Recent Progress in the LACOMERA Project (Large-Scale Experiments on Core Degradation, Melt Retention and Coolability) at the Forschungszentrum Karlsruhe

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ABSTRACT

The LACOMERA Project at the Forschungszentrum Karlsruhe (FZK) is a 3 year action within the 5th Framework Programme of the EU. The overall objective of the project is to offer research institutions from the EU member countries and associated states access to four large-scale experimental facilities QUENCH, LIVE, DISCO-H, and COMET which can be used 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 finally corium concrete interaction and corium coolability in the reactor cavity.

As a result of two calls for proposals, seven organisations from four countries are expected to profit from the LACOMERA Project participating in preparation, conduct and analysis of the following experiments:

QUENCH-L1: Air ingress impact on core degradation. The test has provided unique data for the investigation of air ingress phenomenology in conditions as representative as possible of the reactor case regarding the source term.

QUENCH-L2: Boil-off of a flooded bundle. The test will be of a generic interest for all reactor types, providing a link between the severe accident and design basis areas, and would deliver oxidation and thermal hydraulic data at high temperatures.

LIVE-L1: Simulation of melt relocation into the Reactor Pressure Vessel (RPV) lower head for VVER conditions. The experiment will provide important information on the melt pool behaviour during the stages of air circulation at the outer RPV surface with a subsequent flooding of the lower head.

LIVE-L2: Transient corium spreading and its impact on the heat fluxes to the RPV wall and on the final shape of the melt in the RPV lower head. The test will address the questions of melt stabilisation and the effects of crust formation near the RPV wall for a non-symmetrical melt pool shape.

COMET-L1: Long-term 2D concrete ablation in siliceous concrete cavity at intermediate decay heat power level with a top flooding phase after a phase of dry concrete erosion.

COMET-L2: Generic study of a long-term metal/concrete interaction in cylindrical cavity for intermediate and low decay heat levels through metal phase only.

DISCO-L1: Thermal hydraulic behaviour of the corium melt dispersion neglecting the chemical effects such as hydrogen generation and combustion.
1 INTRODUCTION

The principal objective of the LACOMERA project [1] is to provide the interested partners of the European member countries and associated states a focus on core quenching and on possible core melt sequences in the RPV and in the reactor cavity, to enhance the understanding of severe accident sequences and their control in order to increase the public confidence in the use of nuclear energy. Moreover, it is important to include, as far as possible, partners from the newly associated states. The needs of Eastern, as well as Western, reactors will be considered in LACOMERA project.

Specifically, the experiments in the large-scale facilities concentrate on the following phenomena:
1) Main factors governing the quantity of hydrogen production and melt generation during quenching.
2) Time span of melt relocation to the lower plenum and measures needed to regain coolability.
3) Location of the melt after failure of the RPV under moderate pressure, with different failure positions. Pressure increase in the reactor pit, the sub-compartments and the containment due to thermal and chemical reactions (hydrogen production and burning).
4) Long-term erosion rates during MCCI and ex-vessel melt coolability.

Those issues were highlighted in series of experiments, both in-pile and out-of-pile (CORA, LOFT, BETA, MASCA, DISCO, MACE, COMET). Generally computer models have difficulties in modelling the quenching behaviour and molten pool formation and cooling in the lower head even though the modelling has recently advanced considerably. Some models for the molten pool behaviour in the lower head have been developed, but, until there is enough data to check the models with, they cannot be considered as reliable. The aim of the project 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.

LACOMERA project aims to provide the resources for a better understanding of possible scenarios of quenching and of different core melt sequences. This knowledge shall lead to improved severe accident measures, which are essential for reactor safety and offers competitive advantage for the European industry. As a result of two calls for proposals, seven experiments have been specified to be performed within the LACOMERA project. Seven organisations from four countries are expected to profit from this project.

The paper gives an overview of the experimental facilities and describes results of the experiments performed so far.

2 EXPERIMENTAL FACILITIES

The overall purpose of the four large-scale facilities QUENCH, LIVE, DISCO-H, and COMET at the Forschungszentrum Karlsruhe 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 finally corium concrete interaction and corium coolability in the reactor cavity.

