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Annual technical report

Project 833.2-2003

INVESTIGATION OF CORIUM MELT INTERACTION WITH NPP REACTOR VESSEL STEEL (METCOR)

Phase 2. Second year
(01.01.2004 – 31.12.2004)

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6. Project objective and expected results

Main objective of the current project is to enhance the nuclear reactor safety at severe accidents involving core degradation. The specific subject of the project is the in-depth investigation of physico-chemical phenomena taking place at the interaction of oxidic corium melt and NPP reactor vessel steel.

In order to reduce the radiological impact of beyond-design accidents with core meltdown new designs of NPPs with VVER, PWR and BWR reactors have been developed. They are provided with accident management systems, which ensure the containment tightness and substantial reduction of fission product release beyond it.

One of the measures aimed at a severe accident impact mitigation is the localization of molten corium within the containment. At present three concepts of molten core localization are developed and applied. Two of them are based on the principle of ex-vessel melt retention, one of them has been implemented in the design of EPR reactor. The concept essence is in melt spreading over large horizontal surface followed by its cooling. Another ex-vessel retention concept has been incorporated into the design of VVER-1000-based plants, which have been built in China and India. In accordance with it the relocated melt is retained in a water-cooled crucible. In accordance with the third concept the melt is retained within reactor vessel, the outer surface of which is passively cooled, and a good DNB margin is provided for the cooling water.

Let us consider the concept of the in-vessel melt retention (IVR) in more detail. This concept has been used in the design of medium-capacity NPPs with VVER-440 reactor (Loviisa, Finland), in the designs of AP-600 (Westinghouse, USA), NPP with VVER-640 (SPb AEP, Russia); and it is being further developed for the large-capacity reactors, including the designs of AP-1000 (Westinghouse, USA), BWR-1000 (Framatome ANP, France-Germany), PWR-1400 (KEPCO, Korea).

Previously, in order to justify the IVR efficiency only thermohydraulic aspects of the interaction between molten pool – cooled reactor vessel have been analyzed. The phenomena of physico-chemical interaction of oxidic melt and vessel steel and their influence on the vessel steel ablation depth and kinetics have not been sufficiently studied. They are very complex, in order to develop the methodology and numeric model of these processes it is necessary to perform experimental studies using realistic materials and conditions.

Let us consider possible stages of oxidic melt development in order to determine conditions adequately representing the realistic ones in the test facilities RASPLAV 2 and RASPLAV 3 in the experiments with corium simulant.

As shown by the severe accident calculations performed using codes MELCOR and RATEG-SVECHA-GEFEST, at the early stages of molten pool formation on the bottom of a reactor vessel the oxidic pool has a U-Zr-O composition, in which the fraction of suboxidized Zr can range widely depending on the reactor type and severe accident scenario. At this stage it is important to know quantitative characteristics of interaction between the melt, which is suboxidized and/or oxidized to urania and zirconia stoichiometry, and internal vessel wall at a low oxygen potential of the above-melt atmosphere. The corium oxidation degree can be described as the index of $C = \left(\frac{M_{ZrO_2}}{M_{Zr} + M_{ZrO_2}} \right) \cdot 100$, where M_{Zr} and M_{ZrO_2} - molar masses of suboxidized Zr and oxidized Z (ZrO_2), respectively. A possible range of melt compositions in the reactor at this stage corresponds to the oxidation index range of approx. C 30 - C 100. At this stage it is advisable to conduct experimental studies at the RASPLAV 2, 3 test facilities with a prototypic composition of oxidic corium varying the oxidation index within the mentioned range and modeling oxygen-free atmosphere by a neutral gas (argon or nitrogen).

At the next stage the steel of in-vessel instrumentation starts to relocate into the molten pool. At this, if the initial corium oxidation degree is high (≥ C 70), oxidic corium C→100 is located in the bottom part of the pool, and molten steel containing rather low concentrations of U and Zr is in the top part of the pool. If the melt oxidation degree is low (C < 50), as follows from the experimental results of OECD MASCA and theoretical calculations, due to the extraction of U and Zr by molten steel from suboxidized melt, the molten pool can have a three-layer structure: molten steel enriched with U and Zr in the bottom part, oxidic corium C→100 in the middle part, and molten steel with minor concentration of U and Zr in the top part. At this stage the interaction between oxidic corium and internal wall of reactor vessel takes place; corium oxidation degree is C→100 and oxygen potential in the system is low. The oxidic corium C→100 also interacts with the vessel bottom through the layer of molten steel enriched with U and Zr, at a low oxygen potential of the system. As estimated by J.M. Seiler, the time constant of a transition from the early-stage pool to equilibrium conditions is several hours. Therefore, the duration of the transition period from the initial molten pool with a high degree of metallic Zr and oxidic composition C < 50 to the C→100 composition establishment does not exceed several hours. For this stage the experimental studies at the RASPLAV 2, 3 test facility should concentrate on the prototypic UO_2-ZrO_2 (C 100) melt in the oxygen-free atmosphere as well as on the mentioned prototypic oxidic melt and a layer molten metal enriched with U and Zr located between molten oxides and a steel specimen.

