# ANNEX I

# Work Plan

## I. Summary Project Information

### 1. Project Title

Experimental study of the processes at the corium melt retention in the reactor pressure vessel.

### 2. Project Manager

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### 3. Participating Institutions

#### 3.1. Leading Institution

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| **Short reference:** | | | | | IAE NNC RK | | | | | | |
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#### 3.2. Other Participating Institutions

None

### 4. Foreign Collaborators/Partners

#### 4.1. Collaborators

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#### 4.2. Partners

None

### 5. Project Duration

00 months

### 6. Project Location and Equipment

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| **Institution** | **Location, Facilities and Equipment** |
| **Leading Institution** | Kurchatov-city, Kazakhstan republic, LAVA-B facility for large scale tests, VCG-135 stand for small-scale experiments, equipment for post-test research of corium and reactor pressure vessel samples, computers |

## II. Specific information

### 1. Introduction and Overview

**Overall project objective** – Improvement of the safety assessment of LWR corium in-vessel retention (IVR) under severe accident conditions.

**Specific objective of the project is** the experimental modeling of the thermal and physicochemical processes at the retention of the prototypical corium molten pool on the water-cooled lower head of the reactor pressure vessel (RPV) for estimation of:

- influences of scale, shape of the interface and others 2-D effects on the corrosion processes, which determining the final thickness of the RPV wall;

- influences of the metal-oxidic stratified molten pool structure on the possibility of corium in-vessel retention;

- quantitative characteristics of processes at IVR, which are necessary for development and verification of the models used at IVR validation.

**1.1. Context**

The concept of the melt in-vessel retention offered in particular by T.Theofanous, consists in retention of the corium melt on the lower head at passive cooling of RPV external surface with maintenance of the pre-critical mode of the cooling water boiling. Despite of perspectives and seeming simplicity, this technical decision has the limited application in connection with that for the reliable validation of non-critical cooling water boiling on the external surface of RPV is required the large resource of heat flux density up to critical value (k≥2). It is possible to provide such guaranteed resource at corium melt in-vessel retention of the medium power reactors. Interaction between corium and RPV not cooled outside wall can lead to the penetration of the melt in the reactor containment in high-power reactors (Nel>1000 MW) and others, which are not equipped with system of core melt in-vessel retention. Key questions of the processes research at the in-vessel stage of severe accident are:

1. Structure of the stratified molten pool and its time dependent variation.
2. Distribution of the melt components and fission products between liquid layers and between molten and crystallized material (also in dynamics).
3. Physicochemical aspects and kinetics of the corium interactions with RPV material.
4. Thermal - hydrodynamics of molten pool, conditions of heat transfer both on internal and external RPV surfaces and between the stratified layers, including the crust presence between liquid layers and on boundary surfaces.
5. Stress - deformed condition of the RPV at simultaneous effect of thermal, chemical and mechanical loadings.
6. Not cooled RPV damage character of and the condition of corium penetration in the reactor containment.

Experimental researches on the problem of corium in-vessel retention were performed and are performed for clarification of available uncertainties at the description of the stratified corium molten pool interaction with the water-cooled RPV. These researches are performed in two main directions:

1. Critical heat fluxes on the cooled RPV external surface;
2. Thermal - hydrodynamics and physicochemical processes in corium pool at in-vessel conditions.

Let's note without detailed review of works on the first direction, that there is already an extensive experimental database on critical thermal flow on the external RPV surface accordingly to results of researches: in OKB "Gydropress"/[[1]](#footnote-1)/ on semi-elliptical lower head model of VVER-640 (slice-geometry); in ANL/[[2]](#footnote-2),[[3]](#footnote-3),[[4]](#footnote-4)/ on ULPU-2000 facility; in SNL/[[5]](#footnote-5)/ on SYBL facility; in the NITI on installation "Tank"/[[6]](#footnote-6)/ and "Loop"/[[7]](#footnote-7),[[8]](#footnote-8)/; in CEA on SULTAN facility/[[9]](#footnote-9),[[10]](#footnote-10)/.

