Main outcomes of the European SAFEST project towards a pan-European Lab on Corium Behaviour in Severe Accidents

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ABSTRACT

SAFEST (Severe Accident Facilities for European Safety Targets) is a European project networking the European corium experimental laboratories and CLADS/JAEA, Japan. The duration of the project was 4.5 years and ended in December 2018. Its objective is to address the variety of the remaining severe accident issues related to accident analysis and corium behaviour in Light Water Reactors. The project is a valuable asset for the fulfilment of the severe accident R&D programs that are being set up after Fukushima and the subsequent European stress tests, addressing both national and European objectives. It has the aim of establishing coordination activities, enabling the development of a common vision and research roadmaps for the next years, and of the management structure to achieve these goals.
All-important severe accident phenomena cannot be addressed within the framework of a national research program, therefore optimized use of resources and the collaboration at European and international level is very important. Integrating European severe accident research facilities into a pan-European laboratory for severe accident and corium studies and providing resources to other European partners for better understanding of possible accident scenarios and phenomena is necessary in order to improve safety of existing and, in the long-term, of future reactors.
Roadmaps on European severe accident experimental research for light water reactors and for GenIV technologies has been developed. Joint R&D has been conducted to improve the excellence of the SAFEST facilities: this includes measurement of corium physical properties, improvement of instrumentation, consensus on scaling law rationales and cross comparison of material analyses.
Joint experimental research was a clear objective in the SAFEST project to provide solutions for stabilization of severe accident and termination of consequences for the current GEN II and III plants. Consequently, the knowledge obtained in SAFEST shall lead to improved severe accident management measures, which are essential for reactor safety. In addition, it offered competitive advantages for the nuclear industry and contribute to the long-term sustainability of nuclear energy. The paper will address the main objectives and R&D activities of the project and then will concentrate on the main outcomes of the project.

KEYWORDS
SAFEST, LWR, Severe Accidents, Corium

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 for the populations and to the environment. In the European Union, these national research efforts have been shared in EC-funded projects starting at least in the 4th Euratom Framework Programme. The SARNET2 network [1] has been co-ordinating research on these issues and is currently pursuing this task as a dedicated Technical Area on severe accidents under Nuclear Generation II and III Association (NUGENIA) [2].

The efficiency of cooling reactor core structures and materials during severe accidents either in the core region, in the vessel lower head or in the reactor cavity is a key issue to limit the progression of the accident. This can be achieved either by ensuring corium retention within the reactor pressure vessel (RPV) or at least by limiting the corium progression and, consequently, the rate of corium release into the reactor cavity in case of RPV failure. These issues are covered within the scope of accident management for existing reactors and within the scope of design and safety evaluation of future reactors. The specific objectives addressed creation of a database on coolability of degraded core, debris formation, debris coolability and corium behaviour in the lower head, development and validation of models and computer codes for simulation of in-vessel debris bed and melt pool behaviour, performance of reactor scale analysis for in-vessel corium coolability and assessment of the influence of severe accident management measures on in-vessel coolability.

Currently available data on degraded core reflooding are summarised in the reflood map developed at KIT, which is being constantly updated to include findings from previous and currently running programs on the coolability of the reactor core, taking into account available coolant mass flow rates and the core damage state. Substantial knowledge and understanding of the phenomena governing the coolability of intact rod-like reactor core geometry was obtained in numerous national and international projects. However, major gaps in knowledge still exist in the areas of debris and molten pool behaviour.

There is a 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/PEARL 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 BSAF 1 and 2 benchmarks on Fukushima-Daiichi accidents).

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 PLINIUS experimental platform at CEA. 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 on molten corium-concrete interaction. Concerning Fuel Coolant Interaction (FCI), the OECD/NEA project SERENA2 [7] 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 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, as means 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 NUGENIA TA2/SARNET network, mainly on the basis of the VULCANO (CEA) [8], MOCKA (KIT) [9], HECLA (VTT) [10] and SICOPS (AREVA GmbH) experiments [11]. OECD/NEA/CSNI state-of-the report on molten corium-concrete interaction (MCCI) has also been recently published [12] 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 [13]. 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).

