

MASCA PROJECT: MAJOR ACTIVITIES AND RESULTS

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Abstract

The MASCA Project implies a program of corium tests of different scale and various prototypic composition experiments (with corresponding pre- and post-test analyses) to investigate the influence of chemical composition of the corium mixture on heat transfer in a stratified molten pool (U-Zr-O-Fe(SS)-C(B)) and partitioning of basic corium components and FP between layers. The MASCA Project results would provide the technical support for the assessment of the in-vessel melt pool retention strategy as well as of the ex-vessel phenomena.

The major Project activities included:

1. Development of technology to conduct the high temperature corium tests including design, fabrication and assembly of a large-scale facility capable to heat up and retain molten corium and steel at relevant temperatures under controlled conditions;
2. Performance of a confirmatory large-scale test to confirm the major findings.
3. Performance of small- and middle-scale corium experiments to investigate separate phenomena including:
 - Carbon impact on the corium stratification;
 - Stratification in the solidus-liquidus range;
 - Study of corium components partitioning in the stratified metal-oxide pool;
 - FP partitioning between different phases;
 - Molten metals migration through the oxide porous matrix;
 - Boron behaviour and its impact on the stratification;
 - Measurements of material properties.
4. Performance of salt tests to study heat transfer in the stratified molten pool.

The Project major findings are presented in the paper.

1. Background

The in-vessel retention of a severe accident in the vessel of a light water reactor (LWR) by external cooling of the vessel has been recognized as an attractive accident management measure for both current design reactors and new plant designs based on the passive safety systems.

Since in-vessel melt retention has become an important safety objective for nuclear reactors, it is important to evaluate and model the relevant phenomena that will contribute to melt retention under prototypical accident conditions. At the same time, even if not aiming at in-vessel retention, there is a clear need to understand the convective molten pool behaviour, since melt pools have important implications on the core relocation and the RPV failure mode that both, in turn, have further consequences on the subsequent behaviour of corium outside the vessel, which depends strongly on the melt composition and ejection mode. Furthermore the understanding of oxide-metal behavior is also of interest for various ex-vessel situations involving corium pools or layers of molten core materials.

The in-vessel retention related phenomenology includes a variety of heat transfer and material interaction phenomena [1] such as

- Heat transfer in the debris bed and ceramic melt;
- Chemistry of corium components including UO_2 , ZrO_2 , Zr and components of steel which determine possible melt stratification;
- Thermal and chemical interactions of corium and its components with the reactor pressure vessel;
- Ex-vessel boiling heat transfer in case of the reactor cavity flooding;
- Mechanical behaviour of the vessel under loads caused by internal pressure and thermal stresses.

Numerous experimental studies with simulant materials, such as COPO, ACOPO, BALL, RASPLAV-SALT and SIMECO, dealt with the problem of heat flux distribution around a volumetrically heated molten pool at wide range of Rayleigh numbers. The main focus for these studies has been the thermal loading imposed by the core melt on the reactor pressure vessel (RPV) lower head.

Thermal hydraulic studies of the melt pool behaviour have also included cases where a molten metal (steel) layer could form on top of oxidic corium due to very limited solubility of steel in the oxides (the density of steel being lower than the density of core oxides). The heat-focusing effect of this molten metal layer was of concern, because the vessel walls adjacent to the metal layer were subjected to increased heat fluxes, which could lead to substantial localised melting of the walls.

Experimental programs have also been conducted to investigate the critical heat flux for the boiling process initiated on the outer surface of the vessel due to cavity flooding (external vessel cooling).

Although many experimental data with simulant fluids are available, only limited experimental data with UO_2 melt were available [2, 3]. The scale of corium experiments was too small and distortion of the results due to different factors could be significant. There are obvious differences between prototypic core materials and simulant fluids which were used mostly in the previous experimental studies. These aspects may influence the applicability of the heat transfer results obtained with simulant fluids to reactor conditions and signify a need for the confirmatory experimental and analytical studies of prototypic corium pool behaviour under external cooling conditions. The lack of data related to the behaviour of large convective pools formed by prototypic molten core materials were the reason for the initiations of the new project arrangements.

Studies of the impact of real materials have been performed in the frame of OECD RASPLAV project. It demonstrated that the homogeneous corium melt behaved comparably to simulant materials in natural circulation, therefore previous evaluations based on simulant material data could be scaled to prototypic reactor conditions. It was shown that such a behavior can be expected if molten pool contained oxidic materials.

However, two of the four large-scale RASPLAV tests conducted with suboxidized corium exhibited an unexpected behaviour. Post-test examinations showed that the melt pool, initially of a homogenous composition and density, stratified into two layers of unequal density. The lower layer of a denser material was richer in uranium while the upper lighter layer was richer in metallic Zr. Those results indicated that the behavior of the corium molten pool likely depends upon its composition and zirconium oxidation degree [4]. RASPLAV project dealt with the corium of different oxidation degree. Another subject of interest was the concern about the behavior of steel in contact with corium. As heat focusing effect may change significantly the distribution of heat flux, interactions between molten corium and steel under prototypic conditions is of great importance. In light of these results the interest was to obtain more data with respect to prototypic core materials behaviour at high temperatures.

The MASCA Project started in July 2000 was concentrated on the detailed investigation of the chemical behaviour of corium in contact with structural materials, with emphasis mainly on steel. The MASCA Project implies a program of corium tests of different scale and various prototypic composition experiments (with corresponding pre- and post-test analyses) to investigate the influence of chemical composition of the corium mixture on heat transfer in a stratified molten pool (U-Zr-O-Fe(SS)-C(B)) and partitioning basic corium components and fission products (FP) between layers. The experiments were not directly aimed at reproducing the in-vessel situation because the main goal of MASCA project is to study material interactions rather than molten corium pools as in RASPLAV.

2. Management and Organization

The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA-OECD) has, since 2000, sponsored a collaborative project on Severe Accidents carried out in Russia. This project, entitled the MASCA(MATERIAL SCALING) Project, had the basic objective to provide data on the behaviour of molten core materials chemical interactions under severe accident conditions.

Agreement on the OECD MASCA Project was prepared and signed by the OECD member-states and Russia in July 2000. Signatories to the project included Belgium, Canada, Czech Republic, Finland, France, Germany, Hungary, Republic of Korea, Italy, Japan, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom, and the United States.

The studies in the frame of the Project have been carried out by the Russian Research Centre Kurchatov Institute (RRC KI, Moscow) in co-operation with a number of scientific and research & production associations of Russia: A.P. Alexandrov Research Institute of Technology (NITI, Sosnovy Bor), Luch Scientific Production Association (Podolsk), Nuclear Safety Institute (IBRAE) Russian Academy of Sciences (Moscow).

The management and organisation of the MASCA Project is practically the same as RASPLAV Project one. Overall control and direction of the project was vested in the Management Board (MB) that consisted of one member designated by each of the signatories. The primary function of the MB was to approve the overall and the annual project workscope and budget. The Program Review Group (PRG) was formed from members designated by each signatory. The primary function of the PRG was to be the technical advisor to the MB for project activities. The Program Review Group also provided technical advice and recommendations for the Operating Agent (OA), who was responsible for

implementing the project objectives in accordance with the project agreement and directions from the Management Board.

