ISTC Project No. K-1265

Experimental study of the processes at the corium melt retention in the reactor pressure vessel (INVECOR)

Annual Project Technical Report

on the work performed from May 01,2008 to April 30, 2009

Affiliated State Enterprise “Institute of Atomic Energy” of the Republican State-Owned Enterprise “National Nuclear Center” of the Republic of Kazakhstan (IAE NNC RK)

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1. Brief description of the work plan: objective, expected results, technical approach

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 simulation of the thermal and physicochemical processes at the retention of the prototype molten corium pool on the water-cooled lower head of the reactor pressure vessel (RPV) for estimation of:
- influence of scale, shape of the interface and other 2-D effects on the corrosion processes, which determine the final thickness of the RPV wall;
- influence of the metal-oxide stratified molten pool structure on the possibility of corium in-vessel retention;
- quantitative characteristics of processes at IVR, which are necessary for the development and verification of models involved in IVR justifying.

The Project concerns the category of applied researches. The main results of the Project will be the large-scale experimental data on the structure of molten pool on the RPV model and on RPV steel corrosion depending on the prototypic corium composition and heat load distribution on the reactor vessel. The resultant data may be used for the development of models describing melt behavior at the in-vessel accident phase, verification of the appropriate calculation computer codes in justification of IVR concept for existing and newly-developed projects.
The technique for producing corium melt and the methodology of tests on corium/RPV steel interaction can be improved owing to the involvement of foreign collaborators (CEA, Cadarache) in calculated validation of the electrical melt furnace modes and large-scale test conditions. The collaborators' thermodynamic and physicochemical computer codes will make it possible to interpret small-scale test results in order to use in LAVA-B facility considering the electric melting furnace (EMF) structure.
Engineering developments ensuring melt and retention of corium melt may be used in practice of similar studies and in industry on melting of reactive and radioactive materials.

The engineering approach and methodology provides reproduction in RPV model of basic processes which are specific for IVR requirements.

Induction heating by a method of "hot crucible" is applied to obtaining a prototypic corium melt. Gained corium is discharged from EMF in the experimental section from altitude about 1,7 m after reaching demanded melt temperature. The experimental section is disposed in the melt receiver (MR), representing a cylindrical pressure vessel in volume nearby 5 м3, made of stainless steel. Interior MR surface is coated by a heat insulation for restriction of heat losses.

Restriction of interaction of corium components with carbon at their warming up is fulfilled by a method of molten zirconium spreading on the internal surface of the crucible with the subsequent zirconium carbidization. The analogous method is applied at a protection of an external surface of electrode nozzles of the device for decay heat imitation in the melt.

The RPV model is made of VVER pressure vessel steel in scale nearby 1:12. The size of model and its configuration are determined by amount of the greatest possible corium volume, gained in existing EMF of LAVA-B facility, and also the given requirements of thermal and physicochemical interaction between corium and steel. In this connection wall thickness can not reflect a scale of diameter of model. Thus the demand of filling-up with slumped corium the all semi-elliptical part of model is fulfilled, and under condition of partial displacement of corium by electrodes of the device for decay heat simulation should be filled and a part cylindrical section of model as well.

Imitation of decay heat in corium, being in RPV model is carried out by means of the electrode heater entrained in a melt, via method of a warming up an electric arc of each coaxial electrode (it was accepted to not apply a mode of corium heating existed earlier via an electric current through a melt between electrodes because of hazard of short circuit of currents to RPV model).

Checkout of following concepts is planed during realization of integral large-scale tests:

1) Retention of the prototypic oxide-metal corium melt C-30 in RPV model during not less than 2 hours at imitation of decay heat in corium.

2) Retention of the prototypic oxide-metal corium melt in RPV model during not less than 1 hour with imitation of decay heat in corium and presence of external cooling of vessel with the subsequent stopping of cooling water supply for the organization of a weld penetration of RPV wall on interacting model "focus-effect"/Christophe JOURNEAU, Convection naturelle dans un bain de corium avec dissipation volumique de puissance, *Congres Franзais de Thermique, SFT 2004, Presqu'ile de Giens, 25-28 mai 2004/.*

3) Retention of the prototypic oxide-metal corium melt in RPV model during not less than 1,5 hours with imitation of decay heat in corium and presence of external cooling of vessel with the subsequent stopping of cooling water supply for the organization of a weld penetration of RPV model wall on model of interacting MASCA/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 the tests by scenarios 2 and 3 will consist in a various dipping depth of electrodes in corium pool and/or in a change of external nozzle of coaxial electrodes of the device for decay heat simulation.