In all experiments, simulant material is used to investigate the behaviour of the core material. These simulant materials were especially chosen to be as close to the real core material for the important properties as possible. On the other hand, the use of the simulant material allows covering a wide and broad range of scenarios with the experiments in a relatively small time schedule and for relatively low budget/funding. The experiments, post test investigations and special effect tests can be performed under well defined conditions and can be completely controlled.
2.1 Experiments QUENCH-L1 and QUENCH-L2 in the QUENCH Facility

QUENCH is a series of experiments to investigate quenching with water and cooling with steam of oxidized and partially degraded fuel rod bundle. The main component of the QUENCH test facility [2, 3] is the test section with the test bundle. The test bundle is made up of 21 fuel rod simulators, each with a length of approximately 2.5 m. Twenty fuel rod simulators are heated electrically over a length of 1024 mm, the one unheated fuel rod simulator is located in the centre of the test bundle. Superheated steam from the steam generator and superheater together with argon as a carrier gas enter the test bundle at the bottom. The argon, the steam not consumed, and the hydrogen produced in the zirconium-steam reaction, flow from the bundle outlet at the top through a water-cooled off-gas pipe to the condenser where the steam is separated from the non-condensable gases argon and hydrogen. Hydrogen is analyzed by two different measurement systems: (1) a state-of-the-art mass spectrometer GAM300 located at the off-gas pipe about 2.7 m behind the test section, and (2) a commercial-type hydrogen detection system "Caldos 7G" located behind the off-gas pipe and condenser.

Experiment QUENCH-L1 on air ingress during a spent fuel pool accident was successfully conducted at FZK on 21 July 2004. The main objective of this test was to examine the oxidation of Zircaloy and nitride formation in air. For the first time, an aerosol collection system was deployed, comprising two independent devices: a nickel plate on which a pocket is mounted to collect the larger aerosols, and a ten-stage impactor assembly which was actuated at various times during each of the main phases, concentrating on aerosol release during air ingress and quench. These systems were designed and build by AEKI Hungary and had previously been used in the CODEX tests.

In common with the previous QUENCH experiments, the bundle was heated by a series of stepwise increases of electrical power from room temperature to ~873 K in an atmosphere of flowing argon (3 g/s) and preheated steam (3 g/s). The bundle was stabilized 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 1620 K. This marked the start of the pre-oxidation phase (Fig. 1) to achieve a cladding oxidation of up to 600 µm. The power was controlled to maintain a more or less constant hydrogen production rate of about 5 mg/s after the peak value of 16 mg/s, caused by the previous heat-up. This procedure led to a slow increase in temperature to 1690 K. This phase lasted ~6600 s. Since the oxide thickness could not be measured online, it was estimated on the basis of pre-test calculations done at Paul Sherrer Institute and FZK and online monitoring of hydrogen release. The total hydrogen release from the beginning of the test to this point was 48 g.

To achieve an adequate duration of the subsequent air ingress phase, the bundle was then cooled to a temperature of about 1190 K (axial maximum). This was done by decreasing the electrical power abruptly from 13.2 to 6.9 kW. The temperature was reached after 2400 s. Hydrogen generation dropped rather quickly to about 0.4 mg/s due to this cooling so that nearly no further oxidation occurred. Towards the end of this phase, corner rod B was extracted from the test bundle for later determination of the oxide thickness axial distribution.

In the subsequent air ingress phase, the steam flow of 3 g/s was replaced by 1 g/s of air, but with unchanged argon flow and electric power. This change in flow conditions had the immediate effect of reducing the heat transfer so that the temperatures began to rise again. The temperature increase and oxidation were somewhat slower than expected, and therefore the electrical power was increased to 8 kW. Due to this procedure, oxidation increased such that the heat release eventually drove the temperatures beyond the final target value of 2073 K. The duration of this phase was ~900 s. Complete consumption of oxygen and partial
consumption of nitrogen (about 0.1 g/s) were observed toward the end of this phase. The total uptakes of oxygen and nitrogen were about 84 and 8 g, respectively. At the end of the air ingress phase a second corner rod was removed. An inspection of the two withdrawn corner rods indicated that pre-oxidation was as desired, i.e. the maximum oxide layer thickness prior to quenching amounted to ~600 µm.