Dependence generalizing experimental data of large-scale experiments both the data received on short plates with various orientation of the surface at boiling in large volume/[[11]](#footnote-11)/ are obtained in NITI on the basis of hydrodynamic model of the bubble boiling crisis.

Great volume of researches on thermal- hydrodynamics of the melt pool is performed on COPO and COPO II (Finland) facilities/[[12]](#footnote-12),[[13]](#footnote-13)/, BALI facility (France)/[[14]](#footnote-14),[[15]](#footnote-15),[[16]](#footnote-16)/, SIMECO facility (Sweden)/[[17]](#footnote-17)/, RASPLAV-salt (Russia)/[[18]](#footnote-18),[[19]](#footnote-19)/ in which water, various organic liquids, molten salts and fusible metals were applied as the melt simulant for creation of the stratified pool structure.

The solution of the similar problem is planned in the experiments with hemispherical lower head RPV model on LIVE facility/[[20]](#footnote-20)/ (Fzk, Karlsruhe) in which vanadium oxide is applied as the reactor fuel stimulant and decay heat is modeled using ohmic heater.

Let’s list the basic conclusions by results of the experimental researches received on melt simulators:

1. Satisfactory modeling on the melt pool thermal- hydrodynamics in conditions of its in-vessel retention is achieved;
2. The developed models describe adequately the natural convection of the heat released liquids, focusing effect of the steel layer on the pool surfaces and local thermal loadings on the RPV wall;
3. Calculation uncertainties at the thermal- hydrodynamics processes description are connected to the accuracy of the thermo-physical properties of the melts assignment in many respects.

The RPV stress - deformed condition at simultaneous action of mechanical loadings (from overpressure and overweight) and thermal loadings from the melt were investigated experimentally in many works, concern to number recent LHF experiments in ANL (USA)/[[21]](#footnote-21)/, RUPTHER in IPSN (France)/[[22]](#footnote-22)/ and in FOREVER facility (Sweden)/[[23]](#footnote-23)/.

**1.2. Background**

It is necessary to note, that the primary objective of the core IVR validation can be formulated as the proof of RPV wall integrity at joint action of mechanical, thermal and physicochemical loadings. The above submitted researches were executed on simulators and did not take into account some important features of processes at fuel melt in-vessel retention:

1. Essentially higher temperature of the fuel melt;
2. Special properties of the melt, in particular, character of the phase diagram, the characteristic temperature dependences of density and viscosity;
3. Physicochemical interactions both between stratified layers of molten pool and between melt and RPV steel;
4. Evolution of the melt oxygen potential and influence of this parameter on processes characteristics.

These features can be taken into account only on the basis of experiments with prototypic melts in physicochemical signification. It is necessary to attribute to those the researches in RRC KIAE by programs OECD RASPLAV and MASCA and researches in the NITI by ISTC project METCOR.

Overall objectives of OECD RASPLAV/[[24]](#footnote-24)/ program, which was performed RRC KIAE (1994-2000) were:

1. Studying of the prototypic corium melt behavior in large-scale experiments and obtaining of experimental data on melt interaction with RPV;
2. Studying of the local processes in supporting small-scale experiments,
3. Development of the calculation models describing processes at interaction on the basis of obtained experimental data.

The facility in NSI KIAE has been built for performance of large-scale experiments, in which the method of indirect corium heating from lateral flat induction warmed graphite heaters was realized. 4 large-scale tests have been performed in AW-200 facility accordingly to RASPLAV program.

It should be noted, that character of the realized indirect method of the melt heating via graphite heaters and caused by this the features of AW-200 facility design have limited the experimental capabilities of facility regarding to research of physicochemical processes at corium melt interaction with cooled RPV steel. In particular:

1. Temperature on the steel surface, which interacted with corium in these experiments, was essentially less than specified temperature at melt in-vessel retention.
2. Insufficient heat flux densities from the melt to the steel were realized in the experiments: 90, 130 and 280 kW/m2. For comparison, the validation of in-vessel retention for AP-600 and VVER-440 is performed for density of 350 kW/m2 heat flux. Heat flux can be even higher for the reactors of higher power (AP-1000, for example), for which in-vessel retention is examined.
3. Interaction time did not exceed several hours that can be insufficient for appreciable evolution of physicochemical and corrosion processes. Essential thermal and physicochemical loadings on the RPV are realized during several tens hours at conditions of the melt in-vessel retention.
4. The used technology and refractory materials excluded performance of experiments in the oxidizing environment, and also with completely oxidized compositions included iron oxides.

