Final Report Summary - LACOMECO (Large Scale Experiments on Core Degradation, Melt Retention and Containment Behaviour)

The objective of the LACOMECO project is to offer European Union (EU) research institutions access to four experimental facilities Quench, LIVE, DISCO and HYKA at Karlsruhe Institute of Technology (KIT) which are designed to study the remaining severe accident safety issues, ranked with high or medium priority by the Severe Accident Research Network of Excellence (SARNET) Severe Accident Research Priorities (SARP) group for SARNET. These issues are coolability of a degraded core, corium coolability in the RPV, possible melt dispersion to the reactor cavity, and hydrogen mixing and combustion in the containment. These facilities are unique, without rival in other Member States and therefore could be used for experimental programmes in specific fields of core damage initiation up to hydrogen behaviour.

The access to LACOMECO was widely published, so that the researchers throughout the Member States of the Community and the Seventh Framework Programme (FP7) associated states were made aware of the possibilities open to them. As a result of the call for proposals seven proposals had been received, of which two were for Quench, one for LIVE, one for DISCO and three for HYKA. As a result of the evaluation one experiment was selected for Quench, one for LIVE, one for DISCO and two for HYKA. Due to the great interest of the user selection panel for all three proposals for HYKA, it was proposed by KIT to perform all three tests. Following tests have been performed within the LACOMERA project in cooperation with partners from different countries like Hungary, France, Poland and Slovenia:

- Quench test with slow oxidation in air (Quench-16);
- LIVE test to examine the dissolution kinetics of a pure KNO3 crust by a KNO3 / NaNO3 melt (LIVE-CERAM);
- DISCO test related to ex-vessel fuel coolant interaction (FCI) (DISCO FCI-LAC);
- HYKA tests to investigate detonations in partially confined layers of hydrogen-air mixtures (Dethyd);
- HYKA tests related to hydrogen concentration gradients effects understanding and modelling (Hygrade);
- HYKA test to investigate upward flame propagation in air-steam-hydrogen atmosphere (UFPA).

For the preparation of the tests and for the definition of the experimental conditions, intensive discussions between the partners took place via email exchange and during separate partner meetings or meetings of other European projects, like SARNET review meetings and Quench workshop.

The results of the experiments performed under the LACOMECO project are distributed to the SARNET2 community and are used for the development of models and their implementation in the severe accident codes such as ASTEC. This will help to capitalise the knowledge obtained in the field of severe accident research in the ASTEC code and the scientific databases, thus preserving and disseminating this knowledge to a large number of current and future end-users throughout Europe. Moreover, the knowledge obtained in the project shall lead to improved severe accident management measures, which are essential for reactor safety and in addition offer competitive advantages for the European industry.

The project brought together competent teams from different countries with complementary knowledge. Moreover, the links
with the East European research organisations and utilities was established and maintained. Therefore, the project offered a unique opportunity to join networks and activities supporting VVER safety, and for Eastern experts to get access to large scale experimental facilities in a Western research organisation, thereby improving the understanding of material properties, core behaviour, and containment safety under severe accident conditions.

Project context and objectives:

The objective of the LACOMECO project is to offer EU research institutions access to four experimental facilities Quench, LIVE, DISCO and HYKA at KIT which are designed to study the remaining severe accident safety issues, ranked with high or medium priority by the SARNET SARP group for SARNET. These issues are coolability of a degraded core, corium coolability in the RPV, possible melt dispersion to the reactor cavity, and hydrogen mixing and combustion in the containment. These facilities are unique, without rival in other Member States and therefore could be used for experimental programmes in specific fields of core damage initiation up to hydrogen behaviour. In addition, the experiments performed in the project are designed to be complementary to other European facilities and experimental platforms to form a coherent European nuclear experimental network.