At the next stage of molten pool history, after the oxygen-free atmosphere inside the vessel is replaced with steam-gas atmosphere, the oxidation of top steel layer occurs, oxygen is transported into the underlying oxidic and steel melts with U и Zr dissolved in them, most active reducers get oxidized, and oxides, which have formed in the top and bottom layers, are dissolved in the oxidic corium melt. At this stage the oxidic melt, the initial composition of which UO_2/ZrO_2 (C 100) later transforms into $UO_2/ZrO_2/FeO$, starts to interact with reactor vessel wall at a high oxygen potential in the system (steam-gas above-melt atmosphere). For this stage the experimental studies at the RASPLAV 2, 3 test facility should concentrate on the prototypic molten corium of the mentioned compositions in air and steam-gas atmosphere above the melt.

The project implementation will provide the following information:

1. Quantitative characteristics of vessel steel ablation depending on
   - oxygen potential of the melt, which depends on the melt composition and above-melt atmosphere,
   - presence of molten steel in the suboxidized oxidic melt,
   - vessel steel temperature on the interaction interface.
2. Microstructure, elemental and phase composition of corium ingot, intermediate zone between corium and steel specimen using the posttest analysis data for the development of interaction model.
3. Structural characteristics of vessel steel after its interaction with corium.

The interaction of molten oxidic corium having the composition of $UO_2/ZrO_2/FeO(Fe_3O_4)$ with reactor vessel steel in air and neutral (nitrogen) atmospheres has been experimentally studied during the implementation of the 1st Phase of the ISTC Project № 833 (METCOR1).

The interaction of oxidic corium melt C 100 and suboxidized corium C 32 ($T_{surf.st.}$≈1400ºC) with the reactor vessel steel in neutral (argon) above-melt atmosphere has been experimentally studied during the 1st year of the 2nd phase of the ISTC Project № 833.2 (METCOR 2).

The interaction of suboxidized oxidic coria of different compositions including metal-oxidic corium and reactor vessel steel at the neutral above-melt atmosphere has been experimentally studied during the second year of the 2nd Phase. Main results of this work are presented in the current report.

The interaction of molten corium having the compositions of UO_2/ZrO_2 and $UO_2/ZrO_2/FeO(Fe_3O_4)$ with reactor vessel steel in steam atmosphere will be studied during the 3rd year of the ISTC Project № 833.2 (METCOR2).

Results of the Project can be used for the following purposes:

- to specify numeric models describing the phenomena taking place at the interaction of molten corium and reactor vessel steel;
- to prove and improve the safety of operating and designed VVER, PWR and BWR reactors.

7. Scientific approach and techniques used

The investigations have been carried out on the "Rasplav-3" test facility, in which corium melt is produced by the technique of induction melting in the cold crucible (IMCC). Its schematics is presented in Appendices 1, 2, 3, 4. The test facility has been developed on the basis of previously used “Rasplav-2” facility. Prior to the current investigations “Rasplav-3” underwent modernization, which improved its operational characteristics and capabilities (Appendices1, 2 of the Annual report of the 1st year of Project № 1-833.2-2003).

Steel specimens for the interaction investigations were manufactured from a part of VVER-10000 reactor vessel (steel 15Kh2NMFA-A), and they had K-type thermocouples embedded into them.

An acoustic defect was made near the specimen top – a ∅ 2 mm borehole for the ultrasonic measurements of specimen ablation kinetics.

Before the experimental studies all procured materials had been subjected to the quality control, which included elemental and material-study analyses.

The following on line measurements have been carried out during tests:

- coolant temperature and flow-rate;
- corium melt surface temperature;
- temperature distribution in the steel specimen;
- steel specimen corrosion depth;
- electrical characteristics of the IMCC generator.

During tests surface temperature of the melt was measured continuously by the «RAYTEK» spectral ratio pyrometer. The surface was periodically recorded on video, melt samples were taken for the analysis.

A special technique was used for putting the charge into the crucible in the argon atmosphere. At first ~ 5 mm-thick layer of crushed molten corium was put on the specimen top. The layer had a special composition prepared in separate tests. The charge consisting of oxidic powder and zirconium pins was put on top of the molten corium layer. The molten pool was produced and heated to the predetermined temperature level.