Globally, an important database exists on the phenomena occurring in non-mitigated ex-vessel situations (steam explosion, direct containment heating, corium spreading and molten core concrete interaction, debris bed formation and coolability) and for the support of commercially available core catchers. Nevertheless, there are some remaining uncertainties on application of the results obtained in experiments to reactor conditions.

Moreover, since most of previous severe accident research topics were focused on PWR design and majority of severe accident codes and models were developed for PWRs, only some special experimental series were focused on BWR-type reactors. It was in agreement with the fact that most of the operating light water reactors (LWR) are of PWR type. However, large number of BWR reactors is operated worldwide and in Europe as well.

The Fukushima Daiichi accident demonstrated that some BWR specific design features can play a very important role in severe accident progression. For example, the penetrations for control rods through the lower head most probably affected release and behaviour of molten core in the reactor cavity; however, this phenomenon has to be confirmed after defueling of Fukushima Daiichi plants.

Additionally, the stress tests of nuclear power plants in the European Union pointed out that some BWR special features may have an impact on severe accidents, e.g. the flooding of lower drywell may stabilise ex-vessel molten corium progression. The planned or implemented safety improvements included also some BWR-specific topics. For example, in Germany the development of accident management measures was proposed to protect the building structure surrounding the spent fuel pool in BWRs, which is located outside the containment, against hydrogen combustions or to prevent them. In Finland, the installation of additional emergency diesel generators and of diverse and independent ways of pumping water to the RPV via fire-fighting diesel driven pumps is foreseen in BWR units. Other specific features of BWR design which require further detailed analysis include:

- larger vessel dimensions and mass of water, deeper cavity,
- channels and bypasses in the core, separated by the canisters of fuel assemblies which can influence melt relocation and oxidation of Zircaloy,
- control rod and instrumentation guide tubes in the vessel lower head which can influence formation of in-vessel debris beds, RPV failure mode and timing, possible limitation of flow-rate of releasing melt, mass and composition of the releasing corium,
- nitrogen inertisation of primary containment which may have a significant impact on early core degradation.

All these facts emphasize that the severe accident research for BWR needs further efforts aiming at improvement and optimization of BWR-specific models and validation of them against future experiments, which is one of the main objectives of the SAFEST project.

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 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 facilities are operated by a team of experts who have long and recognised experience in the nuclear safety research. The SAFEST project will contribute significantly to establishment of an integrated pan-European laboratory for severe accident research able to address and successfully resolve the variety of the remaining issues related to the corium behaviour in severe accidents. The way towards the establishment of a pan-European laboratory will clearly depend on conclusions of the roadmap activities planned in the project. This unique consortium will be a valuable asset for the fulfilment of the severe accident R&D programmes that are being set up after Fukushima Daiichi accidents and the subsequent European stress tests, addressing both national and European objectives, in collaboration with major international stakeholders.

In particular, the following topics, all belonging to high-priority issues identified by the SARP group of SARNET [14] and confirmed in the NUGENIA R&D roadmap, are 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. The specific R&D objectives are to create and enhance the database on debris formation, debris coolability and corium pool behaviour in the lower head, to develop and validate the models and computer codes for simulation of in-vessel debris bed and melt pool behaviour.
- 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 [15]). An important point is the thickness of the metallic layer. This is of high priority because it can influence strongly the strategy for in-vessel retention concepts in some of the existing (e.g. VVER-440) and new plant designs.
- Corium behaviour inside BWR-type lower heads including corium relocation into a deep lower head filled with water, significant thermo-mechanical loads on the vessel structures during debris re-heating and re-melting, and high fraction of Zr in the core.
- 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.
- New 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) after a failed in-vessel retention, focusing on jet fragmentation to provide reliable initial conditions for the steam explosion phase and to determine the characteristics of the formed debris bed (particle size distribution, geometrical repartition, chemical state) that are necessary inputs for debris bed coolability issues.
- MCCI for concrete compositions that have not been yet 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 perform experiments, develop and validate numerical models aiming at adequate description of the investigated phenomena and 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 are offered for access to external user groups.

