THE OUTCOME OF THE ALISA PROJECT: ACCESS TO LARGE INFRASTRUCTURES FOR SEVERE ACCIDENT IN EUROPE AND IN CHINA

Gaus-Liu, Xiaoyang; Miassoedov, Alexei
Karlsruhe Institute of Technology (KIT)
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
Xiaoyang.gaus-liu@kit.edu; alexei.miasssoedov@kit.edu

Journeau, Christophe; Cassiaut-Louis, Natalie
French Alternative Energies and Atomic Commission (CEA)
Cadarache Center –Severe Accident Experimental laboratory - Blg 219, French
christophe.journeau@cea.fr; nathalie.cassiaut-louis@cea.fr

Chen, Peng; Zhang, Huiyong; Liao, Yehong
China Nuclear Power Technology Research Institute (CNPRI)
47 F/A Jiangsu Building, Yitian Road, Futian District, Shenzhen, 518026, PR China
chpeng@cgnpc.com.cn; zhanghuiyong@cgnpc.com.cn; liaoyehong@cgnpc.com.cn

Hu, Po; Kuang, Bo
Shanghai Jiaotong University (SJTU)
pohu@sjtu.edu.cn; bkuang@sjtu.edu.cn

Zhang, Yapei; Tian Wenxi
Xi´an Jiaotong University (XJTU)
No.28 Xianning West Road; Xi'an, Shaanxi, 710049, PR China
Zhangyapei@mail.xjtu.edu.cn; wxtian@mail.xjtu.edu.cn

Deng, Jian; Gong, Huojun
Nuclear Power Institute of China (NPIC)
328#, Section 1, Changshun Avenue, Shuangliu County, Sichuan, PR China
Dengjian_npic@163.com; ghjtsing@126.com

Sheng; Feng
South Park, Beijing Future Science & Technology Park, Beijing 102209, PR China
shenfeng@snptc.com.cn

ABSTRACT

The ALISA project (Access to Large Infrastructure for Severe Accidents) is a European FP7 Project (Grant Agreement No: 295421). It is a unique project between European and Chinese research institutions in the area of severe accident research in existing and advanced Light Water Reactors (LWR). The project provides mutual access to large research infrastructures for European and Chinese organizations, thus allowing the optimal use of the resources in the extremely complex field of several accident analyses. Six Chinese facilities from four Chinese research organizations were provided to European users and also six facilities from KIT and CEA provide access to the Chinese partners. The project started on July 1st, 2014 and has four years duration. Two calls for proposals have been undertaken during the project followed by the evaluation and selection of proposals by the User Selection Panel. All the facilities offered for access

in Europe and in China have received proposals. The European facilities are QUENCH, LIVE, DISCO, HYKA at KIT, and KROTOS, VITI at CEA, and the Chinese facilities are COPRA from Xi´an Jiaotong University (XJTU), HYMIT and WAFT from Shanghai Jiaotong University (SJTU), and IVR2D, IVE3D from CNPRI and MCTHBF from Nuclear Power Institute of China (NPIC). The nature of most Chinese proposals reflects the high demand to evaluate the safety design of their own reactor types. Since some EU and Chinese proposals investigate similar phenomena but in different scale and geometry, such as LIVE and COPRA, HYKA, HYMIT and MCTHBF, the comparison of the test results will provide a broader range of applicability. Other proposals investigate different aspects of a same severe accident strategy, such as LIVE and IVR2D/IVR3D. The combined knowledge from the experiments can provide comprehensive understanding of the phenomena of in-vessel melt retention with external cooling.

KEYWORDS
ALISA, LWR, Severe Accident, corium, mutual access

1. INTRODUCTION

Fukushima accident in 2011 highlighted once again the significance and importance of the severe accident management in the nuclear industry. The severe accident research often relates to complex problems involving substantial human and financial resources, and, in general, such severe accident research fields are too wide to allow investigation of all the phenomena by any national programme. Therefore, the Severe Accident research is often carried out in international context to maximise the benefits to all national participants, such as in the frame work of European Project, in SARNET2 [1] and in NUGENIA platform. To ensure the European leadership of the competence in the global severe accident research, communication and cooperation with uprising nations beyond Europe in nuclear safety research is indispensable. China pursues the most rapidly progressing nuclear programs in the world. The Chinese 13th five-year-plan targets 58 GWe nuclear to be operational by end of 2020, plus 30 GWe under construction [2]. It represents significant fraction of the new reactor builds in the energy market and has very ambitious perspectives. Accompanying to the fast development of the advanced reactors in different design, the Chinese Research Programme on severe accident joins to the world top-class league. The Chinese infrastructure on experimental research is characterized with expensive installation, full-scale set-up, prototypical material and reactor specific design. This motivates a strong interest for collaborative research with China.

As discussed in the Strategic research agenda [3], safety research is indispensable in Europe to support long-term operation of existing LWRs. Though the SRA can not 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 Severe Accident Research Network of Excellence (SARNET) [1] [4] 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 by the SARNET SARP group [5]. The objective of this group was 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. The group obtained a consensus on six high priority issues on severe accident management on which research was considered as necessary.

These issues are:

- Core coolability during reflood and debris cooling;
- Ex-vessel melt pool configuration during Molten Corium Concrete Interaction (MCCI), ex-vessel corium coolability by top flooding;
- Melt relocation into water, ex-vessel Fuel Coolant Interaction (FCI);

- Hydrogen mixing and combustion in containment;
- Oxidising impact (Ruthenium oxidising conditions/air ingress for High Burn-up and Mixed Oxide fuel elements) on source term;
- Iodine chemistry in Reactor Coolant System (RCS) and in containment.

2. OBJECTIVES, STRUCTURE AND RULES OF THE PROJECT

The main thrust of ALISA project is towards large scale tests under prototypical conditions addressing the remaining R&D issues on severe accident management in light water reactors [6]. These help the understanding of core degradation, melt formation and relocation as well as core coolability in real reactors by scaling-up and 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 research topics of the ALISA project for the European and Chinese severe accident research is reflected in three aspects:

- The access to large scale experimental facilities for the investigation of the most 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 four high priority issues identified by the SARP group will be addressed in the project.
- The results of the project will be applicable both to the European and Chinese reactor fleet taking into account the main LWR types.
- The project offers a unique opportunity for Chinese experts to get an access to large scale facilities in Western research organisation and vice versa, 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.

The project consortium includes leading European and Chinese organizations in severe accident research:

- Karlsruher Institut für Technologie (KIT)
- Commissariat á l`Energie Atomique et aux Energies Alternatives (CEA)
- China Nuclear Power Technology Research Institute (CNPRI)
- Shanghai Jiao Tong University (SJTU)
- Xi´an Jiao Tong University (XJTU)
- State Nuclear Power Software Development Center (SNPSDC)
- Nuclear Power Institute of China (NPIC)

KIT and CNPRI are the coordinator of the European and Chinese Project respectively. The project had a duration of 48 months and the project work plan is structured in 2 work packages.

- WP1: Severe accident management (SAM)
- WP2: Portal to access to large and unique infrastructures (PALI)

Before the start of the project, a Coordination Agreement (CooA) between the participants of the European and Chinese project were signed. The Euratom coordinator prepared the CooA in close collaboration with the Chinese coordinator using a detailed checklist available in the CORDIS website. The management structure of the two parallel projects is illustrated in Figure 1.

The consortium opened a Transnational Access (TA) program that offers access to 12 severe accident research facilities in Europe and in China. For European organizations access were offered to the following experimental facilities in China: IVR2D (CNPRI), IVR3D (CNPRI), HYMIT (SJTU), WAFT (SJTU), MCTHBF (NPIC) and COPRA (XJTU) facilities. In counterpart, KIT and CEA have offered accesses respectively to the LACOMECO (DISCO, HYKA, LIVE, QUENCH) and PLINIUS (KROTOS, VITI) platforms to Chinese users.