New effects are recently determined in MASCA program performed in co-operation RRC KIAE and NITI, which are important for taking into account at the IVR validation. The effect of uranium and zirconium extraction with the steel melt at interaction with non-oxidized corium melt is one of the most essential. Concentration of uranium and zirconium in resulting metallic melt is assigned by amount of free zirconium in initial corium melt and uranium/zirconium ratio, and also by the weights ratio of steel and corium. Concentration of uranium and zirconium makes so high under certain conditions that the density of metallic melt makes higher than density of oxidic melt, what results in inversion of oxidic and metallic layers. This effect complicates considerably the description of processes at IVR because causes an opportunity of the pool structures existence with the bottom displacement of the metallic melt or even more complex three-layer structures.

Features of physicochemical interaction of corium melt with cooled RPV steel are investigated in RIT by METCOR project. Results of the experiments executed using the method of induction high-frequency heating in the "cold crucible", show that there is he high-temperature corrosion of RPV steel at the characteristic conditions for IVR (melt composition and temperatures, temperatures and heat flux on surfaces, which are faced to RPV steel melt) and at various oxygen potentials:

By oxidation mechanism with formation of oxidic layers from components of steel and corium in the interface, at high oxygen potential of the melt;

- By mechanism of eutectics melting with formation of relatively fusible system U-Zr-Fe-O, at low oxygen potential in the interface, i.e. at presence of metallic zirconium in corium.

Kinetics and final corrosion depth of RPV steel is determined by complex of processes in the melt pool causing by reagents supply to the interface and by temperature conditions in the interface, which set the thickness, composition, properties and evolution of the corium crust on RPV steel surface during corrosion development.

However the specified experiments are executed in small scale (1-2 kg of the corium melt) with bottom displacement of samples. It is the extremely important to determine experimentally for reactor applications of the obtained results the influence of the sizes (scale) and specific 2-D geometry of the pool and real lower head curvature at IVR on features and characteristics of the found corrosion processes.

Topicality of researches by the present Project is caused by the listed above new experimental results in complex with the still present uncertainties, which is complicated its reactor application.

**1.3. Possibilities of NNC RK experimental facilities**

LAVA –B facility, which was built in institute of atomic energy NNC RK during performance of international COTELS and IVR-AM programs in cooperation with NUPEC Company (Japan), will be used for achievement of the Project purposes.

LAVA-B facility as a part of the "Baykal-1" stand complex allows to perform experiments with obtaining of 60 kg of prototypic corium melt (corium on the basis of UO2 with natural enrichment) and the subsequent corium discharging from height about 1.7 m in the experimental section containing the lower head model (LHM) of RPV, equipped with thermocouples and gauges for LHM wall deformation measurement. Melting of initial burden is performed in the electric melting furnace (EMF) via induction heating in the "hot crucible" of LAVA-B facility, which is placed above experimental section.

Temperature of the external wall of the crucible is measured with thermocouples. Temperature of the melt inside crucible is measured with the pyrometer of spectral ratio.

Diameter of LHM is chosen on the principle of total filling of the semi-elliptical part of LHM with the melt considering the possible partial replacement of the corium from LHM with the decay heat simulation device.

Thermocouples for estimation of the temperature field in LHM wall are built on various depths from the external LHM surface and on different distances from the lower point of the semi-elliptical part. This allows to measure the temperature of the wall on various distances from the "corium - steel" interface both in elliptical and in cylindrical parts of LHM Total thermocouples number is 30. It is supposed the installation of the hot thermocouples hot junctions in two planes, which are in different distance from the internal surface of LHM of the bottom and on the external surface of LHM. High-sensitivity thermocouples of CA type are applied to increase of the noise stability of measuring circuits.