2. PROJECT ACTIVITIES

Coordinated by KIT, the SAFEST consortium is small and consisted at the beginning of five research centres (CEA, MTA EK, JRC-ITU, SCK-CEN and UJV), two universities (KIT and KTH), and one industrial partner (Framatome) and forms a balanced mix of expertise in state-of-the-art severe accident management and experimental research. Complementarity and synergy between partners is maximized by identifying overlapping roles in this project and exploiting them by choosing the partner best suited to the identified tasks. The involvement of the industry is beneficial in providing a balanced approach between research and industrial needs. In 2018 JAEA/CLADS, Japan, joint the consortium which showed the importance of SAFEST activities on the international level.

The SAFEST project is divided in 5 work packages which reflect the main goals of the project:
- WP1 Project Management (MANAG)
- WP2 Development of research roadmaps (DRR)
- WP3 Distributed research infrastructure (DRI)
- WP4 Upgrading the capacity of facilities and increasing the quality of R&D (UCF)
- WP5 Preserving and disseminating the knowledge (PDK)

2.1. Development of Research Roadmaps (WP2)

2.1.1 European corium experimental research roadmap

The general objective was to develop a common vision and experimental research roadmaps for the next years, and the management structure to achieve these objectives. The draft of the European corium experimental research roadmap was completed in 2016 with the help of many contributors from the various SAFEST partners [16]. It is based on the research priorities determined by SARNET SARP group as well as those from the NUGENIA Technical Area 2 on severe accidents. It also takes into account issues identified in the analysis of the European stress tests and from the interpretation of the Fukushima-Daiichi accident. The roadmap takes advantage of the current and developing European corium infrastructures and, if necessary, recommends its adaptation. This first version of the roadmap was then officially distributed within SAFEST and NUGENIA stakeholders and was published in open literature [17]. After the collection of remarks, the finalised version of the roadmap has been published in autumn 2018.

2.1.2 Joint Fukushima experimental research roadmap with Japan

Following the Fukushima-Daiichi accident, JAEA experts have contacted European counterparts in order to promote joint R&D activities as well as to solicit scientific and technical support from EU to Japan. As a consequence, a series of meetings between the SAFEST consortium and Japanese organizations were held aiming at assessing long-term goals and proposing experimental support needed for proper understanding and interpretation of Fukushima-Daiichi accident, analysis of collected debris in European and Japanese laboratories and even eventual processing of molten cores.

As a result a report has been published in autumn 2018 [18], which summarizes an overview of ongoing severe accident studies in the area of corium behaviour, and a comparison of research priorities identified in different projects and documents from both the EU and Japan. The research priorities, particularly on reactor core melt (corium) behaviour, were finally suggested for the EU-Japan roadmap which prioritizes research topics most relevant to Japan. They are safety issues of existing and future LWRs and especially Fukushima decommissioning. This relevant R&D can be carried out in the collaboration between EU and Japan. In parallel with this survey a re-evaluation of the SARP priorities in the EU was also carried out separately in a SAFEST report [19]. It is noted that the re-evaluation included a list of new topics proposed many of which are relevant to current concerns in Fukushima.

The resulting roadmap provides useful guidelines for assessment of long-term goals and proposals for experimental support needed for proper understanding, interpretation and learning lessons of the Fukushima accident; analysis of severe accident phenomena; development of accident prevention and mitigation strategies and corresponding technical measures; study of corium samples in European and Japanese laboratories; and preparation of Fukushima site decommissioning.

2.1.3 Joint experimental research roadmap with ROSATOM

Some important issues have been encountered in the development of a Joint EURATOM-ROSATOM experimental research roadmap. Russia carried out much severe-accident related research (for example national R&D related to the ex-vessel core catchers for VVER-1000 and -1200 plants, the OECD and the ISTC projects). However, the current severe accident research collaboration with EU is limited despite the new VVER builds in Finland and Hungary. Russian colleagues of the Joffe Institute together with KTH, Sweden made an application to the Ministry of Education and Science of the Russian Federation for a joint performance of a Russian-European roadmap in the area of experimental research of energy –expensive processes at NPP's. This would have been linked to the SAFEST project and KTH acted as a contact point of the project consortium. Unfortunately, the project proposal has not been funded because of very strong competition within this call. As a consequence, the collaboration between EU and Russian partners has been continued on the basis of individual contacts with particular research centers only. Nevertheless, a roadmap report has been finalized in autumn 2018 focused on the assessment of a roadmap for common severe accident investigation activities between the European Union and the Russian Federation, by summarising and analysing existing joint activities and experimental facilities that can be used for pursuing common research objectives. The experience from past collaboration within the ISTC and the ERCOSAM/SAMARA project between EURATOM and ROSATOM are taken as a basis for the roadmap. In addition, some original EU experimental facilities are listed, which can be used for future collaborations. These collaborations will also involve the analysis of Chernobyl lava, particles and debris samples, and new experimental activities linked to the analysis of the Fukushima Daiichi nuclear power plant accident occurred in 2011.

