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LWR SEVERE ACCIDENT RESEARCH AT THE KARLSRUHE INSTITUTE OF TECHNOLOGY

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Abstract. *The analysis of a late phase of a severe accident in Light Water Reactors at KIT is concentrated on the in- and ex-vessel core melt behavior. The overall objective is to investigate core melt scenarios from the beginning of core degradation to melt formation and relocation in the vessel, possible melt dispersion to the reactor cavity and to the containment, and finally corium concrete interaction and corium coolability in the reactor cavity. The experimental platform includes three large-scale experimental facilities: LIVE to investigate the melt pool behavior in the RPV lower head; DISCO to study the melt dispersion to the reactor cavity and direct containment heating; MOCKA to study molten corium concrete interaction. The experiments are designed to be complementary to other European facilities and experimental platforms, such as CODEX, VULCANO or PLINIUS to form a coherent European nuclear experimental network. They contribute to a better understanding of the core melt sequences and thus improve safety of existing and, in the long-term, of future reactors by severe accident mitigation measures and by safety installations where required. The experimental programs are part of the SAFEST and ALISA projects of the 7th EU Framework Programme. The results of the experiments are used for the validation of codes applied for safety assessment and planning of accident mitigation concepts, such as ASTEC.*

Keywords*: LWR, reactor, safety, severe accidents, experiments.*

1. INTRODUCTION

Severe accidents can cause significant damage to reactor fuel resulting in more or less complete core meltdown and threaten the containment integrity. They are the focus of considerable research, because the release of radioactive products into the environment would have serious consequences. This research also reflects a commitment to the defence-in-depth approach.

As stated in the final draft of the Strategic Research Agenda (SRA) (SNETP, 2009) of the Sustainable Nuclear Energy Technology Platform (SNETP), needs for safety research are identified by both regulators and operators, from their respective perspective. As discussed in the SRA, safety research is still needed to support long-term operation of existing LWRs in Europe. Regarding the issues in severe accidents, the SRA refers to the work carried out in the framework of the SARNET Network (Albiol et al., 2010; Van Dorsselaere et al., 2011; Van Dorsselaere et al., 2012) to conclude to a common view on the ranking of the research priorities in the field. The research priorities on severe accident management (Schwinges et al., 2010; Klein-Heßling et al., 2012) were prepared by the SARNET SARP group.

High priority issues (further research is considered as necessary):
- Core coolability during reflood and debris cooling;
- Ex-vessel melt pool configuration during Molten Corium Concrete Interaction (MCCI), ex-vessel corium coolability by top flooding;
- Melt relocation into water, ex-vessel Fuel Coolant Interaction (FCI);
- Hydrogen mixing and combustion in containment;
- Oxidizing impact (Ruthenium oxidizing conditions/air ingress for High Burn-up and Mixed Oxide fuel elements) on source term;
- Iodine chemistry in Reactor Coolant System (RCS) and in containment.

Medium priority issues (should be investigated further as already planned in the different research programs):
- Hydrogen generation during reflood and melt relocation in vessel;
- Corium coolability in lower head;
- Integrity of Reactor Pressure Vessel (RPV) due to external vessel cooling;
- Direct containment heating (DCH).

Low priority issues (could be closed after the related activities are finished):
- Corium coolability in core catcher with external cooling;
- Corium release following vessel rupture;

- Crack formation and leakages in concrete containment;
- Aerosol behavior impact on source term (in steam generator tubes (SGT) and containment cracks);
- Core reflooding impact on source term.

The phenomena described above are extremely complex; they generally demand the development of specific research. This research involves very substantial human and financial resources and, in general, the research field is too wide to allow investigation of all phenomena by any national program. To optimize the use of the resources, the collaboration between nuclear utilities, industry groups, research centers and safety authorities, at both national and international levels is very important. Therefore the severe accident research activities at KIT are strongly linked to other European facilities and experimental programs such as CODEX, VULCANO and PLINIUS (Journeau et al., 2009). The experimental programs are part of the LACOMECO (Miassoedov et al., 2012) and SAFEST (Miassoedov et al., 2015) projects of the 7th EU Framework Programme, providing experimental resources by offering the severe accident research platform at KIT for transnational access.