There are thermocouples for estimation of environment temperature in the cavity of thermal insulated melt receiver (MR) including position above melt pool directly; gauge for indication of corium jet passage in the LHM, gauges of the gas environment pressure in MR cavity and gauges of moving and deformation of the LHM wall in various points (up to 5 points). Special gauges are intended to measurement of the heat flux through MR wall for an estimation of thermal losses during experiment. Internal volume of MR is about 5 m3. The maximum gas pressure in MR is up to 4 MPa.

There is the system of environment gas sampling from EMF and MR for the subsequent analysis of gas composition at various moments of time during experiment.

Technological equipment of the LAVA-B stand allows simulate the decay heat in corium placed in the LHM using method of alternate current between three electrodes shipped in the melt. Outflow of heat from corium in electrodes is compensated via electro-arc warming-up of the electrodes nozzles having a coaxial design. Electrical power of the equipment for alternate current is about 40 kW, power of the electric arc in each of three electrodes - up to 12 kW. Total electrical power supplied to the melt is about 76 kW.

The set of the technological equipment of LAVA –B facility includes three tanks for cooling water supplying on the corium surface, which is placed in the LHM and on the external surface of LHM. The volume of each tank is 1.8 m3. Thus, external cooling can be performed both via irrigation of the wall from atomizers, and via continuous filling the space between LHM and the technological basis. The temperature of cooling water can vary from 20 to 150 degree C for the internal irrigation, and up to 50 degree C for external cooling.

There is a system of superheated seam supply for warming-up of MR cavity before melt discharging. Tank volume for the steam supply is 1.5 m3, steam temperature on output of the steam and gas generators is about 160 degree C. MR cavity can be filled by nitrogen or argon gas after its warming-up using steam.

System of condensed steam gathering allows estimate weight of the water evaporated at cooling of the external surface of LHM.

Small-scale experiments in VCG-135 stand will allow improve technology of the protective coating both on the graphite crucibles internal surface used in the EMF of induction type for corium melt obtaining and on the external surface of graphite nozzles for electrodes of the decay heat simulation device. Furthermore the data on the intermediate compositions formed during simultaneous heat-up of core components will be received in experiments at VCG-135 stand. The obtained data will be used further during post-test analysis of the corium samples after experiments in LAVA-B facility.

The equipment of material research lab allows perform macro- and micro- structural investigation of uranium contained materials after experiments on interaction of prototypic corium with RPV steel, to study phase and element structure of interaction products, to measure density and electrical resistance of the materials samples.

Experimental researches will be performed with the variation of melt composition, including oxidic-metallic melt usage.

The obtained experimental data on structure of the molten pool, on thermal loadings on the lower head of RPV and degree of RPV steel corrosion damage will be presented in the form, optimum for its use by development of processes models and verification of calculation codes.

Participants of the project have wide experience of designing and manufacturing of facilities for out-of-pile experiments with prototypic corium. Number of experimental researches on LWR corium interaction with the coolant (more than 10 experiments), with concrete (more than 25 experiments) and RPV material (8 experiments on corium interaction with RPV steel including 3 experiments with decay heat simulation) were performed using these facilities. The large series of supporting experiments were performed (more than 100 tests) in the small-scale stand, devoted to research the various ways of protection from corium components interaction with the crucible material (graphite); to studying of corium components interaction among themselves at heat-up to the melting temperature; to research of concrete components thermo stability, and also to studying of electrical resistance of the core materials mix at high temperature.

Results of work are presented in annual scientific and technical reports from 1995 to 2003, reported at the Workshops on severe accident research in Karlsruhe and South Korea, published in scientific works books of NNC RK.

Involved individual experts from Aleksandrov' RIT (Russia) have wide experience on experimental MCCI and IVR research, processes at water supply on the corium melt surface and metals, on release of fission products from corium melt, on phase diagrams of corium.

The basic publications of the Project participants on corium research are listed below.