The access to the facilities is regulated by the rules of call for proposals. Maximum three calls for proposals were planned, two calls were necessary to explore all the facilities and haven been carried out. The evaluation and selection of calls were accomplished by a Proposal Selection Panel. The User Selection Panel was composed of the members of the Executive Group and of 5 were independent and external experts. The selection procedure followed the principles of transparency, fairness and impartiality. In particular, the decision process involved presentation of the submitted proposals, indicating the scientific importance, benefits, complexity and risks of each, followed by a User Selection Panel discussion.
The expected users of the results are: safety authorities, universities, research centres, utilities and power plant and fuel manufacturers. The synthetized experimental outcomes are public to the members in SARNET and NUGENIA groups.

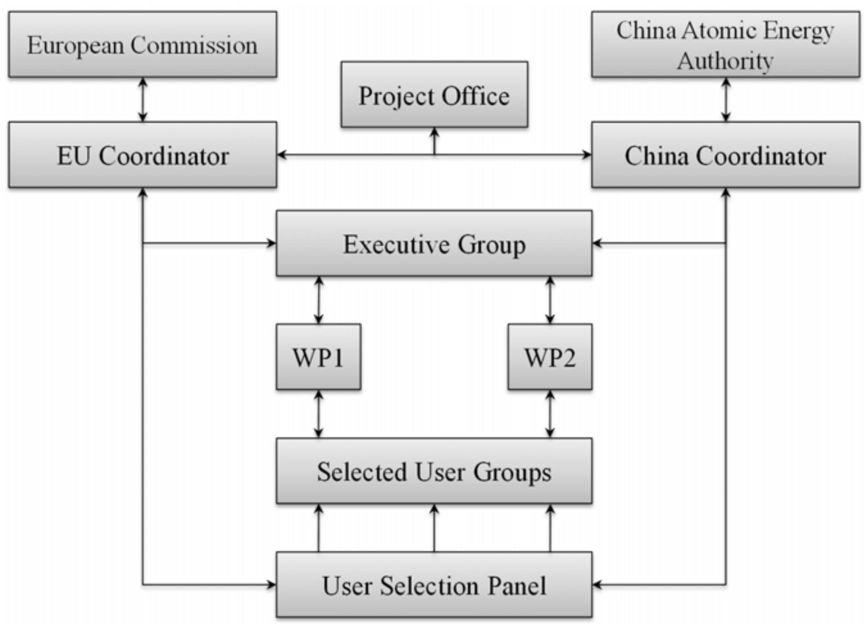


Figure 1. ALISA management structure

3. EXPERIMENTAL PROGRAMME

3.1. QUENCH - Large-scale Tests on the Early and Late Phases of Core Degradation Experiment, Proposed by XJTU

QUENCH-ALISA test was the first large scale bundle test including a prototypical experiment phase in air + steam mixture [7]. The bundle contained 20 heated and 2 unheated rods (#9, #15) with M5® cladding as well as 2 Ag-In-Cd absorber rods (#6, #12 in Figure 2). The test was performed on September 27, 2017. Three typical features of QUENCH-ALISA were: moderate pre-oxidation to ≈ 80 µm of oxide layer (less than in QUENCH-16), a long period of oxygen starvation during the air and steam ingress phase (1770 s instead 800 s for the QUENCH-16 test performed without steam injection during air ingress), and reflood initiation at the melting point of the cladding (≈ 2000 K instead of 1700 K for QUENCH-16).

The claddings of unheated and pressurized rods burst at 1045 K at a heat-up rate of 0.3 K/s. These burst temperature is lower in comparison to burst temperatures observed during the bundle test QUENCH-L2 (T_{pct} = 1138 ± 34 K) due to lower heat-up rate and thinner cladding wall.

The temperature escalation during the air ingress between elevations 150 and 850 mm was significantly stronger than for QUENCH-16 mainly due to additional exothermal cladding oxidation in steam (corresponding additional chemical energy of ≈ 4 kW was even slightly higher than electrical power). The metallographic investigations of the Zry corner rod, withdrawn at the end of escalation, showed formation of ZrN inside α-(ZrO) layer formed above the oxide layer during oxygen and steam starvation.

Releases of aerosols and helium were registered at the beginning of temperature escalation (failure of absorber rods). Simultaneously, the readings of cladding surface thermocouples below elevation of 550 mm indicated the relocation of absorber melt. During the starvation period about 100 and 450 g oxygen and steam were consumed. During the steam consumption period about 45 g hydrogen were released. In the same time a partial consumption of nitrogen (about 120 g) was registered. Initiation of reflood with 50 g/s water caused strong temperature escalation to about 2450 K at elevations between 750 and 1150 mm resulting in about 238 g hydrogen release (128 g for QUENCH-16). During re-oxidation of zirconium nitrides more than 54 g nitrogen were released. Final quench was achieved after about 800 s.

First metallographic investigations of the bundle at elevations between 1090 and 1500 mm show strong cladding oxidation and Zr melt formation below the elevation of 1430 mm. The melt relocated below 1350 mm was completely oxidized. No remaining nitrides or nitrides re-oxidized during reflood were indicated at these upper elevations. Probably, they were dissolved by relocated melt.

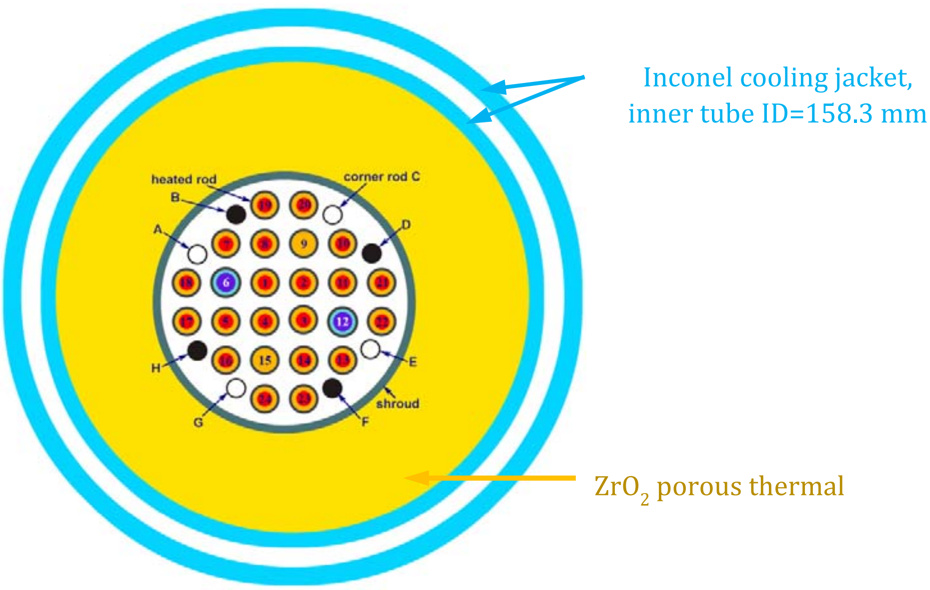


Figure 2. Cross-section of the QUENCH-ALISA bundle

3.2. LIVE - Large-Scale Tests on Behaviour of the Corium Melt Pool Test with Top-cooling, proposed by CNPRI

The main objective of the LIVE program is to study the late in-vessel core melt behavior and core debris coolability both experimentally in large scale 2D and 3D geometry and in supporting separate-effects tests [8]. The main part of the LIVE-3D test facility is a 1:5 scaled semi-spherical lower head of a typical pressurized water reactor. Both transient and the steady state behaviour of the simulated corium melt can be investigated with either top cooling or top insulation condition. The information obtained from the LIVE experiments includes heat flux distribution along the reactor pressure vessel wall in transient and steady state conditions, crust growth velocity and influence of the crust formation on the heat flux distribution along the vessel wall.