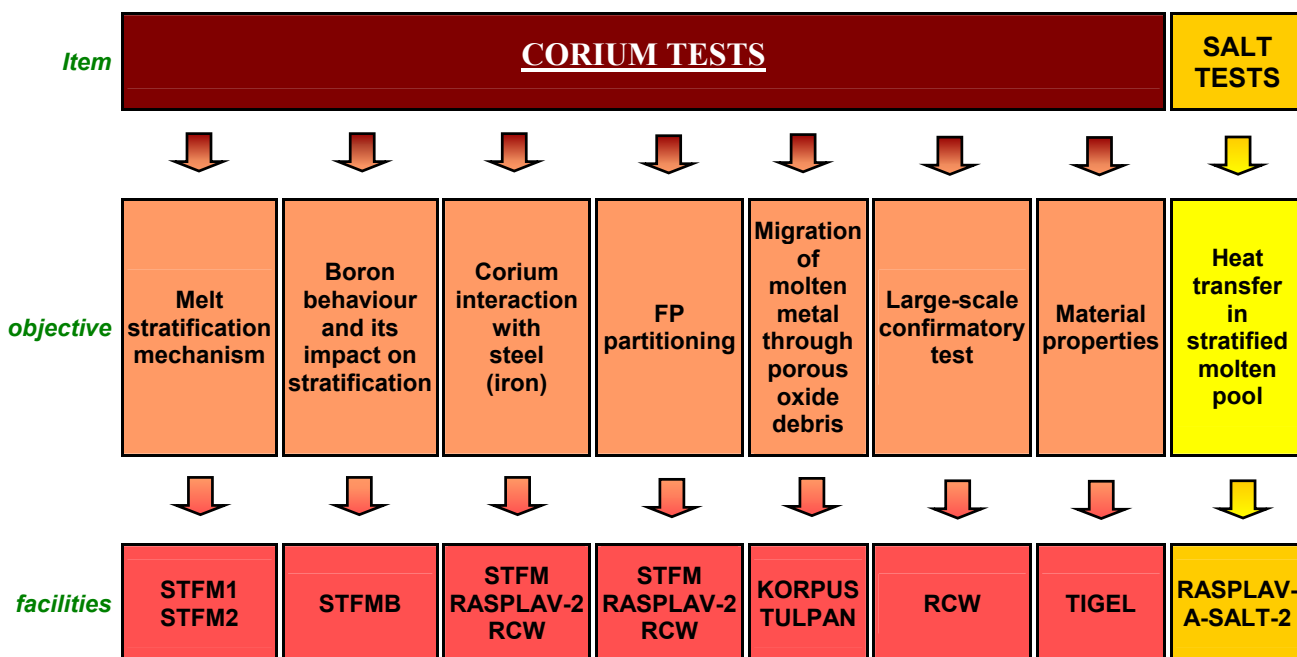
3. MASCA Project Operations

The major goals of the MASCA Project are the following:

- Investigation of the influence of chemical behaviour on heat transfer in stratified molten pools (U-Zr-O-Fe(SS)-C(B));
- Investigation of fission products (FP) behaviour in a molten pool and in particular
- Partitioning of FP between layers in case of stratification;
- Partitioning of FP between phases during melting and solidification;
- Distribution of FP simulants in the melts;
- Expansion of material properties data base;
- Development of computer models describing relevant phenomena.

The Project goals have been achieved through corium tests of different scale, including pre- and post-test analyses and development of computational models, additional measurements of thermo-physical properties of the melts such as density, thermal conductivity and liquidus-solidus temperatures. Separate effects were studied in series of small-scale and middle-scale experiments, an integral test of the AW-200 type was performed to confirm major findings. The key MASCA Project items and corresponding facilities are presented in Figure 1.

Figure 1. Major MASCA Project Activities



Thus the major MASCA Project activities included:

1. Development of technology to conduct the high temperature corium tests including design, fabrication and assembly of a large-scale facility capable to heat up and retain molten corium and steel at relevant temperatures under controlled conditions;
2. Performance of a confirmatory large-scale test to confirm the major findings.

3. Performance of small- and middle-scale corium experiments to investigate separate phenomena including:
 - Carbon impact on the corium stratification;
 - Stratification in the solidus-liquidus range;
 - Study of corium components partitioning in the stratified metal-oxide pool;
 - FP partitioning between different phases;
 - Molten metals migration through the oxide porous matrix;
 - Boron behaviour and its impact on the stratification;
 - Measurements of material properties.
4. Performance of salt tests to study heat transfer in the stratified molten pool.

In the corium experiments in MASCA Project the corium of the different compositions was used. These corium compositions are presented in Table 1.

Table 1. Corium Compositions Studies in the MASCA Project

Corium composition	Zirconium oxidation (%)	Composition (mol. %/wt. %)			U/Zr ratio
		UO ₂	ZrO ₂	Zr	
C-22	22	62/81.8	8.4/5.0	29.6/13.2	1.6
C-32	32	54.5/76.2	14.5/9.3	31.0/14.5	1.2
C-50	50	62/80.4	19/11.3	19/8.3	1.6
C-75	75	56.4/75.2	33.2/20.2	10.4/4.6	1.3
C-100	100	62/78.1	38/21.9	-	1.6

3.1 Carbon impact on the corium stratification

To study the stratification phenomenon in the frame of MASCA project a special attention was paid to the possibilities of melt stratification and separation. Two mechanisms were considered:

- Stratification induced by small amounts of impurities (carbon);
- Separation of components in the solidus – liquidus temperature interval.

A series of 11 small-scale experiments were made to quantify the effect of corium stratification due to small additives of carbon. The experiments were performed at the STFM test facility in a hot tungsten crucible with dimensions $\varnothing 14 \times 0.5$ mm in diameter and 70 mm high. The boundary conditions along the crucible height during experiments were isothermal within the same limits. In all experiments the maximum exposure temperature was $T = 2550^{\circ}\text{C}$. Heating up rate was fast and slow: 500 – 600 $^{\circ}$ /min or 8 $^{\circ}$ /min correspondingly. Cooling down rate was about 50 $^{\circ}$ /min. All experiments except of those which studied stratification kinetics exposure time was 60 min. For studying kinetic effects the exposure time varied in the range 5, 15 and 60 min.

Experiments were conducted using C-32 corium and carbon content in the corium varied between 0.006 to 0.69 wt%. Stratification kinetics of the corium containing 0.3 – 0.36 wt% of carbon was studied in 4 experiments – STFM1(1, 2, 3, 7). The amount of carbon is approximately corresponded to the RASPLAV-AW-1 test. Results of the experiments showed that carbon content in the upper layer increases gradually and decreases simultaneously in the bulk corium. U/Zr ratio exhibits similar behavior. The kinetics is fast enough, after first 15 minutes the process slows down significantly. It is important to note that no impact of the heating rate (8 $^{\circ}$ C/min and 500 $^{\circ}$ C/min) onto the process of carbon redistribution was revealed.

The experiments with the exposure time of 60 minutes were used to analyze the final state as a function of initial carbon content which varied in the range between 0.085 wt% and 0.69 wt%. Results of experiments showed that if carbon content in the initial corium was less than 0.2 wt%, carbon redistribution and change of U/Zr ratio in the corium along the ingot height melt was insignificant. However if carbon concentration in the initial corium exceeded 0.2 wt% significant redistribution of corium components and change of U/Zr ratio along the ingot height was observed: increase of carbon and zirconium concentrations in the top layer and decrease in the middle layer. This was accompanied by the growth of the zirconium based phase in the upper layer.

Two experiments – STFM1/5 and 6 were performed in the argon environment with addition of CO gas (0.1 vol.%) to study the process of corium carbidization from the gas atmosphere. No noticeable increase of the carbon content in the top layer was observed in C – 32 corium containing 0.36 wt% of carbon in comparison with the similar experiment #2 without CO gas addition. Some increase of the carbon content in the top layer (up to 0.1 wt%) and in the bulk corium volume (up to 0.06 wt%) took place in the test #6 with low initial carbon content (0.006-0.009 wt%). This increase of carbon content was found to be insignificant and did not lead to corium stratification into two layers.

3.2 Stratification in the solidus-liquidus range

Six small tests (~ 0.5 kg) were conducted to study possibility of C - 32 corium stratification in the temperature range of $T_{Sol} - T_{Liq}$ into the top liquid layer based on $Zr(O)_x$ and the bottom solid layer based on $(UZr)O_{2-x}$ and to study the stability of corium configuration if such kind of stratification takes place. These experiments were conducted using the same STFM facility. Briquettes and powder of C-32 corium (U/Zr = 1.2 at./at., carbon content 0.006 – 0.009 wt%) were fabricated by pressing of the powder mixture (UO_2 , ZrO_2 , ZrH_2) in accordance with the technique developed for RASPLAV-AW-200-4 experiment.

In STFM2/1-5 experiments tungsten crucibles were loaded with corium particles (1 – 4 mm), porosity of the loading was 30-50%. Heating up in all of the experiments was performed with the rate of 500-600°C/min at the $T > T_{Sol}$. Cooldown rate to T_{Sol} was 50°C/min.

The main results are the follows. For isothermal tests there was no onset of stratification at temperature 2150°C and 2300°C. For the test STFM#2/3 conducted at the temperature of 2200°C post test examination exhibited increase of the light phase $Zr(O)_x$ concentration and corresponding decrease of U/Zr ratio in the top layer. Enrichment of the top liquid layer with zirconium has occurred simultaneously. Concentration of the light phase has decreased and the fraction of the grey phase based on $UZrO_{2-x}$ has increased in the bottom solid layer. The ratio of the light and grey phases fraction in the ingot top and middle parts reached the value of 3.5.