1. Vassilyev Yu., Zhdanov V, Nagasaka H. et al., COTELS Project (1): "Overview of Project to study FCI and MCCI during a Severe Accident", Proc. of OECD Workshop on Ex-Vessel Debris Coolability, November 15-18, 1999, Karlsruhe, Germany.
2. Vassilyev Yu., Zhdanov V, Kato M. et al., COTELS Project (2): "Fuel Coolant Interaction Tests under Ex-Vessel Conditions", Proc. of OECD Workshop on Ex-Vessel Debris Coolability, November 15-18, 1999, Karlsruhe, Germany.
3. Nagasaka H., Sakaki I., Zhdanov V. et al., COTELS Project (3) : "Ex-vessel Debris Cooling Tests", Proc. of OECD Workshop on Ex-Vessel Debris Coolability, November 15-18, 1999, Karlsruhe, Germany.
4. Zhdanov V, Kolodeshnikov A., Nagasaka H. et al, COTELS Project (4) : "Structural Investigation of Solidified Debris in MCCI", Proc. of OECD Workshop on Ex-Vessel Debris Coolability, November 15-18, 1999, Karlsruhe, Germany.
5. Vurim A.D., Zhdanov V.S., Zverev V.V. "Results of testing of model fuel rods BREST-300 type in IGR reactor", Bulletin of NNC RK, Edition 1, January 2000
6. Zhdanov V.S., Malysheva E.V., Kukushkin I.M., "Method of corium retention in the experimental volume", Bulletin of NNC RK, Edition 2, May 2001
7. Zhdanov V.S., Kukushkin I.M., Baklanov V.V., "Phase analysis of multi-component samples of corium", Bulletin of NNC RK, Edition 2, May 2001
8. Zhdanov V.S., Kolodeshnikov A.A., Vassiliev Yu.S., Research of the consequence of severe accidents in light water reactors on COTELS project", Bulletin of NNC RK, Edition 1, March 2002
9. Maruyama Yu, Nagasaka H. Zhdanov V et al. "Recent results of MCCI studies in COTELS project", Proc of Third Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety Kyeongju, Korea, October 13-16, 2002.
10. Maruyama Yu, Nagasaka H. Zhdanov V et al. "Results of LHI tests and associated analyses on in-vessel debris coolability", Proc of Third Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety Kyeongju, Korea, October 13-16, 2002.
11. Zhdanov V.S., Baklanov V.V., Kukushkin I.M., "Research of methods of graphite crucible protection for erosion prevention during refractory oxide materials melting", Bulletin of NNC RK, Edition 2, May 2003.
12. Zhdanov V.S., Baklanov V.V., Malysheva E.V., "Experimental research of limitation effect of LWR core components melt interaction with carbon", Bulletin of NNC RK, Edition 1, March 2004.
13. Zhdanov V.S., Vassiliev Yu.S., Kolodeshnikov A.A., "2-D concrete ablation in MCCI tests", Bulletin of NNC RK, Edition 1, March 2004.
14. Zhdanov V.S., Vassiliev Yu.S., Kolodeshnikov A.A., "Research of concrete degradation MCCI tests", Bulletin of NNC RK, Edition 1, March 2004.
15. Vassiliev Yu., Kolodeshnikov A., Zhdanov V. "NNC facilities short description for severe accident experimental research", Proc of CEG-SAM-6th meeting, Dimitrovgrad, September 14-17, 2004.
16. Zhdanov V., Baclanov V., Malysheva E. "Experimental studying of limitation technique of corium components interaction with carbon", Proc of CEG-SAM-6th meeting, Dimitrovgrad, September 14-17, 2004.
17. Bechta S.V., Khabensky V.B., Vitol S.A. et al., “Experimental studies of oxidic molten corium – vessel steel interaction”, Nuclear Engineering and Design. 210 (2001) p. 193-224.
18. Bechta S.V., Khabensky V.B., Vitol S.A. et al. “Experimental study of ceramic corium melt - steel interaction”, Proc. of International Seminar RASPLAV 2000, Munich, Germany, November14-15, 2000.
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### 2. Expected Results and Their Application

The basic results of the Project will be:

- The improved technology of the prototypic LWR corium melt obtaining and methodology of experiments performance on corium interaction with RPV steel at decay heat modeling;

- The improved instrumentation of the experimental facility;

- Experimental data on structures of molten pool on the RPV lower head obtained in large-scale tests at decay heat modeling in prototypic corium LWR;

- Experimental data on RPV steel corrosion at late phase of LWR core degradation depending on corium composition and distributions of thermal loadings to RPV.