After the system had approached a steady state, which was indicated by stabilized thermocouple readings and temperature of the cooling water after calorimeters, the flow-rate being kept unchanged, the system was maintained stable at a fixed temperature on the specimen top. When the experimental program was completed the HF-heating was disconnected. The melt and specimen were cooled in argon. After the furnace was disassembled the specimen and corium ingot were taken from the crucible and embedded in epoxy for the subsequent cutting.

For the studies of corium-steel interaction zone the prepared templates of corium ingot and steel specimen, as well as the interaction products and melt samples were subjected to post-test analyses, in which the elemental and phase composition, microstructure and material properties were determined.

The following methods and equipment were used for physico-chemical analyses:

Elemental composition.

- X-ray fluorescence (XRF) –spectrometer with PLE device.
- Chemical analysis (ChA) – spectrophotometer-SPh2000.

Phase composition.

- EDX.

Metallo-and ceramography.

- Optical microscopy.
- SEM.

Corium oxidation degree and free Zr in the samples were calculated by the gas-volumometry from the volume of hydrogen, which was released at the interaction with phosphoric acid.

8. Experimental activities and main results of the first year

The work carried out during the first year was in full agreement with the Work Plan, updated experimental matrix and collaborators' recommendations on certain regimes; the results of previous tests had been taken into account. All updates and recommendations were recorded in the Minutes of METCOR2 meetings.

The following was studied in three main tests, which were carried out during the first year:

- Interaction of molten corium C100 with reactor vessel steel in neutral atmosphere above the melt at three temperature plateaus on the hot specimen top ($T^{max}_{surf.steel}$=1075ºC, 1180ºC, 1315ºC and 1434ºC). Test MC5.
- Interaction of suboxidized corium C32 with reactor vessel steel in neutral atmosphere above the melt ($T^{max}_{surf.steel}$ ≈1400ºC). Test MC6.
- Interaction of suboxidized corium C32 with reactor vessel steel in neutral atmosphere above the melt ($T^{max}_{surf.steel}$ ≈1075ºC). Test MC7. Posttest analyses have been made during the second year of the Project.

Additionally to the tests carried out in accordance with the Work Plan matrix auxiliary tests have been performed (Pr1-MC5, Pr2-MC5, Pr-MC6, PrMC7) in order to improve experimental methodology, refine measurement accuracy and analyze ablation mechanism.

The posttest analyses of MC5 and MC6 have been completed and reports have been issued, they are attached as appendixes to the 1st year Annual report.

Two meetings with collaborators have been conducted: January 29, 2003 in Aix-en-Provence, France and September 16, 2003 in St. Petersburg, Russia. The results of the 1st year studies within the Project were used in a presentation made at the Conference ICAPP-04 in Pittsburg, USA, which was prepared jointly with collaborators.

The results of the 1st year of work have been reported at the CEG-CM on January 31, 2003 in Aix-en-Provence, France, and on September 18, 2003 in St. Petersburg, Russia (MC7 in Paris, France in February 2004).

9. Work progress and main results of the reported year

In accordance with the METCOR2 Work Plan and experimental matrix the following activities have been performed during the second year of the Project:

- Posttest and numeric analyses, integrated analysis of test MC7 on the studies of interaction between suboxidized molten corium C32 with vessel steel at $T^{max}_{surf.steel}$≈1150ºC on the interaction interface.
- Experimental studies of suboxidized molten corium C70 with vessel steel at $T^{max}_{surf.steel}$ ≈1400ºC on the interaction interface. Test MC8.
- Experimental studies of metal-oxidic melt with vessel steel at $T^{max}_{surf.steel}$≈1500ºC on the interaction interface. Test MC9.

9.1. Interaction between the suboxidized molten corium (C 32) with reactor vessel steel under neutral atmosphere above the melt ($T_{surf.steel}^{max}$ »1150ºC). Test MC7

The experimental objective of MC7 was to study the vessel steel ablation kinetics during its interaction with suboxidized corium C32 in oxygen-free atmosphere (argon) at $T_{surf.steel}$ ≈1150ºC on the specimen top; to study the influence of the specimen top temperature on the interaction kinetics (other conditions being equal to MC7, in Test MC6 temperature on the specimen top was kept at $T_{surf.steel}^{max}$ ≈1400ºC); and to specify the boundary temperature of the specimen, at which the ablation following the mechanism of eutectic melting stops.

The initial corium was prepared using the charge, which had the mass of 1850 g and the following composition (mass %): 76%UO_2-9,33%ZrO_2-14,67%Zr (of it 150 g was prepared from the ingot produced in Test Pr-MC6, this part of the charge was put on the specimen top in the beginning of the test).

The total duration of the test was 10 hours. The experimental procedure, parameters of the furnace and vessel steel specimen were the same as in Test MC6.