The proposal on LIVE3D investigates the heat transfer of melt pool under three different top boundary conditions (Figure 3). Top insulation with unfrozen melt surface, cold air cooling and rigid top cooling with water and frozen melt surface were proposed as top boundary conditions. The experiment answered the critical issue of the influence of top boundary condition on the upward and downward heat splitting, the melt pool temperature distribution and the pool turbulent pattern.

The test series with 6 heating phases was successfully performed on 27-30 June 2017. A melt pool of eutectic nitrate with 50 mol. % KNO_3 and 50 mol % $NaNO_3$ with 409 mm height was poured in the vessel centrally. Top water cooling, top air cooling and top insulation conditions were carried out subsequently. The test result shows that top water cooling is very effective, which can remove at least 60% of the power in the melt and avoids the heat flux tapering at the upper wall area. Top air cooling with only 3% of the heat removal has no large difference as top insulation condition [9].

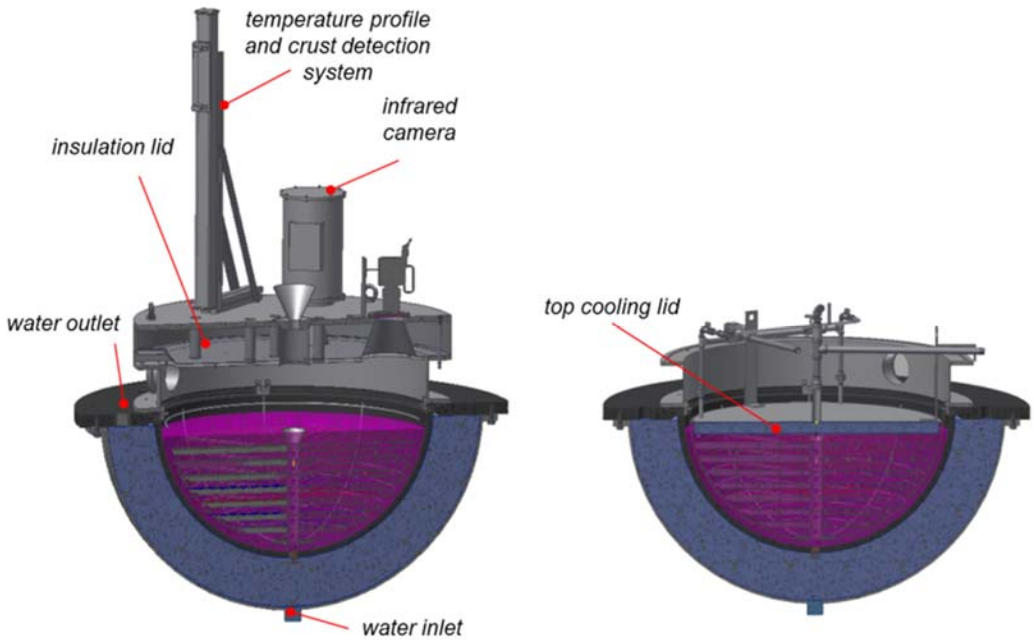


Figure 3. LIVE test facility with top insulation (left) and top cooling (right) conditions.

3.3. DISCO - Large-Scale tests on melt dispersion and on direct containment heating, proposal by SNPSDC

The DISCO facility at KIT is designed to investigate the fluid-dynamic, thermal and chemical processes during melt ejection out of a breach in the PWR pressure vessel lower head [10]. The addressed issues include pressure and temperature excursion in containment, hydrogen production, distribution and combustion in containment and the final locations of corium debris. The facility containment is linearly scaled in 1:18 to a large PWR containment. The reactor cooling system (RCS) and the reactor pressure vessel (RPV) are modelled by a vertical pipe with a volume of 0.08 m³. The breach in the lower head is modelled by a graphite annulus at the bottom, which is initally closed with a brass plate. The reactor pit is made of concrete and installed inside a strong cylindic steel vessel. The horizontal cooling line with flow path to the equipment rooms is simulated with steel cylinders with a scaled annular space model. The equipment room arrangement can be adjusted to the reactor design being investigated. Thermite powder of aluminum and iron oxide is used simulating the corium melt. One experiment is started by igniting the thermit at the upper surface. During the igniting period, the pressure can arise to 2 MPa and the temperature of the iron-alumina to 2100 °C. About 3 to 6 seconds after ignition the brass plug at the RPV bottom is melted and that initiates the melt ejection. The melt is driven out by steam and is dispersed into the dry or wet cavity and beyond.

The DISCO-AP1000 experiment was designed to investigate the consequences of a failure of the In-Vessel Retention (IVR) method in an AP1000 plant during a postulated core meltdown accident. When the lower head of the reactor pressure vessel fails under a residual pressure higher than 0.2 MPa, molten corium will be ejected under pressure into the reactor pit which is flooded with water. The molten corium will fragment into small droplets and interact with the water leading to an intense heat transfer process. The experimental results can be useful to improve the modelling of fuel coolant interaction (FCI), specifically for the geometry of the AP1000 reactor cavity, which is characterized by a narrow gap between reactor pressure vessel and cavity wall and small flow paths out of the reactor pit (Figure 4). Since the DISCO facility simulates also the containment, the experiment can also lead to better understanding of effects of FCI in respect to the containment pressure and its integrity. The initial condition of DISCO test are liste in Table 1. The main results are listed in Table 2.

Table 1. Intial conditions of DISCO test

RPV/RCS pressure, MPa	1.88
RCS volume, m³	0.050
Flow cross-section around vertical RPV	6209 mm² -> 6.4 mm gap
Flow area junction connect cavity and SG-1 and SG-2	Ø 104 mm
Flow restriction at vessel support	3100 mm² -> 3.2 mm gap
Upward direct path from cavity to containment	closed
Containment pressure, MPa	0.1
Containment atmosphere	air
Containment temperature	room
Containment volume, m³	13.5
Cavity water height, mm	965
Cavity water temperature, °C	55
Melt mass, kg (cm³)	15.960
RPV driving gas	N_2
Breach diameter, mm	30

No steam explosion occured. The maximum pressure in the cavity reached 0.6 MPa after 20 ms close to the bottom. It took 2 seconds to reach pressure equilibrium in the containment at 0.2 Mpa. In the containment the pressure reached 0.21 MPa after 3 seconds, the maximum temperature was near 500°C at one location for a short period of time after 2 seconds; the average temperature was between 250°C and 300°C between 4 and 12 seconds after start of blowdown.