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) 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 light water reactors (LWRs) in Europe. Though the SRA cannot integrate all national programmes on safety research carried out in Europe, the platform members agree on the issues that are of highest priority. Regarding the issues in severe accidents, the SRA refers to the work carried out in the framework of the SARNET to conclude to a common view on the ranking of the research priorities in the field. The research priorities on severe accident management were prepared and are being continuously reviewed and updated by the SARNET SARP group. The objective of the group is to review and reassess the priorities of research issues and to propose the results as basis to harmonise and to re-orient research programmes, to define new ones, and to close - if possible - resolved issues on a common basis.

After two years of intense discussions and three meetings of the SARP group, the research and development (R&D) priorities on severe accident management are ranked in four groups:

(1) Six issues are regarded to be investigated further with high priority (further research is considered as necessary):
   (a) core coolability during reflood and debris cooling;
   (b) ex-vessel melt pool configuration during molten corium concrete interaction (MCCI), ex-vessel corium coolability by top flooding;
   (c) melt relocation into water, ex-vessel FCI;
   (d) hydrogen mixing and combustion in containment;
   (e) oxidising impact (ruthenium oxidising conditions / air ingress for high burn-up and mixed oxide fuel elements) on source term;
   (f) 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 programmes):
   (a) hydrogen generation during reflood and melt relocation in vessel;
(b) vorium coolability in lower head;
(c) integrity of reactor pressure vessel (RPV) due to external vessel cooling;
(d) direct containment heating (DCH).

(3) Five issues are assessed with low priority (could be closed after the related activities are finished):
(a) corium coolability in core catcher with external cooling;
(b) corium release following vessel rupture;
(c) crack formation and leakages in concrete containment;
(d) aerosol behaviour impact on source term (in steam generator tubes (SGT) and containment cracks);
(e) core reflooding impact on source term.

(4) Three issues could be closed because of low risk significance and sufficient current state of knowledge:
(a) integrity of RCS and heat distribution;
(b) ex-vessel core catcher and corium-ceramics interaction, cooling with water bottom injection;
(c) FCI including steam explosion in weakened vessel.

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 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 the KIT for transnational access. The LACOMECO experimental platform at KIT includes:

- Quench facility is the only operating experimental facility within the EU for investigations of the early and late phases of core degradation in prototypic geometry for different reactor designs and different cladding alloys, including 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 three-dimensional (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 overall purpose of these test 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, and finally hydrogen-related phenomena in severe accidents. The use of these facilities will provide the interested partners of the European Member States and FP7 associated states a focus on core Quenching, on possible core melt sequences in the 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 this 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 core coolability 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 importance of the LACOMECO project for the European research is reflected in three aspects:

(1) The access to large scale experimental facilities is proposed to investigate all important processes from the early core degradation to late in-vessel phase pool formation in the lower head, continuation to ex-vessel melt situations and to the hydrogen behaviour in the containment. Therefore two high priority and three medium priority issues identified by the SARP group will be addressed in the project, namely:
(a) core coolability during reflood and debris cooling (high);
(b) hydrogen mixing and combustion in containment (high);
(c) hydrogen generation during reflood and melt relocation in vessel (medium);
(d) corium coolability in lower head (medium);
(e) DCH (medium).

(2) The results of the project will be applicable to the European reactor fleet taking into account the main LWRs including Eastern ones (VVER design). A European vision is used to decide priorities in the experimental programme.

(3) The project offers a unique opportunity for Eastern experts to get an access to large scale facilities in Western research organisation to improve understanding of material properties and core behaviour under severe accident conditions, and to become familiar with the high level safety concepts in nuclear power plants.

Specifically, the access to LACOMECO platform shall provide answers to the following questions:

(1) Quench: What are the main factors governing the hydrogen source term, formation and coolability of corium debris and melt behaviour during core Quenching?
(2) LIVE: What will be the time span of melt relocation to the lower plenum, what are the main phenomena governing the corium debris bed formation and what measures are needed to regain the in-vessel debris and core melt coolability?
(3) DISCO: Where will the melt be located after failure of the RPV under moderate pressure, with different RPV failure modes? What is the pressure increase in the reactor pit, the sub-compartments and the containment due to thermal and chemical reactions (hydrogen production and burning)?
(4) HYKA: Is the experimental and theoretical basis of predicting the turbulent combustion, flame acceleration and detonation onset in hydrogen / air mixtures sound enough and how can the hydrogen mitigation measures be improved?

