OVERVIEW OF SEVERE ACCIDENT RESEARCH ACTIVITIES PERFORMED IN THE LACOMECO PROJECT AT KARLSRUHE INSTITUTE OF TECHNOLOGY

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ABSTRACT

The LACOMECO platform provides European organizations access to experimental facilities at Karlsruhe Institute of Technology (KIT) designed to study the remaining severe accident safety issues, including the coolability of a degraded reactor core, corium coolability in the reactor pressure vessel, melt dispersion to the reactor cavity, and hydrogen mixing and combustion phenomena in the containment. The KIT facilities are unique in its specified field and the experiments are designed to complement other European experimental platforms to form a coherent European nuclear experimental network.

The LACOMECO platform includes: 1) QUENCH facility designed for the investigation of early and late phases of core degradation in prototypical geometry for different reactor designs and cladding alloys; 2) LIVE facility, a large-scale 3D facility for the investigation of melt pool behavior in the lower head of reactor pressure vessel; 3) DISCO facility, the only operating facility worldwide able to investigate the melt dispersion to the reactor cavity and direct containment heating; 4) HYKA facility with a number of large and medium scale experimental test vessels addressing hydrogen behavior in containment under well controlled conditions.

Six experiments were defined in the LACOMECO project addressing the high and medium priority safety issues defined by the Severe Accident Research Priorities (SARP) group of the Severe Accident Research Network of Excellence (SARNET). Three experiments have already been performed, the main results obtained are discussed in the paper:

- QUENCH-16 test in the QUENCH facility test aimed at study the slow oxidation of fuel rod bundle in air;
- DISCO-FCI test in the DISCO facility aimed at investigation of ex-vessel fuel coolant interaction;
- HYKA-DETHYD tests in the HYKA facility aimed at investigation of the critical layer thickness for hydrogen-air detonation propagation in semi-confined geometry.

Three experiments will be performed in 2012, the main objectives and the status of the preparation are presented:

- LIVE-CERAM test in the LIVE facility test aimed at examination of the dissolution kinetics of KNO_3 ceramic crust by $KNO_3/NaNO_3$ melt;
- HYKA-HYGRADE test in the HYKA facility aimed at investigation of hydrogen combustion in hydrogen concentration gradients and with obstructed geometries prototypical of conditions in LWR containments:
- HYKA-UFPE test in the HYKA facility aimed at scaling-down of hydrogen combustion phenomena in nuclear power plant containments for numerical code validations.

INTRODUCTION

Severe accidents can cause significant damage to reactor fuel resulting in more or less complete core meltdown and threaten the containment integrity. Such accidents are highly unlikely in light of the preventive measures implemented by operators. However, 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) [1] 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 [2], [3] to conclude to a common view on the ranking of the research priorities in the field. The research priorities on severe accident management [4] were prepared by the SARNET SARP group.

High priority issues (further research is considered as necessary) include:

- 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;
- Oxidising impact (Ruthenium oxidising 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.

These phenomena are extremely complex and 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 programme. To optimise the use of the resources, the collaboration between nuclear utilities, industry groups, research centres and safety authorities, at both national and international levels is very important. This is precisely the main objective of the LACOMECO project, which aims to provide these resources and to facilitate this collaboration by offering four large scale experimental facilities at KIT for transnational access.

These facilities are QUENCH, LIVE, DISCO, and HYKA. Their overall purpose 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 hydrogen-related phenomena in severe accidents. The use of these facilities will provide the interested partners of the European Member Countries and FP7 Associated States a focus on core quenching, on possible core melt sequences in the reactor pressure vessel (RPV), on melt dispersion and on hydrogen behaviour in the containment, to enhance the understanding of severe accident sequences and their control in order to increase the public confidence in the use of nuclear energy.

The main thrust of the LACOMECO project is towards large scale tests under prototypical conditions. These will help the understanding of core degradation and quenching, melt formation and relocation as well as hydrogen behaviour 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 ASTEC.

The work progress and achievements of the LACOMECO project are summarised below.

QUENCH FACILITY

Bundle experiments in the QUENCH facility (Figure 1) are specifically designed to contribute to the reduction in uncertainties and increase in understanding of these issues. This is necessary to reach a proper assessment of the risk posed by quenching of degraded core to full-scale power plants.

The QUENCH program [5] aims not only to determine the amount of hydrogen released during reflood of a test bundle with genuine core materials as cladding and spacer grids, but also to investigate the related high-temperature interactions of

the core materials providing comprehensive data for model development and subsequent implementation into SFD computer codes.
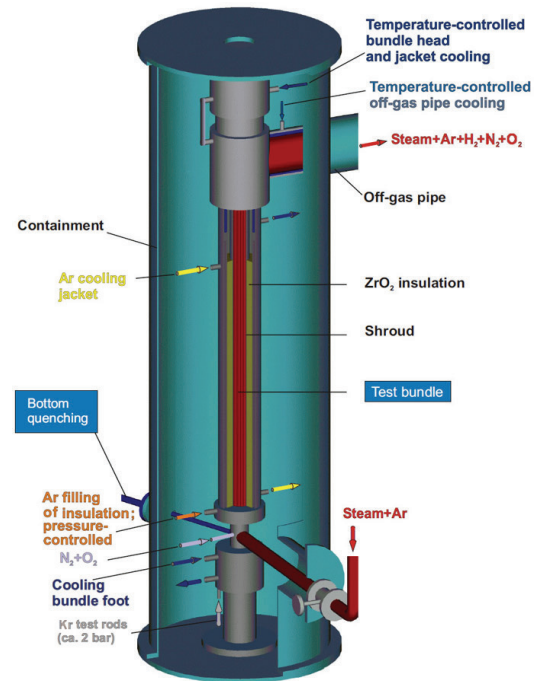
Figure 1 QUENCH facility with containment and test section

The QUENCH test facility can be operated in two modes: (a) a forced-convection mode with steam or air flow together with argon and (b) a boil-off mode with the steam inlet line closed. The system pressure in the test section is usually around 0.2 MPa (max. 0.6 MPa). Quenching can be performed with water or saturated steam from the bottom.