The compositions of phases found during the post test examination are shown in the Table 1. The light phase mainly consists of zirconium $Zr(O)_x$ phase with small amount of uranium while grey phase presents oxide phase $(UZr)O_{2-x}$.

Table 2. Phase Compositions

Phase	Concentration (wt%)			Phase molecular formula
	U	Zr	O	
Light	9.21	85.19	4.79	$(Zr_{0.96}U_{0.04})O_{0.30}$
Gray	74.29	12.10	13.70	$(U_{0.70}Zr_{0.30})O_{1.93}$

Experiment #6 when corium was heated first to 2500°C and then cooled down to 2200°C and exposed for 60 minutes did not indicate significant differences in light phase composition in the top

and middle layers were insignificant, coefficient of the light and grey phase fractions ratio in the layers was 1.7, which is 2 times less than in the #3 experiment. Similar results were observed for the case when corium was exposed first at the temperature of 2200°C and then heated up to 2600°C. The structure of the ingot was found to be rather uniform.

3.3 Study of Corium Components Partitioning in the Stratified Metal-Oxide Pool

The study of the interactions between corium and metals is an important part of the interactions in course of accident. Due to significant melting temperature difference such an interaction can be expected when corium is solid or liquid. Special test series involving different experimental facilities and different experimental conditions has been performed to study the interactions between corium and steel in liquid phase.

The objective of this experimental series was to obtain quantitative and qualitative characteristics of uranium, zirconium and steel components partitioning between different phases. The following facilities were used:

- Small scale STFM facility with the loaded mass about 0.5 kg;
- Middle scale RASPLAV-2 facility with the loaded mass of about 2 kg;
- Large scale RCW facility with the loaded mass about 100 kg.

All these facilities were completely upgraded and modernized to conduct the tests with corium and steel. The facilities rest on using inductive heating and cold crucible technique, which allowed maintaining integrity of the facilities. The detailed descriptions of these facilities are presented in the reports.

In the experiments the following parameters varied: corium composition (variation of oxidation degree and uranium to zirconium ratio), metal composition (experiments with the iron and stainless steel). A total of 16 small, 4 middle and 1 large- scale test were conducted.

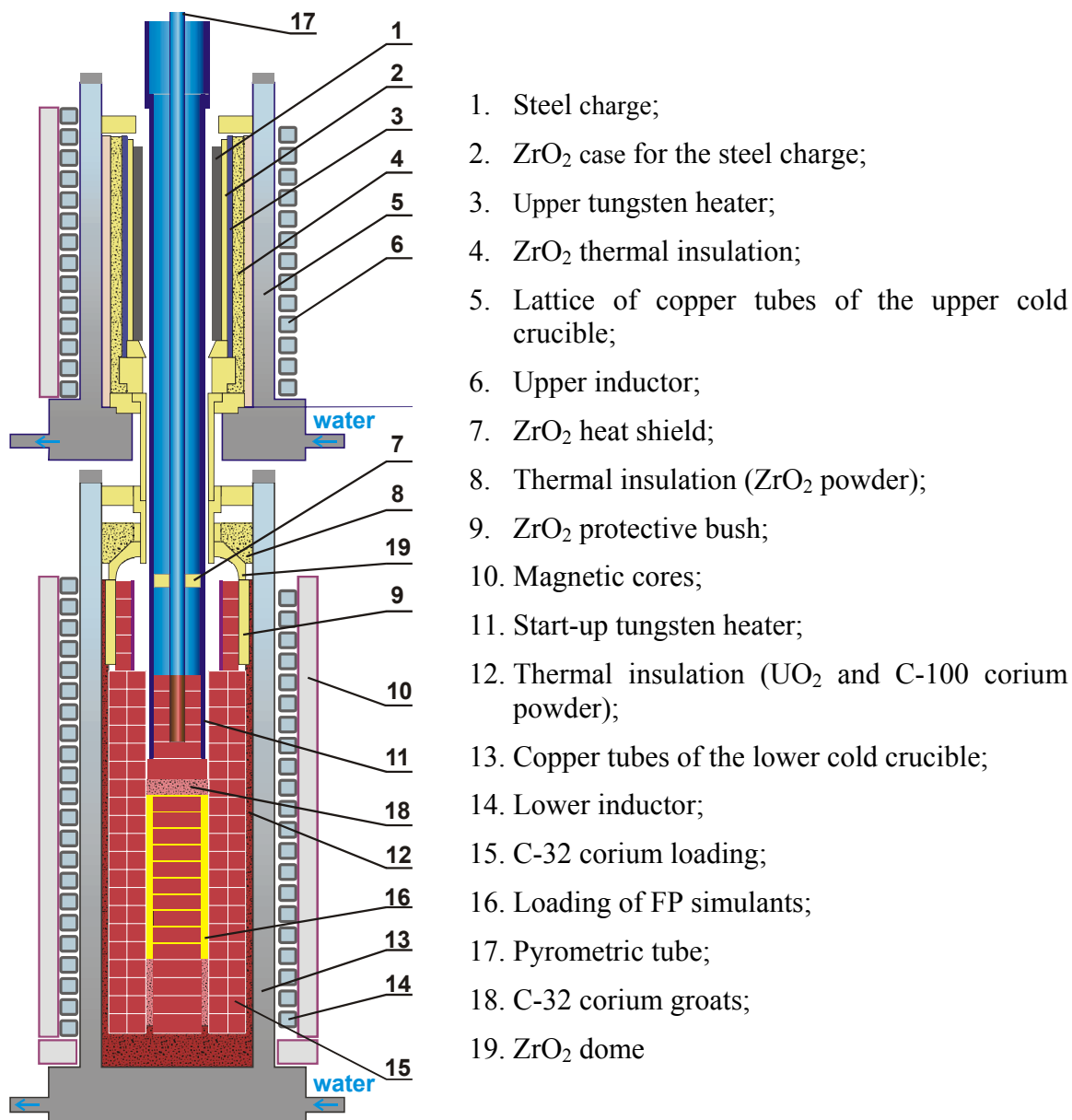
For each test, the temperature was raised above the liquidus temperature of corium. The exposure time for small-scale tests varies between 10 to 60 minutes. The chemical equilibrium was found to be reached because of the small scale of the samples and the stirring due to induction forces. Typical exposure time for medium scale tests was 30 minutes. The metal and oxide samples were carefully examined after the tests.

The large-scale test was conducted with the aim to study scaling effects and confirm the findings of small and medium scale tests. Pretest analyses were performed to assess the power input scenario, melt progression scenario and temperatures during test performance. For the conduction of RCW test the same approach of cold crucible technology was used. The facility consists of two sections each heated separately by its own inductor as it is shown in Figure 2. The facility consists of two sections located vertically one above the other and integrated into one assembly. Each of the melting compartments is located inside the bearing supporting cylindrical lattice made from water-cooled copper tubes and copper headers for water input-output that form a cold crucible.

The corium briquettes and FP simulants were heated and melted in the lower section. After that, steel preform was melted in the upper section, and steel runs down through the discharge channel onto the corium melt in the lower section where they interact. Power necessary for heating and melting of loadings in each section is supplied from the self-contained inductors through the clearances among pipes of the cold crucibles. The depth of the melting compartment in the lower section is 700 mm, the inner diameter is 176 mm. The lower section loading consisted of 26 layers of the C-32 corium ring briquettes and of the loading of FP simulants. The corium briquettes were put on the powder thermal insulation 40 mm thick (the mixture of UO₂ and the C-100 corium powders). The loading of FP

simulants was located in the loading middle part between the levels of 146 и 342 mm from the section bottom.

Figure 2. The RCW Facility Schematics



A layer eight millimeters thick of the powder thermal insulation (the mixture of UO₂ and the C-100 corium powders) was filled between the loading and the cold crucible pipes. The same mixture filled up all clearances between the cold crucible pipes and inductor.

Thermal shields made of ZrO₂ ceramics (the bushing, dome, shield on the pyrotube) were located in the upper zone of the melting compartment (above the melt surface level) to reduce thermal losses upwards and to the walls. The dome was also covered with ZrO₂ powder.

