ABSTRACT

The platform LACOMEKO at Karlsruhe Institute of Technology (KIT) provides 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 RPV, possible melt dispersion to the reactor cavity, and hydrogen mixing and combustion in the containment. These facilities are unique in its own specified field and the experiments are designed to be complementary to other European facilities and experimental platforms to form a coherent European nuclear experimental network.

The LACOMECAL platform at KIT includes: a) QUENCH facility designed for the investigation of early and late phases core degradation in prototypical geometry for different reactor designs and cladding alloys; b) LIVE facility, a large scale 3D facility for the investigation of in-vessel late phase behaviour of in-core melt pool and melt pool in the lower head of RPV; c) DISCO facility, the only operating facility worldwide to investigate the melt dispersion to the reactor cavity and direct containment heating (DCH); d) HYKA including a series of large and medium scale experimental facilities which investigate the whole hydrogen behaviour in containment under well controlled conditions. The LACOMEKO program is founded by European Commission and KIT. It is free of all charge to the interested users and provided all the needed supports to perform the experiments.
- 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.

2. Four issues are re-assessed with medium priority (these items 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).

3. Five issues are assessed with low priority (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 behaviour impact on source term (in steam generator tubes (SGT) and containment cracks);
   - Core reflooding impact on source term.

4. Three issues could be closed because of low risk significance and sufficient current state of knowledge:
   - Integrity of reactor coolant system and heat distribution;
   - Ex-vessel core catcher and corium-ceramics interaction, cooling with water bottom injection;
   - FCI including steam explosion in weakened vessel.

The phenomena described above are extremely complex and 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 LACOMECO project, which aims to provide these resources and to facilitate this collaboration by offering large scale experimental facilities at KIT for transnational access. These facilities in LACOMECO platform include QUENCH, LIVE, DISCO and HYKA. They main purpose of these facilities 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 experiments are designed to be complementary to other European facilities and experimental platforms such as CODEX, 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 main thrust of the projects is towards large scale tests under prototypical conditions addressing high and medium priority issues identified by the SARP group. These will help to understand the core degradation and coolability, in-vessel and ex-vessel core melt behaviour and hydrogen-related phenomena 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 [3].

The four large scale experimental facilities are offered to external partners from EU Member Countries and Associated States within the Transnational Access to Large Research Infrastructures (TALI) Project of the 7th EU FWP. Activities within the LACOMECO project
should be strongly coupled with SARNET2 and if possible with third countries (RF, Ukraine, Kazakhstan) through the ISTC/STCU.

The LACOMECO project has duration of 36 month and it starts from February 2010. Seven proposals have been received from the potential users. After the evaluation by the selection Panel which includes experts of SARNET2 one test in each of QUENCH, LIVE and DISCO and three tests in HYKA were recommended.

2 LACOMECO EXPERIMENTAL FACILITIES

2.1 QUENCH

The QUENCH program was launched in 1996 as a successor of CORA with special emphasis on the quantitative determination of the hydrogen source term. The main component of the out-of-pile QUENCH test facility is the test section with the test bundle. The standard test bundle is made up of 21 fuel rod simulators approximately 2.5 m long, of which 20 fuel rod simulators are heated over a length of 1024 mm. Electric tungsten heater in 6 mm diameter are installed in the rod center and surrounded by annular ZrO2 pellets to simulate fuel pellets. The bundle geometry and most other bundle components (Zr-alloy cladding, grid spacers) are prototypical for Western-type PWRs and very similar to the in-pile PHEBUS bundle.

The central rod is unheated and used for instrumentation or as absorber rod. The heated rods are filled with argon-krypton or helium at a pressure of approx. 0.22 MPa to allow for test rod failure detection by the mass spectrometer. The system pressure in the test section is around 0.2 MPa. Zircaloy corner rods are installed to improve the thermal hydraulic conditions. They are also used for additional thermocouple instrumentation and can be withdrawn from the bundle during the test to check the amount of oxidation and hydrogen uptake during test. The test bundle is surrounded by a shroud of zircaloy, a 37 mm thick ZrO2 fiber insulation, and a double-walled cooling jacket of stainless steel. The shroud provides encasement of the bundle and simulates surrounding fuel rods in a real fuel element (Fig. 1). The whole set-up is enclosed in a steel containment.

Fig. 1: Schematic view of the test section during reflood and cross section of the QUENCH bundle.

