Severe accident facilities for european safety targets. The safest project

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SEVERE ACCIDENT FACILITIES FOR EUROPEAN SAFETY TARGETS. THE SAFEST PROJECT

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ABSTRACT

Severe accident with core meltdown is a threat to the containment integrity. As Chernobyl and Fukushima accidents demonstrate, significant release of radioactive products into the environment can have severe consequences both for people's health and the country's economy. Severe accidents are the focus of considerable research involving substantial human and financial resources worldwide. The research field encompasses many challenging phenomena, complicated by high temperatures and presence of radioactive materials. No individual country has sufficient resources to address all important phenomena within the framework of a national research programme, therefore optimised use of resources and the collaboration at European and international level is very important. One of the main objectives of the SAFEST project of the 7th EU framework programme is integrating European severe accident research facilities into a pan-European laboratory for study of corium behaviour in severe accidents. The resources of this laboratory will be provided to other interested European partners for better understanding of possible accident scenarios and phenomena in order to improve safety of existing and, in the long-term, of future reactors. The SAFEST consortium will be able to address several severe accident issues related to accident analysis and corium behaviour. It will be a valuable asset for the fulfilment of the severe accident R&D programmes that are being set up after Fukushima and the subsequent European stress tests, addressing both national and European objectives.

KEYWORDS
LWR, safety, severe accidents, experiments

1. INTRODUCTION

After the TMI-2 and Chernobyl-4 accidents R&D programmes have been launched worldwide to study severe accidents and to propose means to mitigate their consequences to the populations and to the environment. In the European Union, these national research efforts have been shared in EU-funded projects starting at least in the 4th Euratom Framework Programme. The SARNET2 network has been coordinating research on these issues [1] and is currently pursuing this task as a dedicated Technical Area on severe accidents under Nuclear Generation II and III Association (NUGENIA) [2].

There is significant progress on simulation of in-vessel core coolability, with 2D and 3D simulation codes, focusing on the enhanced coolability of debris beds by lateral and/or bottom water inflow [3], [4]. These phenomena are being investigated in a number of experimental programs including study of multi-dimensional effects on debris bed coolability, e.g. PRELUDE at IRSN [5] and DEFOR at KTH [6]. Many experiments are currently being performed in this domain in several international projects, e.g. in the frame of SARNET within NUGENIA. They are accompanied by numerous efforts on modelling in simulation codes and benchmarking activities among these codes (e.g. OECD/NEA BE-TMI2 benchmark).

For the ex-vessel situation, significant progress has been made in R&D activities started after TMI-2 and Chernobyl accidents. Many experiments are currently performed in this domain in international projects, either in SARNET frame or in the FP7 experimental platform PLINIUS (CEA) [7]. They are accompanied by large efforts on modelling in simulation codes and benchmarking activities among these codes. Other R&D efforts are based on ANL (USA) CCI experiments. Concerning Fuel Coolant Interaction (FCI), the OECD/NEA project SERENA2 has provided a large amount of experimental data on steam explosion, including advanced visualization of premixing (the explosion initial conditions).

As corium molten pool delivers a significant part of the decay heat to the reactor pressure vessel (RPV) lower head, there is little chance to arrest melt progression without cooling. It is nevertheless necessary to study concrete ablation and molten pool configuration in the cavity to verify that there is no risk of early basement melt-through, and to provide the initial conditions for corium cooling phase or transfer to a core catcher. At present, international R&D is mostly performed in the frame of the SARNET network, mainly on the basis of the VULCANO (CEA) [8], MOCKA (KIT) [9], HECLA (UJV) [10] and SICOPS (AREVA) experiments [11]. OECD/NEA/CSNI state-of-the report on molten corium-concrete interaction (MCCI) is also in progress with a significant contribution by the SARNET network. Current 2D oxidic pool MCCI experimental programmes have shown that limestone-rich concretes are almost isotropically ablated while for silica-rich concretes lateral ablation was much larger than vertical ablation. This reproducible behaviour is not yet understood so application of the obtained results to reactor scale or to other concrete compositions (e.g. basaltic) should be done with caution [12]. Furthermore, recent experiments with oxidic and metallic pools have shown phase repartitions which are different from simple-layers assumptions considered in MCCI codes (emulsion or gravity stratification, effect of steel reinforcement).