A pipe of the start-up tungsten heater 65 mm long located along the compartment axis was put into the loading down to the depth ~ 100 mm. Tungsten heater was heated by the inductor field with the frequency 8 – 10 kHz up to the temperature 2500 – 2600 °C. It heats, in its turn, the surrounding

briquettes by the radiationally-conductively up to the formation of electrically closed rings and the occurrence of the necessary electric conductivity in those (at $f = 10$ kHz, $T_{\text{initial heat generation}} \approx 1500$ °C).

A melting compartment of the upper section is formed by a tungsten pipe-heater insulated from the cold crucible pipes by the layers of Al_2O_3 coating (the layer is 10 mm thick) and of ZrO_2 powder (the layer is 14 mm thick). The compartment is supported by heat-insulating rings made from ZrO_2 ceramics.

Inside the compartment, a stainless steel charge (a pipe ~ 9 mm thick) is placed into the case made of ZrO_2 ceramics. The case prevents the contact of melting steel with the heater tungsten.

The power input scenario was estimated in a series of the pre-test calculations before the test in order to assess the characteristic power input and time table of events, which allowed to follow the heating and melting processes. The test was conducted in several phases, namely:

1. Heat up at the moderate level of power up to the target tungsten temperature of about 2200°C;
2. Removal of the starter heater from the crucible after the melt front reached cold walls;
3. Sustained heating of corium at the appropriate power level to provide the corium heating and melting;
4. Heating of steel in the upper section and pouring of that into the melted corium;
5. Quasi-steady state operation.

The starter tungsten heater was removed after the beginning of the radial melting. The sustained heating of the corium loading provided downward motion of the melting front. The thermocouples located in the peripheral area indicated rapid temperature increase. As the heating efficiency increased gradually, the input power was reduced during the third phase to maintain approximately constant melting front velocity.

Post-test examination confirmed most of the results already obtained in smaller scale tests. However, some differences in the final stratification and distribution of phases appeared. The main distinction of the RCW test from the series of tests STF and MA lies in the scale factor. The mass values of the corium and steel interacted in the RCW tests are 20 - 30 times higher than those in the MA-1, 3 tests and ~ 150 times higher than those in the tests of the STF series.

Analysis of the obtained results demonstrated that the scale factor influences the interaction kinetics. In the tests with low masses (~ 300 g of corium), the interaction process is completed within $\tau \leq 15$ min, and the metallic part absorbed uranium up to the concentration 50 mass % relocates onto the pool bottom. In the MA-1 test with the corium mass ~ 1500 g, during the interaction time $\tau \leq 30$ min the metallic part that absorbed uranium up to the concentration ~ 38 mass% relocates onto the pool bottom. In the RCW test with the molten corium mass ~ 45250 g, the lower part seems to be saturated with the uranium up to the concentration 40 – 50 mass %. Total mass of uranium migrated into steel was 3.1 kg. An additional absorption of ~ 2.2 kg of uranium is necessary to achieve uranium concentration ~ 50 mass % in all metallic parts. It is necessary to note that the method of steel introduction into the melt (in the solid or liquid forms, in one part or several parts) as well as the ratio of steel mass to the surface of the contact with the corium may also influence the kinetics of the corium interaction with metal.

In RCW test the scale factor allowing to observe different stages of steel fragmentation, saturation of that with uranium and zirconium and relocation of fragments onto the liquid pool bottom is the peculiar feature of the RCW test in comparison with the tests STF and MA.

3.4 FP Partitioning between Different Phases

Experiments with the corium and steel performed in the frames of MASCA Project showed significant redistribution of major corium components such as uranium and zirconium between metallic and oxide phases. Significant part of uranium, zirconium and oxygen pass into the steel melt due to the interaction of structural steel with a suboxidised corium. The FP series of tests was aimed at the investigations of mechanisms associated with the partitioning of low-volatile fission products between stratified melts of the metallic and oxidic phases. Mo, Ru, Sr, Ba, Ce and La were chosen as the simulants of fission products.

Three experimental facilities were used for study of FP behavior, large scale RCW facility, two middle scale tests MA-3 and MA-4, and a series of small scale experiments performed at the STFM facility. In the tests several parameters such as zirconium oxidation degree, ratio of iron (steel) introduced in the corium and U/Zr atomic ratio.

Initial loading of different components for different experiments are shown in Table 3. As FPs were added in a different chemical forms in the brackets the recalculated amount for the pure species are shown. Material balances made up for each test allowed to demonstrate that the average concentration for each FP in the STFMFe test series was 0.4 ± 0.03 mass %. For MA tests it was slightly higher about 0.53 mass % for each FP simulant.

Table 3. Initial Loading of FP Simulants (grams)

Facility	SrO	BaO	La ₂ O ₃	CeO ₂	Mo	Ru
STFM-FP	1.15 (0.97)	1.15 (1.02)	1.15 (0.98)	1.15 (0.94)	1.15	1.15
MA-3	10.64 (9.0)	10.05 (9.0)	10.55 (9.0)	11.06 (9.0)	9.0	9.0
MA-4	9.46 (8.0)	8.93 (8.0)	9.38 (8.0)	9.83 (8.0)	8.0	8.0
RCW	135 (80)	89 (72.4)	94 (80)	98 (80)	80	71

In the STFMFP series to ensure the uniform FP loading, a part of sintered coria was grinded under nonoxidizing conditions down to the groats of ~ 500 μm typical size into which chosen elements were added in the form of a powder mixture of Mo, Ru, BaO₂, CeO₂, SrCO₃, La₂O₃ in the quantity of 0.4 mass % scaling to metals. Powder mixtures of corium with FP stirred uniformly were loaded into tungsten crucibles of 30 mm inner diameter and ~ 130 mm height. The experiments were conducted in the argon atmosphere in the following mode: fast heating to the temperature of complete melting 2400 – 2600° depending on the corium oxidation degree, 1 – 3 minute exposition and the inductor switching off.

U, Zr, Zr_{free}, Fe were determined by the standard chemical methods. Fission products simulants were determined by the plasma emission-spectrum method. The method sensitivity is as follows: Mo - 0.001; Ru - 0.002; Ba and Sr - 0.0002; Ce - 0.01; and La - 0.001 mass %. The relative error is ≤ 10 %. Simultaneously, the x-ray structural phase analysis was performed.

The analysis of fission products in the corium and the ingot metallic parts was performed by the plasma emission-spectrum method.

The following parameters varied in the STFMFP tests:

- The zirconium oxidation degree. Initial oxidation degree of the corium mixture before the test was about 45% for tests #1, #2, #3, #6, and about 70 for tests #7 and #8. Final oxidation degree was about 65% for tests #1 through #6, and 80 – 85% for tests #7 and #8.
- One tests #6 was performed with the stainless steel.
- Temperature in the tests varied between 2600°C and 2700 °C.

- One test was conducted with the U/Zr ratio equal to 1.6 (FP#2), in all other experiments the ratio was 1.2.

Two MA experiments were conducted at lower temperature about 2500°C and amount of steel added to the corium was higher about 0.1 and 0.2.

The following parameters were chosen as main parameters, which determine the partitioning of FP between phases: temperature, final corium oxidation degree, and U/Zr ratio. Moreover the dependence upon steel (iron) to corium ratio was analyzed. Partitioning coefficient was calculated as ratio of concentrations between metal and oxide phases.

Results of the studies on partitioning of fission products (Mo, Ru, Cr, Ba, La, Ce) in the oxide and metallic melt phases confirmed that metal simulants such as Mo and Ru are concentrated in the metal phase, while oxide component Sr, Ba, Ce, and La are distributed in the oxide corium.

3.5 Molten Metals Migration Through the Oxide Porous Matrix

A series of 10 small (~ 0.5 kg) and 1 medium scale (~ 7 kg) tests were dedicated to the study of molten metal migration through a porous corium debris bed.

Coria of different compositions namely C-32, C-70, C-100 compositions with the atomic ratio of U/Zr = 1.2 were employed in the tests. Most part of experiments was conducted with the corium particles loading with the sizes of particles 1.2 - 3.5 mm, and one test (the K-1 test) was with the corium fragments of ~ 8 × 8 × 10 mm size.