The test bundle, shroud, and cooling jacket are extensively equipped with thermocouples at different elevations and orientations. Additionally, the test section is provided with various pressure gauges, flow meters and level detectors. Hydrogen and other gases are analyzed by spectrometer Balzers GAM300 at the off-gas pipe about 2.7 m behind the test section and by a redundant hydrogen detection system behind the steam condenser.
In general, a QUENCH experiment consists of the following test phases: Heatup, pre-oxidation/pre-conditioning (optional), transient, and quenching/cooldown. The last phase is accomplished by injecting water or saturated steam at the bottom of the test section. Due to the exothermal zirconium-steam reaction the test bundle may experience a temperature excursion up from level 850-900 mm. This temperature excursion leads to the maximum bundle temperature of well above 2000 K and an increased hydrogen generation. The flooding phase is initiated by turning off the flow of 3 g/s superheated steam and injecting water or saturated (cold) steam at flow rates of 15-50 g/s. Cool-down in steam was applied in some tests because of the well defined boundary conditions for code validation.

The QUENCH experiments provide information on main factors governing the quantity of hydrogen production and melt formation during quenching of an overheated rod bundle, physico-chemical behaviour of overheated fuel elements under different reflood conditions, and material interactions of core components at high temperatures, e.g. absorber rods and advanced cladding material behaviour.

2.2 LIVE – Large-scale tests on behaviour of the corium melt pool

The main objective of the LIVE program [6] 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, and analytically using CFD codes in order to provide a reasonable estimate of the remaining uncertainty band under the aspect of safety assessment [7].

The main part of the LIVE test facility is a 1:5 scaled semi-spherical lower head of the typical pressurized water reactor, as shown in Fig. 2 and Fig. 3. 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 from the bottom to the top of the cooling vessel.

The melt is prepared in an external heating furnace designed to generate 220 l of the simulant melt of maximum temperature 1100 °C. Residue melt can be extracted out of the test vessel back into the heating furnace via a vacuum pump equipped on the heating furnace. The volumetric decay heat is simulated by means of 6 heating planes in the test vessel. Each plane can be controlled separately to realize homogenous heating of the melt. The maximum total power of the heating system is 28 kW. The maximum homogenous heating power is about 18 kW. The temperature of the heating system is limited to 1100 °C.

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. The detailed information about the crust formation can be obtained from the three thermocouple trees at different heights. A precise crust detection lance can detect the crust front and measure the crust/melt boundary temperature as well as the melt pool vertical temperature profile. Two video cameras and one infrared camera are used to visualize the convection of the melt pool.

Simulant materials used in the LIVE program should, to the greatest extent possible, represent the real core materials in important physical properties and in thermodynamic and thermo-hydraulic behaviour. Important criteria for the selection are a non-eutectic mixture with a distinctive solidus-liquidus area of about 100 K, and similar solidification and crust formation behaviour as the oxidic corium. For the first test series a binary mixture of NaNO₃ and KNO₃ was chosen. The eutectic composition of this melt is 50-50 mole% [8]. The maximum temperature range between solidus and liquidus is ~60 K and corresponds to a 20-
80 mole% NaNO₃-KNO₃ mixture. This melt can be used in a temperature range from 220°C (solidification) to 380 °C (chemical decomposition). Due to its solubility in water the melt is restricted to dry conditions inside the test vessel.

![Fig. 2: View of the LIVE test section, pouring spouts and heating furnace.](image1)

![Fig. 3: Scheme of the LIVE test vessel.](image2)

The information obtained from the LIVE experiments includes heat flux distribution along the vessel wall in transient and steady state conditions, melt temperature distribution, crust growth velocity and influence of the crust formation on the heat flux distribution along the vessel wall. Complementary to other international programs with real corium melts (like METCOR-P, PRECOS, and INVECOR projects of ISTC), the results of the LIVE experiments provide data for a better understanding of in-core corium pool behaviour. They also allow a direct comparison with findings obtained earlier in other experimental programs (SIMECO, ACPO, BALI, etc.) and are being used for the development and assessment of mechanistic models for description of in-core molten pool behaviour and their implementation in the severe accident codes such as ASTEC [8], [10]. Moreover, the obtaining of 3D data has become more important, as it is now clear that the direct extrapolation of the results of 2D experiments may be inappropriate.

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

The DISCO experimental facility is the only one operating worldwide that can address the critical issues of DCH concerned by the SARP group of the SARNET. These issues include the uncertainty in the code calculations due to the lack of modelling the extrapolation of reactor scale as well as DCH in BWR and the influence of water in the reactor cavity and fission products release during DCH.

The DISCO experiments are designed to investigate the fluid-dynamic, thermal and chemical processes during melt ejection out of a breach in the lower head of a PWR pressure vessel at pressures below 2 MPa with an iron-alumina melt and steam [11]. The main components of the facility (Fig. 5) are scaled about 1:18 linearly to a large PWR: the containment pressure vessel (14 m³), the RPV and reactor cooling system (RCS) (0.08 m³), the cavity and the equipment rooms, which are modelled according to the reactor design being investigated (Fig. 4 and Fig. 6).