The main component is the test bundle that can be a standard PWR or e.g. a VVER -type. The PWR-type test bundle with a pitch of 14.3 mm is made up of 21 fuel rod simulators with Zircaloy-4 rod claddings and spacer grids whereas a VVER-type bundle consists of 31 rods arranged in a hexagonal lattice with a pitch of 12.75 mm. The VVER claddings and spacer grids are made of Zr1%Nb. Each bundle has a total length of approximately 2.5 m with a heating length of approximately 1 m. Heating is electric by tungsten heaters installed in the rod centre and surrounded by annular ZrO_2 pellets. Electrodes of molybdenum and copper connect the heaters with the cables leading to the DC electric power supply capable of 70 kW. The central rod is unheated and used for instrumentation or as absorber rod, e.g. B_4C or Ag-In-Cd to study their influence on core degradation. The test bundle is surrounded by a 2.38 mm thick shroud of Zircaloy together with a 37 mm thick ZrO_2 fibre insulation that extends to the upper end of the heated zone and a double-walled cooling jacket of stainless steel/Inconel. Corner rods are inserted in the bundle to adapt the bundle hydraulic diameter. These rods made of the same material as the rod claddings are either used for thermocouple instrumentation or as probe which can be withdrawn from the bundle anytime during the test to check the degree of oxidation. The test rods are filled to ~0.22 MPa

(maximum 0.6 MPa) with tracer gases, e.g. Kr or He, to detect the onset of the rod failure with the mass spectrometer at the off-gas pipe.

Up to now, 15 bundle tests have been conducted; the main topics investigated are: hydrogen source term during reflood, influence of B_4C [6] and Ag-In-Cd control rods [7] on bundle degradation, effect of air ingress [8] on oxidation and degradation of the core, and specific behaviour of VVER bundle geometry [9] and materials during oxidation and reflood. One test was performed with the complete sequence including boil-off phase, pre-oxidation and reflood. The QUENCH experiments will focus on the analysis of the relocation of cladding and fuel and the formation and cooling of in-core debris beds to gain information on the characteristics of the created debris particles. The main objective of these tests is the investigation of these processes under prototypical boundary conditions for a whole bundle.

For the LACOMECO project a QUENCH test with slow oxidation in air was selected (QUENCH-16) proposed by KFKI/AEKI, Budapest, Hungary [10].

QUENCH-16 test conduct and first results

The high temperature interaction of fuel materials with air results in intense oxidation and nitriding of zirconium components [11]. The oxidation heat can lead to temperature excursion and to the acceleration of bundle degradation. In case of severe reactor accidents air may have access to the core after lower head failure. Air oxidation can be expected in open reactor and spent fuel storage pool accidents as well. The safety significance of air ingress scenarios is emphasized by the formation of gaseous fission product oxides (e.g. ruthenium), which can dramatically increase the release of radioactive materials from the damaged fuel.

The QUENCH-16 bundle test with air ingress focussed on the following phenomena:
- slow oxidation and nitriding of zirconium in high temperature air,
- formation of oxide and nitride layers on the surface of Zr,
- breakaway oxidation of Zr in air, formation of spalling oxide scale,
- reflooding of oxidised and nitrided bundle by water, release of nitrogen.

The determination of the test protocol aimed at achieving the objectives was based on planning calculations by PSI (SCDAP/RELAP5), GRS (ATHLET-CD), and EDF (MAAP-4) [12]. In addition to the definition of the electric power vs. time curve, the main outcome was that the intended oxygen starvation period could be reached only with low air flow rates of approx. 0.2 g/s.

In common with the previous QUENCH experiments, the bundle was heated by a series of stepwise increases of electrical power (Figure 2) from room temperature to a maximum of ~600 °C in an atmosphere of flowing argon (3 g/s) and superheated steam (3.3 g/s). The bundle was stabilised at this temperature, the electrical power being ~4 kW. During this time the operation of the various systems was checked.

In a first transient, the bundle was heated by power increase to about 1200 °C, reached at ca. 4000 s. This marked the start of the pre-oxidation phase to achieve a maximum cladding oxidation of up to 200 µm. The power was controlled via small increments from 10 kW to 11.5 kW, to maintain more or less constant temperatures. In line with pre-test planning calculations about 14 g of hydrogen were produced in this phase which lasted until 6300 s. At this point the power was reduced to 4 kW which effected a cooling of the bundle to 790 °C, as a preparation for the air ingress phase. This phase lasted 1000 s, until 7300 s. Towards the end of this phase, one of the corner rods was extracted from the test bundle for determination of the oxide thickness axial distribution. Preliminary measurement showed a maximum oxide thickness of 133 µm in the bundle what was within the target band.
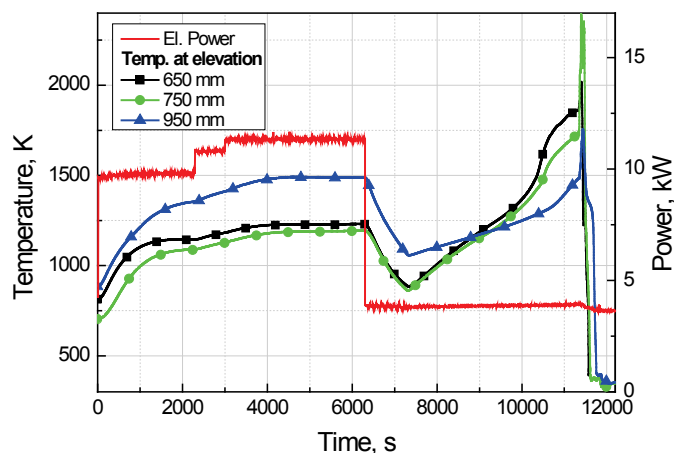

Figure 2 QUENCH-16 test conduct showing electric power input and selected temperatures

In the subsequent air ingress phase, the steam flow was replaced by 0.2 g/s of air, and the argon flow was reduced to 1 g/s. The power was maintained at 4 kW. The change in flow conditions had the immediate effect of reducing the heat transfer so that the temperatures began to rise again.