However, severe accident research needs further efforts aiming at improvement and optimization of models (e.g. BWR-specific design features) and validation of them against future experiments. In particular, the following topics, all belonging to high-priority issues identified by the SARP group of SARNET [13], will be addressed in the SAFEST project, contributing considerably towards understanding and perhaps even closure of these issues:

- Formation and cooling of debris beds and molten corium pools in the reactor core in order to demonstrate effective cooling modes and rates, and coolability limits.
- Influence of control rod and instrumentation guide on debris bed formation and cooling and corium pool coolability for BWRs.
- Though the behaviour of pure oxidic pool in the vessel lower head is quite well understood, the efforts will be focused on scenarios with a large pool of molten corium: heat flux to metal layer in a layered molten pool configuration, including possible 3-layer configuration (observed in OECD/NEA MASCA experiments [14]).
- Corium behaviour inside BWR-type lower heads (relocation into a deep lower head filled with water).

- Database on critical heat flux and external cooling conditions in order to evaluate and design SAM measures for external vessel cooling. Influence of BWR lower head penetrations on melt cooling and its influence on the external convection.
- Location of RPV failure for BWRs, failure timing and modes.
- Phenomena related to the in-vessel retention by cavity flooding (pressurized molten corium jets directly entering water, corium concrete interaction starting underwater) that were not considered previously in experimental and analytical R&D programmes.
- Interaction of corium jets with water in the cavity pool (deep pools for BWRs).
- MCCI for concrete compositions that have not been studied earlier (e.g. basaltic concrete mainly used in Japan and in the USA) focusing on 2D convective heat transfer distribution.
- Two-dimensional concrete ablation caused by oxidic melt as well as by stratified oxide-metal melt in presence of steel reinforcing bars, focusing on metal oxidation during MCCI.
- Long-term MCCI (i.e. longer than 1 day after start of interaction) characterised by high concrete fraction and reduced heat fluxes to the concrete interface.
- Criteria and scaling approaches for extrapolation of the results obtained in small to medium scale experiments to reactor case.

To resolve these issues the partners of the SAFEST project will perform experiments, develop and validate numerical models aiming at adequate description of the investigated phenomena and, if needed, upgrade the SAFEST facilities to be able to address the future research needs. As an important part of the project, the SAFEST experimental platforms and facilities will be offered for access to external user groups. Coordinated by KIT, the SAFEST consortium is small and consists of 5 research centres (CEA, MTA EK, JRC-ITU, SCK-CEN and UJV), 2 universities (KIT and KTH), and one industrial partner (AREVA) and forms a balanced mix of expertise in state-of-the-art severe accident management and experimental research. SAFEST experimental facilities are unique in providing the possibility to perform experiments in specific fields of research on corium behaviour in severe accidents in main types of light water reactors (LWR) including BWRs. There are less than ten currently operating prototypic corium facilities in the world and three of them are located in Europe and belong to the SAFEST consortium. The SAFEST project will contribute significantly to establishment of an integrated pan-European laboratory for severe accident research able to address and resolve the variety of the issues related to the corium behaviour in severe accidents.

2. SAFEST RESEARCH FACILITIES

The activities of the SAFEST research infrastructure are divided into three groups, each one addressing a specific topic.

2.1. In-vessel Corium and Debris Behaviour

The main objective will be to reduce the uncertainties in corium behaviour during the in-vessel phase of severe accidents, either in the core region or in the vessel lower head. The goal is to find a way to terminate or limit the progression of the accident. This can be achieved either by ensuring corium retention within the RPV or at least by slowing down or limiting the corium progression into the containment. These issues are related to operational objectives: for existing reactors, severe accident management (SAM) optimization, safety evaluation and design improvement; for Gen III reactors, SAM definition, and evaluation of design and safety. The experiments will concentrate on the formation and cooling of corium debris beds and molten pools in order to demonstrate effective cooling modes and rates and coolability limits. In cases when retention is not possible, melt release conditions will be addressed. Experiments in six facilities of the SAFEST infrastructure are included in this topic.