The reflood was initiated by turning off the air flow, switching the argon injection to the top of the bundle, rapidly filling the lower plenum of the test section and injecting 50 g/s of water. The power was reduced to 4 kW after a further 10 s to simulate decay heat. Right at the beginning of reflood, there was indication of a short and mild temperature excursion in the upper part of the bundle, leading to maximum measured temperatures of about 2200 K at 950 mm elevation and to ~1400 K at the levels above the heated zone. However, cooling was established almost immediately, and complete quenching of the bundle was achieved after about 100-150 s. A modest release of hydrogen, i.e. ~5 g was observed during the early part of the reflood. About 60 % or 5 g of the nitrogen previously taken up was released.

The evaluation of the hydrogen release rates with help of the mass spectrometer data gives 47.3 g of total hydrogen generation up to the end of the pre-oxidation phase, 0.3 g shortly before the quench phase, and 5.2 g of hydrogen release during the quench phase, hence about 53 g of H₂ in total.

![Figure 1: Test QUENCH-10 overview. Temperatures at elevations 850 and 950 mm, electrical power input and quench water injection. Main test phases: pre-oxidation, intermediate cool-down, air ingress, quench](image)

The main objective of the QUENCH-L2 experiment will be the study of the boil-off behaviour of a flooded bundle. The test will be of a generic interest for all reactor types, providing a link between the severe accident and design basis areas, and would deliver oxidation and thermal hydraulic data at high temperatures. The test is planned for May 2005.

### 2.2 Experiments COMET-L1 and COMET-L2 in the COMET Facility

The test facility is able to investigate different scenarios of molten core concrete interaction and the possibility of cooling the ex-vessel melt. It is presently used to investigate a core catcher concept, which is based on water injection into the core melt from below. Due
to the resulting strong evaporation process, the melt is fragmented and forms a porous bed which is coolable and can be stabilized [4].

In these tests, the corium melt is simulated by Fe and Al₂O₃ melt with an initial temperature of more than 2000 °C, which is produced by a thermite reaction in a special crucible. By using different oxide additives, the solidification temperature of the melt is lowered and the solidus-liquidus temperature range is increased. The melt is poured into the test device. Decay heat simulation throughout the test is achieved by an induction heating coil under the device, which is able to induce about 500 kW/m² into the melt. For cooling investigations, the experimental device may be fabricated of different layers. A first sacrificial concrete layer serves to lower the initially high temperature of the molten core. After erosion of this layer, the melt comes into contact with a specially designed porous water layer, which injects water into the melt from the bottom. As required, the cooling insert can be modified to allow, for example a longer phase of concrete erosion.

The test crucible itself is designed to withstand a pressure build-up of 20 bar, which might occur due to melt/water interactions at the initial phase of cooling. In the off-gas pipe, a complete system of aerosol and gas measurement is installed. Additionally, the water supply rate and the steam release rate are measured. In the specially-designed cooling device, thermocouples are installed to detect the erosion front progression in the upper concrete layer and to give temperature information at the lower, water-filled levels of the device.

Experiments in the COMET facility generally consist of the following phases:

- Up to 1000 kg of melt is generated in an external crucible by thermite reaction, resulting in steel melt (Fe + Cr, Ni, Zr, ...) and oxide melt (Al₂O₃ + CaO + SiO₂ + FeO ...).
- Melt is then poured into test crucible at an initial temperature of 2000 – 2300 K, depending on type of generated melt. Steel melt is at the bottom, oxide on top (corresponding to reactor situation after admixture of eroded concrete).
- The steel fraction is continuously heated by electrical induction heating with total power from 100 – 500 kW (simulation of decay heat). Internal heating of the oxide phase is however not possible, so that the oxide is heated by convection and conduction from the steel layer. Therefore, erosion in the actual experiments is mostly dominated by the metal phase.
- End of experiment defined by maximal concrete erosion.

Following types of concrete can be used in the COMET facility: siliceous, siliceous/limestone, limestone, serpentine (Mg₃Si₂O₇·2H₂O in Eastern plants), etc., possibly in combination with refractory ceramic liner.