After some time measurements demonstrated gradually an increasing consumption of oxygen, accompanied by acceleration of the temperature increase at certain locations starting at about 10200 s. The faster increase was most marked at the mid elevations of the bundle. Oxygen was completely consumed at 10500 s. Shortly before that time, partial consumption of the nitrogen was first observed, indicating local oxygen starvation which promoted the onset of nitriding. Following this, the temperature continued to increase until water injection was initiated at 11335 s when the maximum observed temperature was ca. 1600 °C at the 650 mm elevation. Thus there was a period of 835 s complete oxygen consumption and hence starvation in at least part of the bundle (Figure 3). The total uptakes of oxygen and nitrogen were about 58 and 29 g, respectively. The generally limited rate of temperature increase was the result of a rather low air flow rate, probably not untypical of reactor or spent fuel pond conditions. Toward the end of the air ingress phase a second corner rod was removed. Some local spalling of the oxide scale was observed from preliminary examination at elevation 300-900 mm. The

oxidation and nitriding state has yet to be determined, from corner rod and bundle examinations.
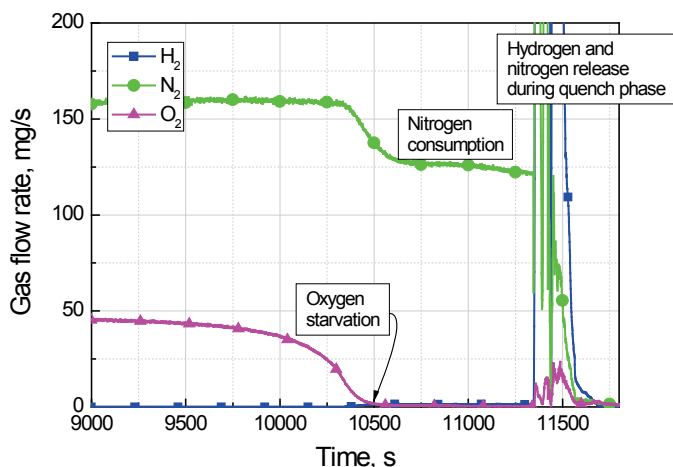
Figure 3 Off-gas analysis showing consumption of oxygen and nitrogen during air ingress phase and release of hydrogen and nitrogen during quench phase

Then reflood was initiated at 11335 s by simultaneously turning off the air flow, switching the argon injection to the top of the bundle, first rapidly filling the lower plenum of the test section with 4 kg of water, and continuing by injecting 53 g/s of water. The power remained at 4 kW during the reflood.

Almost immediately after the start of the reflood there was a temperature excursion in the mid to upper regions of the bundle (500 to 1400 mm), leading to maximum measured temperatures of about 2150 °C. Some bundle degradation is to be expected at these temperatures. Cooling was established at the hottest location ca. 70 s after the start of injection, but was delayed further at other locations. Reflood progressed rather slowly, perhaps due to the high temperatures and partial degradation, and final quench was achieved after about 500 s. In line with the temperature escalations, a significant quantity of hydrogen was generated during the reflood. There are also indications of nitrogen release during the quench phase.

The shroud experienced similar temperatures to the bundle. As would be expected at such temperatures, the shroud failed ca. 40 s after initiation of reflood. Detection of Kr by the mass spectrometer indicated a first small failure of a fuel rod simulator soon after the start of oxygen starvation during the air ingress phase, and quite possibly further failures also during this phase. The first videoscope inspection at the position of withdrawn corner rod B shows an intensive degradation of the oxide layer with partial spalling at bundle elevations between 450 and 750 mm. A preliminary inspection of the withdrawn corner rods indicated that pre-oxidation was as desired.

After the test the facility was dismantled for post-test examinations which include investigation by videoscope, embedding in epoxy resin, and metallographic examination with optical and, if necessary, scanning electron microscope. In parallel, the recorded data are being processed for further analyses by participants within the LACOMECO and SARNET

programmes. The test will be used for benchmark calculations in the WP5-COOL of SARNET2.

LIVE FACILITY

Cooling of core debris and behaviour of the stratified corium melt pool in the lower head are still critical issues in understanding of PWR core meltdown accidents [13], [14].

The main objective of the LIVE program at is to study the late in-vessel core melt behaviour and core debris coolability both experimentally in large scale 3D geometry and in supporting separate-effects tests [15], and analytically using CFD codes [16] in order to provide a reasonable estimate of the remaining uncertainty band under the aspect of safety assessment.

The main part of the LIVE test facility is a 1:5 scaled RPV of a typical pressurized water reactor (Figure 4). The inner diameter of the test vessel is 1 m and the wall thickness is 25 mm. The material of the test vessel is stainless steel. To simulate the decay heat, heaters are used, which provide in different layers a representative and homogeneous heating of the melt in the lower head. The core melt is simulated by different materials. These materials should, to the greatest extent possible, represent the real core materials in important physical properties and in thermo-dynamic and thermo-hydraulic behaviour. Important criteria are that the simulant melt should be a non-eutectic mixture of several components with a distinctive solidus-liquidus area of about 100 K, and that the simulant melts should have a similar solidification and crust formation behaviour as the oxidic corium. To investigate special problems a mixture of nitrates is used with a melting temperature of about 350 °C, and with a phase diagram similar to the expected core melt. To study the debris melting and coolability, the use of V_2O_5 oxide is planned with a melting temperature of approximately 1000 °C. These compositions provide a sufficiently high melting temperature and, due to their phase diagram, allow a comparison with the core melt in various scenarios of core meltdown.
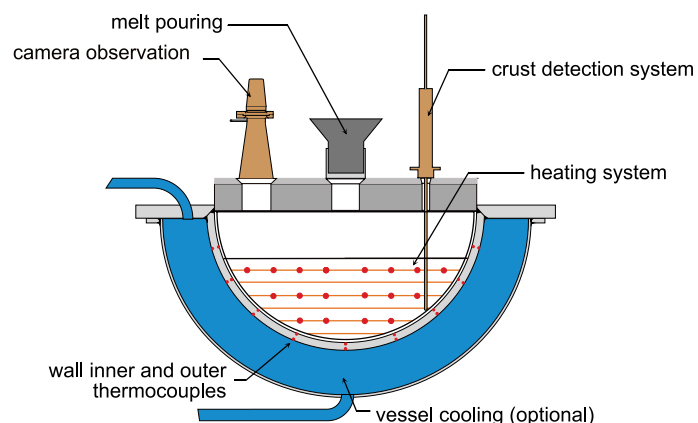
Figure 4 Scheme of the LIVE facility

Due to the ability to flood the melt in-vessel, the possible cooling the melt due to particle bed formation and/or gap

cooling with a resulting stop of the anticipated accident can be investigated at different stages of the accident scenario.