To answer these questions the LACOMECO project has:

(1) planned and carried out one experiment in the QUENCH facility that simulates as closely as possible key scenarios of a reactor core degradation for main classes of European light water reactors;
(2) conducted one experiment in 1:5 scaled RPV geometry in the LIVE facility with different melt masses and relocation modes to study debris remelting and cooling mechanisms, to quantify heat flux distribution, crust formation and stability, and possible cooling modes;
(3) performed one experiment in a scaled reactor geometry in the DISCO facility at prototypical pressures and temperatures to simulate melt dispersion in the containment after the RPV failure;
(4) performed three experiments in the HYKA facility to investigate the hydrogen-related phenomena in severe accidents, including hydrogen distribution, hydrogen combustion and hydrogen mitigation measures.
SARP issues, which are addressed in the LACOMECO project, are:

(a) core coolability during reflood and debris cooling;
(b) melt relocation into water, ex-vessel FCI;
(c) hydrogen mixing and combustion in containment;
(d) hydrogen generation during reflood and melt relocation in vessel;
(e) corium coolability in lower head.

At present, knowledge of various core melt sequences and the consequences of possible operator actions are not yet sufficient as they are too dependent on specific characteristics of the power plant under consideration. LACOMECO aims to provide the resources for a better understanding of possible scenarios of core Quenching, different core melt sequences and hydrogen behaviour for different reactor designs. This knowledge shall lead to improved severe accident management measures, which are essential for reactor safety and in addition offer competitive advantages for the European industry.

The results of the experiments performed under the LACOMECO project will be distributed to the SARNET2 community and will be used for the development of models and their implementation in the severe accident codes such as ASTEC. This will help 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.

One of the main achievements of the SARNET Network of Excellence (NoE) was the review and reassessment of the priorities on severe accident research issues on which research was still considered as necessary. The activities within the LACOMECO project will allow advancing considerably towards understanding and perhaps evening closure of these issues. It will thereby optimise the resources (both available expertise and experimental facilities) to focus on these issues given the reduction of national budgets.

The project brought together competent teams from different countries with complementary knowledge. Moreover, the links with the East European research organisations and utilities was established and maintained. Therefore, the project offered a unique opportunity to join networks and activities supporting VVER safety, and for Eastern experts to get access to large scale experimental facilities in a Western research organisation. They thereby improved their understanding of material properties, core behaviour, and containment safety under severe accident conditions.

Project results:

The LACOMECO project was structured in five work packages (WPs). The main science and technology (S&T) results for each work package are summarised in the following sections.

WP0: Management

This WP covers all administrative, legal and financial issues.

At the beginning of the project, the project executive group widely published the access to LACOMECO, so that the researchers throughout the Member States of the Community and the FP7 associated states were made aware of the possibilities open to them. Call for proposals with deadline of 30 April 2010 was advertised on a dedicated website on the internet and information about the call for proposals was distributed at international conferences and through emails. New Member States were particularly encouraged to participate. As a result of the call for proposals seven proposals had been received. The proposals were distributed in the relevant SARNET2 work packages for comments, improvements and recommendations on experiment performance. Following the SARNET review, LACOMECO user selection panel meeting was
held on 8 July 2010 in Bratislava. The objective was to prepare recommendations to the European Commission (EC) regarding selection of experiments to be performed in the Quench, LIVE, DISCO, and HYKA facilities, arising from the first call of proposals. From the seven proposals, two were for Quench, one for LIVE, one for DISCO and three for HYKA. One test was to be selected for Quench, LIVE, and DISCO and up to two for HYKA. The decision process involved presentation of the proposals by the responsible person at KIT, indicating for example the complexity, benefit and risk of each, followed by a group discussion. As a result of the evaluation one experiment was selected for Quench, one for LIVE, one for DISCO and two for HYKA. Due to the great interest of the user selection panel for all three proposals for HYKA, it was proposed by KIT to perform all three proposed tests.