The main objective of the COMET-L1 experiment was to study (1) the long-term erosion of the concrete by a two component metal plus oxide melt during the absence of water, and (2) the consequence of top flooding when water is added to the surface of the hot melt during concrete erosion. This experiment is complementary to the present OECD-CCI tests that are carried out at Argonne National Laboratory (ANL) with pure oxidic corium.

The special objective of the first phase of this test is the 2-d concrete erosion in a cylindrical concrete cavity, evaluating the lateral vs. axial erosion rates by a sustained heated, simulated corium melt. This shall allow improved predictions of time and location of the potential basement penetration. Heating of the melt is achieved by simulating the nuclear decay heat by inductive heating of the lower steel phase overlaid by an oxide phase which receives the heat by convective heat transfer from the steel layer. Layering of steel below the less dense oxide melt is typical for the long-term concrete erosion, where the addition of light oxides produced by concrete ablation will decrease the oxide layer density. The power density in the steel is maintained at a low power level representing late accident conditions. After substantial concrete erosion, it was planned to start the second phase of the test by adding water to the surface of the melt. Emphasis of the flooding process is on the potential
retardation or stop of concrete erosion and on those processes that could generate a coolable corium bed, such as crust cracking and melt eruptions. Pre-calculations were performed by the partners to design the details of the test installation, and to delineate the decay power and the expected timing during the test.

The experiment has been performed on July 10, 2004. The crucible was fabricated from siliceous concrete (outer dimensions: 1100 mm diameter, 1050 mm high). The inner cavity, to which the melt is supplied, has an initial inner diameter of 600 mm. The crucible was instrumented with 88 thermocouples positioned at well-defined locations in the concrete to detect the response of the concrete and the actual position of the erosion front. Video and a high-tech infrared camera observe the surface of the melt from the hood of the crucible throughout the test. Chemical analysis and volume fluxes of the off-gas generated from the decomposing concrete are registered throughout the test.

The initial mass of the melt supplied to the crucible is 460 kg steel melt (90 w-% Fe, 10 w-% Ni), layer height 25 cm, plus 467 kg oxide melt. The oxide, overlaying the metal melt, is 56 w-% Al₂O₃ plus 44 w-% CaO and was designed to have a wide freezing range with a low solidus temperature. The height of the oxide layer in the cavity without void corresponds to 55 cm. The melt was generated externally by a thermite reaction and poured into the cavity with an initial temperature of 1640°C. Because of the planned low internal heating rate, partial crust formation at the concrete interfaces was expected already during the first phase of the test. The power that could be deposited in the melt by induction heating was 120 kW after completion of the melt pour, rising to 160 kW at 958 s, when the electrical power supply failed and unfortunately could not be re-established.

The interaction of melt and concrete in the first period of the test until some 250 s is characterized by significant agitation and some splashing of the melt, caused by substantial gas release from the decomposing concrete. In this time period, axial and lateral erosion rates of the cavity are similar and mainly controlled by the initial overheat of the melt. With cooldown of the melt to a stationary lower temperature (Fig. 2) as defined by the simulated decay power, and due to concurrent onset of crust formation in the metal phase, the erosion rate reduces. Based on the current analysis of the test data, downward erosion in this phase is more pronounced than radial erosion. Some eruptions, which occur during the stationary heating phase, indicate sudden release of gas and melted concrete masses, which may have accumulated under a crusted metal melt, and penetrated or removed parts of the crust. This process correlates with a clear increase of the heating power, as heating efficiency improves when the metal phase comes closer to the induction coil.

Due to its low solidus temperature, the oxide melt remains liquid and well stirred with a relatively low viscosity. In some periods a thin surface crust forms, which is however removed when periods of more intense gas release occur. The erosive action of the oxide melt is minor; partly because of the low overheat of the oxide related to the “melting” temperature of the siliceous concrete.