The information obtained from the LIVE experiments includes heat flux distribution along the reactor pressure vessel wall in transient and steady state conditions, crust growth velocity and influence of the crust formation on the heat flux distribution along the vessel wall. Supporting post-test analysis contributes to characterization of solidification processes of binary non-eutectic melts [17].

For the LACOMECO project the test aimed at investigation of dissolution kinetics of a pure KNO_3 ceramic crust by a $KNO_3/NaNO_3$ melt was selected (LIVE-CERAM). The test was proposed by CEA, Grenoble, France.

Preparation of the LIVE-CERAM test

The experiment aims at examination the dissolution kinetics of a pure KNO_3 ceramic crust by a $KNO_3/NaNO_3$. The test will simulate ablation of a ceramic refractory core-catcher by a lower temperature multi-component melt in a severe accident. There exist only scarce data on such corium/refractory material interaction. Former experiments addressed mainly the final steady state situation and used smaller scales. No detailed data are available for transient corium/refractory material interaction in 3D geometry. There is large interest of the international scientific community for core-catcher design methodologies considering not only steady state situations but also transient behaviour. However, only scarce data exist on corium-refractory material interaction for the design of refractory liners for core catchers and for protection of concrete walls, which should be applied in LWRs and LMFBRs. The experiments at CIT (Saint Petersburg) addressed mainly the final steady state situation. Simultaneous corium-concrete-zirconia interaction experiment has been performed by AREVA (Erlangen, Germany) in small scale [18]. No detailed transient data are available for corium-refractory material interaction for 2D geometry.
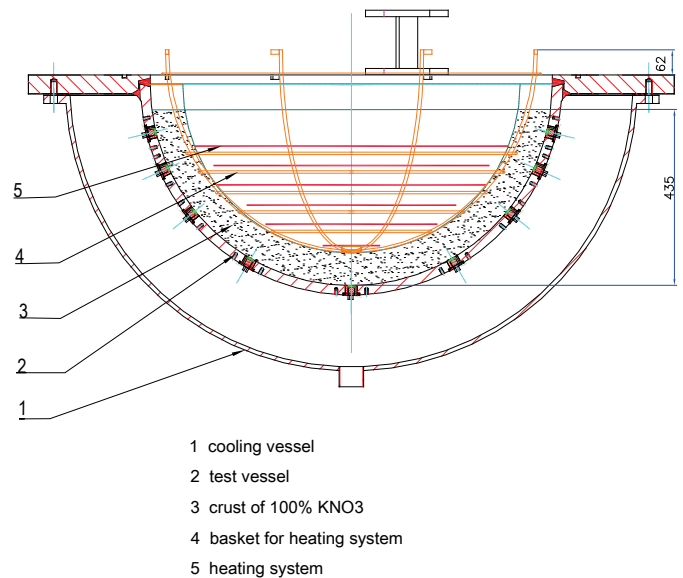
Based on this background LIVE-CERAM experiment will provide data of transient 2D corium-refractory material interaction. The experiment should simulate the ablation process of a high-melting temperature refractory material by low-melting temperature corium. Due to the dissolution of the refractory material into the boundary area and in the bulk corium, the boundary layer and the bulk melt are expected to be gradually enriched in the refractory material, which leads to an increase of bulk melt melting temperature and boundary temperature.

In the LIVE-CERAM experiment, the initial pure KNO_3 (melting temperature of ~340°C) simulates the refractory material, and the eutectic mixture of 50 mol% KNO_3 - 50 mol% $NaNO_3$ (melting temperature of ~222°C) simulates the corium. A ~8 cm crust of pure KNO_3 should be firstly generated along the semi-spherical vessel wall; afterwards the eutectic melt is poured in the vessel. During the ablation process, the liquid melt is homogenous heated and its temperature should not exceed the melting temperature of the pure KNO_3. The evolution of melt temperature and interface temperature are measured at several latitudes.

The test conditions have been defined as following:

Generation of KNO_3 crust:
- The heating basket and all the heating elements should be repositioned 63 mm higher, so that the gap between the heating elements and the vessel wall is 8 cm (Figure 5). Heating elements remain in the vessel during the creation of the crust.
- The KNO_3 melt will be poured into the vessel and heterogeneously heated. The power density in the lower part of the pool will be higher than the upper part. After the desired crust thickness is reached the melt will be extracted. Since a gap will be formed between the crust and the vessel wall after cooling down, the gap will be filled by pouring KNO_3 melt in the vessel again and overflowing the original crust. The vessel is externally cooled by water with flow rate of 1.3 kg/s during crust formation. No external water cooling will be performed during the gap filling.
- The height of KNO_3 crust is 435 mm and the height of the eutectic melt pool is 385 mm to avoid the overflow of the liquid melt into the gap between the vessel and the KNO_3 layer.
- Four thermocouple trees are mounted at polar angles 0°, 37°, 52° and 66°. The distance between neighbour thermocouples is 0.5 cm at polar angle 52° and 66°, and 1 cm at polar angle 0° and 37°. The length of the trees will be ~10 cm (2 cm longer than the layer thickness of the KNO_3 crust).
- The vessel is externally cooled by water with flow rate of 1.3 kg/s.