Table 2: Results concerning pressure and water ejection

Blow down pressure	MPa	1.88
Duration of blow down	s	2
Time point and of pressure peak in cavity	ms / MPa	20 / 0.59, 180 / 0.46, 780 / 0.3
Pressure increase in containment	MPa	0.11
Water level / volume	m/l	0.965 / 3445
Maximum pressure in containment	MPa	0.21

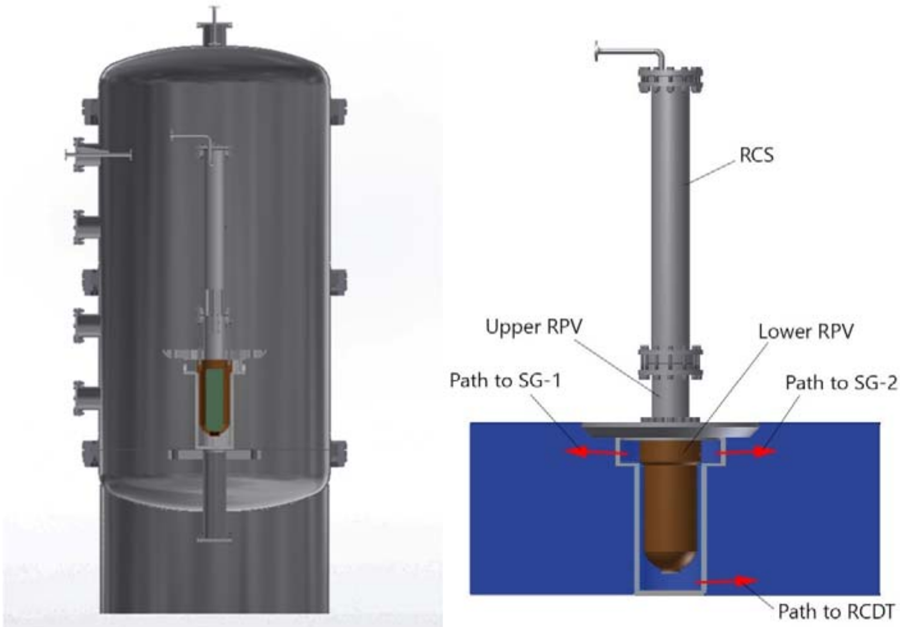


Figure 4. DISCO facility and the test configuation in ALISA test

3.4. HYKA - Impact of H_2 Mixture Non-Uniformity and Ignition Position, Proposed by SJTU

HYKA at KIT provide a number of large test vessels to investigate containment safety and hydrogen combustion [11]. In HYKA it is possible to investigate the whole spectrum of hydrogen phenomena. Research on different hydrogen sources and their distribution behavior 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, i.e. slow and fast deflagration and detonation. Stagnant or controlled air flow conditions can be simulated in horizontal or vertical orientation. The high vessel design pressures allow test parameters also beyond safety considerations. The largest safety vessel A2 with main dimensions of 6 m in inner diameter and 9 m in height provides an empty test volume of about 220 m^3 (Figure 5).

The subjects of ALISA HYKA experiments are: a) the effect of mixture non-uniformity and ignition position on flame propagation regimes and maximum combustion pressure in comparison with uniform mixture of the same amount of hydrogen; and b) the ignition/extinction phenomena in presence of steam and/or water mixture. HYKA-A2 facility was involved. The dynamics of the combustion process are measured with the temperature, pressure, acoustic and optical observation using Background Oriented Schlieren Method (BOS). Four test campaigns were successfully conducted from June to September 2016.

- "Cold" (without combustion) testing of spray structure;
- Flame propagation experiments for center ignition point with uniform hydrogen concentration of 6%, 6.5%, and then 7%;
- Flame propagation experiments with center ignition for three different vertical hydrogen concentration gradients of 14 % → 0 %, 12 % →2 % and 10 % → 4 %, that the hydrogen amounts are equal to 7% of average concentration;
- One test with upper ignition point and vertical hydrogen concentration gradient of 14 % → 0 %;
- Two tests studying the effect of water stray on flame propagation with center ignition point and vertical hydrogen concentration gradient of 14 % → 0 %.

The test results show very strong influence of hydrogen stratification ion the pressure escaltion. The maximum pressure increases 10 times for stratified hydrogen mixture with the same amount of hydrogen equal to 7 % H_2 in average.

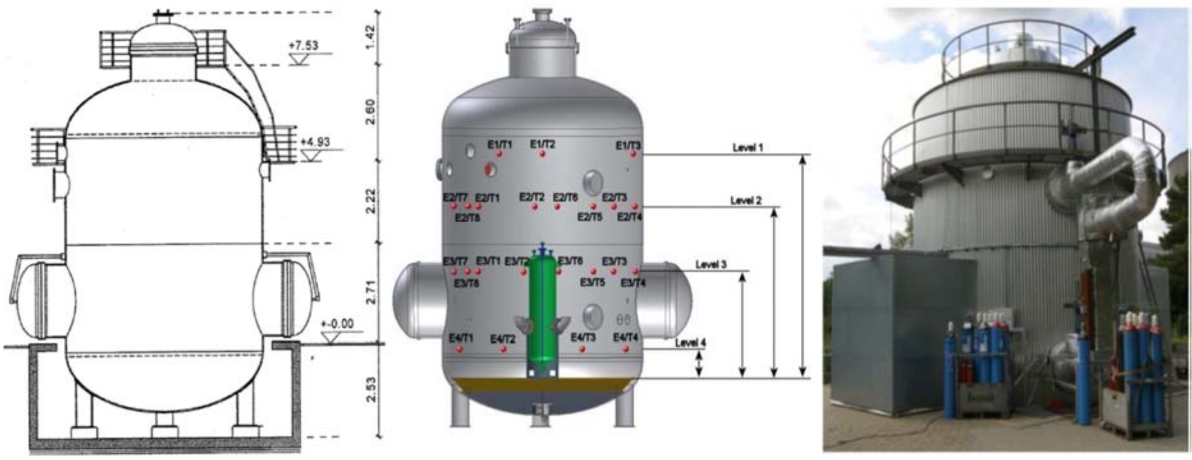


Figure 5. HYKA-A2 facility: main dimensions and side view

3.5. KROTOS - the Effect of Water Pool Depth on FCI, proposed by City University Hongkong

KROTOS facility at CEA (Figure 6, left) is dedicated to fuel coolant interaction (jet fragmentation, debris formation, steam explosion, etc.) [12] [13]. The facility consists of four main parts: the furnace, the transfer channel, the test section and the X-Ray radioscopy system. The furnace is a water cooled stainless steel container designed to withstand 4 MPa pressure. It is equipped with a three-phase cylindrical heating resistor made of tungsten. In order to avoid heat losses, the heating element is surrounded by a series of concentric reflectors and closed by circular lids made of molybdenum. A tungsten crucible is hanged inside the heating element; its net volume is 1 liter and allows the melting of up to 6 kg of corium. The facility is developed to operate in inert atmosphere or vacuum at temperatures up to 2800 °C. The transfer channel is a vertical tube connecting the furnace and the test section. A fast hydraulic ball valve is positioned at the top and melt release cone are placed at the bottom of the transfer channel. The test section consists of a pressure vessel with a test tube inside. Both are made of strong tempered 7075 aluminum alloy, characterized by low attenuation of X-ray radiation. The pressure vessel is provided with a number of feed-through for gas connections, instrumentation and a view window. The test tube is a free standing cylinder filled with water. Its internal diameter is 0.2 m; its height is 1.6 m. A pressurized gas trigger (150 bars) is positioned at the bottom to activate the steam explosion after the premixing phase of the FCI. Both the chamber and the test tube are heavily equipped with instrumentation in order to follow the premixing, the propagation and the explosion phases and thus to provide maximum information on FCI.

The proposed KROTOS test is similar to past KROTOS test KFC [14], but with shallower water pool depth (645 mm vs. 1245 mm in previous KROTOS tests at CEA Cadarache). The test has been successfully conducted on November 17th, 2016. 5.2 kg of corium (80 wt.% UO_2, 20 wt. % ZrO_2) have been melted and heated to a measured temperature of 2831 °C, which has a superheat of about 180°C. Corium has been successfully released and poured in the 645 mm deep water pool at an initial temperature of 60 °C. A continuous and coherent jet is observed. When the jet reached the prescribed depth, the trigger has been actuated leading to a steam explosion. At this time, only about half of the corium melt has been injected in the test section. A significant volume of water has been splashed out of the test vessel. Corium pouring has been halted by the pressurization induced by the explosion, then resumed. A large quantity of debris has also been found in the lower part of volume between the test section and the facility containment. They are assumed to have experienced the steam explosion and to have been projected out of the test section. There are fine (sub-millimetric) black debris and larger (millimetric) white-greenish debris.