The molten metals were presented by the steel of the St30 quality, stainless steel 12X18H10T, and by the alloy of stainless steel (85 mass %) and zirconium (15 mass %)

The corium fragments and particles were produced by cutting or crushing of the corium sintered briquettes (the C-32 corium was sintered under the temperature 1700°C, the C-70 and C-100 coria were sintered under the temperature 2000°C). The particle fractions were prepared by the altering bolting through the riddle with openings of 1.2 and 3.5 mm. illustrates the size distribution of the corium particles.

One test was made with 1cm debris to show the effects of surface tension and wettability. The metal consisted of either steel or a alloy of Zr and steel. The temperature was deliberately chosen in a relatively low range (between 1900K and 2300K) above the melting temperature of the metallic alloy, however lower than the corium melting temperature. In some cases, the melt progression through the particle bed was observed whereas in other cases there was no metal penetration. Chemical interactions between the solid particles and the liquid metal were observed and samples were analyzed to measure compositions.

Most tests were performed in the KORPUS facility in the argon atmosphere [5]. The heating device consisted of a resistive graphite heater of a cylindrical geometry and up to 20 kW power. A tantalum cup in which studied test assemblies were placed was located in the heater. As a rule, one test assembly was placed into the heating device in each test. In one case three test assemblies, K-7, K-8, and K-9, were tested simultaneously in one heating device. Test conditions for these assemblies were the same ones. Energy to heat a test assembly was transferred by the radiation from the graphite heater to the tantalum cup and from the Ta cup to the test assembly. As K test series was conducted in a carbon heater three supporting tests were conducted to study the possible carbon influence on the test results.

The T-8 test was performed in the TULPAN facility [5] to study the interaction of the C-32 corium particles with stainless steel in non isothermal conditions and in a larger scale. One of the goals was to determine the depth to which molten steel may penetrate through the porous debris. The goals

for the post-test examination was also to study interactions occurred during penetration. The TULPAN facility represents a gas-vacuum induction furnace with a graphite heater. The inductor power at the frequency 1000 Hz is up to 250 kW. The temperature gradient was maintained by the radiation from the outer surface of the test unit. TULPAN T-8 test conducted in the vertical temperature gradient indicated that the penetration of steel was observed up to the temperature about its melting point.

Results of experiments demonstrated several mechanisms for the penetration of molten metal in the porous debris:

1. Filling of the open porosity among particles by liquid metal. This process depends upon the debris particle size, the wettability of the corium particles and surface tension which are in turn depend upon composition and temperature;
2. The interactions between molten metals and corium particles near the contact area between phases. The depth of such penetration did not exceed ~ 3.2 mm.
3. In some cases (under the temperature higher than 1800°C) the metal migration by the mechanism "vaporization-condensation" on the surface of particles located deeply in the loading was found

3.6 Boron Behaviour and Its Impact on the Stratification

In case of a severe accident control rods fabricated with a use of boron carbide may be one of the basic boron sources for the corium melt in the reactor vessel. A total mass of B_4C , as it follows from the reference [6], may range for different reactor types from 270 kg (VVER-1000) up to 900 kg (BWR). This corresponds to 0.25 and 0.5 mass% of the core mass for each case. Earlier [7], on studying carbon impact on the behaviour of the suboxidized C-32 corium, it was shown that the melting and further freezing resulted in the stratification of that into two layers at the concentration of carbon in the initial corium higher than 0.2 mass%.

Therefore, the existence of similar stratification phenomena in the corium may be also expected in the presence of boron. On studying the impact of boron carbide, it is of an additional interest to determine the opportunity for carbon and boron combined impact on the stratification processes in the suboxidized corium as well as the partitioning of boron and carbon between the oxide and metallic melt phases of the core.

Three small scale experiments have been conducted with the corium containing the boron carbide in the STFM facility [8]. The first experiment have been performed in a tungsten crucible and was similar to the experimental series with the carbon, all other experiments have been performed in a cold crucible like the series with the corium and iron.

Corium was made from the initial components, namely: uranium oxide (UO_2), zirconium oxide (ZrO_2), zirconium hydride (ZrH_2), and boron carbide (B_4C). The initial materials in the form of powders were thoroughly blended, pressed and sintered in the furnaces with metal heaters in the atmosphere of purified argon in protective casks made of tantalum. Then discs of corium were sintered at the temperature about 1900°C during 1 hour. Discs containing additionally 0.5 mass% of boron carbide were sintered under the temperature $\sim 2150^{\circ}\text{C}$ during 15 minutes. The actual content of basic elements and carbon were analysed in the produced corium compositions.

Metal Fe was employed in the test studying boron partitioning between oxidic and metallic phases. The presence of impurities Mn - 0.21, Si - 0.15, and C - 0.05 mass% were found in the composition of iron. The scenario for two experiments included heating up to the temperature 2550°C within 20 minutes, exposure during 30 minutes and cooling down to 1800°C within 15 minutes. Post test examination included chemical and phase composition analysis of the samples taken from the ingot.

3.7 Measurements of Material Properties

The primary objective of the material properties measurements was to expand the database obtained during RASPLAV Project. New data were obtained for the C-32 corium and for metallic phase formed during interaction of molten corium with the steel. The following material properties were measured:

- Viscosity, density and liquidus temperature for C-32 corium
- Electric conductivity, thermal conductivity, viscosity, and the temperatures for phase transitions as well as the spreading temperature for metallic phase.

The experimental techniques and the full set of data obtained were presented in the report MP-TR-12 [9].

The viscosity of C-32 corium was measured using the method of damping of torsional oscillation of a cylinder filled with studied liquid similarly to the measurements performed during the RASPLAV project. The values of kinematic viscosity for the corium C-32 were measured within the temperature range 2380-2600 °C. It should be noted that measured viscosity for C-32 corium is very close to that measured earlier for the C-22 corium. Up to 2200°C the system behaves as a solid body and is characterized by a low damping factor that is practically independent of the temperature. Under the temperatures higher than 2370°C, the system is characterized by a high damping factor that decreases slowly with the temperature increase. This behaviour is typical of normal liquids. Within the temperature range 2200 - 2370°C, the system is characterized by a noticeable growth of the damping factor with the temperature increase. This temperature range may be considered as a simultaneous existence of a solid and liquid phases.

The special facility was developed, designed and fabricated to measure the density by modified hydrostatic weighing method. Data on the C-32 corium density were obtained within the temperature range 2482 – 2585°C. During the RASPLAV Project the C-32 density was also measured simultaneously with the surface tension. The value for density $7.49 + 0.44 \text{ g/cm}^3$ for the temperature of 2470 – 2580°C was obtained which is consistent with the current data.

The liquidus temperature of the corium was measured by three different techniques. These techniques were developed within RASPLAV&MASCA Projects:

- Viscosity technique
- Gas Bubble Technique
- Thermogram recording technique.

All these three different technique gave very close results presented in Figure 3

The material properties of metallic phase were measured for the samples cut out of the metallic part of the ingot obtained in the T-7 test. The results of chemical analysis are presented in Table 4.

One of the most important characteristics of the material is electric conductivity. The measurement of electric conductivity and its temperature dependence allows to judge about the nature of chemical linkage between the components of the studied material. The method employed for the study consist of the measurements of the Volt-Ampere characteristic of the sample. The temperature coefficient for specific resistance was determined by the least-squares method. Table 5 presents the specific resistance of the studied sample under 20°C and the temperature coefficient. Figures in round brackets are the measurement errors (dispersion). The same table contains also the values of for pure iron [10], zirconium [11], and uranium [12]. It is seen that specific resistance of the alloy under study

is very close to that of zirconium and the temperature coefficient of specific resistance – to that of uranium.