Table 1 gives the maximum temperature on the steel surface near the specimen axis; the average density of the heat flux to the specimen top and its magnitude within a 15-mm spot in the beginning of the regime.

Table 1

Calculated and experimental values of power, heat flux and temperature

Heat flux density, average, MW/m^2	Heat flux density, Ø 15 mm, MW/m^2	Power into the top calorimeter, calculated, kW	Power into the top calorimeter, experimental, kW	Maximum temperature of steel surface near the specimen axis, ºC
0,82	1,1	1,2	1,39	1153

The details of Test MC7 and posttest analyses are provided in Appendix 1. This section gives a summary of its results.

The molten pool was produced, after the specimen top temperature reached ~1150ºC, the vessel steel ablation kinetics was studied during ~36000 s. in the temperature stabilization regime. In the end of the test the generator was disconnected and the ingot with specimen was cooled in the argon atmosphere.

During MC7 the melt surface temperature was continuously measured by the spectral ratio pyrometer RAYTEK through the water-cooled shaft sparged with argon. Maximum temperature on the melt surface (without crust) was ~2400ºC.

After the test the corium ingot with steel specimen was included into the epoxy resin and cut. They were used for making templates for the posttest studies.

The measured interaction parameters including the data on of steel ablation measured by the ultrasonic sounding; posttest physicochemical and metallographic analyses; numeric modeling of specimen temperature conditions provided the following information:

1. There are three main zones in the axial section of crystallized corium and steel specimen: a) crystallized corium, which has vertical changes in chemical composition near the crust; b) interaction zone shaped as an irregular lens of the crystallized metallic melt formed in

the steel specimen body under the top surface and separated from corium by the crust; c) steel specimen with a thermal impact zone, which is located under the interaction zone.

2. The steel specimen ablation goes in three stages:

- Incubation period lasting ~10000 s., during which the chemical composition on the corium-steel interface changes.
- Slow ablation period lasting 8000 s., during which steel corrodes at an average speed of $2{,}86\cdot10^{-5}$ mm/s. In the end of this period a liquid having eutectic composition is formed on the interaction interface. The steel specimen corrosion depth at this stage is ~0,2 mm.
- Intensive ablation period lasting ~8000 s., during which steel ablation follows the mechanism of eutectic melting. The steel ablation rate at this stage was $\sim10^{-4}$mm/s., and it did not stabilize in the end of the test. The local ablation maximum is ~2,9 mm.

3. The interaction zone after the test presents the crystallized metallic melt, which has the following characteristics:

- Average chemical composition of the crystallized metal from the interaction zone has the following mass % ratio of elements:

  U/Zr/Fe/Cr/Ni/Mn/Si/O = 43,95/2,15/49,63/1,58/0,72/0,45/0,4/1,11. 80 % of the crystallized melt structure is the eutectics having the following composition: U/Zr/Fe/Cr/Ni/O=40,35/2,26/53,44/1,66/0,78/1,51 (mass %). Other 20 % of the total volume are grains of solid metallic solutions, which can be described as $U(Zr)Fe_2(O)$ and $Fe_4(O)Zr(U)$.
- All physicochemical processes in the interaction zone occur in the 1150-1030ºC temperature range. In accordance with calculations, the temperature level, at which the ablation of steel specimen interacting with molten corium C30 stops, is within 1030-1100ºC. At this solidus temperature (eutectics temperature) of the metallic specimen from the interaction zone is $T_{sol}\approx1096$ºC. It was determined by the differential thermal analysis (DTA) using the SETSYS Evolution-2400 device. This temperature is close to the boundary temperature, at which the steel specimen ablation stops; and this is an evidence of ablation following the mechanism of eutectic melting.
- The boundary of a steel specimen interaction zone has an irregular saw-toothed shape. The surface enveloping the teeth of that boundary is a spherical segment, which is located in the boundary temperature region. Such a character of interaction zone proves that the interaction process in the test has not reached equilibrium, and that the interaction did not progress evenly, due to the non-uniformity of chemical structure it started along some priority channels,. It is also confirmed by the observation that near the interaction boundary steel specimen has small regions saturated with U and Zr as a result of inter-grain diffusion.
- The interaction zone has large pores having uneven internal edges. Possible reasons for their formation are: oxygen release during crystallization; liberation of CO_2, which forms at the oxidation of carbon diffused from steel; ingot shrinking. The MC7 interaction zone pore volume is also explained by the fast crystallization of the zone due to a low temperature level in it (1030-1150ºC) and its small volume, also by the stable presence of crust between the melt and interaction zone, which prevents the gas release.