1 cooling vessel
2 test vessel
3 crust of 100% KNO3
4 basket for heating system
5 heating system

Figure 5 Position of the heating basket for the generation of 8 cm thick crust layer

Ablation test:
- The melt pouring temperature is about 260°C. The maximum melt pool temperature is 330°C, which is slightly lower than the melting temperature of KNO_3

(334°C). The maximum heating element surface temperature is allowed to be slightly higher than the maximum bulk melt temperature.

- The melt is heated with 7 kW homogenously at beginning. If the melt temperature reaches 330°C after some time, the heating power will be reduced. After the decrease of melt temperature the heating power will be increased to 7 kW again and will be kept at this level until the steady state will be reached.
- The criterion for the end of the test is the approach of steady melt temperature and the steady crust temperature at polar angles 52° and 66°.
- Melt samples are taken every 15 minutes at beginning and then every 30 minutes. Residue crust will be analysed after the test.
- Two measuring positions with the crust detection lance are foreseen.

Due to the complexity of the experiment such as substantial modifications of the test facility and the heating system, there is necessity to perform additional pre-tests to check the feasibility of crust generation method and pre-test calculations. Up to now, a number of pre-tests were performed [19]. The aim was to gain experience on building the KNO_3 crust including extraction procedure and facility performance.

DISCO FACILITY

The SARNET partners concluded that the uncertainty in the code calculations of Direct Containment Heating (DCH) is still too large to assess the risk of containment failure for certain reactor geometries due to the lack of validated models, especially for the extrapolation to reactor scale [20].

When the reactor cavity is flooded with water, the situation is even less clear. Most of the studies are related to the Fuel Coolant Interaction that can turn to a strong steam explosion. All experiments related to FCI are performed with conditions with low velocity jets (gravitational pour). However, in a real ex-vessel situation, it is possible that the vessel is still pressurized at its failure time, which induces, even for low pressure, a melt ejection with high velocity. Also, the water in the pit is relatively confined and cannot so easily escape from the pit. There is then a lack of data to validate the models in such situations.

The DISCO facility was initially designed to perform scaled experiments related to DCH that simulate melt ejection from the reactor pressure vessel to the reactor cavity after the RPV failure under low system pressure during severe accidents in LWRs [21]. These experiments are designed to 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 with an iron-alumina thermite melt (~2000 °C) and steam. The position, size and shape of the failure can be varied. The containment is modelled by a pressure vessel with a volume of 14 m³, rated at 1 MPa. The combined volumes of the reactor pressure vessel and reactor cooling system (RCV) are modelled by a vessel with a volume of 0.08 m³, rated at 2 MPa and 220 °C. The geometry of the reactor pit and reactor sub-compartments is adapted according to the investigated reactor type. The atmosphere in the containment is variable (inert, air, steam or a mixture, including hydrogen). For the LACOMECO project the test aimed at investigation of ex-vessel fuel coolant interaction experiment in the DISCO facility was selected (DISCO-FCI). The test was proposed by IRSN, Fontenay aux Roses, France, to bring additional data with a geometrical configuration more closely related to the reactor situation.

This experiment represented a FCI test as much as a DCH and is of great interest to reactor safety The main phenomena are the use of the $Fe-Al_2O_3$ thermite melt in a steam/air/hydrogen atmosphere and the injection of the melt under pressure into the flooded reactor pit. This pressured melt injection into the water is also an aspect that is relatively little researched. The main objectives of the test are:

- to confirm/infirm the behavior of the flow computed with MC3D code where relatively strong spontaneous interactions are reported during premixing (no triggering);
- to characterize the debris;
- to estimate the hydrogen production;
- to assess the possibility of combustion in such situation.

The test was not triggered (for the purpose of obtaining a steam explosion) and only the premixing was investigated. However, a spontaneous explosion could have happened. In order to facilitate the analysis, it was not requested, in contrast with the usual requirement in DISCO DCH tests, to have a precise fully representative reactor geometry. The purpose of the tests is clearly to highlight a physical behavior and to help for the code qualification. Therefore a simplified 2D geometry of a large pit with no access corridor was considered (Figure 6) and central break at the RPV bottom was investigated.
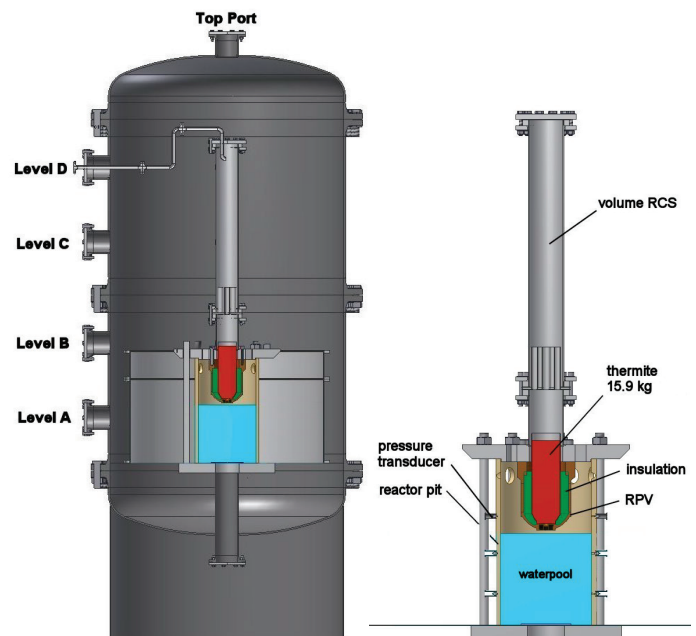
Figure 6 Containment pressure vessel and internal structures of RPV/RCS vessel and cavity in the DISCO-FCI experiment

Geometry and initial conditions of the test are given in Table 1.

Table 1 Geometry and initial conditions of the DISCO-FCI test.