After the unexpected end of heating at 959 s, the melt cools down only very slowly. Some flooding process is initiated by the operator after 3000 s, bringing water to the outer surface of the concrete crucible only, namely to its bottom and sidewall. This has, however, negligible influence on the melt in the crucible and the inner concrete structure, as heat conduction through the concrete is very small. Permanent flooding of the melt surface at 4770 s quenches the hot surface of the crusted melt, which is still hot and bright in the bulk. However, the registered temperatures near the inner concrete interface are 1100 to 1200°C at that time and show no significant change due to the presence of water on the crusted surface. Very slow reduction of this temperature to 400 – 600°C at 28000 s shows that cool-down is controlled by transient heat conduction, and water ingress through suspected cracks is not effective.
Evaluation and documentation of the experiment is ongoing. The data will complement existing and upcoming experiments, such as the CCI-1 experiment at ANL. The results are important for safety assessment and planning of accident mitigation concepts.

The second experiment COMET-L2 will concentrate on the generic study of a long-term metal/concrete interaction in cylindrical cavity for intermediate and low decay heat levels through metal phase only. The test is scheduled for May 2005.

![Graph showing Temperature vs Time](image)

**Figure 2:** Maximum and minimum melt surface temperatures in COMET-L1

### 2.3 Experiment DISCO-L1 in the DISCO Facility

The DISCO test facility is designed to perform scaled experiments that simulate melt ejection scenarios under low system pressure during severe accidents in Pressurized Water Reactors (PWR). 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 a PWR pressure vessel at pressures below 2 MPa with an iron-alumina melt and steam [5]. In the frame of these Direct Containment Heating investigations the following issues are addressed: final location of corium debris, loads on the reactor pit and the containment in respect to pressure and temperature, and the amount of hydrogen produced and burned.

The experiment DISCO-L1 scheduled for October 2004 is being prepared. The reactor geometry to be modelled is that of the French 1300 MW plant. The reactor pressure vessel is surrounded by a mostly cylindrical pit which has many three-dimensional elements (Figures 3 and 4). Among these elements, there is a pit bottom access with a floor level at the same height as the pit bottom. The corridor is connected to the pit bottom by a door. It is vented into the reactor containment. Perpendicular to this is a rectangular niche that connects the pit bottom to a concrete wall which houses the penetrations of the instrumentation lines leading to the RIC (in-core reactor instrumentation). Above the niche and up to the lower end of the pressure vessel, the pit is surrounded by a cylindrical wall. Further upwards begins a section, where eight rectangular volumes house the flux measurement chambers. These volumes are supposed to be empty. The gap that is formed by the pit around the pressure vessel and the measurement chambers end up in the pit top annulus which is the pit volume above the vessel support ring. Through this annular space the main cooling lines lead from the vessel into the
adjacent subcompartments. The pit top annulus and the subcompartments are connected to the containment.

The main differences to the geometry investigated up to now are (1) the large height between pressure vessel bottom and cavity floor, (2) the direct connection from the reactor pit to the containment, and (3) the three-dimensionality of the cavity.

Initial conditions in the DISCO-L1 experiment are shown in Table 1. The pressure at failure may deviate from the intended value, because the temperature of the nitrogen gas inside the vessel that is heated through the thermite melt cannot be predicted exactly. The initial temperature of the containment atmosphere and walls may be lower than 100 °C due to insufficient electric heating capacity.

Table 1: Initial conditions planned for the experiment DISCO-L1

<table>
<thead>
<tr>
<th>Breach hole diameter at reactor scale [m]</th>
<th>$D_b = 0.5$</th>
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<tbody>
<tr>
<td>RPV pressure at failure [MPa]</td>
<td>$P_{RPV} = 1.6$</td>
</tr>
<tr>
<td>Gas composition in RPV</td>
<td>100% $N_2$</td>
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<tr>
<td>Containment initial pressure [MPa]</td>
<td>0.2</td>
</tr>
<tr>
<td>Containment initial temperature [°C]</td>
<td>$\approx 100$</td>
</tr>
<tr>
<td>Initial gas composition in the containment</td>
<td>100% $N_2$</td>
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2.4 Experiments LIVE-L1 and LIVE-L2 in the LIVE Facility

The LIVE experimental facility (Fig. 5) is designed to study the late phase of core degradation, onset of melting and the formation and stability of melt pools in RPV. Additionally, the regaining of cooling and melt stabilisation in the RPV by flooding the outer RPV will be investigated.