4. A thermal influence zone is formed in the steel specimen near the interaction zone. Its depth from the specimen top is 16 mm. It has the Widmanstatten pattern of low-carbon steel in the high-temperature influence zone close to the interaction boundary and in a lower temperature region it transforms into the changed grain size of the original ferrite-pearlite structure. The lower boundary of the thermal influence zone practically coincides

with the 760ºC isotherm calculated at modeling the specimen temperature field, which confirms the numeric model correctness.

5. Corium ingot is separated from the interaction zone by the crust, which remained solid throughout the whole interaction period. The products of interaction between molten corium and steel specimen have partially migrated into the oxidic melt as a result of diffusion processes on the metal-oxide boundary. The crystallized corium has a distinct boundary between the part having original composition with admixtures of iron and chrome and the zone adjacent to the crust, which, compared to the original corium, has a substantial U enrichment, Zr depletion and a noticeable concentration of iron. Closer to the interaction boundary corium has a higher U concentration (from 52,2 to 72 mass %) and lower Zr concentration(from 29,8 to 11 mass %). Content of Fe drops in the direction from the interaction boundary to the corium bulk (from 14 mass % to 3,5 at the 0,5 mm distance).
6. Experiment MC7 differs from MC6 only by the temperature level on the steel specimen top ($T^{max}_{surf.steel}$=1150ºC in MC7 and $T^{max}_{surf.steel}$=1400ºC in MC6). Therefore, by comparing main interaction characteristics in these tests the influence of interaction front temperature can be estimated. Here is the summary of comparison:

- Steel ablation mechanism in both tests is the same – it is steel dissolution in the superheated eutectic melt of Fe/U/Zr.
- In MC7 the interaction kinetics is less intensive than in MC6. For this reason, though the interaction period was the same in both tests, in MC7 the interaction process has not reached equilibrium.
- The average MC7 interaction zone composition has a high U and Zr enrichment degree and inclusions of $U(Zr)Fe_2(O)$ grains, and the average composition of MC6 has the dendrites of doped iron as the primary crystallization phases. Eutectics temperature and composition are close in both tests (T_{sol}≈1079ºC in MC6 and T_{sol}≈1096ºC in MC7).
- In accordance with calculations the boundary temperature, at which the interaction stops in MC7, is 1030-1100ºC, and in MC6 it is 1100-1200ºC.
- The MC7 interaction zone features large pores, and MC6 interaction zone looks solid, but there is a large pore between the interaction zone and crystallized corium.
- MC 6 had no crust between the interaction zone and corium, and the corium part had globular inclusions from the interaction zone. In MC7 the crust was present during the whole interaction period, and no inclusions from the interaction zone were observed in corium.

9.2.Interaction between the suboxidized molten corium (C 70) with reactor vessel steel under neutral atmosphere above the melt ($T_{surf.steel}^{max}$ »1400°C). Test MC8

The experimental objective of MC8 was to study vessel steel ablation kinetics during its interaction with suboxidized molten corium C70 in the oxygen-free atmosphere at $T_{surf.steel}^{max}\approx$1400ºC on the specimen top, to investigate the influence of melt oxidation degree on the interaction kinetics (Test MC6 had corium composition C32, other conditions being the same), and to specify the specimen boundary temperature, at which ablation following the mechanism of eutectic melting stops.

The initial corium was prepared using the charge, which had the mass of 1850 g and the following composition (mass %): $UO_2$74%-$ZrO_2$19,7-Zr6,3 (of it 150 g was prepared from the ingot produced in Test Pr1-MC8).

The total duration of the test was 12 hours. The experimental procedure, parameters of the furnace and vessel steel specimen were the same as in Test MC6.

Table 2 gives the maximum temperature on the steel surface near the specimen axis; average density of the heat flux to the specimen top and its magnitude within a 15-mm spot in the beginning of the regime.

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Table 2

Calculated and experimental values of power, heat flux and temperature

Heat flux density, average, MW/m^2	Heat flux density, Ø 15 mm, MW/m^2	Power into the top calorimeter, calculated, kW	Power into the top calorimeter, experimental, kW	Maximum temperature of steel surface near the specimen axis, ºC
0,94	1,35	1,85	1,68	1425

The details of Test MC8 and post test analyses can be found in Appendix 2. This section gives a summary of its results.

The molten pool was produced, after the temperature on the specimen top reached ~1400ºC (1350ºC in accordance with indications of a thermocouple embedded into the specimen near the top) the vessel steel ablation kinetics at its interaction with molten corium through the crust was studied during 12 hours in the temperature stabilization regime. In the end of the test the generator was disconnected and the ingot with specimen was cooled in the argon atmosphere.

During the test the melt surface temperature was continuously measured by the spectral ratio pyrometer RAYTEK through the water-cooled shaft sparged with argon, it was 1700 ^{o}C. It should be noted that in accordance with predetermined experimental conditions a crust was present on the molten pool surface during the whole period of interaction.