Containment volume	m³	13.88
Containment height	m	4.5
Containment diameter	m	2.17
Cavity volume	m²	0.2034
Cavity height	m	0.984
Cavity diameter	m	0.540
Flow nozzles (8x cut out area)	m²	0.0603
Flow area into con. (8 holes)	m²	0.0688
Containment pressure	MPa	0.2
Containment temperature	°C	100
Containment atmosphere		air/steam
RPV: Breach diameter	mm	30
RPV: Driving pressure	MPa	0.6
RPV: Amount of thermite	kg	10.64
Water pool	l/°C	125 / 85

The test results include:
- conditions at the end of interaction: melt dispersal, water dispersal;
- characterization of melt debris (fragmented part, size spectrum);
- break opening characteristics;
- pressures in the RPV/RCS vessel, cavity, and containment vessel;
- temperatures in the RPV/RCS vessel, cavity, and containment vessel;
- gas composition to determine the amount of hydrogen produced by oxidation of the melt.
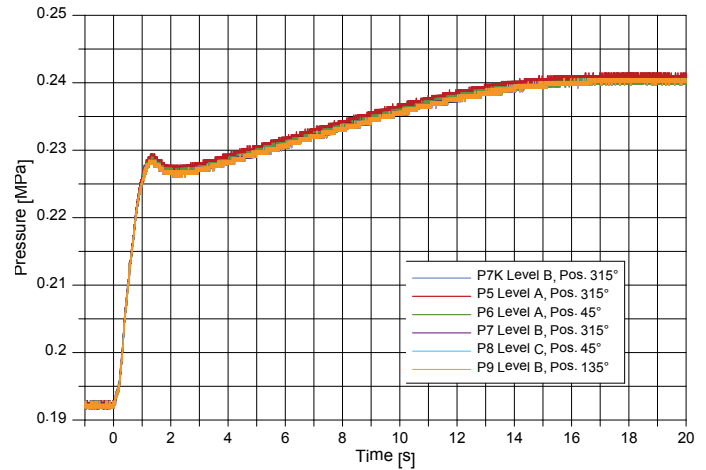
Pressures measured in the cavity and in the containment are given in Figure 7 and Figure 8.
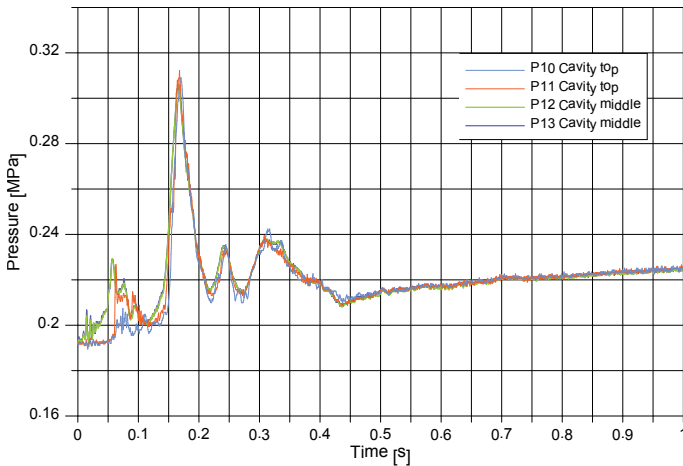
Figure 7 Pressures in the cavity

Shortly after the ignition, the temperature in the RPV rises very sharply and the pressure also increases but levels again before the valve connecting the accumulator opens. The pressure in the RCS/RPV and in the accumulator balances at about 0.8 MPa for a short period. This is 0.2 MPa more than the planned pressure at the time of blowdown. However, the pressure increases again up to 1.0 MPa then the brass melt plug

evaporated and the blowdown starts. Due to the melt-water reaction, the pressure in the cavity shows some peaks during the first 0.3 seconds. Only one peak reaches a maximum of 0.31 MPa. The water in the cavity completely swept out into the containment and the pressure in the vessel rises up to 0.24 MPa. The containment gas temperature increased from about 100 C to about 114°C during the first second. At late times (> 8 s) some thermocouples registered a local increase to 130 C, all positioned higher than 170 cm above floor.

Figure 8 Pressures in the containment

Size distribution of particles collected in the cavity, subcompartments and in the containment revealed that of the melt ejected out of the RPV, 70 % were found in the cavity, mainly as crusts, and approximately 27 % each in the subcompartment and containment vessel. Since the subcompartment was not covered, no clear separation between the two locations can be drawn.

HYKA FACILITY

HYKA offers experimental possibilities for containment safety research in Europe through a number of large test vessels named A1, A2 and A3 which are qualified and approved for operation with hydrogen combustion. The tests can be made under uniform stagnant or non-uniform dynamic conditions, as well as in horizontal or vertical orientation. In HYKA it is possible to investigate the whole spectrum of hydrogen phenomena. Research on different hydrogen sources and their distribution behaviour can be conducted, as well as experiments with different ignition sources in different geometries. One of the most attractive features of HYKA is the capability for well-controlled, medium to large scale combustion experiments, covering all three combustion regimes (subsonic and sonic deflagration and detonation).

An important outcome of the research activities in the DCH domain within SARNET was the understanding, that the combustion of hydrogen produced by oxidation during melt ejection from the RPV as well as of the hydrogen initially present in the containment can be the dominant phenomenon for containment pressurization. It is now clear that the uncertainty in the combustion rate under these conditions was too large for the assessment of containment integrity for certain

reactors. Dedicated combustion codes are presently not capable to reproduce the results obtained in a first series of experiments with hydrogen release conducted in the DISCO facility at KIT. Moreover, the need for hydrogen combustion tests at a scale larger than 1:18 was stressed by the SARNET partners. Without those, the uncertainty in the extrapolation of experiments to reactor scale would still remain too large to assess the containment integrity for certain reactor geometries.

For the LACOMECO project the following three test series were selected.

## Detonations in partially confined layers of hydrogen-air mixtures (DETHYD)

These experiments were proposed by Warsaw University of Technology, Warsaw, Poland and were successfully completed in 2011. This work complements a series of experiments on critical conditions of flame acceleration and detonation transitions in a semi-confined horizontal layer of hydrogen-air mixtures in presence of obstructions [22], [23] with a difference that proposed work will be done without obstructions. The objective of current tests was to investigate critical layer thickness for hydrogen-air detonation propagation in semi-confined geometry. Semi-confined combustion scenarios are very important from practical point of view because light, flammable gas released in confinement will accumulate at the top of the room. These phenomena may take place in containments of nuclear reactors or in tunnels. When detonation propagates in smooth tube, the critical tube diameter d* for steady-state detonation propagation is in a relation with detonation cell size λ: d*$\cong\lambda$. The detonation cell size is an integral characteristic of detonable mixture which takes into account gas dynamics and kinetics properties of the mixture. The smaller the detonation cell size is, the higher the detonability of the mixture. Critical layer thickness h^* where the detonation may propagate and its relationship with detonation cell size λ for semi-open geometry is unknown.