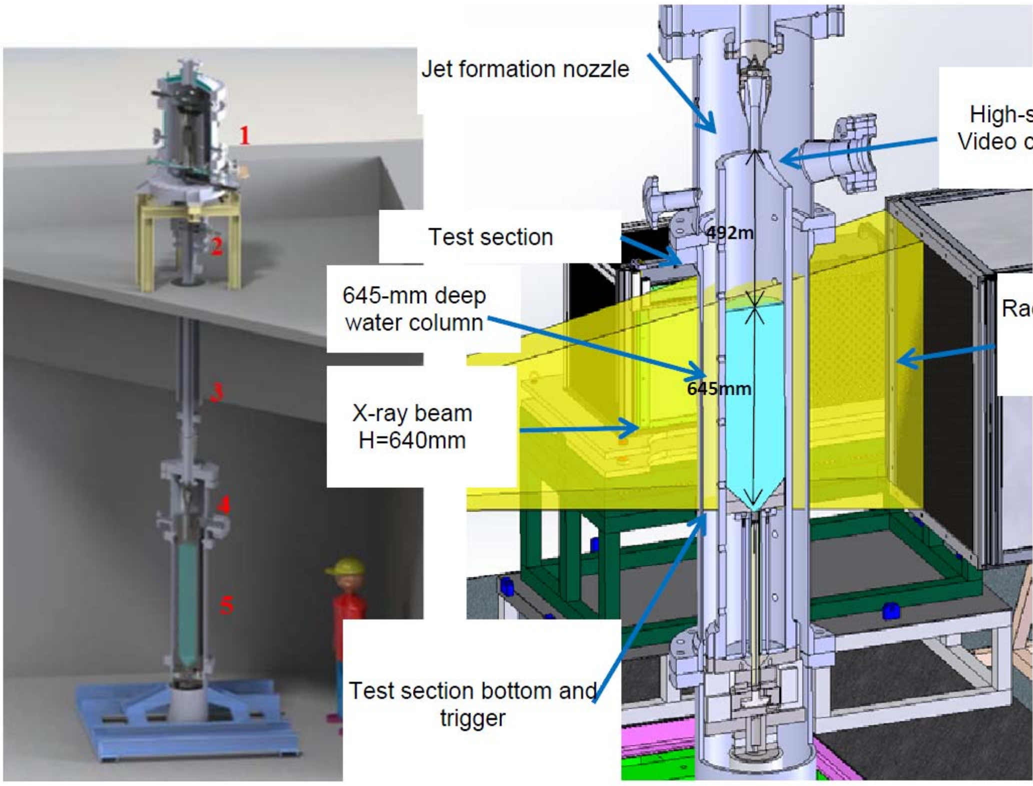


Figure 6. KROTOS facility: Left: general sketch (deep water configuration) – Right: zoom on test section (shallow water configuration)

3.6. VITI - Corium Thermos-physical Propertie Measurments

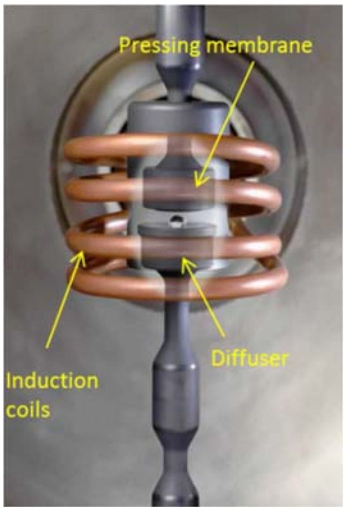
Two VITI facilities at CEA (Figure 7) were involved to perform viscosity and surface tension measurements on corium. The Levitated Droplet measurement provides the data of droplet density, surface tension and viscosity [15]; the VITI-MBP using bubble pressure method by immersion of capillary tube in corium, and can measure the density and surface tension of the corium bubble.

The experimental techniques are crucible heating and levitating droplet technique for contactless measurements of thermophysical properties. VITI facility allows studying solidification process of corium oxide melt (from 1000 K up to 3000 K) at different atmospheres (reductive, neutral and oxidant) in various ranges of temperatures. The sample is put in a crucible of suitable material. The aerodynamic levitation configuration enables to obtain thermo-physical properties of materials. The liquid droplet stands on a thin (<100 mm) gas film passing through a graphite pressurized porous membrane (diffuser). A second graphite membrane (pressing membrane) stands above the droplet and is moved to reach the required pressing amplitude. The droplet is then relaxed by mechanically releasing the pressing graphite membrane, and the relaxation time constant to the equilibrium state is measured. The sample is heated by thermal radiation from the inductively heated graphite susceptor. The coupling of these two sources of heating limits thermal gradient inside the droplet. A bi-chromatic pyrometer is used to measure surface temperature of the droplet between 1300 K and 2800 K and two video cameras allow to measure precisely and continuously the radius of the droplet. Density is deduced from droplet volume; surface tension is obtained from droplet shape while viscosity is deduced from the relaxation time obtained by processing of the high speed video. Online gas spectroscopy measurements are performed.

Three corium samples representing three scenarios are measured. Their compositions are given in Table 3. Sample 1 ist a sample from KROTO test, whereas Sample 2 and 3 must be firstly fabricated. Surface tension and density are measured with VITI-MBP.

Table 3. Compostion of samples for VITI measurements

	composition, wt %	**Scenario**
1	80% UO_2, 20% ZrO_2	VITI-ALISA in-vessel scenario
2	46.1%UO_2, 15.2%ZrO_2, 19.1% SiO_2, 5.1% CaO, 0.1% MgO,1.8% Al_2O_3, 3.3% Fe_2O_3, 7.1% FeO, 2.2% Cr_2O_3	LOCA-Ex-vessel
3	33.9% UO_2, 11.3% ZrO_2, 29.6% SiO_2, 6.7% CaO, 0.2% MgO, 2.4% Al_2O_3, 0.7% Fe_2O_3, 8.7% FeO, 6.5% Cr_2O_3	Loop-ex-vessel retension



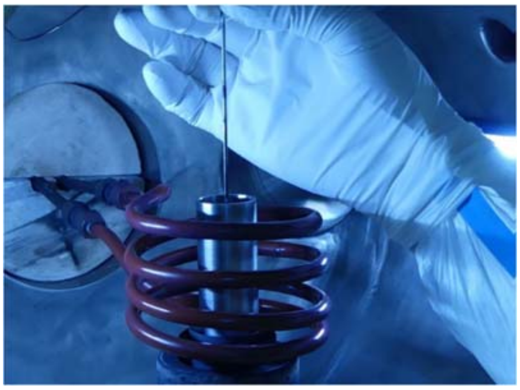


Figure 7. VITI levitation (left) and VITI-MBP setups (right)

3.7. IVR2D – CHF and External Cooling Characterisitics of Two Corium Heat Flux Profiles, Proposed by KIT

The two-dimensional IVR facility at CNPRI (Figure 8) is designed to investigate the External Reactor Vessel Cooling (ERVC) of the lower plenum of RPV in order to achieve in-vessel melt retention. The objectives of the experiment are the identification of Critical Heat Flux (CHF) along the outer wall of RPV, optimization and verification of the flow channel, the characteristics of two-phase flow in different flow conditions, the effect of coolant additives on CHF, etc. The test facility is a full scale 2D facility with a 7.6 m high nature circulation loop. 24 heating sections generate a maximum heating power of 1.2 MW, corresponding 2.4 MW/m². The ALISA experiment in the IVR-2D facility is focused on the influence of the penetrations in the RPV lower plenum on the natural convection and CHF. The test was performed in 2017 using two different heat flux (HF) distribution profiles in the lower head: the LIVE HF curve simulates an homogenous oxide pool with the heat flux distribution described in Eq. (1); and the ULPU curve (Eq. (2)) similates a two-layer pool with an upper light metallic layer [16] :

$$y = 4.2636x^3 - 1.6669x^2 - 0.1577x + 0.3258 \quad (1)$$

$$q(\theta) = \begin{cases} 0.45676\theta^3 - 0.21008\theta^2 + 0.04273\theta + 0.12425 & (0° \le \theta \le 64°) \\ 0.7636 & (\theta > 64°) \end{cases} \quad (2)$$

where:

θ	Polar angel
$q(\theta)$	Local heat flux at angel of θ
$q_{\_ave}$	Averaged heat flux at related area

Several baffles were installed in the flow channel to simulate the structure of the RPV lower head insulation. The depth of the cooling channel declines from bottom (334 mm) upwards to 118 mm (at polar angle 90°). An additional reduction at the outflow (Polar angle 90°) of 15% was realized according to the wish of KIT.