The model of the RPV contains the aluminium-iron oxide thermite. The experiment is started by igniting the thermite electro-chemically at the upper surface of the compacted thermite powder. The valve connecting the RPV-RCS vessel and the accumulator is opened.
when the thermite reaction has started, and steam enters the pressure vessel. The pressure balance in both vessels is reached quickly and the valve is automatically closed again. About 3 to 6 seconds after ignition the brass plug at the bottom of the RPV vessel is melted by the 2400 K hot iron-alumina melt. That initiates the melt ejection. The melt is driven out of the breach by the steam and is dispersed into the cavity and beyond. 10 s after blow-down the fans in the containment are started again and 5 min thereafter post-test gas samples are taken.

Standard DISCO test results include: pressure and temperature history in the RPV, the cavity, the reactor compartment and the containment, post test melt fractions in all locations with size distribution of the debris, video film in reactor compartment and containment (timing of melt flow and hydrogen burning), and pre- and post-test gas analysis in the cavity and in the containment. The gas analysis allows determining the amount of produced, burned and remaining hydrogen.

2.4 HYKA

The HYKA facility provides unique research capabilities for investigation of hydrogen related phenomena in containment during severe accidents: hydrogen distribution, hydrogen
combustion and hydrogen mitigation measures [12]. These phenomena are ranked as high priority issues by the SARP group of the SARNET NoE [12][14].

HYKA offers a number of large test vessels which are qualified and approved for operation with hydrogen combustion. The tests can be performed under stagnant or under controlled air flow conditions, as well as in horizontal or vertical orientation. Due to the high vessel design pressures test parameters are not restricted by safety considerations. Highly energetic experiments can be performed on the KIT premises with all necessary infrastructure.

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. 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 (slow and fast deflagration and detonation). The main technical details of the different HYKA facilities are summarised in the Table 1.

### Table 1: Main parameters of the test vessels of the HYKA facility.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Dimensions (m)</th>
<th>Volume (m³)</th>
<th>Design pressure (bar)</th>
<th>Phenomena</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>cylindrical vessel</td>
<td>Φ=3.4 L= 12.0 (horizontal)</td>
<td>98</td>
<td>100</td>
<td>turbulent combustion, flame acceleration, detonation, vented explosions</td>
</tr>
<tr>
<td>A2</td>
<td>cylindrical vessel</td>
<td>Φ= 6.0 L=10.5 (vertical)</td>
<td>220</td>
<td>10</td>
<td>turbulent combustion with mixture gradients, standing diffusion flames, vented explosions, interaction of recombiners with containment flows, test of deliberate ignition mitigation schemes</td>
</tr>
<tr>
<td>A3</td>
<td>cylindrical vessel</td>
<td>Φ= 2.5 L=8.0 (vertical)</td>
<td>33</td>
<td>60</td>
<td>hydrogen distribution, stratification, recombiner and igniter tests, uniform and non-uniform mixtures</td>
</tr>
<tr>
<td>A6</td>
<td>cylindrical vessel</td>
<td>Φ=3.3 L=3.1 (vertical)</td>
<td>22</td>
<td>40</td>
<td>as A1, two large vents (0.8 m) (H_2) distribution in closed rooms, integrity of mechanical structures</td>
</tr>
<tr>
<td>A8</td>
<td>cylindrical vessel</td>
<td>Φ=1.8 L=3.0 (horizontal)</td>
<td>9</td>
<td>100</td>
<td>fast deflagrations and detonations at high initial pressures</td>
</tr>
<tr>
<td>FTC</td>
<td>rectangular flow test chamber</td>
<td>8.5x5.5x3.3 airflow (\leq 24,000) m³/h</td>
<td>160</td>
<td>1.07 static 1.7 dynamic</td>
<td>studies on vented combustions (up to 16 g (H_2)), testing of (H_2) local detonations in closed spaces</td>
</tr>
</tbody>
</table>

### 3 PROPOSALS FOR LACOMECO EXPERIEMENTS

Seven proposals had been received, of which two are for QUENCH, one for LIVE, one for DISCO and three for HYKA. As a result of the evaluation the following recommendations were made:

- **WP1 QUENCH**
  Two proposals were received:
  “Investigation of air oxidation on VVER bundle type” from INRNE, Sofia, Bulgaria.
  “QUENCH test with slow oxidation in air” from KFKI/AEKI, Budapest, Hungary.

Group opinion was that the proposal of the KFKI/AEKI is the more interesting one as it addresses the work currently underway at KIT concerning role of nitriding in the Zircaloy
oxidation in air/steam mixtures. The other proposal from INRNE was more general and will be a partner of the KFKI/AEKI proposal with pre-test modelling using ASTEC to assess and refine test parameters as well as participating in post-test analysis. PSI would also support the work with model analysis using MELCOR and SCDAP/RELAP. The test addresses the SARP high priority issue of oxidising impact on source term. Moreover, by using the PWR bundle geometry, prototypical Zr-alloy cladding combined with bottom flooding, the test will extend the database on the air ingress issues available from the QUENCH-10 and PARAMETER SF4 experiments. This experiment links with WP7.3 and WP8.1 of SARNET2. WP5 should also be informed and they should be able to provide some support with other codes (MELCOR, ATHLET-CD). Timing of the test will be during the JPA3 of SARNET2. However, pre-test analysis could be done in JPA2.