During the LACOMECO project, several project meetings were organised. Furthermore, intensive discussions of the test preparation and experimental conditions between the partners involved in different experiments continuously took place via email exchange and during meetings of other European projects, like SARNET review meetings, Quench workshop, etc.

For the planning and conduction of the experiments, in total 11 accesses to the test facilities at KIT-G were provided for the different user groups.

Cooperation with other projects has been established, e.g. between LACOMECO and SARNET2 projects. Links between the LACOMECO project and PLINIUS severe accident platform of CEA Cadarache were also established. A first joint workshop was held in October 2010 in Aix-en-Provence (FR).

WP1: Quench

Core coolability during reflood and corium debris cooling as well as in-vessel hydrogen generation during reflood and core melt relocation are ranked as high and medium priority issues by the SARP group of the SARNET NoE. Bundle experiments in the Quench facility 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 programme 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. The Quench bundle experiments are supported by an extensive separate-effects test programme which is performed to generate comprehensive data for model development and subsequent implementation into SFD computer codes.

The Quench test facility can be operated in two modes:

(a) a forced-convection mode with a flow of approximately 3 g/s of superheated steam of approximately 600 degrees of Celsius 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. Top Quenching is prepared in the design of the facility but has not yet been realised.

The main component is the test bundle that can be a standard pressurised water reactor (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 ZrO2 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. B4C 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 ZrO2 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 approximately 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.

As a result of the evaluation of the user selection panel, the following experiment to be performed in the Quench facility was selected:

Title: Quench test with slow oxidation in air
Organisation: KFKI/AEKI, Budapest, Hungary

Air ingress experiment Quench-16 was designed to extend the currently existing database on the transient behaviour during air ingress on a dried out and partially oxidised bundle. A primary test objective was to investigate nitride formation during prolonged oxygen starvation to provide conditions for studying the reaction between partially oxidised cladding and nitrogen. Extensive pre-test analytical support was provided by GRS (ATHLET-CD), EDF (MAAP4) and PSI (SCDAPSim and MELCOR-186) to determine test conditions to meet the objectives, taking into account the uncertainties concerning air oxidation behaviour. The different treatments of air oxidation modelling provided mutual confirmation of the predicted behaviour. The experiment was successfully conducted at KIT on 27 July 2011 i.e. in month 18 of the project with a minor delay of 2 months as compared to the original planning. Mild preoxidation was followed by a planned cool-down before the switch to air flow initiated a gradual temperature rise which accelerated as more and more of the oxygen was consumed. During the period of complete consumption, some of the nitrogen was consumed and zirconium nitride was formed. A strong oxidation excursion took place during the reflood, possible triggered by the degraded state of the oxide layer due to the oxygen starvation and the reaction with nitrogen.

The results of the experiment were presented at the 17th and 18th International Quench Workshops in November 2011 and 2012, correspondingly, as well as at the International Conference ICAPP’12 in June 2012, International Conference on Safety in Reactor Operations TopSafe 2012 and published as Scientific Report KIT-SR 7634 (Karlsruhe, 2013). Joint paper on the results of the pre-test calculations was presented at the ERMSAR-2012 Conference in March 2012. The test will be used for benchmark calculations in the WP5-COOL of SARNET2.

WP2 LIVE

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. They were ranked as high and medium priority issues by the SARP group of the SARNET NoE.

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. Uncertainties in modelling these phenomena and in the application to reactor scale will undoubtedly persist. 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. These phenomena have a strong impact on a potential termination of a severe accident.