2.1.1. QUENCH: early and late phases of core degradation

Bundle experiments in the QUENCH facility at KIT [15] are designed to study the early and late phases of core degradation in prototypic geometry for different reactor designs and different cladding alloys for a proper assessment of the risk posed by quenching of degraded core to full-scale power plants. The main component of the QUENCH test facility (Fig. 1) is the test section with ~2.5 m long test bundle which is made up of 21 fuel rod simulators and four corner rods. The fuel rod simulators are held in position by five grid spacers, four are made of Zircaloy-4 and the one at the bottom of Inconel-718. Except the central rod all rods are heated. Heating is electric by 6 mm diameter tungsten heaters of length 1024 mm installed in the rod centre. Electrodes of molybdenum and copper are connected to the tungsten heaters at one end and to the cable leading to the DC electrical power supply at the other end. The tungsten heaters are surrounded by annular ZrO_2-TZP pellets. The rod cladding of the heated and unheated fuel rod simulators is Zircaloy-4. The facility can be operated in two modes: a forced-convection mode (typical for most QUENCH experiments) and a boil-off mode. The system pressure in the test section is around 0.2 MPa absolute. The off-gas including Ar, H_2 and steam is analysed by a mass spectrometer located at the off-gas pipe. The test bundle, shroud, and cooling jacket are extensively equipped with sheathed thermocouples at different elevations with an axial step of 100 mm. There are 40 high-temperature (W/Re) thermocouples in the upper hot bundle region and 32 type K thermocouples in the lower “cold” bundle. Other bundle thermocouples are attached to the outer surface of the rod cladding. Additionally the test section incorporates pressure gauges, flow meters, and a water level detector.

2.1.2. CODEX: early and late phases of core degradation

The CODEX facility at MTA EK [16] is designed for studies of the early phase of core degradation with electrically heated fuel bundles in steam or air atmosphere. The bundle contains seven fuel rods arranged on a hexagonal lattice (VVER type) or nine rods in square arrangement (PWR type). The peripheral rods are electrically heated with tungsten bars. The central rod is not heated and is used for instrumentation. Two or three spacer grids are used to fix the bundle. The cladding material is Zr1%Nb (VVER type) or Zircaloy (PWR type). The fuel pellets are simulated by MgO pellets to allow temperature in the bundle around 2000 °C and above. The shroud is made of a 2 mm thick Zr2%Nb alloy and thermally insulated by a layer of ZrO_2. The test section is connected to the preheater and to the cooler sections as coolant inlet and outlet respectively. The preheater unit is able to supply either hot gases (including air) or steam to the test section. An additional junction is connected to the bottom part of the bundle to inject cold gas or water. The instrumentation of the facility includes measurements of operational parameters such as heating power, gas and water flow rates, temperatures, water level and pressures. Thermocouples are placed in several positions in the thermal insulation, on the thermal shield, on the shroud external surface, on the fuel rods and inside of the central unheated rod. Hydrogen concentration in the released gas is also measured. After the experiments the post-test examination of the bundle is carried out with several techniques, including metallography, SEM and microprobe analysis.

2.1.3. LIVE: behaviour of the corium melt pool

The LIVE test facility at KIT [17] concentrates on the investigation of the evolution of the in-vessel late phase of a severe accident, including e.g. formation and growth of the in-core melt pool, characteristics of corium arrival in the lower head, and molten pool behaviour after the debris re-melting in large scale 3D geometry with emphasis on the transient behaviour. The main part of the LIVE-3D test facility is a 1:5 scaled semi-spherical lower head of the typical pressurized water reactor. The diameter of the test vessel is 1 meter. The upper area of the test vessel can be covered by an insulated or a cooled lid. The test vessel is enclosed in a cooling vessel to simulate the external cooling. The volumetric decay heat is simulated by means of 6 separately controlled heating planes in the test vessel. The maximum temperature of the heating system is limited to 1100 °C. The temperatures of the vessel wall inner surface and outer surface are measured to be able to calculate heat flux distributions. Additionally, up to 80 thermocouples are positioned within the vessel to measure the temperature distribution in the melt pool and in the crust. A precise crust detection lance can detect the crust front and measure the crust/melt boundary temperature as well as the melt pool vertical temperature profile. KNO_3–$NaNO_3$ mixtures are selected as simulant material for the experiments both in non-eutectic and in eutectic mixtures.