The power distrubtion in all test sections increased proportionally in small steps. The power distribution is shown in Figure 9. In the LIVE HF test, CHF occured in zone 20 (angle 78°7) with the value of 1392 kW/m². The test was repeated with even smaller power steps, and provided a more accurate CHF of 1360 kW/m^2, the total heating power as CHF arrived was 293 kW: In ULPU test, flow fluctuation occured as the total heating power exceeded 330 kW, and CHF didn't happen at this moment. The same phenomena occured during the repeated test. ULPU test shows that the flow unstability is another thread of external cooling in a nature circulation, and it is a strong function of the total power, HF distribution and the static pressure or loop height of the coolant.

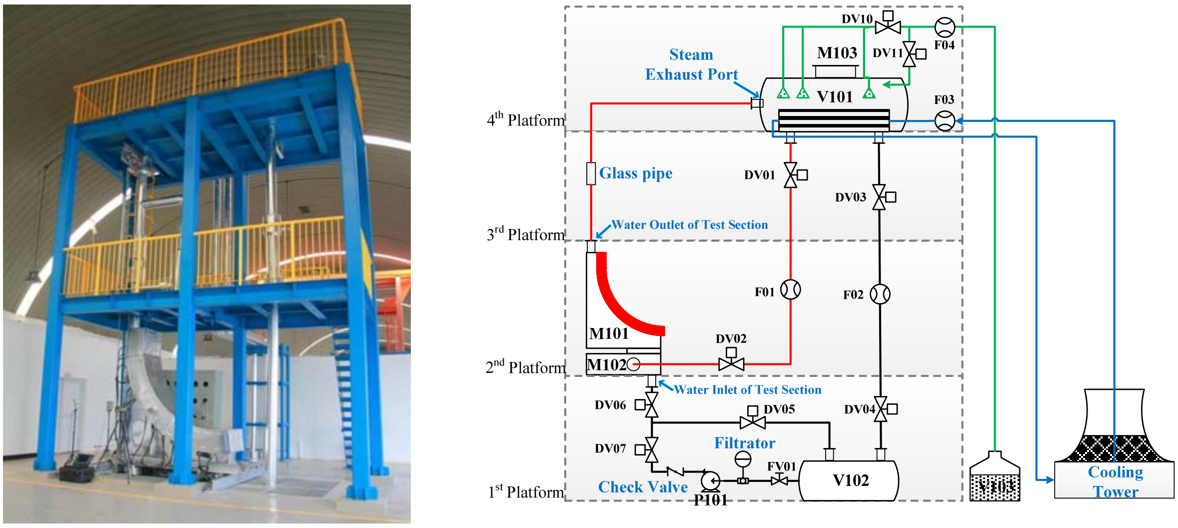


Figure 8. Left: IVR-2D facility and test section, right: Schematic diagram of primary system of test facility.

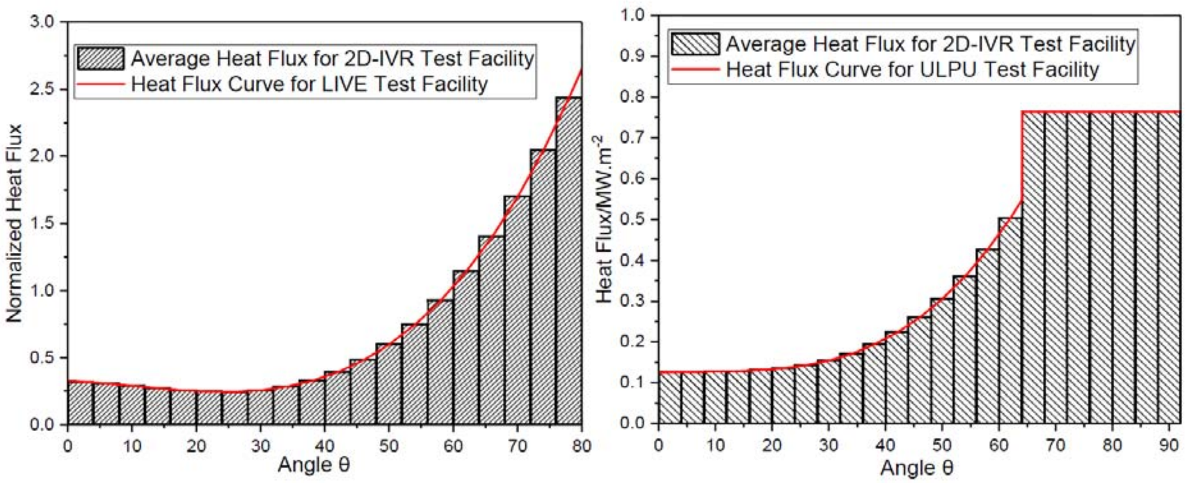


Figure 9. Heat flux profile definition, left, LIVE-HF profile, right, ULPU profile

3.8. IVR3D – External Heat Transfer under Non-Symmetry Gap, Proposed by IRSN

IVR3D test facility at CNPRI studies three-dimensional vessel external cooling under integrated reactor component mode. The aim is to compare critical heat flux (CHF) under different cooling channel geometries and two-phase flow patterns of the coolant. The research program includes a) investigation of two-phase coolant circulation process of natural convection, venting and condensation and b) determination of the CHF in 3D geometry. This new facility was constructed and put into operation in 2017. The 1:5 scaled RPV lower head has a wall outer diameter of 0.92 m and a height of 1.68 m. The total height of the facility is 2.8 m. The simulation of RPV wall heat flux is realized with copper heating block bordered with stainless steel outer surface. The maximum heat flux is 1.8 MW/m^2. The instrumentation includes high-speed camera, temperature measurement at different level and the high-frequency pressure sensors. The IVR-3D test in the ALISA project will study the effects of the influence of non-symmetrical top conditions due to venting and non-symmetrical gap around the RPV on the CHF. The proposal was postphoned beyond the project period due to technique problems of the facility.

3.9. COPRA - Transient and Steady Melt Pool Behavior, Proposed by EDF and KIT

The COPRA facility (Figure 10) at XJTU is designed to study the natural convection heat transfer in corium pools with high Rayleigh numbers up to 10^{16} [17]. The test vessel is a two-dimensional 1/4 circular slice. With an inner radius of 2.2 m, it simulates CNNC's ACP-1000 in full scale. The inner width of the slice is 20 cm. All the vertical walls of the vessel are kept thermally insulated. The curved vessel wall thickness is 30 mm and is enclosed with a regulated external cooling path. The top surface of the vessel is either in adiabatic boundary condition with an insulated upper lid, or be cooled by a specially designed cooling device. The main objective of the proposed experiment is to gain knowledge about the transient evolution of a layer evolving towards steady-state convection. The background is the lacking knowledge of the melt pool transient heat transfer. In the tests two steady-state boundaries are supposed: a) adiabatic boundary condition on the top of the pool and adiabatic boundary condition on the side at the beginning of the experiment, and b) after a defined time, the curved vessel wall boundary is changed quickly to isothermal condition by flooding. The lateral heat flux, related to the lateral Nusselt number, the evolution of pool temperature, and the time required to reach fully established convection are the main interests of the investigation. The test results can be compared with BALI experiments due to the similar geometry and with LIVE tests due to the same simulant material.