The main objective of the LIVE program at KIT-G 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 computational fluid dynamics (CFD) codes in order to provide a reasonable estimate of the remaining uncertainty band under the aspect of
The main part of the LIVE test facility is a 1:5 scaled RPV of a typical NoE PWR. 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 degrees Celsius, and with a phase diagram similar to the expected core melt. For different melt masses in the lower head the heat flux through the vessel wall can be determined by thermocouples at the inner (IT) and outer (OT) vessel wall, which provide a 3D picture of hot zones in the wall and possible failure modes of the lower head. Due to the ability to flood the melt in-vessel, 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 RPV 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 characterisation of solidification processes of binary non-eutectic melts. Complementary to other international programmes with real corium melts (like METCOR-P, Precos, and Invecor projects of the International Science and Technology Centre (ISTC)), the results of the LIVE experiments provide data for a better understanding of in-core corium pool behaviour. The results of the LIVE experiments allow a direct comparison with findings obtained earlier in other experimental programmes (Simeco, ACOPO, 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. Moreover, the obtaining of 3D data has become more important, as it is now clear that the direct extrapolation of the results of two-dimensional (2D) experiments may be inappropriate.

As a result of the evaluation of the user selection panel the following experiment to be performed in the LIVE facility was selected:

Title: Dissolution kinetics of a pure KNO₃ crust by a KNO₃/NaNO₃ melt (LIVE-CERAM)
Organisation: CEA, Grenoble, France

The experiment aimed at examination the dissolution kinetics of a pure KNO₃ crust by a KNO₃/NaNO₃ mixture. There exist only scarce data on corium / refractory material interaction. Former experiments addressed mainly the final steady state situation or used smaller scales. No detailed data are available for transient corium/refractory material interaction in 3D geometry. The test was performed using simulant materials (KNO₃ as refractory material (melting temperature of about 340 degrees Celsius) and a KNO₃-NaNO₃ melt at the azeotropic composition (melting temperature of about 222 degrees Celsius). This is an excellent simulation of the refractory core-catcher ablation by a lower temperature multi-component melt in a severe accident. It addressed two SARP issues: Corium coolability in lower head and ex-vessel melt pool configuration during MCCI. Pre-test and post-test analysis was done by KIT (CONV) and CEA (various models). This is a good example of a use of in-vessel facility for an ex-vessel research and so increasing the value and application of the facility.

The LIVE-CERAM test programme included several trials for the formation of the KNO₃ liner and two ablation tests. Due to the complexity of the experiment, substantial modifications of the test facility and the heating system were necessary. The LIVE-CERAM test programme started then with several pre-tests to check the feasibility of crust generation method and with pre-test calculations. These pre-tests have been performed in October 2011, i.e. in month 21 of the project with 9 months delay as compared to the original planning. The final test for the formation of the KNO₃ liner was performed in December 2011. The ablation test I was successfully conducted on the 24 - 25 January 2012 and the ablation test II on the 1 March 2012.
The LIVE-CERAM test provided an original insight into dissolution of refractory material by a volumetrically heated pool. The test results clearly show that dissolution of solid refractory material can occur in a non-eutectic melt. Dissolution stops when the liquid is saturated in refractory species for the actual interface temperature. Ablation of the refractory layer ultimately stops when the heat flux (delivered by the melt to the refractory) can be evacuated by conduction through the residual thickness of the ceramic, with T_{interface} = T_{liquidus} (actual liquid composition). The final steady state corresponds to a uniform interface temperature distribution. As the pool composition is also uniform in the final steady state (due to convective mixing), the convection in the pool is governed by thermal natural convection and the heat flux distribution is similar to the heat flux distribution that would be obtained for a single component pool.

The LIVE-CERAM results were distributed to SARNET2 WP5-COOL and WP6-MCCI partners for analysis and interpretation.

WP3: DISCO

The DCH issue was assessed as medium priority by the SARP group of the SARNET NoE meaning that the programmes are to be continued as planned or at reduced effort. The involved SARNET partners (KIT-G, IRSN, GRS, EDF and TUS) concluded that the uncertainty in the code calculations 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.