The overall purpose of the research is to investigate core melt scenarios from the beginning of core degradation to melt formation and relocation in the vessel, possible melt dispersion to the reactor cavity and to the containment, molten corium concrete interaction and finally hydrogen-related phenomena in severe accidents. The main thrust of the experiments is towards large scale tests under prototypical conditions addressing high and medium priority issues identified by the SARP group of SARNET. These helps to understand the core degradation and coolability, in-vessel and ex-vessel core melt behavior in real reactors in two ways – firstly by scaling-up and secondly by providing data for the improvement and validation of computer codes applied for safety assessment and planning of accident mitigation concepts, such as e.g. ASTEC (Bandini et al., 2010).

2. SEVERE ACCIDENT RESEARCH FACILITIES FOR CORE MELT STUDIES AT KIT

The experimental platform at KIT for investigations of core melt behavior includes the following facilities:

- LIVE facility concentrates on the investigation of the whole evolution of the in-vessel late phase of a severe accident, including e.g. formation and growth of the in-core melt pool, characteristics of corium arrival in the lower head, and molten pool behavior after the debris re-melting in large scale 3D geometry with emphasis on the transient behavior.
- DISCO is the only operating facility available worldwide for integral DCH investigations. It is designed to perform scaled experiments that simulate melt ejection from the RPV to the reactor cavity after the RPV failure under low system pressure during severe accidents in LWRs. These experiments investigate the fluid-dynamic, thermal and chemical processes during melt ejection out of a breach in the lower head of an LWR pressure vessel at pressures below 2 MPa.
- MOCKA facility is a large-scale test facility to study molten corium concrete interaction in stratified geometry with melt mass up to 3200 kg.

Although the LIVE, DISCO and MOCKA facilities can only perform experiments with simulant materials, the tests can be considered as prototypic for the following reasons: the selected materials represent, to the greatest extent possible, the important physical properties of the real core materials, and the large scale used allows extrapolation to the reactor case. Moreover, there is considerable flexibility and variability in the facilities due to the rather simple handling techniques. Pre-tests, parallel separate-effects tests and post tests can be performed in one hand. These tests can be seen as complementary to tests with UO_2 in other research centers.

2.1 LIVE – large-scale tests on behavior of the corium melt pool

A number of studies have already been performed to pursue the understanding of a severe accident with core melting, its course, major critical phases and timing and the influence of these processes on the accident progression (Kymäläinen et al., 1997; Theofanous and Angelini, 2001). Uncertainties in modeling these phenomena and in the application to reactor scale still persist (Van Dorsselaere et al., 2006). These include e.g. formation and growth of the in-core melt pool, relocation of molten material after the failure of the surrounding crust, characteristics of corium arrival in residual water in the lower head, corium stratifications in the lower head after the debris re-melting.

The main objective of the LIVE program at is to study the late in-vessel core melt behavior and core debris coolability both experimentally in large scale 2D and 3D geometry and in supporting separate-effects tests (Miassoedov et al., 2011), and analytically using CFD codes in order to provide a reasonable estimate of the remaining uncertainty band under the aspect of safety assessment. The LIVE-3D test facility is the first facility which allows the investigation of a heated melt in a 3D geometry of a lower plenum of a RPV (Gaus-Liu et al., 2010). Other test facilities had only a 2D geometry (BALI (Bernaz et al., 2001), SIMECO (Kolb et al., 2000) and COPO (Kymäläinen et al., 1994)) or were performed without heating of the melt (ACOPO (Theofanous et al., 1997)). To compare the experimental results of 3D experiments in LIVE-3D with 2D experiments, the LIVE-2D test facility was also constructed and a series of tests have been performed.

The main part of the LIVE-3D test facility is a 1:5 scaled semi-spherical lower head of the typical pressurized water reactor, as shown in Fig. 1 and Fig. 2. The diameter of the test vessel is 1 meter. The top area of the test vessel is covered with an insulated lid. The test vessel is enclosed in a cooling vessel to simulate the external cooling. The cooling water inlet is located at the bottom and the outlet is positioned at the top of the cooling vessel.

The melt is prepared in an external heating furnace designed to generate 220 l of the simulant melt at a maximum temperature of 1100 °C. The heating furnace is equipped with a vacuum pump; so it is possible to extract the residual melt out of the test vessel back into the heating furnace.

