPLAV-3 provides capabilities of experimental studies of highly suboxidised corium/steel molten systems with miscibility gap.

RASPLAV-2 and-3 test facilities have a number of advantages when the simulation of real corium behaviour under severe accident conditions is required. They are:

- possibility to work with uranium-containing corium;
- possibility to modify corium melt composition in the course of tests;
- addition of metallic species;
- possibility to work in air, steam and inert above-melt atmospheres;
- power release into the melt while maintaining its purity close to the initial composition;
- high melt superheating;
- no test duration limits;
- compatibility and compactness of melting devices.

RASPLAV-2 and -3 test facilities are equipped with a computer-based data acquisition systems for the logging and initial processing of:

- coolant temperatures and flow rates;
- corium melt temperature;
- temperature distribution across the steel bottom specimen;
- electrical characteristics of IMCC power source;
- corrosion rate of steel specimen.

Elementary and phase analyses of samples are made in order to study mechanisms of corium melt-metal material interaction. Two methods to be used are XRF and XRD analyses.

Specimen post-interaction macro- and microstructure is to be determined by material analysis methods, such as electron scanning microscopy, metallography and ceramography. These methods were verified during the implementation of international projects ISTC-64, ISTC-833.1, CIT, ENTHALPY, OECD/MASCA.

For the calculation of temperature transients with spatial finite-element models, available thermo-physical data and boundary conditions corresponding to those of conducted tests will be used.

Before the experiments, the liquidus temperature (T_{liq}) will be evaluated for the specified corium composition.

For the experimental study of corium melt - steel interaction the specimens are placed at the crucible bottom or added from the top, depending on the specified experimental characteristics. Before the test, the heat flux of the specimen will be determined.

During the course of the project, the equipment and instrumentation may possibly be upgraded and modified to enable the extensive parameter variation to be adapted to new objectives of the experiments.

7. Technical Schedule

7. Технический календарный план

	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 5	Quarter 6	Quarter 7	Quarter 8	Quarter 9	Quarter 10	Quarter 11	Quarter 12	Man-days
Task 1 Experimental setup preparation and adjustment. Adaptation of methodologies. Finalization of experimental matrix.	Meeting with collaborators												
Man-days	**120**				**107**				**105**				**332**
Task 2 Interaction of suboxidized/oxidized core melt with vessel steel (Experimental matrix, Section 1)				Annual report									
Man-days	**640**	**640**	**632**	**630**									**2542**
Task 3 Interaction of metal/oxide suboxidized core melt with vessel steel (Matrix, Section 2.1)								Annual report					
Man-days					**530**	**640**	**630**	**590**					**2390**

Task 4 Interaction of oxidic corium with vessel steel in steam. (Matrix, Section 3.1)												Annual report	
Man-days									**525**	**630**	**630**	**630**	**2415**
Task 5 Integrated analysis of completed tests, experimental series and all experimental and numeric studies.				Meeting with collaborators				Meeting with collaborators				Final report. Meeting with collaborators	
Man-days		**120**	**110**	**126**	**105**	**110**	**110**	**168**	**105**	**105**	**105**	**126**	**1290**
TOTAL	**760**	**760**	**742**	**756**	**742**	**750**	**740**	**758**	**735**	**735**	**735**	**756**	**8969**

8.2. Managerial responsibilities

Diagram of the organizational structure for the project and indicate the relationships among personnel.