Moreover, the available experimental data from DCH tests in the DISCO facility clearly demonstrated that the scaling of combustion of hydrogen jets in air-steam-hydrogen atmospheres must be established by applying combustion codes (e.g. COM3D, REACFLOW), and the resulting H2 combustion data (enthalpy, etc.) must be transferred to the codes modelling DCH. Combustion and heat loss models still need further improvements. However, experiments at a single scale are not sufficient to achieve this. Therefore additional tests addressing the combustion of hydrogen jets in air-steam-hydrogen atmospheres at different scales are necessary. This issue is ranked as high priority by the SARP group of the SARNET NoE and is clearly linked to the WP4 HYKA, where these topics will be addressed.

The consequences of DCH are essentially related to the reactor cavity geometry. Therefore an experimental database has been established for the plant types EPR, French PWRs and some of VVERs. For other plant specific geometries, the experiments must still be conducted. The recent studies indicated that the need to investigate DCH in boiling water reactors (BWR) may arise. Moreover, other still unresolved issues are the influence of water in the reactor cavity and fission products release during DCH and its impact on the overall source term, which has not sufficiently been investigated before. The DISCO experimental facility is the only one available worldwide, that can address these critical issues.

The DISCO facility 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 are devised 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 (approximately 2000 degrees Celsius) 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 RPV and reactor cooling system are modelled by a vessel with a volume of 0.08 m³, rated at 2 MPa and 220 degrees Celsius. 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).

As a result of the evaluation of the User Selection Panel the following experiment to be performed in the DISCO facility was selected:

Title: Ex-vessel FCI experiment in the DISCO facility
Organisation: IRSN, Fontenay aux Roses, France

This experiment is related to a DCH test using a pit full of water and so 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-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 FCI (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 Organisation for Economic Cooperation and Development (OECD) SERENA-II project. Although there is a certain risk of steam explosion, the risk is considered as low because of the strength of the facility construction as well as the probability of its occurrence (no external triggering and limited mass of melt). Topics addressed in this test were ranked as high (FCI) and medium (DCH) priority issues by the SARP group of SARNET.

Due to the complexity of the experiment like substantial re-design and modifications of the cavity and RPV and necessity to perform additional pre-test analysis, the test was successfully performed on 14 September 2011, i.e. in month 20 of the project with 8 months delay as compared to the original planning.

The pit geometry was close to a French 900 MWe reactor configuration at a scale of 1:10. The fuel was a melt of iron-alumina with a temperature of 2 400 K. The nozzle diameter was set to 0.03 m which corresponds to 0.30 m diameter break in reactor scale. There was no hydrogen initially present in the test and the pressure in containment was set to 1 bar of air and 1 bar of vapour. The water level in the pit was about 0.54 m, just below the nozzle, at a temperature of 85 degrees Celsius. The containment pressure increased by 0.04 MPa and reached about 0.24 MPa. The pressure in the cavity was characterised by several peaks. The highest peak cannot be assimilated to a steam explosion. The water inside the cavity (initial 125 kg) has been totally ejected. Concerning the debris, 66 % of the initial fuel mass (10.62 kg) remained in the cavity mainly as compact crusts. The fraction of fuel transported respectively to subcompartment and containment were about 10 and 17 %. The amount of hydrogen produced by oxidation is about 3% of total moles of gas. The results of the test were distributed to SARNET2 WP7-CONT partners for analysis and interpretation.

WP4: HYKA

In the case of a severe accident with and without failure of the RPV, the containment is the ultimate barrier to the environment. 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. In this work package phenomena are addressed that are ranked as high priority issue by the SARP group of the SARNET NoE.

HYKA offers new experimental possibilities for containment safety research in Europe through a number of large test vessels which are qualified and approved for operation with hydrogen combustion. The tests can be made 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-G premises with all necessary infrastructure nearby (control rooms, data acquisition, gas preparation and filling systems, workshops).

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).