After cooling in the argon atmosphere the ingot and specimen were removed from the crucible. During the removal the oxidic corium ingot separated from the steel specimen, and they were enclosed into epoxy resin separately and cut along the axis. They were used for making templates for the posttest studies.

The measured interaction parameters including steel ablation measured by the ultrasonic sounding; posttest physicochemical and metallographic analyses; numeric modeling of specimen temperature conditions provided the following information:

1. There are three main zones in the axial section of crystallized corium and steel specimen: a) a ~65 mm zone of crystallized corium, which does not have any substantial vertical differences in the ingot microstructure; b) interaction zone shaped as an irregular lens of the crystallized metallic melt formed in the steel specimen body under the top surface and separated from corium by the ~1 mm-thick crust; c) steel specimen with a thermal impact zone, which is located under the interaction zone.
2. Similar to MC6 the steel specimen ablation goes in two stages.
   - At the early stage an insignificant specimen corrosion to the depth of ~0,2 mm followed by the formation of a liquid layer having the eutectic composition is observed. The initial stage, which included the incubation period, lasted ~9000 s., which is much shorter than in tests MC6 and MC7 (~18000 s.). This shorter incubation period compared with MC6 and MC7 can be explained by the increased volume fraction of solid solutions based on $U(Zr)O_2$ in the C70 crust, which actively transport U to the interaction boundary and contribute to the faster accumulation of eutectic liquid necessary for the start of the intensive interaction stage.
   - Intensive ablation lasted ~30000 s.. In the beginning the specimen ablation rate was ~1,17 mm/h., after which it gradually decreased to 0,32 mm/h. and stopped before the heating disconnection. The final maximum depth of the interaction zone, in accordance with the posttest analyses, was ~6,7 mm in the axis zone, in accordance with direct ultrasonic measurements it was ~7 mm, which shows their good agreement.
3. The interaction zone after the test is a crystallized metallic melt, which has the following characteristics:
   - It has a dendrite microstructure with the dendrites of iron having minor admixtures of chrome, nickel, manganese and eutectic zones between dendrites. There are dendrites with a very fine structure. Eutectic zones have similar compositions in different parts of the interaction zone (~35 mass % U; ~3,5 mass % Zr; ~60 mass % Fe, the rest -Cr, Ni, Mn). The eutectic temperature calculations using the adjusted thermodynamic model are ~1024-1050ºC.
   - The physicochemical processes in the interaction zone occur in the 1425-1200ºC temperature range. In the beginning U diffuses from the crust and at first forms UFe_2 compound on the crust-steel boundary, later, after the Fe concentration increases, a liquid-phase region is formed, which makes the interaction process faster. The key role of uranium in the formation of eutectic melt is likely to have two reasons: first, as it is evident from the experimental data, the inter-grain diffusion rate considerably exceeds the Zr diffusion rate; second, the temperature of UFe_2-Fe eutectics -1055ºC is considerably lower than $ZrFe_2$-Fe eutectics - 1337ºC.
   - In accordance with calculations, the boundary temperature, at which the ablation of a steel specimen interacting with molten corium C70 stops, corresponds to the 1200ºC isotherm.
   - The interaction zone is a crystallized homogeneous solid melt having inclusions of cubic crystals of intermetallide $Zr(U)Fe_2$, most of which are located to the “interaction zone – steel” boundary. A large pore space is observed between the interaction zone and corium ingot. Gas pores are found along the boundary between the interaction zone and steel; and the central part has the separation of interaction zone from steel.
4. The interaction zone is separated from corium ingot with a crust, its composition is quite different from the initial one. The crust microstructure is layered, it has alternating layers

of $U(Zr)O_2$ solid solution and layers containing the following phases: iron-based, $Zr(U)Fe_2$ intermetallide-based and $U(Zr)Fe_2$ intermetallide-based. In accordance with EDX analysis the crust has 17 mass % of steel components. In some parts the $Zr(U)Fe_2$ intermetallide-based phase is distributed within the matrix of $U(Zr)O_{2-x}$ solid solution as globule inclusions. Iron content in such parts is ~12 mass %.

5. The steel specimen microstructure below the interaction zone boundary to the depth up to 3 mm consists of large ferrite fractions, which have carbon content up to 0,02 %. Numerous fine pores are observed to the depth up to 2 mm from the boundary. Further, to the depth up to 25 mm from the plane of initial top surface the microstructure of metal is ferrite-pearlite, which was formed when steel heated up beyond the critical point was cooled down from the austenite condition. Below 25 mm and ~750ºC temperature the initial pearlite structure has not undergone any changes.