2.1.4. RESCUE: cooling of the outer surface of reactor pressure vessel

The RESCUE facility at CEA [18] is a 4 m high mock-up designed to study the efficiency of in-vessel retention (IVR) safety systems. The mock-up is composed mainly by a water reservoir, vessel and the IVR test section scale at $1/10^{th}$ in azimuth. The test section reference gap is 30 mm in the cylindrical part and 60 in the bottom head and can be modified by inserting or pulling out baffles. The facility can be operated in two modes: natural convection or forced circulation (5 m^3/h maximum flow). The inner wall of the vessel has grooves containing heating wires. The total maximum power is 360 kW and the maximum heat flux is 400 kW/m^2. Twelve separately controlled zones allow variable heat flux profiles. The bottom head is more discretized in order to study effects of corium stratification, and especially the focusing effect. Transient profiles can be applied at a rate of up to ±15 $kW/m^2/min$. Standard measurements include temperature (wall and fluid), pressure, flow rate, water level, power and the heat flux through the vessel wall, void fraction in the fluid.

2.1.5. CERES: cooling of the outer surface of reactor pressure vessel

The CERES facility at MTA EK [19] investigates the whole spectrum of phenomena of cooling of the flooded outer surface of VVER-440 reactor vessel in large scale for a wide range of thermal-hydraulic parameters (Fig. 2). The scaling ratio of CERES is 1:40 for the external surface of the reactor vessel and 1:1 for the elevations to provide driving forces for the natural circulation. The length of coolant channel section is 900 mm from the elevation of 1300 to 2200 mm. The gap size of coolant channel is 20 mm if the vessel is cold and it is in symmetric position in the cavity. If the vessel is in asymmetric position, the vessel wall can contact the cavity wall causing the most narrow gap size. To measure the effect of coolant channel contraction on the heat transfer, two different asymmetric channels were constructed. Coolant flows to the bottom of vessel model through the flooding line and enters the coolant channel at the lower end of the vessel model. It leaves the coolant channel at elevation of 6.850 m, as in the real plant, then enters the hermetic compartment model and cooled down by the condenser of CERES loop. The heaters are grouped in three parts: two in the bottom of reactor vessel model and one at core elevation. Heating power is provided by 296 electrical heating elements with a power of 0.5 to 2.0 kW each (maximum available power is 500 kW). The maximum heat flux in the bottom part amounts to 80 kW/cm^2 and 18 kW/cm^2 at the core elevation level. The instrumentation allows measurement of wall temperature, coolant temperature and coolant level, mass flow rate and electric power. The 120 channel data acquisition system is used for organizing the whole recording, collecting and processing the measured data.

2.1.6. POMECO: coolability of porous media

POMECO test facilities at KTH [4] are focused on the coolability quantification of debris beds formed in a hypothetical severe accident in LWRs, when the molten corium is relocated into a water pool, fragmenting and forming a particulate debris bed on the water pool bottom for both in-vessel and ex-vessel scenarios. The POMECO-FL facility was designed to investigate adiabatic air/water single/two-phase flow characteristics in particulate beds. The focus of the on-going research in the facility is to obtain the effective particle diameter and the two-phase flow friction law of a prototypical particulate containing multiple particles sizes and irregular shapes. The coolability of such debris beds is investigated in the POMECO-HT test facility using about 30 litres of electrically heated corium debris simulants. The facility features flexibility of reconfiguration and a maximum heat flux of 2.1 MW/m^2, which enable coolability investigation on various beds of a broad range of particles with either top-flooding or bottom-fed schemes. The facility is also well instrumented with two differential pressure transducers installed to measure the pressure drops. The bed can be quenched from top by an overlying water pool and from bottom by using downcomers or forced injection of water.

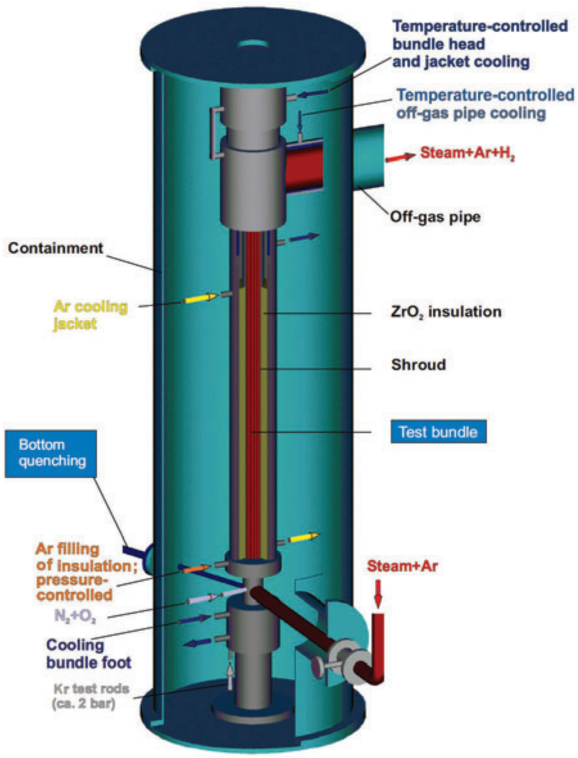

Figure 1. QUENCH containment and test section.