The simulant material is the eutectic mixture of 50 mol % $NaNO_3$- 50 mol % KNO_3. Table 4 shows the procedure to create different transient states. The transients include: the evolution of melt pool from the melt pouring to a temperature homogenous state on quasi adiabatic boundary condition; the evolution of melt pool after the external cooling had been initiated, after the second melt pool and the change of power density. Figure 10 right shows the evolution of melt temperature during these transient phases.

Table 4. COPRA test definition

Test matrix of first experiment	Lateral cooling	Heating power	Pool height
First melt pouring	No	-	1330mm
Homogeneous state	No	-	1330mm
Lateral cooling starting	Yes	18kW	1330mm
Second melt pouring	Yes	-	1900mm
First power changing	Yes	28kW	1900mm
Second power changing	Yes	24kW	1900mm

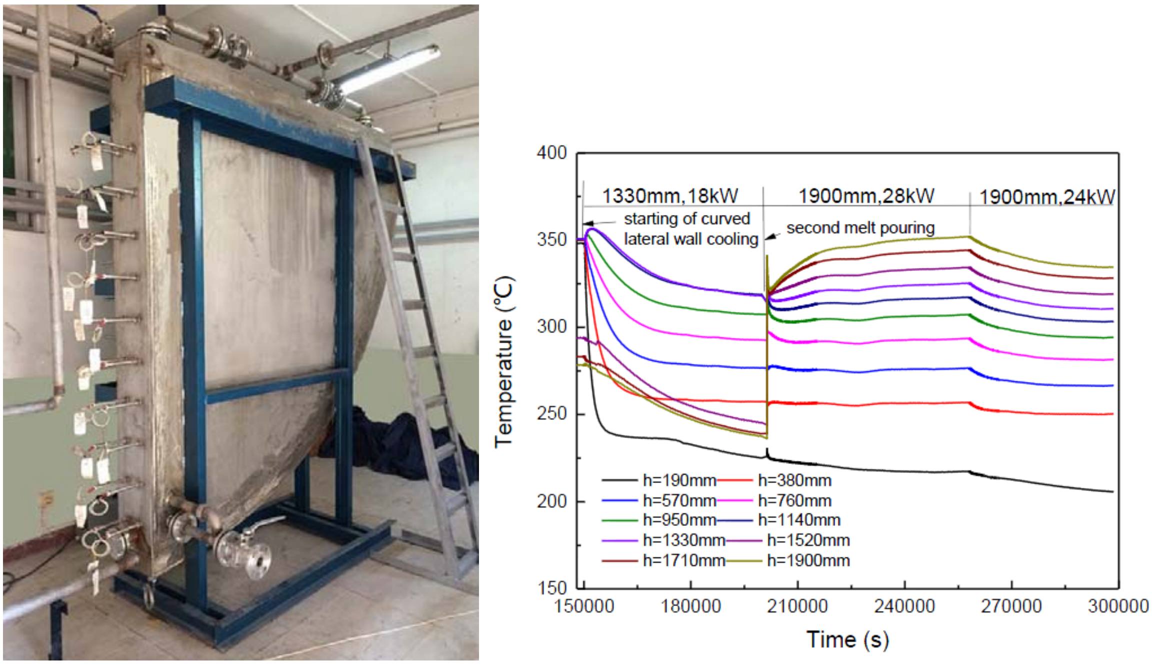


Figure 10. Left: test vessel of the COPRA facility, right: melt temperature response during the transient phases

3.10. HYMIT - Upward Flame Propagation in a Homogeneous Gas Atmosphere, proposed by JSI

The HYMIT facility (Figure 11) at SJTU is a medium-scale hydrogen mitigation test facility designated for investigations of hydrogen recombination and combustion behavior. The facility is designed to test the characteristics of current available ignitor and passive autocatalytic recombiners (PAR) as well as new hydrogen mitigation technologies. It can be operated with hydrogen concentrations between 0 and 30 vol.%, as well as steam concentrations between 0 and 50 vol %. The main part of the facility is a steel cylinder tank which is 4 meters high and 2 meters in diameter. The tank volume is about 12 m^3. The content of gas mixture, gas temperature and pressure and speed of flame can be measured with gas analyzer, thermocouple arrays, piezoelectric pressure sensors and photodiode array respectively. The focus of the ALISA experiment is hydrogen deflagration with upward flame propagation in a homogeneous air-steam-hydrogen atmosphere. The purpose of the experiment was to perform a test with conditions similar to the ones in previous experiments in other vessels, with a similar shape but a larger volume: THAI vessel, with a volume of 60 m^3, and HYKA A2 vessel with a volume of 220 m^3. This will enable the investigation of the influence of scaling from small to large volumes on the characteristics of hydrogen deflagration (eventually leading to adequate modelling of hydrogen deflagration in containments of real nuclear power plants), as well as to further develop theoretical models of flame propagation. The experiment was conducted successfully in October 2016. A homogeneous mixture of air, hydrogen and steam was ignited at the vessel centre line, near the vessel bottom. Hydrogen burning did occur. The combustion was almost complete, as the measured final hydrogen concentration at three different points was less than 0.1 vol.%.

Figure 11. HYMIT facility

3.11. WAFT – Formation of Rivulets and Film Boiling, Proposed by GRS

The WAFT facility (Figure 12) is dedicated to study Passive Containment Cooling System (PCCS) of GEN-III plants. The facility consists of a stainless plate (5 m long, 1.2 m wide) mounted on a metallic frame allowing for plate inclination. The surface of the plate undergoes a preparation by painting with organic zinc to maintain designated wettability. The plate surface is heated by heating oil, and the power can reach 100 kW/m^2. A parallel plate 30 cm apart from the test plate with visualization windows constitutes a part of a rectangular channel which enables the simulation of the air gap between the containment steel envelope and the metallic baffles in the reference passive reactor design. A blower at the bottom of the channel simulates the natural circulation air flow occurring in the reference plant conditions. Variation of the reference air velocity from 0 to 12 m/s is allowed. The water film distribution box is mounted on the top of the facility to ensure uniform water film distribution of the inlet. The water film and air temperatures are measured with thermocouples, and water film thickness is measured with optical sensor, air flow velocity is measured with hot-wire anemometer, the surface wave velocity is measured with high-speed camera, and heat flux is measured with heat flux sensors. The experiment planned in the ALISA project will investigate the formation of rivulets (change of wetted surface fraction). The results will be used for the validation of the applied minimum energy principle used inside existing rivulet model of the COCOSYS code. Additional investigation of specific boundary conditions will include film boiling to validate heat transfer model under these conditions and “closed chimney” (no atmospheric flow) to validate heat transfer model under steam rich bulk conditions. Due to the postphone of the performance. results of early experiments were provided for the validation of COCOSYS.

Figure 12. Left: WAFT facility, right: test section of the WAFT facility

3.12. MCTHBF - Dilution of H_2 under Vertical Steam Jet in Lower Position, Proposed by JSI and Partners

MCTHBF (Figure 13) is a medium-size hydrogen mitigation test facility at NPIC. The main part is a steel cylinder tank which is 5 meters high and 2.8 meters in diameter. The tank volume is about 21 m^3. It is designated to test the hydrogen recombination and combustion behavior. The mixed gas content, gas temperature and pressure and speed of flame can be measured with gas analyzer, thermocouple array, piezoelectric pressure sensors and photodiode array. It can deal with hydrogen concentrations between 0 and 35 vol.%, as well as steam concentrations between 0 and 40 vol %. The experiment in the MCTHBF facility within the ALISA project investigates stratrificaion of atmosphere containing hydrogen in the upper part of the vessel and a low-momentum vertical air jet [18]. Helium simulates H_2, and air simulates the steam jet. The topic of studies includes scaling from small to large volumes by comparing results of pther previous experiments and validation of lumped-parameter and CFD codes.