2.1.4 European safety research roadmap for next generation plants

Safety research roadmap for Gen IV plant safety has also been developed taking advantage of the knowledge and expertise obtained for existing reactors as well as on specific safety characteristics of considered Gen IV designs. The SAFEST facilities are able to perform unique experiments aimed to investigate severe accident phenomenology of LWR reactors. The objective of the report is assessing the possibility to extend the application field of the SAFEST facilities to the GEN IV reactor technology issues, in particular focusing on the three technologies sustained by the Strategic Nuclear Energy Technology Platform (SNETP): Gas-cooled fast reactors, lead-cooled fast reactors and sodium-cooled fast reactors. The SAFEST partners expressed their assessment over selected phenomena of the core degradation and post-accident phases of severe accidents. This roadmap report has to be intended as a first step towards a detailed roadmap for R&D concerning severe accident for GEN IV reactors.

2.2 Experiments in the SAFEST Distributed Research Infrastructure (WP3)

Being one of the most important activities of the project, the experimental facilities of the SAFEST partners are integrated into a pan-European laboratory for severe accident and corium studies and are offered to external organizations who are interested in performing the tests. The activities of the SAFEST distributed research infrastructure are divided into three groups, each one addressing a specific topic:

- In-vessel corium and debris behaviour;
- Ex-vessel corium and debris behaviour;
- Corium properties.

After publishing the rules of access to the SAFEST facilities in October 2014, two calls for proposals were announced attracting the interested users to specify the experimental requirements and conditions. Following each call, the user selection panel with the help of independent international experts evaluated the proposals and selected a short-list of user groups. Together with facility operators the user groups prepare, perform, analyse and document the experiments. Total of 16 experiments have been selected to be performed in the SAFEST test facilities until the end of the project, Table I.

Table I. List of experiments performed in SAFEST.

	Test facility	Title / Objective of Experiment	Proposing Organisation
1	MISTEE, KTH	Investigation of material effect related to steam explosion in MISTEE at KTH Sweden	IRSN, EDF, CEA (France), JSI (Slovenia)
2	COMETA, UJV	Kinetics of UO_2-B_4C interaction (KUBI) [20]	CEA (France)
5	SES, KTH	Investigation of stratified steam explosion phenomena [21]	EDF, CEA, IRSN (France), IKE (Germany), JSI (Slovenia)
3	DEFOR, KTH	Debris beds formed from FCI in presence of a control rod guide tube in BWRs [22], [23]	KIT (Germany)
4	SICOPS, AREVA	MCCI for prototypic BWR corium and concrete compositions [24]	SSM (Sweden)
6	CERES, MTA EK	Extension of experimental justification of in-vessel retention strategy for VVER-440 reactors addressing specific aspects of real operational conditions	Bohunice NPP (Slovak Republic)
7	DISCO, KIT	Investigation of scaling effect during FCI premixing in the DISCO facility [25]	IRSN (France)
8	FLF, ITU	Performance of a series of measurements for Zr-rich U-Zr-O ternary system	SSM (Sweden)
9	CODEX, MTA EK	CODEX-AIT-3: simulation of air ingress reactor accident with steam and oxygen starvation and without quench	KIT, IKE, GRS (Germany), CEA, IRSN, EDF (France), PSI (Switzerland), LEI (Lithuania), IBRAE (Russia)
10	MOCKA, KIT	Investigation of the efficiency of the protection structure of cable penetrations in some Nordic BWRs [26]	SSM (Sweden)
11	QUENCH, KIT	Study of BWR-specific important phenomena like influence of control rod blade on bundle degradation and top spray cooling efficiency	SSM (Sweden)
12	LIVE, KIT	Study of the focusing effect and its dependence on the metal layer thickness [27]	IRSN (France)
13	MISTEE, KTH	Investigation of oxidation effect related to fuel coolant interaction in MISTEE	IRSN, EDF, CEA (France), JSI (Slovenia)
14	FLF, ITU	Emissivity measurements for the reduction of the uncertainties relative to the focusing effect	EDF, CEA, IRSN (France), KTH (Sweden), KIT, HZDR (Germany)
15	VULCANO, CEA	Crust-free concrete containing corium melt interaction with siliceous concrete [28]	KIT, GRS (Germany)
16	VITI, CEA	Thermo-physical measurements of in-vessel prototypic metallic alloys compositions	ITU (Germany), KTH (Sweden)