Figure 2. Test section of the CERES facility.

2.2. Ex-vessel Corium and Debris Behaviour

In the case of a severe accident with vessel melt-through, the containment is the ultimate barrier between the corium and the environment. The issue considered in this task is the threat to the containment integrity due to ex-vessel steam explosions (energetic fuel-coolant interactions), and molten corium-concrete interaction. The coolability of debris beds formed during melt ejection from the vessel into a deep water pool (like in Nordic-type BWRs and some other PWR and BWR designs) will be studied. The major objective is to provide new data and understanding of ex-vessel fuel-coolant interaction, debris bed formation, coolability and corium-concrete interaction, by using innovative approaches to address more prototypical phenomena and to achieve significant progress toward the closure of these issues. Experiments in eight facilities of the SAFEST infrastructure are included in this topic.

2.2.1. DISCO: melt dispersion and direct containment heating

The DISCO facility at KIT [20] is 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. The main components of the facility are scaled about 1:18 linearly to a large PWR. The model of the containment pressure vessel has a height of 5.80 m and a total volume of 14 m^3. The reactor pit is made of concrete and is installed inside a strong steel vessel. The main cooling lines are modelled by eight horizontal steel cylinders with a scaled annular space around each of them, modelling the flow path leading into the equipment rooms. The equipment rooms are modelled according to the reactor design being investigated. The RPV model serves as crucible for the generation of melt by a thermite reaction between iron oxide and aluminium. The breach in the lower head is modelled by a graphite annulus at the bottom, which is closed with a brass plug. The experiment is started by igniting the thermite electro-chemically at the upper surface of the compacted thermite powder and the brass plug at the bottom of the RPV vessel is melted by the 2100 °C hot iron-alumina mixture. That initiates the melt ejection. The melt is driven out of the breach by the steam and is dispersed into the cavity and beyond. Standard test results are: pressure and temperature history in the RPV, the cavity, the reactor compartments and the containment vessel, post-test melt fractions in all locations with size distribution of the debris and pre- and post-test gas analysis in the cavity and the containment.

2.2.2. KROTOS: medium-scale fuel coolant interaction tests

KROTOS facility at CEA [20] is dedicated to steam explosion studies. The facility (Fig. 3) consists of four main parts: the furnace, the transfer channel, the test section and the X-ray radioscopy system. The furnace is designed to prepare about 5 kg of corium at more than 2850 °C. The transfer channel is used to transfer the crucible containing the melt to the test section. The test section consists of a pressure vessel with a test tube inside. Both are made of strong tempered 7075 aluminium alloy, characterized by low attenuation of X-ray radiation. The test tube is a free standing 1.6 m long and 0.2 m diameter cylinder filled with water. At the bottom of the test tube a pressurised gas trigger (150 bars) is positioned. Both the chamber and the test tube are equipped with thermal, optical and pressure instrumentation in order to follow the premixing, the propagation and the explosion phases, thus providing maximum information on FCI. The X-Ray radioscopy system has been specifically developed and assembled on KROTOS facility. The 6 MeV X-ray radioscopy system is used to trace the fragmentation of the melt within the coolant, allowing the three phases (water, void and melt) to be clearly distinguished.

2.2.3. SES: FCI during melt spreading underwater

The SES facility at KTH is an experimental facility for investigation of FCI in stratified melt coolant configuration and underwater melt spreading. The facility consists of 45kW medium-frequency generator, induction furnace with a SiC crucible for melt preparation, melt delivery funnel, impact pale, and a test section (water pool). The test section is an opened stainless steel rectangular container: 0.8 m deep, 1x1 m wide positioned 800 mm above the ground on the supporting frame. The lateral walls are equipped with Plexiglas windows allowing visualization of the melt delivery and spreading. The bottom of the test section is a 10 mm thick stainless steel plate. Its central part, the impact plate, is a separate construction with reinforced support, which stands on 4 dynamic force sensors each allowing force measurement in the range from 0 to 330 kN with overall maximum of 1320 kN. The SES facility can be used to obtain insights on energetics of steam explosion, melt spreading dynamics and development of melt-coolant premixing layer. Interactions between molten binary oxidic melt mixtures at temperatures up to 1600 °C and masses up to 80 kg with large shallow water pool at temperatures up to 95 °C can be studied in the SES facility.