Figure 3. Comparison of Liquidus Measurement by Three Different Techniques

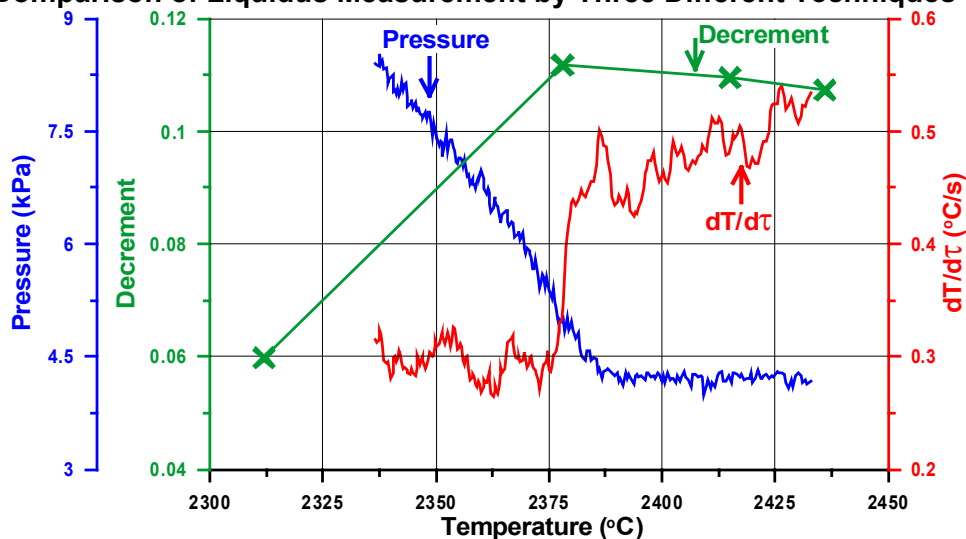


Table 4. The “Metallic Body” Chemical Analysis

Sample composition (mass %)							U/Zr (at./at.)
U	Zr	(Zr+Fe+U) _{free}	Fe	C	Nb	O (diff.)	
27.2	13.26	*	59.37	0.143	*	0.03	0.79

* - not measured

Table 5. Specific Resistance (ρ) and Temperature Coefficient of that (α) of the Alloy and Its Components

Material	T (°C)	$\rho \cdot 10^8$ (Ohm · m)	$\alpha \cdot 10^3$ (1/K)	Reference
Alloy under study	20	43 (4.3)	2.38 (0.17)	This work
Fe	20	9.8	6.2	[37]
Zr	27	43.5	3.8	[38]
U	25	25 - 34	2 – 2.8	[39]

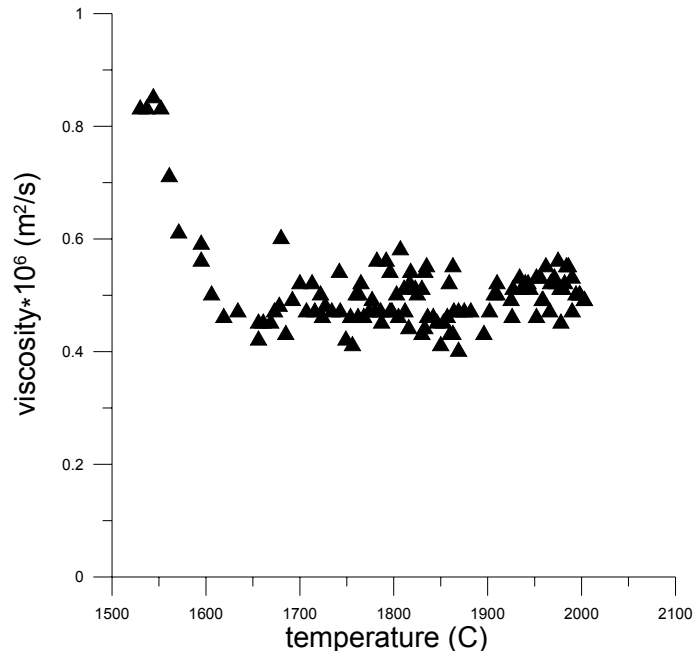
For the thermal conductivity measurement the sample was placed between the heater and heat receiver. The heater and heat receiver were fabricated from copper to minimize the temperature gradients. The copper heater was heated by an electric coil. The technique for thermal conductivity measurement is based on the solution of the non-steady-state heat conductivity equation. The tests were performed with different power applied to the heater. In Table 6 averaged thermal conductivity data are presented.

Table 6. Thermal Conductivity Data Obtained in Tests

#	T(°C)	Thermal conductivity (W/(m·K))	Number of experimental points	Dispersion due to statistic (W/(m·K))	Dispersion due to systematic error (W/(m·K))	Total dispersion (W/(m·K))
1	113 - 201	13.68	989	0.39	1.3	1.3
2	49 - 134	12.32	2075	0.98	1.3	1.6
3	152 - 216	13.39	353	0.21	1.3	1.3
4	84 - 174	13.53	1381	0.42	1.3	1.4
	84 - 216	13.53	2753	0.41	1.3	1.4

The viscosity measurements were performed for the samples synthesized artificially from pure metals. This compound consisted of the uranium, zirconium and iron. The gross formula of the composition ($U_{0.44}Zr_{0.56}Fe_{0.8}$) is close to that of the sample produced in the T-7 test. The method of damping of torsional oscillation of a cylinder filled with the melt was used to measure the “metallic body” viscosity. Up to the temperature 1380°C, the system behaves as a solid body and is characterized by a low damping decrement. Under the temperature higher than 1600°C, the system is characterized by a high decrement factor that does not practically depend on the temperature. This area may be construed as a liquid with a low fluidity activation energy. The intermediate area of 1380 - 1600°C is characterized by the non-monotone behaviour of the damping decrement and may be construed as a two-phase area with simultaneous presence of the solid and liquid phases. Kinematic viscosity was calculated in the area of the theory applicability. Figure 4 illustrates kinematic viscosity versus the temperature.

Figure 4. The “Metallic Body” Viscosity versus the Temperature



The technique for the determination of T_{spread} of metallic phase consisted in the observation of the sample condition through the optical micropycrometer which allows the observation of the liquid phase appearance in the form of a film or drops, trickling of that on the surface up to complete melting. The

experiment was conducted in the inert atmosphere to prevent the change of chemical composition of samples. The temperature increased with a constant rate. The samples of the metallic phase were taken from the ingot obtained at the RCW facility.

Table 7. Results on Density, Chemical and X-Phase Analyses of the RCW Ingot Samples

Sample	Density, g/cm ³	Chemical composition, mass%						Phase composition and grid parameter, nm
		U	Zr	Fe	Gr	Ni	C	
#1 top	9.03	23.09	10.20	43.2	11.55	8.01	0.058	(UZr)Fe ₂ (a=0.699)+solid solution of UO ₂ (a=0.542) +traces of Zr(C,O)
#2 middle part	9.85	38.89	13.53	31.6	8.36	5.43	0.042	(UZr)Fe ₂ (a=0.702)+ solid solution of UO ₂ (a=0.544) +traces of Zr(C,O)
#3 bottom	10.72	51.96	20.10	16.6	4.04	2.93	0.19	(UZr)Fe ₂ (a=0.7127)+phase X+ solid solution of UO ₂ (a=0.545) + Zr(C,O) (a=0.466)

The spreading temperature obtained varied from 1770⁰C in the top sample to 2430⁰C for the samples taken from the bottom of the ingot.

3.8 Salt Tests

RASPLAV salt tests were an important part of the RASPLAV project. There were two major goals of those tests, namely (1) justification of the major decisions for the preparation and interpretation of the corium tests, and (2) studies of complementary heat transfer phenomena, which can potentially influence the analysis and interpretation of tests. The list of phenomena of interest included (a) crust formation along cooled boundaries of the pool from the eutectic salt mixture, and (b) crust formation from the non-eutectic composition [13].

The RASPLAV Salt facility was designed to simulate and study thermal processes of interaction between the molten corium and the reactor vessel wall using molten fluorine salts (NaF-NaBF₄, LiF-NaF-KF, LiF-NaF-ZrF₄). The design of the RASPLAV Salt facility is similar to the RASPLAV corium facility. The facility represents slice geometry with the characteristic radius of the semicircular section of 200 mm. The test wall 20 mm thick was cooled by the secondary salt mixture. The test wall was instrumented with thermocouples, which allowed to measure temperature and heat flux through the test wall. Moreover, the moving frame with many thermocouples provided melt pool temperature throughout the melt volume and boundary layers. Molten salt forming the lower pool was LiF-NaF-ZrF₄ with the melting temperature of 558⁰C, while for the upper pool the composition LiF-NaF-KF with melting temperature of 454⁰C was used. The difference in the melting points of both salts was 104⁰C large enough to allow simulation of peculiarities in the heat transfer. Upon completion of the RASPLAV Project the RASPLAV-A-Salt was updated to perform the test series specified within the framework of the MASCA Project.