- WP2 LIVE

A single proposal was received from CEA, Grenoble, France (LIVECERAM). However it was of great interest as it proposed to examine in 2D and 3D tests the dissolution kinetics of a pure KNO₃ crust by a KNO₃/NaNO₃ melt. This would be, in the opinion of KIT, an excellent simulation of the refractory core-catcher ablation by a lower temperature multi-component melt in a severe accident. It would address two SARP high priority issues: core coolability during reflood, and ex-vessel melt pool configuration during MCCI. Pre-test and post-test analysis could be done by KIT (CONV) and CEA (various models). Additional support could come from KTH (effective convectivity model). Further support could be expected from IBRAE (ISTIC Project THOMAS). This is a good example using in-vessel facility for an ex-vessel research and so increasing the value and applicability of the facility. The project will require two tests in which the first experiment aims to produce the refractory layer. This will give additional data on single component melt behaviour in comparison with multi-component melts.

- WP3 DISCO

This had a single proposal “Ex-vessel fuel coolant interaction experiment in the DISCO facility” from IRSN, Fontenay aux Roses, France and related to a DCH test using a pit full of water and so represented a FCI test as much as a DCH. This aspect was of great interest to User Selection Panel. The main phenomena are the use of the Fe-Al₂O₃ thermite melt in a steam/air/H₂ atmosphere and the injection of the melt under pressure into the flooded pit. This pressured melt injection into the water is also an aspect that is relatively little researched. This is linked to fuel coolant interaction (WP7.1) and to debris formation (WP5.3) as well as MCCI (WP6.3) and H₂ behaviour in containment (WP7.2) of SARNET2. This will also be linked to the ongoing OECD SERENA-II project. Topics addressed in this test were ranked as high (FCI) and medium (DCH) priority issues by the SARP group of SARNET.

4. WP4 HYKA

Three proposals had been received for use of three different vessels of the HYKA facilities.

The first proposal “Upward flame propagation experiment in air-steam-hydrogen atmosphere” from JSI, Ljubljana, Slovenia was to make a comparison with smaller-scale test in the THAI facility with HYKA test to see if the scales of experimental facility could be quantitatively or qualitatively extrapolated. The experiment should be performed in the 220 m³ HYKA-A2 vessel having the same aspect ratio as power plant containment.

The 2nd proposal “Detonations in partially confined layers of hydrogen-air mixtures (DE-THYD)” from WUT, Warsaw, Poland was to find experimentally the critical conditions for the deflagration-to-detonation transition and detonation propagation in partially confined layers of hydrogen-air mixtures and to provide high quality experimental data on overpressures and flame propagation velocities required for numerical code validations. For
this experiment HYKA-A1 vessel (100 m$^3$ volume and 100 bar maximum pressure) should be used as a safety vessel.

The 3rd proposal “Hydrogen concentration gradients effects understanding and modelling with data from experiments at HYKA (HYGRADE)” from CEA, Saclay, France was H$_2$ combustion in increasing and decreasing hydrogen concentration gradient and with obstructed geometries prototypical of conditions in PWR containments. The main objective of the proposal is to obtain well qualified data on flame propagation/detonation conditions for model validation (TONUS and CASTEM codes developed at CEA). The experiment should be performed in the HYKA-A3 vessel (33 m$^3$ volume and 8 m height).

Though only two experiments were planned in HYKA, there was a great interest in all three of proposals. It was proposed to the User Selection Panel that with some adaptation of the HYKA-A3 vessel all experiments could be accommodated. The panel strongly supports the KIT proposal to perform all three tests since they all address the high priority SARP issues and therefore will contribute to the reduction of uncertainties in the hydrogen risk domain, and especially addressing scaling aspects will improve the accuracy of modelling.

The selected proposals were recommended to be circulated to the relevant SARNET2 Work Packages for their information and potentially receive further comments for improvement, or offers of support with analysis and interpretation, of the tests.

4 CONCLUSION

The LACOMECO experimental platform at KIT provides four large scale facilities to external partners from EU Member countries and associated states to study premium issues in the area of severe accident safety. These facilities are unique to investigate core melt scenarios from core degradation to melt formation and relocation in the vessel to possible melt dispersion to the reactor cavity and hydrogen related phenomena. The research issues are ranked as high and medium priorities by SARNET and the program is complementary to other European platform to form a coherent European nuclear network.

ACKNOWLEDGMENTS

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