2.2.4. DEFOR: debris bed formation and agglomeration of particles

The DEFOR facility at KTH [22] provides data about the influence of pool depth and subcooling, melt jet diameter, and initial melt superheat on the fraction of agglomerated debris. The experiments help to understand the underlying physical phenomena of debris agglomeration. The results are being used for development and validation of computer codes used for prediction of properties and coolability of debris beds. DEFOR facility is composed of a 45 kW medium-frequency (up to 50 kHZ) induction furnace for melt generation, a melt delivery funnel, and a coolant tank with glass windows for visual imaging of transient melt-coolant mixing and debris formation. The simulant material melt, typically a binary oxide mixture of Bi_2O_3-WO_3, is generated in a SiC crucible or in a double crucible of SiC as a back-up for Zirconia crucible. The liquid melt is delivered to the funnel by tilting the crucible (Fig. 4). The delivery funnel is conical with a replaceable discharge nozzle up to 25 mm in diameter. The test section is an open rectangular tank (2 m tall, with cross section 0.5 x 0.5 m).

2.2.5. MISTEE: characterization of the multi-phase flow during FCI

The MISTEE facility at KTH [23] is designed to provide high-quality data for steam explosion under well-controlled conditions equipped with a synchronized precise optical photography and X-ray visualisation systems. The visualization and quantitative characterization of complex multi-phase flows related to FCI is achieved by using a fast synchronous imaging system which includes a high speed (up to 100.000 fps) digital photography and a high speed (up to 8.000 fps) X-ray radioscopy, with advanced post-test image processing and analysis. The facility is used to perform experiments dedicated to obtain a basic understanding of micro-interactions during steam explosion, with the objective to identify mechanisms limiting the explosivity of molten corium during FCI. The facility can also be applied to investigate the characteristics of boiling, bubble dynamics and multiphase flow and is currently being upgraded for use of prototypic corium.

Figure 3. KROTOS facility.

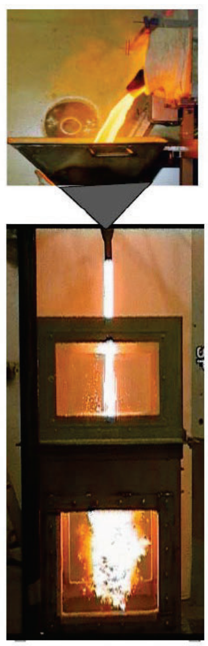

Figure 4. DEFOR facility.

Figure 5. Cross-section of the MOCKA crucible.

2.2.6. MOCKA: molten corium concrete interaction

The experiments in the MOCKA test facility at KIT [9] investigate the two-dimensional concrete erosion in a cylindrical crucible (Fig. 5). To allow sufficient time and material for the erosion process, the cavity of the crucible is fabricated as a massive concrete structure. Different types of concrete can be used in the MOCKA facility: siliceous, siliceous/limestone, limestone, serpentine ($Mg_3Si_2O_7 .2H_2O$, used in East

European plants). The simulant melt is generated by ignition of the thermite mixture (aluminium with iron oxide) in a concrete crucible with initial temperature around 1850 °C. In current tests the total mass of the melt is 450-500 kg, the maximum mass of the melt can be up to 3 tons. To extend the duration of the interaction with the concrete, a succession of additions of pure thermite and Zr metal from the top into the oxide layer is implemented. The additional enthalpy generated by the thermite reaction and exothermal oxidation reactions of Zr is mainly deposited in the oxide phase. To detect the time dependent erosion front and to control the course of the experiment the crucible is instrumented with type K thermocouples embedded in the concrete. In most cases, their failure indicates the arrival of the melt front.