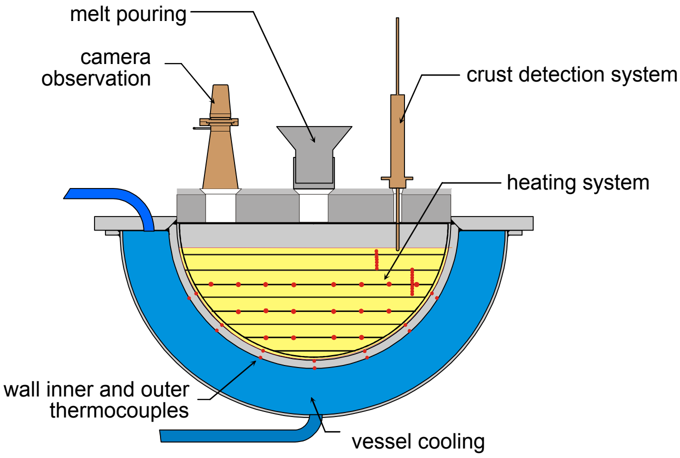


Figure 1. Scheme of the LIVE-3D test vessel

Figure 2. View of the LIVE-3D vessel with heating coils

The melt can be poured from the heating furnace into the test vessel either centrally or near the vessel wall. A vacuum pump extracted the residual melt at the end of test back to the heating furnace uncovering the solid crust formed in the experiment.

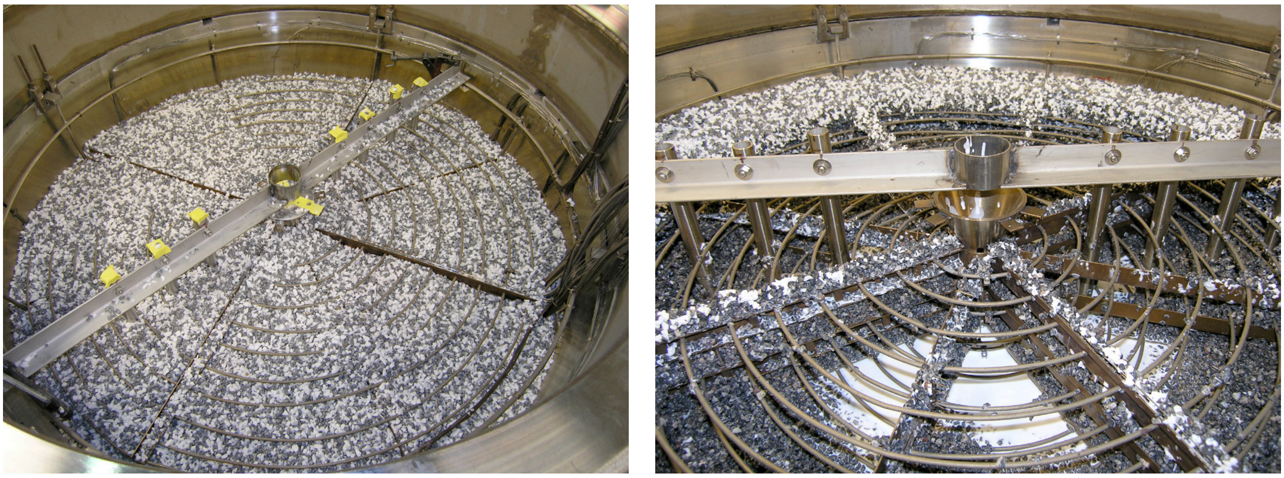
The volumetric decay heat is simulated by means of 6 heating planes in the test vessel. Each heating plane consists of a spirally formed heating element with a distance of ~40 mm between each winding. The heating elements are shrouded electrical resistance wires and are located in a special cage to ensure the correct positioning. All heating planes together provide a maximum power of about 28 kW. To realize a homogeneous heating of the melt, each plane can be controlled separately. In the case of homogeneous heat distribution the maximum heating power is limited to ~18 kW. The maximum temperature the heating system can provide is limited to 1100 °C.

To investigate both the transient and the steady state behavior of the simulated corium melt, an extensive instrumentation of the test vessel is realized. The temperatures of the vessel wall inner surface and outer surface are measured at 5 latitudes and 4 locations at each latitude. Heat flux distribution through the vessel wall can be calculated based on these temperatures. Additionally, 80 thermocouples are positioned within the vessel to measure the temperature distribution in the melt pool and in the crust.