RPV model is equipped with a set of thermocouples built-in in wall on various depth from an external surface and in various areas on altitude and an azimuth (in the lowermost point of model, in a semi-elliptical zone, in a cylindrical zone, and also in the cylindrical zone which is not filled with corium) for measurement of the profile of heat fluxes.

Deformation of RPV model wall is measured by displacement gauges in the chosen points in a clearance between exterior wall of model and the technological base.

Cooling water is supplied from below in a clearance between RPV model and the technological base, and drained from the upper zone. Heating of water and its flow rate, supplied for cooling,

is measured by correspondent gauges. The water flow rate can be controlled for providing of the given test requirements.
The amount of the evaporated water at external cooling is estimated via application of system of the steam condensation which is a part of the test facility.
Small-scale experiments are fulfilled in facility of induction heating, equipped by measuring tools of temperature, pressure inside of work chamber and by system of a gas sampling during experiment.
Post-test investigation is fulfilled after each experiment.
As per the scope of the Project, 4 tasks are expected for implementation. All tasks are assigned for achievement of the Project objective – to obtain experimental data on IVR processes.
Task 1 Modernization of test facilities and optimization of melting process and simulation of decay heat.
Task 2 Calculation support of experiments
Task 3 Large-scale experiments
Task 4 Post-test analysis
Each task is phased according to the investigation lines.

2. Technical progress during the first year

Works during 1st year were performed on Tasks 1, 2 and 4 according to the Technical schedule. It is executed within the framework of Task 1.

Subtask 1.1 "Improvement of the method of application of the protective coating on the internal surface of graphite crucible".
In connection with delay in delivery of graphite products the works on protective coating application on an internal surface of large-scale crucibles were not performed.
In addition to the work plan small-scale experiment on the protective coating stability on the graphite surface against molten steel attack. It has been found as a result of experiment, that interaction of the melt with protective coating material occurred at the steel warming up above melting point, but presence of the metallic zirconium in the melt slowed down this process.

Subtask 1.2 "Working off of coating application method on an external surface of graphite nozzles of electrodes in VCG-135 facility".
As a result of numerous experiments the optimum configuration of an external surface of an external graphite electrode nozzle, and also a way of placing on it of initial zirconium was chosen. Nozzles with a coating were tested in 2 large-scale calibrating experiments with a warming up and melting of initial components of prototypic corium.
It was revealed, that as a whole the coating provides protection against interaction of corium components with carbon at a heat. Nevertheless, reliability of a coating depends both on quality of the coating and on graphite type applied to manufacturing of electrodes nozzles.

Subtask 1.3 "Working off of warming up and melting of corium into experimental section".
In the given set of 2 large-scale experiments the mode of melting of loading of initial prototypic corium components and reliability of work of the device for modeling of a decay heat in the corium pool has been checked.
2 preparatory large-scale tests (TOP-6, TOP-7) on heating and melting of 12 kg of initial loading of corium C-30 have been performed in the framework of subtask 1.3. Heating was conducted during 2…2,5 hours at the specific power higher than 1,5 kW/kg at electrical power of plasmatrons 18…19 kW.

Effect of smoke on the pyrometer sighting line used for temperature measurement at the corium warming-up and melting in electric melting furnace of induction type has been estimated during separate test in the small-scale facility.
Results of large-scale calibration experiments have confirmed overall the possibility of performance of integral tests according to the Work plan of the project.

Subtask 1.4 "Testing of a design and operation modes of the electrode simulator of decay heat in corium".
At the third stage of work a series of experiments on mounting and testing of new set of equipment for plasmatrons power supply has been executed for increase of number of plasmatrons in one test section up to 5. As a result of numerous experiments power of device for decay heat modeling was increased up to 90 kW.
Complex starting-up and adjustment operations with the device for decay heat imitation, established in test section have been executed.