2.2.7. VULCANO: spreading of prototypic corium melt and MCCI

The VULCANO facility at CEA [8] is a rotating plasma arc furnace able to melt about 80 kg of corium at temperatures of up to 3000 °C (in- or ex-vessel corium) and to pour the melt in a dedicated test section. The major advantage of this technique is the possibility to melt a wide spectrum of compositions (from UO_2-ZrO_2 to mixtures with some metals and/or concrete decomposition products). The typical mass of molten oxides is in the 30 to 60 kg range. Metal melting furnaces using induction heating technology are also available to add metals to the melt. Melt generation by a thermite reaction has also been developed enabling the melting of some specific corium compositions thanks to exothermal redox reactions. Corium can be poured into a crucible in which radioactive decay heat will be simulated by a 150 kW inductor device. The following phenomena can be studied in the tests:

- corium spreading on various types of substrates (ceramic, metal, concrete…),
- corium solidification,
- corium pool thermo-hydraulics,
- corium progression in debris bed,
- long-term interaction of corium with different materials (e.g. core catcher),
- validation of corium cooling strategies and/or devices.

2.2.8. SICOPS: medium-scale MCCI with prototypic corium melt

The SICOPS facility at AREVA is used for studies of different phenomena of the interaction of molten corium with concrete or other sacrificial material and with protective material and to generate data on thermophysical and thermochemical processes during interaction of melt with concrete or other material. The experiments are performed in a cold crucible with sustained heating and with material mass of up to 20 kg (both simulant and prototypic materials) and with a generator power of maximum 100 kW. The cold crucibles have diameters of up to 20 cm. The melt temperature can be measured with thermocouples and the melt surface temperature with a pyrometer. The facility is equipped with several cooling circuits to determine power input into the crucible and heat losses. Furthermore, it can be run with different gases inside the test vessel and an off-gas measurement with an online gas mass spectrometer or oxygen sensors can be applied. Samples taken from the melt as well as the materials solidified inside the crucible after the end of a test can be analysed by various methods, e. g. optical microscopy, SEM/EDX, chemical analyses. The facility is mainly used for tests on corium-concrete interaction (1D, 2D) with oxidic and mixed metallic/oxidic melts and for material studies with high-temperature melts (up to ~3000 °C).

2.3. Corium Properties

Modelling of corium behaviour and interpretation of experiments require qualified data on corium physical properties and on corium phase diagrams (which result from its chemical thermodynamic properties). Due to high temperatures (1200-3000 °C) of corium melts and large range of corium compositions, only limited data exist on corium properties at least for some particular compositions. For corium phase diagrams, a substantial amount of work has been performed and is available in the NUCLEA database [24] that still needs to be completed for several important corium compositions. However, some properties, in particular viscosity and surface tension, are not sufficiently known. Therefore the specific objectives will be to improve the existing corium properties database and to provide validated data for severe accident codes. Experiments in three facilities of the SAFEST infrastructure are included in this topic.

2.3.1. VITI: thermophysical and thermochemical properties of corium

The VITI facility at CEA [25] has been developed to perform viscosity and surface tension measurements on corium by aerodynamic levitation up to 2500 °C. Corium samples containing depleted uranium with a mass from a few milligrams to 100 grams can be studied in the tests. The facility can also be used for small mass experiments for properties estimation or material compatibility tests. The facility consists of an induction heater located in an enclosure, which allows controlling the atmosphere (Fig. 6). Portholes are used for video camera imaging and optical pyrometry measurements. Two techniques are available: levitating droplet technique for contactless measurements and crucible heating. VITI uses aerodynamic levitation of a droplet between two gas diffusers. This system allows contactless heating and measurement of the sample. The shape at rest is controlled by density and surface tension. The relaxation of a droplet after the deformation or the damping of resonances is linked to viscosity, density and surface tension. The VITI facility may also be used for small crucible (typically 5 cm^3) experiments. For example, chemical diffusion measurements have been made by an in-corium electrochemical technique. A special furnace with hafnium dioxide ceramics is available, so that the tests can be performed in oxidizing conditions.

2.3.2. FLF: melting behaviour of corium compounds

The FLF facility at JRC-ITU (Fig. 7) utilises a laser heating/melting combined with fast pyrometry to study the melting behaviour of pure compounds and binary systems under various atmospheres. The heating agent is a Nd:YAG 4.5 kW continuous wave (cw) laser programmable with a complex power/time profile, allowing thermal cycles of variable duration from a few ms up to some minutes, in order to optimize heating and cooling rates. Experimental parameters can actually be optimized according to the sample features (volatility, chemical stability etc.) and the kinetics of the phase transformations under investigation. Temperature is measured on the heated sample surface by means of fast pyrometers. In addition, a novel method has been applied to determine phase transitions based on the detection (via a suited low-power (mW) probe laser) of changes in surface reflectivity that may accompany solid/liquid phase transitions. Experiments are carried out in an autoclave under medium-high pressure (from a few tenths up to a few hundred MPa) of an inert gas (helium or argon) in order to suppress as much as possible evaporation phenomena in highly volatile samples, and to study the behaviour of phase transition points as a function of pressure. With this set-up, it is possible to mount small scale samples (up to 1 g) in an alpha-shielded glovebox. It is thus possible to investigate the high temperature behaviour of samples containing trans-uranium elements (particularly Pu and Am).