In the frames of MASCA projects test series at the RASPLAV salt facility were conducted in the two liquid layers configuration. The objectives of tests were as follows:

- Simulation of the focusing effect of the heat flux when the heating of the upper payer is due to the convective heat transfer from the bottom pool. For these cases the situation with and without

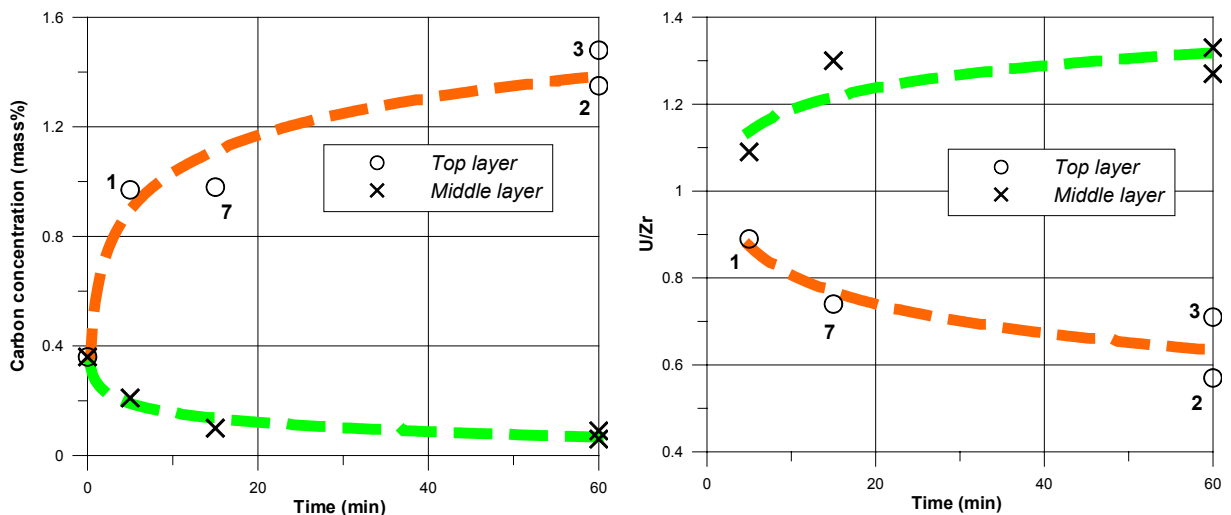
- top crust is considered. For the first case the convection pattern in the upper layer is uncoupled with the convection in the lower layer. The second case presents coupled convection in both layers.
- Study of the focusing effect as a function of dimensionless numbers such as Biot (Bi) and Nusselt (Nu_{up} , $Nu_{s,d}$) numbers.
 - Verification of correlations for upward and downward heat transfer under variable conditions at the top pool surface from isothermal to almost adiabatic.

4. Findings

4.1 Melt Stratification Mechanism

Different possibilities for corium stratification were studied in a series of small-scale experiments. Stratification observed in the large scale RASPLAV AW-1 test can be explained by small amount of carbon 0.3 – 0.4 wt.%. Small-scale experiments indicated that there is some threshold value of about 0.2 wt.% above which carbon produce a top layer enriched with zirconium. Carbon content in the upper layer increases up to 1.5 wt.%, while in the bulk oxide phase the amount of carbon does not exceed 0.1 wt.% [7]. This effect can be explained by the formation of zirconium carbides and oxycarbides.

Figure 5. Carbon Concentration (a) and U/Zr Ratio (b) in the Top and Middle Layers versus Exposure Time at the Temperature of 2550°C



Stratification kinetics was fast enough; the characteristic time varies between 6 and 12 minutes. As characteristic dimensions of the RASPLAV-AW facility were approximately 4 – 5 times larger than expected characteristic time for large-scale tests might be 20 times larger (between 2 and 4 hours).

Another mechanism for melt stratification was the influence of the heating up rate which may lead to separation of corium components. This mechanism was partially confirmed by experiments performed in the STFM-2 series. At the temperature of 2200°C the upper part of ingot was enriched with zirconium based phase ZrO_x with relatively small amount of uranium. At this temperature level the ratio of areas occupied by light and gray phases reached the value of 1.4 (Experiment STFM#2/3) while the average value at higher temperature was about 0.5 – 0.6. However experiments showed that this stratification was unstable; increase of temperature up to 2500°C led to practical disappearance of the differences between upper layer and bulk corium.

4.2 Interactions of Corium with Steel (Iron)

In a series of small and middle scale tests with iron and stainless steel it was clearly demonstrated that molten steel (iron) extracts some metallic zirconium and uranium from suboxidized corium leading to the increase of metal phase mass and density and consequently to a possible change of layer configuration [14, 15, 16, 17, 18]. Uranium transport to the metallic phase is closely related to the existence of free zirconium in the initial suboxidized corium. The amounts of U and Zr atoms transferred to the metallic phase depend upon metal mass and corium oxidation degree.

Steel concentration increases with the increase of the relative steel content in the corium, but the concentration of uranium and zirconium is decreasing with the increase of the steel (iron) content in the tests.

Concentrations of U and Zr decrease with the increase of zirconium oxidation degree. There is also some dependence upon metal content, however this dependence is rather weak. The iron concentration increases gradually with the increase of the zirconium oxidation degree and also iron concentration is increasing with the increasing of the mass of metal added to the melt.

A very small amount of iron goes into the oxide phase (less than 1% wt.). After interaction, the degree of oxidation of the oxide phase is increased. Increasing of steel to corium ratio leads to increasing of oxide phase oxidation degree approaching almost complete oxidation for large amounts of steel (iron) content in the test.

Density of metal phases depends mainly on the ratio of U to steel or iron while the most relevant factor for oxide phase density is corium oxidation degree.

4.3 FP Partitioning

Sufficient improvement of the knowledge of fission product spatial and chemical distributions in the melt pool was achieved in the MASCA Project. It was confirmed that there is a partition of the fission products between the metallic and oxidic phases. Elements with a stable oxide form under the test conditions can be found essentially in the oxide phase, while the other elements are found in the metallic phase. In each respective phase, the elements are uniformly distributed. For the compositions studied, the distribution of fission products between the oxidic and metallic liquids is in agreement with the predictions of thermodynamic calculations [19]

The FP partitioning coefficient between the oxidic and metallic phases $K_o = X_{met}/X_{cor}$, depends on the melt parameters such as temperature, corium oxidation degree, U/Zr ratio.

4.4 Migration of Molten Metal Through Porous Oxide Debris

Molten steel demonstrated good ability to penetrate into the corium if the temperature of steel exceeds its melting point by 350 K. At the temperature of 1600°C steel penetrated only if the size of pores is large enough. However at temperature higher than 1800°C, steel penetrate not only in the debris formed by particles of 1.2 - 3.5 mm, but also through the corium briquettes with the low porosity (about 10%). TULPAN T-8 test conducted in the vertical temperature gradient indicated that the penetration of steel was observed up to the temperature about its melting point [5].

However the composition containing the alloy of stainless steel and zirconium (85 % SS + 15 % Zr) demonstrated weak wettability and consequently the penetration ability even in the cases when superheating above the melting point was 400 – 500°C. The wetting angle was assessed to be ~ 150°.

Improvement of understanding about the zirconium and stainless steel alloy penetration into the porous medium of the corium particles, it seems expedient to continue studies in the line of the temperature range increase (up to 2300°C) and employment of other alloys composition.

At low temperature, slightly above steel melting (1900K), a limited interaction was observed between steel and partially oxidized corium debris (solid). There was formation of Fe-Zr and Fe-U eutectic mixtures. For fully oxidized debris, no interaction was observed. Similar observations at higher temperatures would be interesting to quantify the kinetics of interactions between liquid steel and solid corium (tests described above have shown that the liquid-liquid interaction at high temperature is rather fast to reach equilibrium).

Debris experiments have also shown that the progression of molten steel into the debris bed is limited by capillarity and wettability effects which become important for small particles (2-3 mm). This shows that, at low temperature, the phenomena governing metal progression into the oxide debris are more important than the chemical phenomena to determine the total amount of dissolved materials. Such transient effects need further investigations.

4.5 Boron Behaviour and Its Impact on the Stratification

The performed tests have shown that boron carbide decomposes on contacting the suboxidized C-32 corium under the temperature lower than 1800°C generating mainly zirconium oxycarbide and diboride. On introducing small quantities of B₄C into the corium composition, a significant non-uniformity in boron partitioning along the ingot height takes place due to the melting. The upper zone is enriched in boron mainly in the composition of the refractory compound ZrB₂ [8].