9.3. Interaction between molten steel and suboxidized corium (C 32) with reactor vessel steel under neutral atmosphere above the melt ($T^{max}_{surf.steel}$ »1500°C). Test MC9.

The experimental objective of MC9 was to study the vessel steel ablation kinetics during its interaction with suboxidized corium C32 after the introduction of stainless steel, its melting and inversion of layers in the molten pool at $T^{max}_{surf.steel} \approx 1500$ºC on the specimen top and in the oxygen-free atmosphere (argon); to study the post-inversion thermochemical impact of molten steel on the vessel steel specimen ablation; and to specify the boundary temperature of the specimen, at which its ablation stops; to study the ablation mechanism.

The initial corium was prepared using the charge, which had the mass of 1800 g and the following composition (mass %): 76,2 % UO_2+ 9,3 % ZrO_2+ 14,5 % Zr, of it 5 mm of molten corium C32 having the particle size < 50 µm, which was produced in Test Pr1-MC6. 200 g of stainless steel 8X18HIOT was introduced into the molten pool.

The total duration of the test was ~ 10 hours. The furnace and vessel steel specimen characteristics were the same as in Tests MC6 and MC7.

Table 3 gives the maximum temperature on the steel surface near the specimen axis; average density of the heat flux to the specimen top and its magnitude within a 15-mm spot in the beginning of the regime.

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Table 3

Calculated and experimental values of power, heat flux and temperature

Heat flux density, average, MW/m^2	Heat flux density, Ø 15 mm, MW/m^2	Power into the top calorimeter, calculated, kW	Power into the top calorimeter, experimental, kW	Maximum temperature of steel surface near the specimen axis, ºC
1,1	1,43	2,19	2,03	1510

At present the posttest physicochemical and metallographic analyses of the ingot, transition zone and steel specimen samples are in progress, as well as the detailed modeling of specimen temperature conditions and the interaction mechanism analysis. For this reason this section presents only primary experimental results.

After the molten pool was produced the predetermined steady temperature of 1400ºC measured by the top thermocouple was reached at 4200s. At 4633 s. the first portion of steel was put on the molten pool surface, and at 4654 s. – the second portion. In 70 s. after the addition of the second portion the molten steel sank. The introduction of metal was accompanied by a sharp drop in the melt and specimen temperature (~ by 400ºC), increase of the crust thickness at the generator load reduction. By increasing power deposition into the melt the temperature regime of the molten pool and steel specimen was restored only at 5660 s. Starting from this moment the temperature profile in the specimen and, correspondingly, on its top reached the calculated stable value. Further on, in accordance with the experimental procedure, during 10 hours the vessel steel ablation kinetics at its interaction with corium, which had a steel layer enriched with U and Zr in the bottom part, was studied in the stable temperature conditions. It should be mentioned that due to the unforeseen drop in the melt and corium temperature, which was caused by the decrease of power during the melt introduction, the thickness of oxidic crust on the specimen surface before steel inversion exceeded the thickness corresponding to the initial steady-state regime.

After the 10-hour studies of the steel specimen ablation kinetics at the steady temperature regime, at 50220 s. of the test, the generator was disconnected and the ingot with specimen was cooled in argon. After the test the corium ingot with steel specimen was included into the epoxy resin and cut along the axis in order to determine the ablation depth, interaction front boundary and to prepare templates for posttest analysis.

The first results of MC9 experimental studies are as follows:

- Similar to tests MC6-MC8, the interaction of molten corium with vessel steel specimen follows the mechanism of eutectic melting. A specific feature of Test MC9 is the interaction of metallic melt containing U and Zr with the vessel steel specimen.
- Test MC9 does not have the incubation period of ablation, which was typical of MC6-MC8. The vessel steel ablation kinetics is characterized by the decrease of ablation rate at the reduction of vessel steel temperature on the interaction front, up to the ablation stop when the boundary temperature is reached.
- The final ablation depth of the steel specimen was 15,6 mm, the depth of thermal impact zone in the specimen was 29 mm.
- In accordance with calculations, the boundary temperature, at which the steel specimen ablation stops, corresponds to the 1080 ± 20 ^{o}C isotherm, and the isotherm, which corresponds to the lower boundary of the thermal impact zone, is ~ 730 ^{o}C.
- An intensive release of steel components from the molten pool took place in the course of the test. Taking into account the deposition in the transport lines, the total release of steel was $\sim$ 285 г, which included 192 g of steel introduced into corium and molten steel transported into the melt from the interaction zone.
- In the course of the test the molten pool structure and composition underwent changes caused by the volatilization of steel components, partitioning of melt components, which followed the mechanisms studied within the MASCA experimental program, and mass transfer between the metallic and oxidic melts.
- The phenomena mentioned above have probably influenced the interaction zone structure, which was different from tests MC6-MC8. On the macro-level, the MC9 interaction zone is a three-layer structure, which is separated from steel by the shrink cracks, and it is separated from the crystallized corium by a large pore, which can be of shrink origin or caused by the gas release. The interaction zone layers have the following composition, mass.%: U:Zr:Fe(Gr, Ni) =12:5:80 (4) - lower layer; 9:12:77(3) – middle layer 9:12:77(3) and 14:9:73(4) – top layer.