2.3.2. COMETA: corium heating and melting techniques

The COMETA facility at UJV [26] is a cold crucible induction furnace designed for several kilograms of corium that can be melted and analysed including melt sampling, aerosol and melt composition analysis. The cold crucible was constructed for powder oxide materials melting with melt temperatures up to 3000 °C. The facility was adopted for the operation with radioactive materials (in particular with UO_2) and intended for simulating real corium melts. The cold crucible has an experimental capacity of about 1 kg of initial corium batch (250 cm^3 volume of the melt) and can reach a melt temperature of 3000 °C. The power supply in this facility is a high-frequency generator which provides a power of up to 60 kW in the melt at a frequency of 4.5 MHz. The movable frame enables the subsequent directed crystallization of the corium melt. The system is equipped with full computer control and measurement evaluation.

Figure 6. VITI facility.

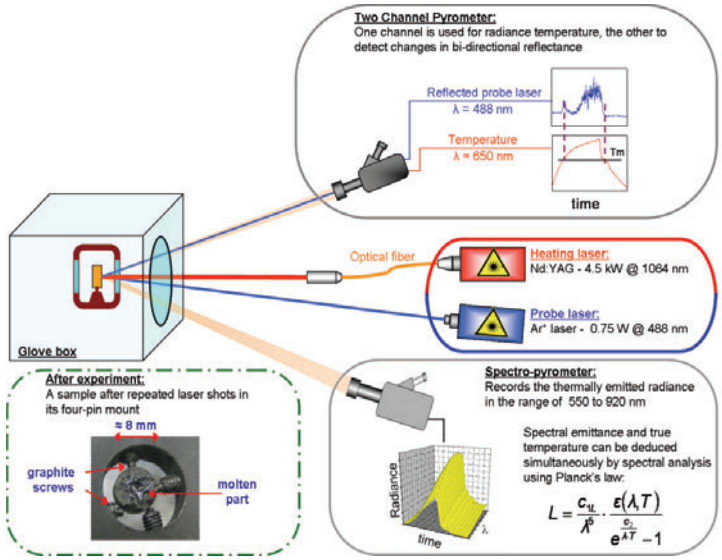

Figure 7. Scheme of the FLF facility.

3. CONCLUSIONS

Joint experimental research is a clear objective of the SAFEST project to provide solutions for stabilisation of severe accident and termination of consequences for the current Gen II and III plants. A direct outcome from the project will be progress towards creation of an integrated pan-European laboratory for study of corium behaviour in severe accidents. By strengthening the links between the main European corium facility operators and by improving the capabilities and performance of the SAFEST experimental facilities, this laboratory will be a valuable asset for the fulfilment of severe accident R&D programmes which are being set up after Fukushima and the subsequent stress tests both at the national level and at the European level. Indeed, the project encompasses a very large spectrum of severe accident phenomenology dealing with corium (mainly oriented towards LWRs, even though several aspects of Gen IV severe accidents can be studied in some of the SAFEST facilities). This laboratory shall build links with other countries out of Europe such as the Japan, Russian Federation, USA and China.

Another result of the SAFEST activities will be a better understanding of physical background of severe accidents and prototypic corium behaviour. It will benefit the EU utilities and safety organisations, which will be able to validate (either directly through the access to the SAFEST infrastructure or indirectly through R&D) the hypotheses for severe accident scenarios and propose pertinent procedures for accident mitigation taking into account experimental results. The experimental results will be used for the development and validation of models and their implementation in the severe accident codes such as MELCOR, MAAP and ASTEC. This will help to capitalise the knowledge obtained in the field of severe accident research in severe accident codes and scientific databases, thus preserving and diffusing this knowledge to a large number of current and future end-users. Consequently, the knowledge obtained in SAFEST shall lead to improved severe accident management measures, which are essential for reactor safety. In addition it will offer competitive advantages for the nuclear industry and contribute to the long-term sustainability of nuclear energy.

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