2.3 Upgrading the Capacity of Facilities and Increasing the Quality of R&D (WP4)

SAFEST experimental facilities are unique in performing experiments to study corium behaviour in severe accidents including both experiments with simulant materials and experiments with prototypic corium. The latter are necessary for phenomenological analysis and for model validation. However, since most research topics in the past were focused on PWR design, there are clear needs for improvement and upgrading of SAFEST facilities towards BWR-specific features. The increase of experimental capabilities and overall quality of R&D to meet current and projected challenges is another very important task.

The facility upgrading is considered as a continuous process to share good practices and improve the capabilities of the existing facilities. For the medium and long-term support the roadmaps (described in section 2.1) will serve as a definite basis for the directions of the upgrading of facilities to meet the future needs. As an example of upgrading of SAFEST facilities towards BWR-specific features, the following activities have been considered:

- QUENCH facility at KIT: high temperature degradation of BWR mock-up assembly containing the fuel rod simulators, the channel box and the absorber blade. Data on cladding oxidation and hydrogen generation and release, material degradation and relocation (including melting and relocation of control blade materials) are measured during the test and obtained in the post-test material analysis.
- DISCO facility at KIT: interaction of corium melt jet with water in a deep pool, focusing on jet fragmentation to provide reliable initial conditions for the steam explosion phase and to determine the characteristics of the formed debris bed (particle size distribution, geometrical repartition, chemical state) that are necessary inputs for debris bed coolability issues.
- DEFOR facility at KTH: influence of BWR control rod and instrumentation guide tubes on melt jet fragmentation in water in the reactor cavity and debris bed formation.
- SICOPS facility at AREVA: MCCI for prototypic Nordic BWR corium melt and concrete compositions.
- MOCKA facility at KIT: a two-dimensional large scale MCCI caused by stratified oxide-metal thermite melt with concrete typical for Nordic BWRs addressing also the influence of steel rebars in the concrete on the ablation progression.
- FLF facility at JRC: study of melting and crystallization behaviour of BWR-specific corium compositions to assess the quasi-binary section of ternary U-Zr-O diagram in the domain of U/Zr atomic ratio close to 0.9 and Zr oxidation index close to 20-30%.

Besides the upgrading of SAFEST facilities towards BWR-specific features, a lot of interesting and important work has been performed within the work package 4 concerning:

- Measurements of thermophysical properties (density and surface tension) of corium in the VITI test facility which has been adapted to new measurement techniques (Sessile Drop, Maximum Bubble Pressure) within SAFEST project.
- Joint research to improve the quality, precision and durability of high temperature instrumentation including the installation of high-temperature fixed-point eutectic cells for temperature calibration in VITI.
- A round robin analysis of a corium sample of SICOPS test A19. Within this analysis the measurements from CEA Marcoule, CEA Cadarache, UJV Rez and ITU Karlsruhe will be compared.

2.3.1 Recommendations for selecting simulant materials and scaling approaches

Some of the SAFEST experiments are conducted in scaled-down test facilities, and in the majority of cases with simulant materials. For experiments, a complete similitude between test facility and full scale plant conditions cannot be achieved. Consequently, it is necessary to: (1) give rationales to select simulant materials for the experiments; (2) assure that the important processes of interest are well scaled; and (3) assess the effects of distortions (when present) on processes and/or parameters relevant to a nuclear power plant accident scenario.