In the experiments a rectangular 3 x 9 m channel with various gas layer thicknesses of 8, 5, 3 and 2 cm was used. The hydrogen-air mixture layer thickness was controlled by thin (10 μm) plastic film. The channel was placed in cylindrical 100 m^3 safety vessel as shown in Figure 9 and Figure 10.
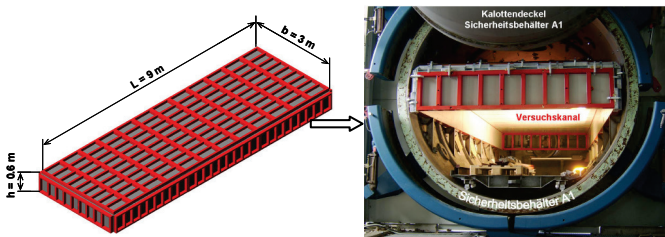
Figure 9 Main dimensions of thin layer box (left) and a photo of the thin layer box installed in the safety vessel (right)
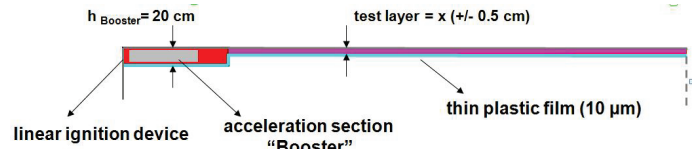
Figure 10 Cross-section of the investigated geometry

To assure uniform flame and detonation front special "linear ignition device" with exploding wire and 60 cm length acceleration section were developed. Due to the acceleration section run-up distance for detonation was lower than 1 m. Instrumentation was composed of 15 dynamic pressure transducers (13 at the top – along the ceiling symmetry line, 2 on the ground), 20 ionization sensors and 48 sooted plates (40 in test section, 8 in "booster"). The sooted plates were used to indicate detonation propagation range in the test layer.

The conducted experiments show that critical thickness h^* of flammable hydrogen-air mixture is equal to 3 cm (see Table 2), which corresponds to the relation with detonation cell size λ: h*$\approx3\lambda$. In one case with 3 cm layer thickness detonation attenuation was recorded at the distance lower than 2 m. At the second test for 3 cm layer thickness detonation propagates up to the end of the tested geometry. For 2 cm layer, detonation failed at the distance lower than 1 m.

Table 2 Main results of DETHYD experiments

Test #	% H$_2$	Layer thickness [cm]	Detonation propagation
1	30	8	Yes
2	30	5	Yes
3	30	3	No
4	30	3	Yes
5	30	2	No

Recorded pressures and velocities (Figure 11) confirm that for 2 cm and 3 cm layer thickness (tests 3 and 5) detonation attenuation occurs. For these cases detonation propagation ranges are in accordance with sooted plates indications. After detonation, attenuation velocities vary in the range of 150 - 600 m/s, overpressures are in the range of 0.1 – 0.25 MPa which corresponds to the fast deflagration regime. For the cases with detonation present up to the end of the geometry, overpressures are in range of 1.3 – 3.1 MPa and velocities are ~ 2000 m/s, which correspond to the stable C-J detonation regime.
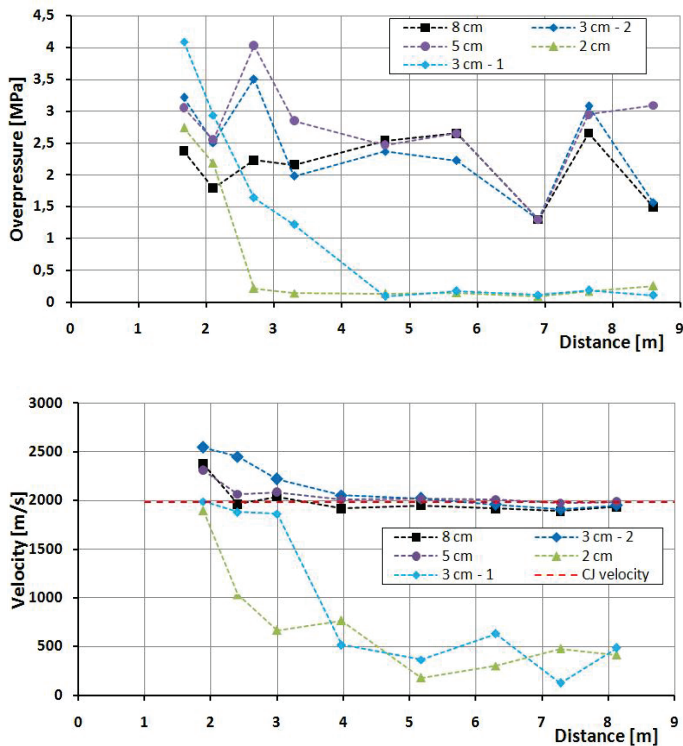
Figure 11 Overpressures and velocities for different layer thickness

Hydrogen concentration gradients effects understanding and modelling with data from experiments at HYKA (HYGRADE)

These experiments were proposed by CEA, Saclay, France. The main objective will be to investigate H_2 combustion in hydrogen concentration gradients and with obstructed geometries prototypical of conditions in PWR containments. These will be tests with ignition with a decreasing H_2 concentration gradient and ignition with an increasing H_2 concentration gradient. The forthcoming experiments will extend previous experimental data on the flame propagation in non-uniform hydrogen-air mixtures with decreasing or increasing hydrogen concentration gradient [24], [25]. The main objective is to obtain well-qualified data on flame propagation regimes in non-uniform hydrogen-air mixtures in large-scale for validation of CASTEM code developed at CEA.