The introduction of 0.5 mass% of B₄C into the C-32 corium results in the considerable increase of the produced liquid-metal phase due to the interaction with the melt based on Fe. The produced metallic ingot is enriched in boron and zirconium that results in significant reducing of its density. This results in the fact that the oxidic corium composition shifts to that of the C-100 corium.

Several tests conducted with a boron carbide addition (which may come from molten control rods) demonstrated peculiarities of the behavior of oxide and metal phases. For the suboxidized corium the effect of boron carbide was similar to chemical effects observed in the RASPLAV tests with carbon. Zirconium carbides and borides were observed in the post-test examination of ingots. With an addition of iron, the effect of phase separation became more pronounced. The amount of metal phase became larger, new phases were also observed. This effect needs further investigations.

5. Conclusions

In the framework of MASCA Project the technology has been developed to conduct the high temperature corium tests including design, fabrication and assembly of a large-scale facility capable to heat up and retain molten corium and steel at relevant temperatures under controlled conditions. The experimental facilities used in MASCA are actually well suited for the study of any metal-oxide mixture at high temperature because the interactions between the corium and the crucible are very low.

Sufficient improvement of the knowledge have been achieved on the following items:

- Melt stratification mechanisms;
- Stratification phenomenon in iron containing melts;
- Fission product spatial and chemical distribution in the melt pool;
- Molten metal migration into the debris bed;
- Boron effect on the stratification.

The discovered and quantified phenomena of component partitioning between the oxidic and metallic phases during the interaction of suboxidized corium and steel can be used for the development and verification of corresponding models describing the molten pool behaviour. Precise measurements of the material properties and the composition of metallic and oxidic phases provide important data for validation of thermodynamic databases.

The MASCA Project results obtained with corium compositions prototypical of power reactors would provide qualitative and quantitative data for assessments of the in-vessel melt pool retention strategy as well as for ex-vessel phenomena.

Nevertheless new studies will be needed to reduce a number of uncertainties including uncertainties on the phase equilibria for U-Zr-O-Fe mixtures, on the physical properties of mixtures and alloys (liquidus and solidus temperatures, densities, thermal conductivity, viscosities), and uncertainties about the transposition of MASCA results to models for reactor cases, including scaling effects, the influence of an oxidizing atmosphere and the impact of non-uniform temperatures.

References

- 1 T.Okkonen, In Vessel Core Debris Cooling Through External Flooding of the Reactor Pressure Vessel, presented at the OECD/CSNI/NEA Workshop on Large Molten Pool Heat Transfer, Grenoble, France, March 9-11, 1994. pp.29-42.
- 2 L.Baker, Jr. et al. Heat Removal from Molten Fuel Pools, Proceedings of the International Meeting on Fast Reactor Safety and Related Physics, Chicago, Illinois, 1978.
- 3 G.Keyser, The SCARABEE BF1 Experiment with a Molten UO₂ Pool and its Interpretation, presented at the OECD/CSNI/NEA Workshop on Large Molten Pool Heat Transfer, Grenoble, France, March 9-11, 1994. pp.207-225.
- 4 RASPLAV Application Report, OECD RASPLAV Seminar, Munich, 2000.
- 5 V. Asmolov, Yu. Degaltsev, O. Schakh, S. Abalin, I. Semenov, I. Isaev, K. Pechalin, B. Gershman, A. Ignatochkin, A. Grafsky, V. Vlasov, Yu. Utkin, A. Kovalev, Study of the Molten Metal Migration in the Oxide Porous Matrix, MP-TR-5, July 2003
- 6 B. Adroguer, Impact of B₄C Control Rods on the Core Degradation under Severe Accident Conditions, 9th PRG RASPLAV Meeting, Cadarache, 14-16 Oct. 1998.
- 7 V. G. Asmolov, Ye. V. Astakhova, Yu. G. Degaltsev, Ye. K. Dyakov, A. Yu. Kotov, V. M. Repnikov, T. V. Trushkina, V. V. Vlasov, V. Yu. Vishnevsky, Yu. M. Utkin, V. N. Zagryazkin, Study of Carbon and Separation Impact on Suboxidised Corium Stratification, MR-TR-2, June 2001г.
- 8 V.G. Asmolov, Ye.V. Astahova, V.Yu. Vishnevskiy, E.K. Dyakov, V.N. Zagryazkin, A.Yu. Kotov, V.M. Repnikov, Investigation of B₄C Impact on U-Zr-O Corium Stratification and the Processes of Its Interaction with the Melt Based on Fe, MP-TR-7, September 2002
- 9 V.Asmolov, S.Abalin, S. Beshta, A.Merzlyakov, V.Vishnevsky, A.Kotov, V. Repnikov, Measurement of Physical Properties, MP-TR-12, June 2003
- 10 N.I. Koshkin, M.G. Shirkevich, Handbook on Elementary Physics, Moscow, Nauka, 1972, (Russ.)
- 11 V.E. Peletzkii, E.A. Belskaya, Electrical Resistance of Refractory Metals, Moscow, "Energoizdat", 1981. (Russ.)
- 12 J.J. Katz, E. Rabinovitch, The Chemistry of Uranium, v.1, NY, 1951.
- 13 V.Asmolov, S.Abalin, A. Surenkov, I.Gnidoy, B.Barkovsky, N.Komissarova, D.Chuvilin, Yu.Rybakov, V.Strizhov, V.Semenov, Study of Thermal Hydraulic Processes in a Stratified Molten Pool, MP-TR-13, December 2003
- 14 V. Asmolov, V. Khabensky, S. Beshta, V. Gusarov, S. Vitol, Ye. Krushinov, Yu. Degaltsev, V. Vlasov, Yu. Utkin, MA-1 Experiment: Post-Test Analysis Results, MP-TR-1, November 2001
- 15 V.G. Asmolov, V.B. Khabensky, S.V. Behta, S.A. Vitol', E.V. Krushinov, S.Yu. Kotova, E.K. Kalyago, N.E. Kamensky, A.V. Lysenko, V.G. Bliznyuk, V.R. Bulygin, E.V. Shevchenko, V.S. Granovsky, V.V. Martynov, V.V. Gusarov, V.I. Al'myashev, M.D. Tolkachyov, M.R. Pavlov, V.V. Vlasov, Yu.G. Degaltsev, Yu.M. Utkin, The MA-2 Experiment: Zirconium and Uranium Partitioning between Oxide and Metallic Phases of Molten Corium, MP-TR-6, March 2002

-
- 16 V. Asmolov, V. Khabensky, S. Beshta, Ye. Krushinov, S. Vitol, V. Gusarov, S. Yu. Kotova, V. Almyashev, Yu. Degaltsev, The MA-3 and MA-4 Tests: Zirconium and Uranium Partitioning between Oxide and Metallic Phases of Molten Corium, MP-TR-9, February 2003
 - 17 V.G. Asmolov, Ye.V. Astahova, V.Yu. Vishnevskiy, Yu.G. Degaltsev, E.K. Dyakov, V.N. Zagryazkin, A.Yu. Kotov, V.M. Repnikov, T.V. Trushkina, Yu.M. Utkin, V.O. Chernyshov, Study of the Liquid Steel Behaviour in the Molten Corium in STFMFe Test Series, MP-TR-8, February 2003
 - 18 V.G. Asmolov, S.S. Abalin, Yu.A. Veselkin, V.Yu. Vishnevskiy, V.V. Vlasov, Yu.G. Degaltsev, Ye.K. Dyakov, I.F. Isaev, A.N. Kiselev, N.P. Kiselev, A.M. Kovalev, A.G. Ol'khovskiy, K.V. Pechalin, I.M. Semenov, V.F. Strizhov, T.V. Trushkina, V.S. Uglov, Yu.M. Utkin, V.V. Chudanov, A.E. Aksenova, V.A. Pervichko, I.M. Khazanovich, RCW Post-Test Analysis Results, MP-TR-11, September 2003
 - 19 V.G. Asmolov, Ye.V. Astahova, V.Yu. Vishnevskiy, E.K. Dyakov, V.N. Zagryazkin, A.Yu. Kotov, V.M. Repnikov, V.S. Uglov, Yu.G. Degaltsev, Yu.M. Utkin, T.V. Trushkina, Partitioning of Fission Products between the Corium Melt Metallic and Oxidic Phases Resulting from the STFM-FP Tests, MP-TR-10, June 2003