### 3. Meeting ISTC Goals and Objectives

The project will be performed within 36 months, in work will be occupied on the average 78 persons from whom 45 persons have been earlier connected to development and researches in the field of military techniques.

Work is in fully performed IAE NNC RK with participation of separate experts of other organizations including Russian specialists.

The given Project:

- Will help the experts earlier connected to development of military techniques and arms, to be reoriented on activity on civil subjects;

- Will support applied researches in the peace purposes, especially in the field of nuclear safety and protection of the environment;

- Will promote integration of scientists from Kazakhstan Republic into the world community.

Thus, the Project completely corresponds to ISTC goals.

### 4. Scope of Activities

Performance of 4 tasks is provided according to the contents of the Project. All tasks are intended for achievement of the Project objectives – obtaining of experimental data on IVR processes.

Task 1 Modernization of facilities and optimization of melting technology and imitations of decay heat.

Task 2 Calculation support of experiments

Task 3 Large-scale experiments

Task 4 Post-test analysis

Each task is divided into stages according to the appropriation.

#### Task 1

|  |  |  |
| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| For performance of tests on task 3 and the post-test researches on task 4 are performed:  - Development of protection coating application technology on the internal surface of the graphite crucible. It includes experiments in the small-scale stand on protection coating application and checking its stability in extreme conditions, the description of heating modes for large-scale crucible, application of the protection coating on the large-scale crucible\*).  - Development of protection coating application technology on the external surface of graphite nozzles of electrodes using VCG-135 stand.  - Development of melting and corium discharging modes in the experimental section without decay heat simulation. Various ways of corium cooling in experimental section are applied in the given group of 3 experiments\*\*).  - Development of design and operating modes of the electrode decay heat simulator.  - Design and manufacturing of RPV models and details of experimental facilities.  \*) Heating modes of large-scale crucible are specified with collaborators participation.  \*\*) Burden heating modes of EMF for LAVA –B facility are specified with collaborators participation. | | 1-IAE NNC RK |
| **Description of deliverables** | | |
| 1 | Technical information in quarterly reports | |
| 2 | Experimental facility and tests methods description | |
| 3 | Chapter in the annual report | |

#### Task 2

|  |  |  |
| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| For performance of tests on task 1 and the post-test researches on task 4 are performed:  - Calculation modeling of the melt pool in LHM and definition of heating efficiency, distribution of heat fluxes and temperatures on LHM internal surface;  - Calculation and optimization of external cooling system of LHM;  - Calculation temperature and stress - deformed conditions of LHM (pretest and the posttest calculations);  Note. All calculations at performance of a task 2 are performed with collaborators participation. | | 1-IAE NNC RK |
| **Description of deliverables** | | |
| 1 | Technical information in quarterly reports | |
| 2 | Chapter in the annual report | |

#### Task 3

|  |  |  |
| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| Performance of large-scale experiments with maintenance of the energy release in the melt pool, which is hold in he RPV model \*):  - oxidic corium C-70;  - Oxidic-metallic corium C-30+10wt% of steel.  - Oxidic-metallic corium C-30+10wt% of steel\*\*).  \*) The matrix of experiments and corium composition can be specified as agreed with collaborators.  \*\*) Steel will be added in the melt outside EMF. | | 1-IAE NNC RK |
| **Description of deliverables** | | |
| 1 | Quarterly reports and reports on experiments | |
| 2 | Chapters in annual reports | |

#### Task 4

|  |  |  |
| --- | --- | --- |
| **Task description and main milestones** | | **Participating Institutions** |
| Post-test analysis of he corium samples and RPV steel including:  Cutting of the corium ingot and sampling;  XRD\*);  Metallographic;  Element analysis;  Generalization of experiments results\*\*);  Preparation of the experimental data file for a database\*\*).  **\*)** XRD data processing is performed with collaborators participation.  \*\*) Is performed with collaborators participation. | | 1- IAE NNC RK |
| **Description of deliverables** | | |
| 1 | Quarterly reports and reports on experiments | |
| 2 | Chapters in annual reports | |
| 3 | Final report on Project | |
| 4 | INVECOR database | |

The circuit of listed Tasks correlation is shown on fig. 1.