The LIVE test facility is under preparation, first commissioning tests are expected at the end of 2004. In the first stage, the LIVE facility consists of the hemispherical test vessel, a volumetric heating system in the test vessel to simulate the decay heat, a heating furnace to generate and pour the simulated corium melt, and a multitude of instrumentation to characterize the status of the melt. The test vessel is a 1:5 scaled RPV of a typical PWR with
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no penetrations of the lower head, and is equipped with different measurement techniques like heat flux sensors (Fig. 6), which provide a 3D picture of hot zones in the wall, and thermocouples. For the first and second phase of the experimental programme, only the hemispherical bottom of the RPV is realised with a diameter of 1 m. This hemispherical bottom is closed by an upper lid and different openings in this upper lid allow the pour of melt to the central region or close to the perimeter of the lower head. To investigate the influence of different external cooling modes on the heat flux, the test vessel can be cooled by water or air at the outer surface. For this purpose the test vessel is surrounded by a second cooling vessel. The cooling medium is injected at the bottom of the cooling vessel and leaves the vessel at the top.

The simulant melt is produced in a separate heating furnace and is discharged into the test vessel via a heated spout. The furnace is combined with a suction device to allow the extraction of the residual melt out of the test vessel back into the heating furnace to investigate the remaining melt crust.

The experiments will be carried out with different simulant materials. The first melt is a binary mixture of NaNO₃ and KNO₃ with temperatures up to about 350 °C. This melt mixture shall allow, at a moderate temperature level, the basic phenomenological studies of the important physical processes in the lower RPV head. In an advanced stage, the second melt that can be used, is a binary mixture of V₂O₅ with CuO, MgO or ZnO with temperatures up to 900 °C. The simulated corium melt is continuously heated by an array of electrical heater grids to simulate the decay heat of the corium melt.

The experimental program consists of three different phases. In LIVE1, the investigations will concentrate on the behaviour of a molten pool, which is poured into the lower head of the RPV taking into account possible 3D effects. The melt pool can be purely oxidic or, in a later stage, a pool with an oxide and metal melt. The objective is to determine the time dependent local heat flux distribution to the lower head, and the development of crusts, depending on internal melt heating and external cooling modes. Furthermore, the gap formation between the RPV wall and the melt crust as well as the role of phase segregation of a non-eutectic, binary melt on the solidification behaviour shall be investigated. In LIVE2, the experiments will be extended to allow multiple melt pours and the presence of water in the lower head. The third phase LIVE3 will deal with processes during in-core melt pool formation, the stability of the melt pools in the core region during different cooling modes and relocation processes after crust failure.

Two experiments are planned in the LIVE facility within the LACOMERA project:
- LIVE-L1 (end of 2004): Simulation of melt relocation into the RPV lower head for VVER conditions. The experiment will provide important information on the melt pool behaviour during the stages of air circulation at the outer RPV surface with a subsequent flooding of the lower head.

- LIVE-L2 (mid 2005): Transient corium spreading and its impact on the heat fluxes to the RPV wall and on the final shape of the melt in the RPV lower head. The test will address the questions of melt stabilisation and the effects of crust formation near the RPV wall for a non-symmetrical melt pool shape.

3 CONCLUSIONS

Four large-scale experimental facilities at Forschungszentrum Karlsruhe (QUENCH, LIVE, DISCO, and COMET) are offered to external partners from EU member countries and associated states. Their 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 finally corium concrete interaction and corium coolability in the reactor cavity. These help in the understanding of core degradation and quenching, melt formation and relocation as well as melt coolability in real reactors in two ways – firstly directly by scaling-up and secondly indirectly by providing data for the improvement and validation of computer codes. Although the facilities can only perform experiments with simulant materials, the tests can be considered as prototypic since the selected materials represent in important physical properties the real core materials.

Large-scale experiments being performed within the LACOMERA project aim to provide data for a better understanding of possible scenarios of quenching and of different core melt sequences. This knowledge shall lead to improved severe accident measures, which are essential for reactor safety and offers competitive advantage for the European industry.

REFERENCES