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 the hydrogen initially present in the containment can be the dominant phenomenon for containment pressurisation. 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 (e. g. COM3D) 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. This issue can be addressed in the experiments performed in the e.g. A2 vessel of the HYKA facility.

Three proposals had been received for use of three different vessels of the HYKA facility. Though only two experiments were originally planned in HYKA, the user selection panel expressed a great interest in all three of them. The panel strongly supported the KIT proposal to perform all three tests (with some adaptation of the HYKA-A3 vessel) 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 following experiments have been selected to be performed in the HYKA test facility:

**Title: Detonations in partially confined layers of hydrogen-air mixtures (DETHYD)**
**Organisation: WUT, Warsaw, Poland**
The experimental series DETHYD was successfully completed in March 2011 i.e. in month 13 of the project with a minor delay of 2 months as compared to the original planning. The objective 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. 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. The experimental series were performed using a rectangular 3 x 9 m channel with various gas layer thicknesses: 8, 5, 3 and 2 cm. The hydrogen-air mixture layer thickness was controlled by thick (10 µm) plastic film. The geometry was placed in cylindrical 100 m³ safety vessel. The experiments show that critical thickness of flammable hydrogen-air mixture is equal to 3 cm. 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 was suppressed at the distance lower than 1 m. Joint paper on the results of the experiments was presented at the ERMSAR-2012 Conference in March 2012.

**Title: Hydrogen concentration gradients effects understanding and modelling with data from experiments at HYKA (Hygrade).**
**Organisation: CEA, Saclay, France**
The objective of the experiments performed in the framework of HYGRADE project was to investigate the flame propagation in an obstructed large scale facility A3 with initially vertical hydrogen concentration gradients. The experimental campaign, including facility reconstruction, preliminary ‘cold’ experiments to create proper hydrogen concentration gradient and main part with combustion experiments, took time from 28 August 2011 to 13 March 2012. Therefore the experimental campaign started in month 19 of the project with 2 months delay as compared to the original planning caused by a serious reconstruction of the A3 vessel.

Tests have been performed with ignition with a decreasing H2 concentration gradient and ignition with an increasing H2 concentration gradient with the main objective of obtaining well qualified data on flame propagation / detonation conditions for model validation (TONUS and Castem codes developed at CEA). The positive and negative concentration gradients were in the range from 8 to 13 % of hydrogen in air. The processes of flame acceleration from quasi-laminar to sonic flames or even detonations were also investigated depending on hydrogen concentration gradient and ignition positions.

**Title: Upward flame propagation experiment (UFPE) in air-steam-hydrogen atmosphere**
**Organisation: JSI, Ljubljana, Slovenia (Ivo Klenjak, Marko Matkovic, Borut Mavko)**
The Reactor Engineering Division of the Jozef Stefan Institute (JSI) from Slovenia submitted a proposal for an experiment on
hydrogen combustion in the HYKA A2 experimental facility in April 2010. The title of the proposed experiment was UFPE. The proposal was subsequently reviewed by independent experts and accepted by KIT in the fall of 2010. The UFPE experiment was not foreseen in the original LACOMECO planning and was executed additionally according to the proposed specification on 12 March 2012.

The main goal of the experiment was the scaling-down of hydrogen combustion phenomena in a containment of nuclear reactor for numerical code validations. THAI facility experiments were going to be reproduced in 2 - 4 times larger scale facility A2 in order to compare both data with respect to study scaling effect on integral combustion characteristics like maximum combustion pressure and temperature, time of combustion or hydrogen consumption rate.

The results of the experiments were compared to the results obtained in the THAI facility. The maximum observed pressure 5.04 bar was similar to the pressure, measured in the THAI HD-22 experiment. This suggests that the wider HYKA A2 facility did not affect the completeness of combustion. The maximum measured temperature 1 018 degrees of Celsius was about 120 degrees Celsius higher than the maximum measured in the THAI HD-22 experiment. This suggests that the wider vessel caused an even more intense combustion. However, as the temperature increase is necessarily limited by the heat of combustion and thus by the available hydrogen, no significant further temperature increase is expected in an actual containment. The upward flame propagation velocity (about 3.1 m / s) was similar to the one observed in the THAI HD-22 experiment. In addition, the radial flame propagation velocity (about 0.8 m / s) was estimated to be more than 3 times lower than the upward flame propagation velocity. The results of the UFPE experiment will be useful for validation of computer codes used in safety analyses, both at the local instantaneous scale (CFD codes) and integral scale (lumped-parameter codes).