A gradual break up of helium layer was observed, which is in line with the early observation in other scales. The difference in this test a homogenous evolution of local helium concentration in this test.

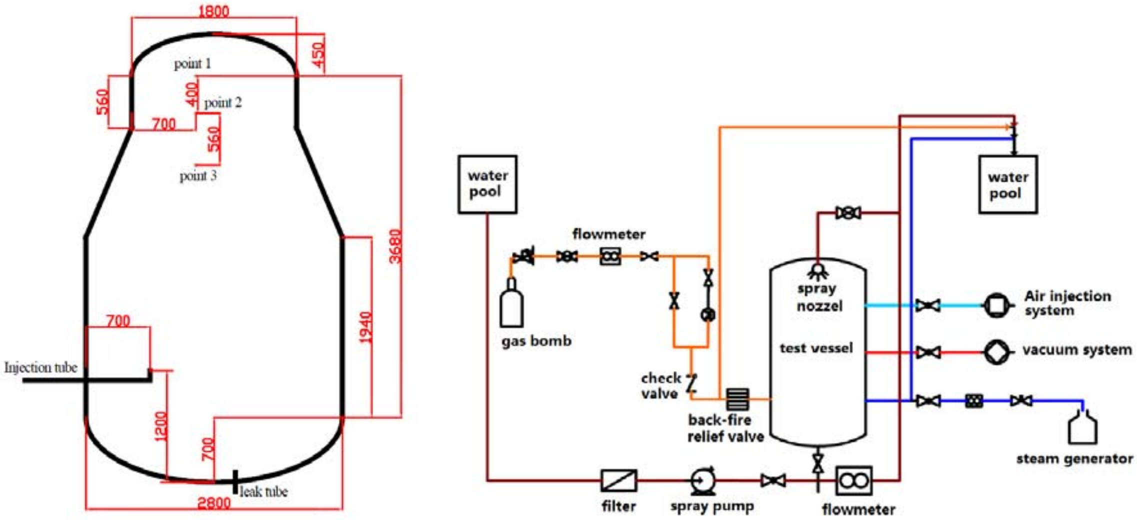


Figure 13. Sketch of MCTHBF vessel and the auxiliary components

4. CONCLUSIONS

Enhanced transnational access to ALISA large research infrastructure allow the optimal use of the R&D resources in Europe and in China in the complex field of severe accident analysis for existing and future power plants. This research involves 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 European and Chinese levels is very important. This is precisely the main objective of the ALISA project, which aims to provide these resources and to facilitate this collaboration by providing state-of-the-art large-scale experimental platforms in Europe and in China for transnational access. Large-scale facilities of the ALISA project are designed to resolve the most important remaining severe accident safety issues, ranked with high or medium priority by the SARP group for SARNET NoE. These issues are coolability of a degraded core, corium coolability in the RPV, possible melt dispersion to the reactor cavity, molten corium concrete interaction and hydrogen mixing and combustion in the containment. The major aspect is to understand how these events affect the safety of existing reactors and how to deduce soundly-based accident management procedures. 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.

A wide range of European and Chinese organizations have participated in preparation of the experimental proposals and in the preparation and analysis of the experiments. Due to strong links to other European projects, ALISA offers a unique opportunity for all partners to get involved in the networks and activities supporting safety of existing and advanced reactors and to get access to large-scale experimental facilities in Europe and in China to enhance understanding reactor core behaviour under severe accident conditions.

5. ACKNOWLEDGMENTS

The authors gratefully acknowledge funding by Euratom to support the work within the ALISA project under the Grant Agreement 295421.

6. REFERENCES

1. T. Albiol, "SARNET: Severe accient research network of excellence," *Progress in Nuclear Energy,* pp. 2-10, (2010).
2. "Nuclear Power in China," World Nuclear Association. Online.. Available: http://www.world-nuclear.org/information-library/countryprofiles/ (2018).
3. "Stratetic Research Agenda,". Online. Available: www.SNETP.eu. (2009).
4. J.-P. Van Dorsselaere, "Status of teh SARNET Network on severe accidents," in *ICAPP´10*, Sab Diego, California, (2010).
5. B. Schwinges, C. Journeau, T. Haste, L. Meyer and W. Tromm, "Ranking of severe accident research priorities," *Progess in Nuclear Energy,* vol. 52, pp. 11-18, (2010).
6. A. Miassoedov, X. Gaus-Liu, Y. Liao and P. Chen, "ALISA Project: Access to large infrastructures for severe accidents in Europe and in China," in *NURETH-17*, Qingdao, China, (2018).
7. J. Stuckert, M. Steinbruck, J. Kalilainen, T. Lind and Y. Zhang, "First results of the QUENCH-ALISA bundle test," in *NUTHOS-12*, Qingdao, China, (2018).
8. X. Gaus-Liu and A. Miassoedov, "LIVE Experimental results of melt pool behaviour in the PWR lower head with insulated upper lid and exernal cooling," in *ICONE21*, Chengdu, (2013).
9. X. Gaus-Liu, T. Cron, B. Fluhrer, A. Miassoedov, L. Zhang, J. Xu and H. Zhang, "Experimental study of the melt pool heat transfer in LWR lower head under different upper boundary conditions," in *NUTHOS-12,* Qingdao, China, (2018).
10. L. Meyer, G. Albrecht, C. Caroli and I. Ivanov, "Direct containent heating intergal effects in geometries of European nuclear power plants," *Nuclear Engineering and Design,* vol. 239, pp. 2070-2084, (2009).
11. T. Jordan and W. Breitung, "FZK metholodody for analysis of hydrogen behaviour in containments," in *Proc. of Conference on numerical flow models for controlled fusion*, Porquerolles, (2007).
12. N. Cassiaut-Louis, N. Chikhi, P. Fourquart, P. Piluso, C. Journeau, W. Zhou and Y. Liao, "Experiments linked to Fuel-Coolant Interaction within the Euro-Chinese Project ALISA," in *NURETH-17*, XI´an, China, (2017).
13. I. Huhtiniemi and D. Magallon, "Insights in steam explosions with corium melts in KROTOS," *Nuclear Engineering and Design,* vol. 204, pp. 391-400, (2001).
14. V. Tyrpekl, P. Piluso, S. Bakarjieva, D. Niznansky and J.-L. Rehspringer, "Protopypica corium oxidation and hydrogen release during the Fuel-Coolant Interaction," *Ann. Nuclear Engineering,* vol. 75, pp. 208-218, (2015).
15. P. Piluso, J. Monerris, C. Journeau and Cognet, "Viscosity measurements of ceramic oxides by aerodynamic levitation," *Int. J. Thermodynamics,* vol. 23, pp. 1229-1240, (2002).
16. Z. Lei, J. Xu, D. Wei, H. Zhang, X. Gaus-Liu and A. Miassoedov, "Experimental Investigation of IVR nature circulation characteristics and CHF: 2DIVR-ALISA tests," in *NUTHOS-12*, Qingdao, China, (2018).
17. Y. Zhang, S. Luo, Y. Zhou, Z. Xu, D. Zhang and S. Qiu, "The first results of COPRA-ALISA experiment," in *NUTHOS-12*, Qingdao, China, (2018).
18. H. Gong, Y. Wang, Y. Zan, P. Li, I. Kljenak, E. Studer and A. Bentaib, "Experiment of light gas layer erosion in small-scale MCTHBH containment experimental facility," in *NUTHOS-12*, Qingdao, China, (2018).