The detailed analysis of the MC9 interaction is in progress, it will be given in the report, which will be delivered in the second quarter of 2005.

10. Current stage of the project progress

The activities of the 1st year of the Project have been performed in full compliance with the Work Plan and updated experimental matrix, which was developed during the discussions of tests with collaborators and recorded in the Minutes of the meetings.

11. Cooperation with foreign collaborators

The foreign collaborators within this project are:

1. Dr. Walter Tromm, Germany

   Institut für Kern-und Energitechnik (IKET), Karlsruhe.
2. Dr. David Bottomley, Germany

   EUROPÄISCHE KOMISSION, Joint research Center Institut für Transurane (ITU), Karsruhe.
3. Dr. Manfred Fischer, Germany

   Framatome ANP GmbH, Erlangen.
4. Dr. Gerard Cognet, France

   CEA/DEN/DSNI, Saclay.
5. Dr. Florian Fichot, France

   IRSN/DRS/SEMAR/CEN, Cadarache.
6. Dr. Ole Kymäläinen, Finland

   Fortum, Vantaa.
7. Dr. Paecal Piluso, France

   CEA/DEN/DTN, Cedex.
8. Professor Frank-Peter Weiss, Germany

   Forschungszentrum Rossendorf (FZR), Dresden.

During the second year of project implementation the close cooperation with foreign collaborators included: detailed discussion and joint analysis of completed tests; updating experimental matrix and introduction of appropriate modifications into the planned tests; discussion of subjects and direction of work for the project continuation.

The discussion of experimental results and exchange of opinions during the 2nd phase of METCOR took place both at joint meetings and by e-mail. Along with that the results of studies carried out during the 2nd year of work have been reported at two CEG-CM meetings.

The 4th meeting of the METCOR2 Steering committee together with European collaborators took place on February 10, 2004 in Paris (France). The project contractor team made the following presentations: a) project status; b) results of tests MC7 and Pr1-MC7 and posttest analyses; c) plans for the future. A decision on the changes in the Work Plan before the end of 2004 was taken on the basis of collaborators’ proposals and discussion. In MC8 the interaction of suboxidized corium C70 with vessel steel will be examined. Other experimental parameters are the same as in MC6.

On February 12, 2004 the 5th CEG-CM meeting took place in Paris (France), at which the results of METCOR2 studies during September 18, 2003 – February 12, 2004 were reported.

The 5th meeting of the METCOR2 Steering committee together with European collaborators took place on September 14, 2004 in Dimitrovgrad (Russia). The project contractor team made the following presentations: a) project status; b) test MC8 and posttest analysis results; c) analysis of tests MC6, MC7 and MC8 on the interaction of suboxidized corium with vessel steel; d) plans for the nearest future.

On September 16, 2004 the 6th CEG-CM meeting took place in Dimitrovgrad, at which the results of METCOR2 studies during February 12, 2004 – September 16, 2004 were reported.

12. Perspectives of further research

The work plan and experimental matrix taking into account the recommendations recorded in the Minutes of the project Steering Committee have been fulfilled.

During the third and final year of METCOR2 implementation the posttest physicochemical analyses of Test MC9 will be completed and the final report prepared. The experiments on the interaction of molten corium having the composition UO_2+ZrO_2 (C100) and UO_2+ZrO_2+FeO_y with vessel steel in steam atmosphere and different temperature levels on the specimen top will be conducted. The results produced during the 1st and 2nd stages of METCOR Project will be summarized in a special report , which will contain recommendations on using the produced data for the in-vessel melt retention provided with outside water cooling at a severe accident at a NPP with VVER reactor.

Project manager, Professor	V.B. Khabensky
General Director of the Aleksandrov RIT, Professor	V.A. Vasilenko

Appendix A

Personnel involvement during the 2nd year

Category	Man-days during the second year	Incremental man-days	Total
Category I	1918	4816	6180
Category II	798	1860	2279
Category III	106	286	360
Category IV	40	71	150

Appendix B

Main procured equipment during the 2nd year

The following equipment has been procured in accordance with Work Plan:

Power supply unit ADC7480/12A with analogue control ($2872.9).

Project manager, Professor	V.B. Khabensky