The experiments on flame propagation regimes will be performed in an obstructed large scale facility A3 with vertical hydrogen concentration gradient. The processes of flame acceleration from quasi-laminar to sonic flames or even detonations will be investigated depending on hydrogen concentration gradient and ignition positions. Positive and negative concentration gradient in the range from 8% to 13% of hydrogen in air will be tested. Critical conditions for flame acceleration-deceleration and quenching of the flame due to hydrogen concentration gradient will be main scopes of the project.

A serious reconstruction of the A3 vessel is already started. This includes fabrication of two flanges (of 1 m outer diameter) at the top of the vessel and a system of obstacles with varied blockage ratio (BR = 0.3 and BR = 0.6). All previously made metal structures inside the vessel A3 like ramps with hand rails have been extracted from the vessel to provide regular geometry of obstructions. Two possibilities to fabricate the obstacles structure are considered: (1) removable wooden obstacles; (2) stable metal obstacles like metal grid or metal plates fixed on thick metal rods. First option means one time use of the obstacles per experiment but it is less expensive.

Preliminary "cold" experiments (without ignition) on helium (or hydrogen) distribution in presence of obstacles are planned. Gas filling system to create the linear helium/hydrogen distribution is designed. The problem is to provide a linear ascending/descending hydrogen concentration profile in vertical/axial direction the and quite uniform hydrogen concentration in horizontal level. The gas filling system will be tuned against experimental helium/hydrogen distribution to provide required concentration gradient. A sampling probes method will be used to control real distribution of light gas (helium/hydrogen). In order to visualize the light gas distribution in smaller scale (1:50) with the same aspect ratio (H/D) can be done with transparent cylinder model using high speed shadow photo Background Oriented Schlieren (BOS) method.

Pressure sensors (PCB type), silicon photodiodes and ion probes are planned to be used in forthcoming experiments with hydrogen combustion. Several sampling probes will control required hydrogen concentration gradient just before each experiment. Amount of sensors and their position will be specified by KIT and CEA. The data acquisition system with 1 MHz sampling rate will be used to record pressure, light and ion probe signals. The result will be a pressure- or light- or ion current signal-time history.

Upward flame propagation experiment in air-steam-hydrogen atmosphere (UFPE)

These experiments were proposed by JSI, Ljubljana, Slovenia. The main goal of these experiments is the scaling-down of hydrogen combustion phenomena in a containment of nuclear reactor for numerical code validations. THAI facility experiments [26] are going to be reproduced in about four times larger scale facility A2 in order to compare both data with the purpose to study scaling effect on integral combustion characteristics like maximum combustion pressure and temperature, time of combustion or hydrogen consumption rate. The problem to be solved is to answer can the phenomena observed in a scaled-down experimental facility be extrapolated to an actual containment, and, if yes, how should that extrapolation be performed.

The experiments will be performed in the HYKA A2 vessel (total volume V = 220 m^3, internal diameter D = 6 m, height L = 9.1 m) in order to study upward propagation. Initial experimental conditions of the reference THAI experiment have to be prepared inside the A2 vessel: pressure 1.5 bar; temperature 90 °C; 10% hydrogen/air mixture with 25% of steam; lower ignition position.

Several principal measures have to be done to provide the required experimental conditions. The vessel has to be equipped with gas filling system including steam-generator. The gas filling procedure can be the following: (1) preparing of dry hydrogen-air mixture; (2) heating up to the temperature 90 $^{\circ}$C; steam injection up to the pressure P=1.5 bar. Sampling probes method will be used to control uniformity of the mixture before experiments. 10 to 20 thermocouples will be installed inside the A2 vessel to record local temperature and to control thermal uniformity of the mixture.

High speed shadow photo (Background Oriented Schlieren technique) combined with pressure sensors (PCB type), silicon photodiodes and ion probes are planned to be used in forthcoming experiments. Acoustic sensors can be used to record acoustic effects under combustion process. High speed cameras will record top view and side view of flame development. Amount of sensors and their position will be specified by JSI and KIT. The data acquisition system with 1 MHz sampling rate will be used to record pressure, light and ion probe signals. The result will be a pressure- or light- or ion current signal-time history. Post processing of BOS images will be required to visualize flame shape and its position.

CONCLUSIONS

The LACOMECO project at KIT provides to European research institutions access to several experimental facilities which are designed to study the remaining severe accident safety issues, including the coolability of a degraded core, corium coolability in the RPV, possible melt dispersion to the reactor cavity, molten corium concrete interaction and hydrogen mixing and combustion in the containment. These facilities are unique in providing experimental programmes in specific fields of core damage initiation up to hydrogen behaviour and are designed to be complementary to other European facilities and experimental platforms to form a coherent European nuclear experimental network.

The LACOMECO experimental platform at KIT includes:
- QUENCH facility is the only operating experimental facility in EU for investigations of the early and late phases of core degradation in prototypic geometry for different reactor designs and different cladding alloys, incl. analysis of the relocation of cladding and fuel and the formation and cooling of in-core debris beds to gain information on the characteristics of the created particles.
- 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 behaviour after the debris re-melting in large scale 3D geometry with emphasis on the transient behaviour.
- HYKA experimental facilities are among the largest available in the world. In combination with the high static and dynamic pressures the experimental facilities are designed for, a unique experimental centre especially for combustion experiments in confined spaces is available with HYKA. Due to the different orientations and sizes the set of large and strong experimental vessels offers a flexible basis for scientific experimental work on reactive hydrogen mixtures.
- 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.

The activities within the LACOMECO project are strongly coupled with other European projects, such as SARNET2, as well as with third countries (Russian Federation, Ukraine, Kazakhstan) through the ISTC and the STCU. They could be extended to activities with other countries cooperating of the EURATOM research programme.

The experimental results are used for the development of models and their implementation in the severe accident codes such as ASTEC. This helps to capitalise the knowledge obtained in the field of severe accident research in the ASTEC code and the scientific databases, thus preserving and diffusing this knowledge to a large number of current and future end-users throughout Europe.

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