Binary melts of KNO_3–$NaNO_3$ are selected as simulant melts for the experiments both in non-eutectic mixture of 80 mole% KNO_3–20 mole% $NaNO_3$ and in eutectic mixture of 50 mole% KNO_3–50 mole% $NaNO_3$ (eutectic temperature is 225 °C). The solidus temperature and the liquidus temperature of the non-eutectic composition are about 225 °C and 284 °C, respectively ((Berg and Kerridgeb, 2004). These melts can be used in a temperature range from 220 °C (solidification) to 380 °C (chemical decomposition). Due to its solubility for water the applicability of such melts is restricted to dry conditions inside the test vessel.

Recently two tests to investigate the melting process of a debris bed with materials having different melting temperature were performed. The debris bed in the LIVE-L8C experiment was composed of a homogeneous mixture of a low melting temperature non-eutectic of 80 mole% KNO_3–20 mole% $NaNO_3$ and granite particles, each amounted 50% of volume fraction (Fig. 3 a)). The height of the debris bed was 400 mm. The test vessel was insulated at the top. External cooling with water was performed after the phase of preheating debris. In addition to the temperature measurements, possibility of post-test visual observation inside the debris bed was realized using seven steel tubes as place holders, which were inserted in the debris bed at different radial positions. The test started with preheating of the debris bed to the temperature slightly below the melting temperature of the nitride mixture. Thereafter the power was increased stepwise and progressive melting of the nitride particles inside the debris bed was observed.

During the preheating of debris bed, the low thermal conductivity of debris (~0.25 W/(m·K)) resulted in a low power input rate and large temperature gradient in the debris. The maximum temperatures were located at a height of about 300 mm. In the second phase of the experiment the power was increased to 15 kW. The low melting temperature nitride particles started to melt and the molten material was relocated to the lower part of the debris bed. Some 47 min after the initiation of second phase the upper layer of the debris bed collapsed due to the void generation inside the debris bed. The breakdown of the upper debris layer continued during approximately one hour and the central area of the top two planes of heating elements was uncovered (Fig. 3 b)). After switching of the uncovered heating elements the residual power in second phase was reduced to 7 kW to achieve the temperature steady state condition. In the third phase of the test the power was increased from 7 kW to 10 kW. During the second and third phases the nitride particles were molten in the upper debris bed region whereas a thin loose debris layer preserved its form on the lower area near to the vessel wall. Increasing the total power inside the debris bed intensified the heat flux focusing effect in the vessel wall area where the molten pool had direct contact with the vessel wall.



a) b)

Figure 3. Debris bed a) before b) and after b) the LIVE-L8C test

2.3 DISCO – large-scale tests on melt dispersion and DCH

In case of a core meltdown accident in a PWR, liquid corium containing metals and oxides may relocate into the lower head of the reactor vessel. If the lower head fails in this condition, with an in-vessel pressure higher than the containment pressure, the molten corium will be forcefully ejected into the reactor pit, finely fragmented and eventually transported outside the reactor pit. The efficient heat transfer from the melt particles to the gas, together with combustion of hydrogen previously released into the reactor building and produced during melt dispersion, will heat-up and pressurize the containment atmosphere. These processes, referred to as direct containment heating, may endanger the integrity of the containment.

Moreover, if the reactor pit is flooded with water during the vessel failure, a fuel coolant interaction may occur. This phenomenon may have numerous consequences from positive, e.g. fast melt cooling, to very negative, when an energetic steam explosion was to occur. The knowledge and understanding of FCI is not complete and therefore the models used for its prediction are quite uncertain. One major reason for the uncertainty is the particular configuration under which the ex-vessel FCI may occur compared to those investigated up to now in available experiments. The melt could be ejected with high velocity even if the differential pressure to the containment is small. However, the effect of the jet velocity on the characteristics of the mixing between the melt and the water is not well understood and is subject of various interpretations. Therefore, it was decided to take advantage of the DISCO facility at KIT, which was used to simulate at a small scale the melt ejection out of a weakly pressurized reactor vessel (Meyer et al., 2009), to perform an FCI experiment with a configuration close to a real plant geometry. This was done by adding water into the reactor pit and including some modification of the reactor pit geometry. The experiment (Miassoedov et al., 2014) was performed in collaboration with the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in the frame of the LACOMECO project.