**Scheme of tasks 1-4 correlation**



Fig. 1

Results are discussed with collaborators after finishing of each intermediate stage. Updating of work plans and the experiments matrix can be made accordingly to discussion results.

### 5. Role of Foreign Collaborators/Partners

The following forms of co-operation with foreign collaborators will be realized in the project:

1. Discussion and specification of tests matrix;
2. Collaborator performance of the supporting pre-test calculations of EMF on the basis of the data received in small-scale experiments and constructive circuit of EMF, and also the pre-test and the post-test calculations of corium pool in LHM using CEA computer codes;
3. Development of XRD data of material samples, which are obtained during small-scale and large scale experiments;
4. Operative information exchange during Project performance and collaborators participation in the final INVECOR database formation;
5. Discussion of the reporting;
6. Organization of meetings and seminars;
7. Preparation of joint reports and articles.

### 6. Technical Approach and Methodology

The technical approach and methodology provides modeling in LHM the basic processes, characteristic for IVR conditions.

Induction heating using "hot crucible" method is applied to obtaining of prototypic corium melt. Obtained corium is discharged from EMF in experimental section from height about 1.7 m after achievement of the required melt temperature. The experimental section is placed in the MR, which is the cylindrical hermetic vessel about 4.5 m3 in volume with stainless steel wall. Internal MR surface is covered with the thermal insulation layer for restriction of heat losses.

Limitation of corium components interaction with carbon at the heat-up is performed using method of zirconium melt application on the crucible internal surface with the subsequent zirconium carbiding. The similar method is used at protection of electrodes nozzles of the device for decay heat simulation in corium.

The model of the RPV lover head is made of VVER RPV steel in scale about 1:10. The size of LHM configuration are determined by amount of the possible maximum corium volume, obtained in the existing EMF of LAVA-B facility and also the preset conditions of thermal and physicochemical interactions between corium and steel. Thickness of the wall can not reflect the scale of LHM diameter in this connection. Thus the requirement of hemi-elliptical part of LHM filling with discharged corium is kept, and cylindrical part of LHM should be partly filled under condition of partial corium replacement with electrodes of the decay heat simulation device.

Modeling of decay heat in corium, placed in LHM, is performed using the electrode heater shipped in the melt via heating-up of electrodes by an electric arch due to electrode nozzles coaxial design (method of the alternating current through the melt between electrodes will be not used due risk of short circuit between electrodes and LHM wall what can cause non-desirable processes).

Verification of the following concepts is planned during performance of integrated large-scale experiments:

1) Retention of prototypic oxidic corium melt C-70 in RPV model within not less than 2 hours with imitation of decay heat in corium and presence of RPV external cooling.

2) Retention of prototypic oxidic-metallic corium in RPV model within not less than 1 hour with imitation of decay heat in corium and presence of RPV external cooling with the subsequent stopping of cooling water supply for the organization of RPV wall penetration accordingly to interaction model by СЕА /Christophe JOURNEAU, Convection naturelle dans un bain de corium avec dissipation volumique de puissance, *Congres Français de Thermique, SFT 2004, Presqu'ile de Giens, 25-28 mai 2004*/.

3) Retention of prototypic oxidic-metallic corium in RPV model within not less than 1 hour with imitation of decay heat in corium and presence of RPV external cooling with the subsequent stopping of cooling water supply for the organization of RPV wall penetration accordingly to interaction model by METCOR /S.V. Bechta, V.B. Khabensky, V.S. Granovsky et al. “New Experimental Results on the Interaction of Molten Corium with Reactor Vessel Steel”, Proc. Of ICAPP’04, Pittsburgh, PA USA, June 13-17, 2004, Paper 4114/.

Difference in technical realization of experiments under scenarios 2 and 3 will consist in various depth of electrodes dipping in the corium pool and/or in change of the shape of external nozzles of coaxial electrodes of the device for decay heat modeling.