Subtask 1.5 "Design and manufacture of test section and details of the experimental facility".
The experimental section for integral test has been equipped with gauges for temperature and RPV wall deformation measurement. It has been covered with thermal insulating package and put in the concrete base.
Coaxial plasmatrons of new design and units of device for decay heat modeling have been fabricated accordingly to new developed design. Device has been mounted in the test section for the first integral test performance.
Units of test section for the second integral test performance have been fabricated.
Test cells for performance of large scale calibrating tests TOP-6 and TOP-7 for warming-up and melting of C-30 corium have been fabricated.

It has been executed accordingly to Task 2.
Computer modeling of the molten corium pool in RPV model and distribution of the heat fluxes and temperature fields on the inner surface of RPV model have been specified on the base of the results of calibrating tests including data in the zone of the preponderant position of the electric arc burning in the coaxial plasmatrons.
Pre-test calculations of the stress-deformed state of the RPV model have been performed considering the results of the calibrating tests.
Thermal calculations of the test section with device for decay heat modeling for warming-up and melting of 60 kg of C-30 corium initial components without preliminary melting have been performed.

It has been executed accordingly to Task 4.
Results of 4 large-scale tests on heating and melting of prototypic corium initial components in mix C-30 (TOP-4…TOP-7) have been investigated. Researches included, as the first step, vertical section of experimental cell with hardened corium melt. In the course of researches were studied:

- State of protective coating on the graphite nozzles of electrodes of coaxial plasmatrons;
- Phase composition of corium samples after the tests depending on sampling placement.

Small-scale experiment on research of interaction of "corium melt/steel", "steel melt/uranium dioxide" and "steel melt/corium" have been completed. Also results of these tests have been investigated.

3. Technical progress during the year of reference

- compliance with tasks and milestones as described in the work plan

Works current year on Task 1, 2 and 4 are carried out according to the Plan of works. The planned beginning of performance of the Task 3 (Performance of 3 large-scale experiments with imitation of decay heat in the melt pool, being in RPV model), most likely, will not take place even in 13th quarter in connection with suspense of a question of delivery of graphite for manufacturing of details of the electro-melting furnace. Preparation of the test sections for the second and third integral tests is planning in parallel to the preparation and performance of the first integral test.
Preparation of the equipment for test section disassembling after integral tests (post-test research) is executed.

- achievements of the past year

<u>Subtask 1.1 performance.</u>
As a result of tests on protective coating stability research data on interaction kinetics and on measures of interaction rate decrease due to presence of corium components in the melt have been obtained (Appendix 2).

<u>Subtask 1.2 performance.</u>
On the basis of earlier developed (in the 1st year) techniques the satisfactory coating was applied on the 2 plasmatrons nozzles, made from R4340 graphite (available in institute). Nozzles with a coating were tested in structure of plasmatrons during the performance of large-scale calibration experiments TOP-6, TOP-7. In the conditions of monotonous heating and at use of qualitative graphite the coating has prevented interaction of graphite with oxidic corium components.

<u>Subtask 1.3 performance.</u> Results of experimental researches are gained on:
At performance of calibration large-scale experiments TOP-6, TOP-7 following parameters (Appendix 2) were reached:

- Electric power of plasmatrons in a range 17 … 19 kW;
- Average temperature of corium 2500 … 2700 °C;
- Temperature of thermally insulated walls of experimental assemblage 800 … 950 °C;
- Duration of experiment up to 2,5 hours.

Following was found during the experiments:

- Duration of experiment can be not less than 2 hours at every plasmatrons power 18 kW;
- Plasmatrons life-time is limited by erosion of an internal nozzle of plasmatrons in case of usage of ARV-1 graphite (made in Russia);
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- Application of R4340 graphite (made by SGL Carbon Group) will allow to increase duration of integral experiment up to 2,5 hours.