The generic representation of the DISCO facility and the arrangement of the reactor pit zone are shown in Fig. 4. The DISCO facility is composed of several parts simulating the containment, the reactor coolant system (RCS), the RPV, the pit and sub-compartment. The containment geometry characteristic is related to a French P'4 reactor with a length scale of approximately 1:10 but it does not reproduce precisely a given reactor. The pit zone was modified in order to obtain a large water pool. The corium melt is simulated by a thermite iron-alumina melt with initial temperature of about 2400 K, obtained from a thermite reaction initiated directly inside the RPV vessel a few seconds before its delivery to the pit through a nozzle. The delivery occurs as a result of the melting of a brass fuse inside the nozzle. Before the delivery, the vessel pressure can be adjusted through a steam accumulator placed outside of the containment vessel and connected to the RCS vessel. To be conservative the tests were performed with a central hole at the lower bottom head. The nozzle diameter was set to 0.060 m (0.030 m in case of the LACOMECO experiment) corresponding roughly to 0.60 m (0.30 m) at reactor scale. The gas initial composition in the DISCO containment can be modelled by different mixtures of air, steam and hydrogen. The water level in the reactor pit was set to ~0.54 m, just below the nozzle outlet. The water temperature at the beginning of the test was set to 85 °C to keep the subcooling in the range close to the expected one during the accident.

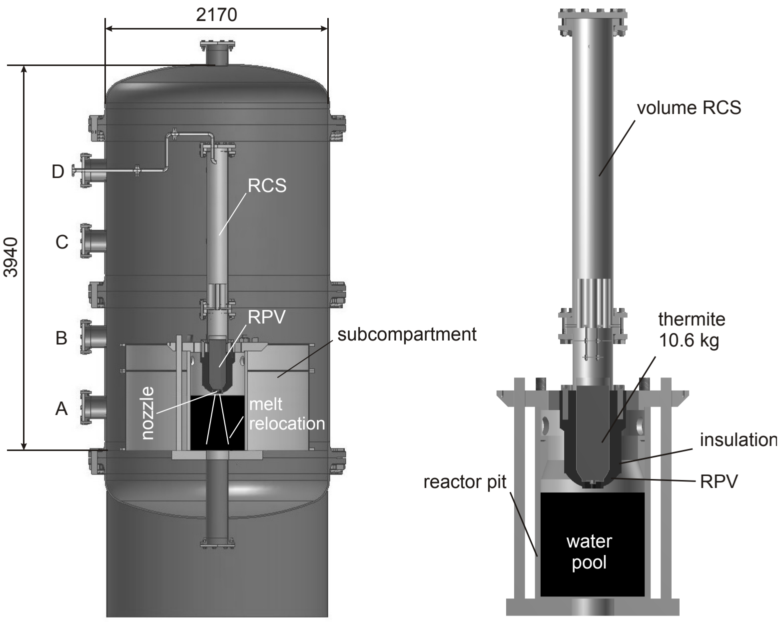


Figure 4. Scheme of the DISCO facility and of the cavity for the test

The major issues addressed in the experiments were the investigation of melt fragmentation processes for high velocity melt jets through a precise analysis of the size of the debris found. The debris bed characteristics are important for its coolability. The pressurization of the pit and the containment and the hydrogen production and combustion provide information for assessing the load on structures. The melt and water dispersion out of the pit during the process are initial conditions for MCCI. To investigate the impact of water on hydrogen production and combustion, the data were compared with those of the dry DCH tests.

The corium was modeled by an iron–alumina melt at the temperature of 2400 K that was driven by steam, and a prototypic atmosphere in the containment was applied. For comparison and modeling purposes the test was conducted without pre-existing hydrogen and the pressure in containment was set to 1 bar of air and 1 bar of steam. To be conservative the test was performed with a central hole at the lower bottom head. The nozzle diameter was set to 0.030 m which corresponds to 0.30 m diameter break in reactor scale. The water level in the pit was about 0.54 m, just below the nozzle, at a temperature of 85 °C.

The containment pressure increased by 0.04 MPa and reached about 0.24 MPa. The pressure in the cavity was characterized by several small peaks (Fig. 5). The highest peak (0.1 MPa of pressurization, at 0.017 s) cannot be ascribed to a steam explosion. The water inside the cavity (initial 125 kg) has been totally ejected. Concerning the debris, of the initial melt mass (10.62 kg thermite melt plus 1.0 kg molten steel) 16% remained in the RCS/RPV vessel, 60% remained in the cavity mainly as compact crusts. The fraction of melt transported to subcompartment and containment were about 9 and 15 % respectively. The size distribution supplied by sieved analysis (Fig. 6) indicated a tendency to small particles with a mean Sauter diameter of 160 µm, a median size diameter of 0.4 mm and a mean mass size diameter of 0.7 mm. The results of the experiment shall be compared with calculations of the MC3D code at IRSN (Meignen, 2008).