LHM is equipped with the set of the thermocouples built in the wall on different depth from the external surface and in various zones on height and azimuth (in the lowest point of model, in the hemi-elliptical zone, in the cylindrical zone, and also in the cylindrical zone which is not filled with corium) for measurement of the heat flows profile.

LHM wall deformation is measured in the chosen points using displacement transducer established in the clearance between LHM external wall and the technological basis.

Cooling water is supplied from below in the clearance between LHM and the technological basis, and removed from the upper zone. Heating and the flow rate of the cooling water is measured by corresponding gauges. The water flow rate can be adjusted for maintenance of the preset experiment conditions.

The amount of the evaporated waters at external cooling is estimated using steam condensation system, which is included in experimental facility.

Post-test researches are performed after each experiment including operations from the following list:

1. The analysis of gas samples composition from EMF and MR using chromatograph "Tsvet-800";
2. Particulate debris removal and its fragmentation analysis using sieving device "Fritsch";
3. LHM longitudinal section with solidified melt (or without melt at absence of strong coupling between corium and LHM wall, - in this case debris ingot is cut separately from LHM) using available cutting machine;
4. Investigation of section plane;
5. Measurement of LHM wall corrosion/penetration depth in the LHM section plane;
6. Fabrication of powder specimen from fragmented debris and debris ingot;
7. Fabrication of metallographic specimen from LHM wall samples;
8. Fabrication of specimen from interface area;
9. Powder specimen element analysis using roentgen-fluorescence spectrometer "Spectroscan" and time-of-flight mass spectrometer "Lasma-2000";
10. Phase analysis of powder specimen using X-ray diffractometer "DRON", which is equipped with digital registration device\*);
11. Density measurement of powder specimen and ingot specimen using standard and individual devices;
12. Measurement of specific electrical resistance of powder samples and ingot samples using individual devices;
13. Re-melting of debris samples in the small-scale stand and subsequent repeated phase and element analysis of resulting compositions.

\*) X-Ray diffractogram identification is performed with foreign collaborators participation.

### 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** |  |  |  | Report |  |  |  |  |  |  |  |  |  |
| **Person\*days** | 1490 | 1490 | 1420 | 1290 | 1130 | 640 |  |  |  |  |  |  | 7460 |
| **Task 2** |  |  |  |  | Meeting |  |  |  |  |  |  |  |  |
| **Person\*days** | 890 | 570 | 460 | 465 | 460 | 480 | 490 | 510 | 510 | 510 | 510 | 590 | 6445 |
| **Task 3** |  |  |  |  | Pre-test | Pre-test | 1st test | Report  Extended seminar | 2nd test | 3rd test | Database preparation | Report |  |
| **Person\*days** |  |  |  |  | 870 | 985 | 1060 | 1040 | 1060 | 1060 | 990 | 990 | 8055 |
| **Task 4** |  |  |  |  |  |  |  |  |  |  |  | Final report,  INVECOR database  Seminar |  |
| **Person\*days** |  |  | 820 | 820 | 910 | 990 | 870 | 970 | 960 | 970 | 960 | 980 | 9250 |
| **TOTAL** | 2380 | 2060 | 2700 | 2575 | 3370 | 3095 | 2420 | 2520 | 2530 | 2540 | 2460 | 2560 | 31210 |

### 8. Personnel Commitments

#### 8.1. Individual participants

### Leading Institution: Short name

#### Category I (weapon scientific and technical personnel)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Name** | **Birth**  **Year** | **Scientific Title** | **Weapon**  **Expertise Ref.** | **Function in project** | **Daily rate**  **(US$)** | **Total days** | **Total grants**  **(US$)** |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
| **Total:** | | | | | |  |  |

#### Category II (other scientific and technical personnel)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Name** | **Birth**  **Year** | **Scientific Title** | **Function in project** | **Daily rate**  **(US$)** | **Total days** | **Total grants**  **(US$)** |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
| **Total:** | | | | |  |  |

#### Category IV (personnel, who will work less than 10% of project duration)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Number of persons** | Function in project | **Daily rate**  **(US$)** | Total days | **Total grants**  **(US$)** |
|  |  |  |  |  |
|  |  |  |  |  |
| **Total:** | | |  |  |

#### 8.2. Managerial responsibilities

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