Potential impact:

The activities within the LACOMECO project will allow advancing considerably towards understanding and perhaps even closure of the most important remaining severe accident safety issues, ranked with high or medium priority by the SARP group for SARNET NoE. The aim is not only to understand the physical background of severe accidents but to provide the underpinning knowledge that can help to reduce the severity of the consequences. It is crucially important to understand the whole core melt sequences and identify opportunities to lower the risk. This can be done by:

(a) altering the timing or magnitude of reflooding the degraded core;
(b) in-vessel melt retention in the lower plenum of the RPV;
(c) ensuring the upper bound of system pressure at vessel failure by dedicated depressurisation valves;
(d) installation of devices or implementing accident management procedures to mitigate melt dispersion into the containment;
(e) implementation of hydrogen mitigation measures in the containment (ignitors, recombiners etc.).

The results of the experiments performed under the LACOMECO project are used for the development of models and their implementation in the severe accident codes such as ASTEC. This will help to capitalise the knowledge obtained in the field of severe accident research in the ASTEC code and the scientific databases, thus preserving and disseminating this knowledge to a large number of current and future end users throughout Europe. Moreover, the knowledge obtained in the project shall lead to improved severe accident management measures, which are essential for reactor safety and in addition offer competitive advantages for the European industry.

The project brought together competent teams from different countries with complementary knowledge. Moreover, the links with the East European research organisations and utilities was established and maintained. Therefore, the project offered a unique opportunity to join networks and activities supporting VVER safety, and for Eastern experts to get access to large scale experimental facilities in a Western research organisation, thereby improving the understanding of material properties, core behaviour, and containment safety under severe accident conditions.
Strong links were established between the LACOMECO and SARNET2 projects, thus improving coordination, pool expertise, and avoiding unnecessary duplication of work:

The results of the LACOMECO experiments are open to SARNET2 partners for joint analysis and interpretation of the experimental results and for code improvements and benchmarking, e.g. the ASTEC code. For example, Quench-16 and HYKA UFPE experiments are being used for blind benchmarking of severe accident codes.

Links between the LACOMECO project and PLINIUS severe accident platform of CEA Cadarache were also established. A first joint workshop was held in October 2010 in Aix en Provence (FR). This successful cooperation resulted in a new European - Chinese project 'Access to Large Infrastructures for Severe Accidents' (ALISA). In this project, severe accident research facilities of LACOMECO and PLINIUS platforms will be opened for transnational access for Chinese researchers.

Furthermore, the results of the LACOMECO experiments were presented and published at different meetings, conferences and in several publications, like:

- LACOMECO session at the annual international Quench workshop;
- annual ERMSAR conferences;
- 'Nuclear Energy for New Europe' (NENE) Conference 2010 in Portoro, Slovenia;
- NENE (Nuclear Energy for New Europe) Conference 2012 in Ljubljana, Slovenia;
- TopSafe 2012 conference in Helsinki;
- International Symposium of Hazards, Prevention and Mitigation of Industrial Explosions (ISHPMIE-9) conference 2012, Cracow, Poland;
- International Congress on Advances in National Power Plants (ICAPP 2012) conference in Chicago, United States (US);
- International Conference on Nuclear Engineering (ICONE-20) conference 2012 in Anaheim, US;
- ANS Winter Meeting and Nuclear Technology conference 2012 in San Diego, US;
- HEFAT2012 (Heat transfer, fluid mechanics and thermodynamics) conference, Malta.

Project website: http://www.kit.edu/lacomeco

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