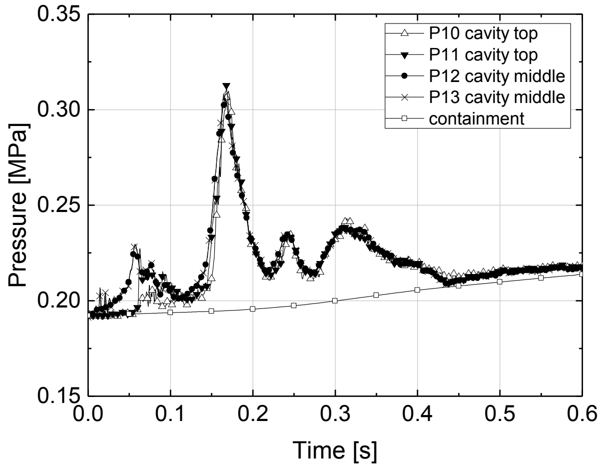


Figure 5. Pressures in the steam accumulator, RCS/RPV, cavity and containment

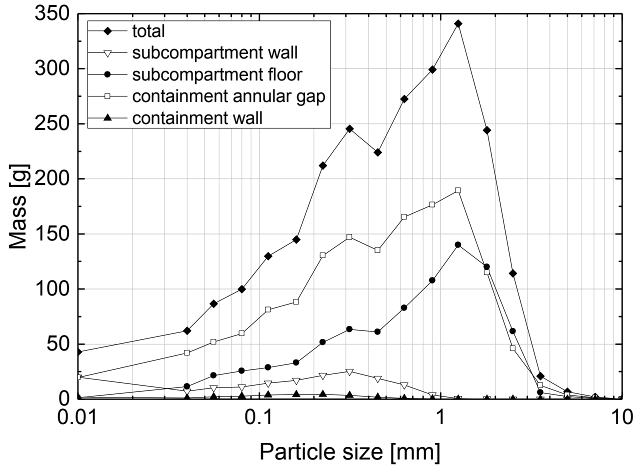


Figure 6. Mass distribution of the collected particles

2.4 MOCKA –large-scale experiments on molten corium concrete interaction

The MOCKA facility is designed to investigate the corium/concrete interaction in an anticipated core melt accident in LWRs, after the metal melt is layered beneath the oxide melt (Alsmeyer, 1987). The experimental focus is on the cavity formation in the basemat and the risk of a long-term basemat penetration by the metallic part of the melt (Foit et al., 2012).

In all MOCKA experiments a cylindrical concrete crucibles with an inner diameter of 25 cm are used. Both the sidewall and the basemat are instrumented with Type K thermocouple assemblies to determine the concrete erosion as a function of time. The initial melt consists of 42 kg Fe together with 4 kg Zr, overlaid by 68 kg oxide melt (initially 56 wt.% Al2O3, 44 wt.% CaO). The initial height of the metal melt was about 13 cm. The melt temperature at start of interaction was approximately 2273 K. The initial temperature was estimated form the reaction enthalpy of the used thermite taking into account the temperature measurements from the former BETA tests. The CaO admixture lowers the solidus temperature and the viscosity of the oxide melt. The resulting solidus temperature of approx. 1633 K is sufficiently low to prevent a formation of an initial crust at the oxide/concrete. The internal heat generation in the oxide phase is simulated by a succession of additions of pure thermite and Zr metal to the melt from the top being the first of a kind heating method realized for high temperature melts worldwide. The heat generated by the exothermal oxidation reactions of the continuously added Zr is deposited in the oxide phase. Due to density-driven phase segregation the metal melt at the bottom of the crucible is fed by the enthalpy of the Fe melt which is generated in the oxide phase by the thermite reaction of the added thermite. Approximately 80 % of the heating power was deposited in the oxide phase and 20 % in the iron melt. In this way a prototypic heating of both melt phases was achieved.