<u>Subtask 1.4 performance.</u>
Results of experimental researches are gained on:
a) Stability of device for decay heat imitation operation on the base of 5 coaxial plasmatrons;
b) Water flow rate in the ducts of cooling of plasmatrons and external (thermal insulated one) surface of RPV model;
c) Flow rate and the way of optimal gas mix in the inter-electrode space of coaxial plasmatrons;
Results of tests on device for decay heat imitation research are shown in Appendix 2.

Subtask 1.5 performance.
Test section for the first integral experiment has been fabricated and assembled, which includes:

- RPV model made from carbon steel into which wall samples of RPV steel 15ChA2MNFA equipped with thermocouples are inserted;
- Thermal insulating package on an external surface of RPV model;
- Concrete base for experimental section;
- Device for imitation of decay heat in corium pool, which includes 5 coaxial plasmatrons;
- Gauges of moving/deformation of RPV model wall;
- Pipes for water cooling system for copper parts of plasmatrons and for external surface of RPV model;
- Pipes for gas mix supply in the inter-electrode space of coaxial plasmatrons.

Photos of the details set forth above are shown in Appendix 1, figure A1-1.
Units of experimental section for the second integral test have been prepared (Appendix 1, figure A1-2.

It is gained on the Task 2:
1) Results of calculation of the heat exchanger hydraulics resistance in the tract of gas drainage from the electric melting furnace (Appendix 2).
2) Results of calculation of the stress-deformed state of RPV model considering the results of large-scale calibrating experiments including data on the zones of the preponderant position of the electric arc burning in the coaxial plasmatrons (Appendix 2).
3) Results of thermal calculations of the experimental section with the device for decay heat modeling for warming-up of 60 kg of corium C-32 components without preliminary melting (Appendix 2).

It is gained on the Task 4:
1) Results of research of the zirconium coating on an external surface of graphite nozzles of coaxial plasmatrons after tests with heating of initial components of prototypic corium during more than 2 hours (Appendix 2).
2) Results of phase analysis of corium after 4 large-scale calibration experiments on heating and melting of initial components of prototypic corium (Appendix 2).
3) Results of tests on interaction research of "corium melt/steel", "steel melt/uranium dioxide" and "steel melt/corium".
4) Results of research of protective coating stability against molten steel attack (Appendix 2).

4. Current technical status

- Operations are executed according to the schedule, except for the Task 3 (integral large-scale experiments). The graphite materials used in the electro-melting furnace are necessary for performance of works on the given Task. In connection with delay in delivery of necessary materials experiments cannot be begun earlier than 13th quarter.

- refining next year schedule if necessary

In case of the successful delivery of graphite materials in the 13th quarter beginning the integral tests will been performed during 13th and 14th quarters (including post-test calculations and post-test research).

- recommendation for changes of the work plan, if necessary

Shift of a beginning of the Task 3 performance to 13-th quarter from 8/1/2007 is necessary due to late delivery of needed materials.

5. Cooperation with foreign collaborators

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

No
- signature of protocols (with short description)

No

- research carried out jointly

No

- trips to/from foreign collaborators

Meetings with foreign collaborators were organized, as a rule, during contact expert group meetings (CEG-SAM). In the past year such meeting was in September, 2008 (Kiev, Ukraine) Meeting with members of CEA Cadarache and JRC-ITU Karlsruhe in Kurchatov-city (Kazakhstan) was in November, 2008.

- workshops, topical meetings organized by the project team

Meeting in the framework of experimental programs coordination (ECO-NET) was in Kurchatov-city (Kazakhstan) (November, 2008).

- joint attendance to international conferences

No

6. Problems encountered and suggestions to remedy

The main problem which can cause the delay of large-scale experiments beginning is very long-term procedure of purchase and delivery of equipment and the materials necessary for Project performance. Probably, this problem is called by remoteness of institute from the majority of potential suppliers, also by necessity of customs procedures and change of materials export/import rules.

7. Perspectives of future developments of the research/technology developed

The results gained within the third year of activity on Project are basis for preparation and performance of the large-scale experiments provided by the Work plan of the Project.

Attachment 1: Illustrations attached to the main text (4 pages)
Attachment 2: Other information, supplements to the main text (126 pages)
Attachment 3: Abstracts of papers and reports published during the year of reference (8 pages)