The draft of recommendations for selecting simulant materials and scaling approaches was prepared by KIT and contains two major parts: (1) Severe accident scaling methodology (SASM) and (2) Application of the scaling approach to SAFEST experimental facilities. As a guideline to describe the scaling of SAFEST experimental facilities an outline of the scaling methodology is given, which was developed by a Technical Program Group (TPG) that was established by the USNRC in 1989 [24]. It consists of 11 steps which should be followed in formulating the methodology. They are divided in 3 elements, which are (1) experimental requirements, (2) evaluation and specification for experiments and testing and (3) data base acquisition and documentation. As such these 3 elements and 11 steps are like a roadmap for the development of the SASM and provide a guide to follow for each of the experimental facilities in the SAFEST Project, in order to derive results which could be applied to the plant scale and plant conditions. The 11 steps are described. They may involve some exploratory experiments and testing before the envisaged experiments are performed. The steps also involve identification of similarity criteria and development of models and closure relations and even separate effect tests to improve understanding of key processes (or phenomena).

The document has been finalised in February 2019. The description of the scaling methodology for the DISCO facility at KIT provided an example of what needed to be done for other experimental facilities in the SAFEST project and for the other experiments that needed to be performed on the various facilities. This document will be of great benefit to the EU research programs on corium behaviour in severe accidents.

2.4 Preserving and Disseminating the Knowledge (WP5)

The objective of this work package is to provide the necessary supporting and coordination activities for preserving, increasing, keeping updated and disseminating the knowledge obtained in the SAFEST project, leading to a significant increase of the overall competence and abilities of the consortium.

Three workshops on information exchange on engineering issues related to corium experiments, including high temperature instrumentation, measurement techniques, heating methods, experimental artefacts, post-test examinations and analysis methodology has been held. The workshops has been hosted by CEA Cadarache, KTH Stockholm and MTA EK Budapest and included visits of the facilities and detailed technical discussions aiming at dissemination of the best experimental practices within the consortium. At all workshops at least one representing person of each institute was present and at the last workshop, JAEA could join for the first time.

During the second workshop, it has been possible to organize a special session for Doctorate and post-doctorate students involved in SA research among the different SAFEST partners. 5 students from KIT, JRC, CEA and KTH presented their work to the attendant SAFEST partners. This session was very interesting to promote scientific exchanges between young scientists and to train the future European research of excellence.

A mobility program has been established within the SAFEST project where researchers could be delegated to other consortium laboratories for education and training in order to share the expertise and to increase their level of competence. During SAFEST 2 researchers/students could use this possibility. In 2014, one PhD student from KIT was delegated for 3 months to KTH. He worked on the analysis of severe accident sequences by coupling the PECM model from KTH with the MELCOR code. Another student from ITU could use this opportunity to participate to the 5th Severe Accident Phenomenology short course (NUGENIA/SARNET) which was held in Stockholm in July 2015.

3 CONCLUSIONS

Direct outcome from the SAFEST project will be progress towards creation of an integrated pan-European laboratory for study of corium behaviour in severe accidents. Indeed, it encompasses a very large spectrum of nuclear reactors severe accident phenomenology dealing with corium (mainly oriented at LWRs, even though several aspects of Gen IV severe accidents can be studied in some of the SAFEST facilities). By strengthening the links between European corium facility operators, preparing a common roadmap for future EU research and improving the capabilities and performance of experimental facilities, this laboratory is a valuable asset for the fulfilment of severe accident R&D programs which are being set up after Fukushima-Daiichi and the subsequent stress tests both at the national level and at the European level.

Due to the links that are established with other European projects or platforms (e.g. CESAM, IVMR, NUGENIA/SARNET, etc.) the SAFEST project offers a unique opportunity for all parties 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 to enhance understanding of reactor core behaviour under severe accident conditions.

The main results of 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 organizations, which will be able to validate (either directly through the access to the SAFEST distributed 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 ASTEC, MELCOR, ATHLET-CD. This helps to capitalize the knowledge obtained in the field of severe accident research in the severe accident codes and scientific databases, thus preserving and diffusing this knowledge to a large number of current and future end-users in Europe.

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