An important finding from the MOCKA tests with limestone/common sand (LCS) concrete is that the cavity erosion behavior is different in comparison to the CCI-2 test performed at Argonne National Laboratory with the same type of concrete (Farmer et al., 2004). MOCKA tests in the LCS concrete crucibles exhibited a highly pronounced lateral ablation. The lateral/axial ratios of the ablation depth for the MOCKA tests are approximately 3 in contrast to 1 estimated for the CCI-2 experiment. MOCKA tests on siliceous concrete without rebar have shown more pronounced downward erosion by the metal melt. The post-test section of the MOCKA 6.3 concrete crucible is shown in the Fig. 7 (the orange line indicates the initial height (13 cm) of the metal melt and the red line marks the outer surface of the LCS cylindrical crucible.). The final maximum downward erosion was 50 mm, the lateral erosion by the metal melt was 120 mm and the final ablation by the overlying oxide exceeded 120 mm. Approximately 75 % of the heating power is deposited in the oxide phase and 25 % in the metal melt. In this way a rather prototypic heating of both melt phases can be achieved. The power input was estimated to be 454 kW to the oxide melt and 142 kW to the metal melt.

The efficient heat transfer from the metal melt leads to a fast decrease in temperature, therefore, the concrete ablation will be influenced by crust formation processes. The progression of the concrete erosion found in MOCKA 6.3 test is depicted in the Fig. 8. During the early phase of the interaction, the observed low erosion rate of 0.7 mm/min is a consequence of the formation of a stable crust at the metal/concrete interface. This low concrete erosion rate gave rise to a considerable heat-up of a rather thick layer of concrete behind the slowly moving melt front. Decomposition of concrete during heat-up starts with evaporation of physically bound water around 100 °C. Dehydration of chemically bound water occurs up to 550 °C. Decarbonation of $CaCO_3$ from the cement and carbonate aggregates occurs from 700 to 900 °C. Liquid phases start to form between 1100-1250 °C. The subsequent increase of the temperature and of the mass of the metal melt due to the continuous addition of thermite caused a melting of the crust at about 1700 s and, consequently, a start of a somewhat faster progression into the thermally damaged concrete. A maximum lateral progression of approx. 6 mm/min of the metal melt front was estimated. Similar behaviour, i. e. a fast removal of a thermally destructed concrete was also observed in experiments which were performed within the SURC, ACE and CCI programs as well as in other MOCKA tests.

Figure 7. Cross-section of the MOCKA 6.3 crucible

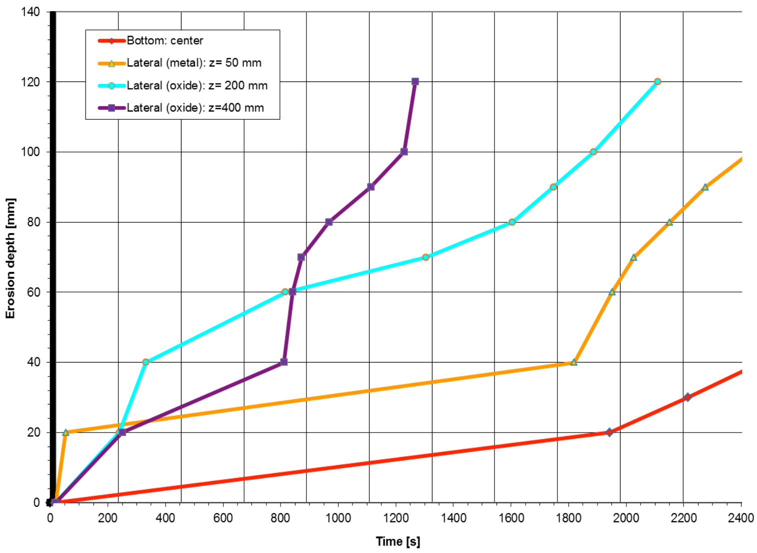


Figure 8. Erosion depth as a function of time in the MOCKA 6.3 test

3. CONCLUSIONS

The severe accident research platform at KIT includes several experimental facilities which are designed to study the remaining severe accident safety issues, including the corium coolability in the RPV, possible melt dispersion to the reactor cavity and molten corium concrete interaction. These facilities are unique in providing experimental programs in specific fields of core damage initiation up to hydrogen behavior and are designed to be complementary to other European facilities and experimental platforms to form a coherent European nuclear experimental network.

The experimental programs are strongly coupled with other European projects, such as PLINIUS and SARNET2. The experimental results are used for the development of models and their implementation in the severe accident codes such as e.g. ASTEC. This helps to capitalize the knowledge obtained in the field of severe accident research in codes and the scientific databases, thus preserving and diffusing this knowledge to a large number of current and future end-users.

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