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

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B. Fluhrer et al.

Institute for Nuclear and Energy Technologies
Severe accidents are the focus of considerable research involving substantial human and financial resources worldwide

- too many challenging physical phenomena, complicated further by high temperatures and presence of radioactive materials
- no individual country has sufficient resources (both human and financial) to address all important phenomena in the framework of a national research programme

Requirements for the evaluation of the corresponding risks and update of former evaluations

- uniform use of the best state of knowledge on severe accident phenomenology and qualified computer tools and appropriate methodology
- taking into account notably the inevitable evolutions in reactor operations (new type of fuel, higher burn-up, extension of plant life, new generations of reactors)
Project background (2/2)

- Necessity of integrating major European severe accident research facilities into a pan-European laboratory:
  - severe accident and corium studies
  - providing resources to other interested European partners for better understanding of possible accident scenarios and phenomena
  - improving safety of existing and, in the long-term, of future reactors

- European project SAFEST (Severe Accident Facilities for European Safety Targets) networking the European corium experimental laboratories and CLADS/JAEA, Japan.

- The duration of the project was 4.5 years and ended in December 2018.
Eight European partners + CLADS (Japan), coordinated by KIT

Karlsruhe Institute of Technology (KIT, Germany)

Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA, France)

Royal Institute of Technology (KTH, Sweden)

Centre for Energy Research, Hungarian Academy of Sciences (MTA-EK, Hungary)

Joint Research Centre Karlsruhe (JRC, Karlsruhe)

Framatome GmbH (Germany)

Belgian Nuclear Research Centre (SCK CEN, Belgium)

UJV Řež, a.s. (UJV, Czech Republic)

CLADS joined SAFEST as a partner in 2018
CLADS contribution to the SAFEST activities (1/2)

- CLADS was established in April 2015 in JAEA as a R&D centre for advanced decommissioning science and is aimed at being an international hub for R&D on decommissioning, and promoting cooperation in R&D and human resource development among government, industry and academia.

- In 2017, CLADS expressed the interest to join SAFEST as an official partner. From this time, CLADS joined the SAFEST meetings.

- In September 2018, CLADS officially joined the SAFEST project with the aim of collaborating with the European institutes and expanding its research activities and achieving the broadest possible scientific base to its programme.

- Development of joint research roadmap to focus future joint R&D on the stabilisation and termination of severe accidents in PWRs and BWRs.

- Contribution to the experimental innovation and testing programme by adding a range of advanced, even unique, high temperature test facilities and testing to the overall programme.
The following severe accident facilities in Japan and related experiments were opened for the SAFEST partners:

- Laser heating (LAHF) facility and the light-concentrating heating furnace to study fuel cladding behavior at very high temperatures and MCCI.

- Large-scale Equipment for Investigation of Severe Accidents in Nuclear reactors (LEISAN) has been constructed to study the effects of the B4C absorber in BWR geometry. This experiment is being done in parallel to the QUENCH-20 test at KIT within the SAFEST WP3 and so considerably complements and extends the value of the individual tests.

- Participation of SAFEST labs in the analysis of Fukushima samples (organized via SAREF, SAFEST labs will be considered with high priority).

- Involvement in the TCOFF project on fuel debris characterization.
Project main goals

- **Development of research roadmaps** to focus future European R&D on the stabilisation and termination of severe accidents in PWRs and BWRs.

- **Creation of an integrated pan-European laboratory for severe accident research** able to address and successfully resolve the wide variety of issues related to severe accident analysis and corium behaviour.

- **Establishing the access to the SAFEST research infrastructure** to investigate all important phenomena from the early core degradation to corium pool formation in the lower head, and ex-vessel melt situations.

- **Continuous improvement and upgrading of the SAFEST infrastructure** to increase the experimental capabilities and overall quality of R&D to meet current and future challenges.

- **Application of the results** of the project to the European light water reactors.
European corium experimental research roadmap (CEA)

- Development of a common vision and experimental research roadmap for the next years.
- Based on the research priorities determined by the SARNET SARP group as well as those from the NUGENIA TA2 on severe accidents.
- 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.
- Draft of the roadmap was completed in 2016 and was officially distributed within SAFEST and NUGENIA stakeholders and was published in open literature.
- After collection of remarks, the final version of the roadmap has been published in February 2019.
WP2 - Development of Research Roadmaps (2/5)

Joint experimental research roadmap with Japan (KTH)

- 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.
- The resulting roadmap provides useful guidelines for:
  - Assessment of long-term goals;
  - 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.

- November 2018
Joint experimental research roadmap with ROSATOM (JRC)

- The development of an EU-Russia joint roadmap has been more problematic.
- No official bilateral co-operation has been implemented in the last five years between European and Russian partners, despite some serious attempts.
- Within the SAFEST consortium, several tentative contacts have been taken with Russian organisations in order to discuss the further development of common severe accident research with the EU.
- Finally in 2016, Ioffe Institute and KTH jointly submitted the proposal “Roadmap for Russia collaboration with Europe on Experimental Research of Energy Intensive Processes at NPP” to the Russian Ministry of Science and Education. → has not been funded because of very strong competition in the call.

- The collaboration between EU and Russian partners has been continued on the basis of individual contacts with particular research centers only.
Joint experimental research roadmap with ROSATOM (JRC)

- Nevertheless a roadmap has been finalized in **November 2018**:  
  - Focused on the assessment of a roadmap for common severe accident investigation activities between EU and Russia.
  - Summary and Analysis of existing joint activities and experimental facilities.
  - Experience from past collaboration within the ISTC and the ERCOSAM/SAMARA projects are taken as a basis.
  - In addition some original EU experimental facilities are listed, which can be used for future collaborations.
  - Future collaborations will involve the analysis of Chernobyl lava, particles and debris samples, and new experimental activities linked to the analysis of Fukushima-Daiichi nuclear power plant accident occurred in 2011.
European safety research roadmap for next generation plants (SCK_CEN)

- Development of safety research roadmap for next generation plant safety taking advantage of the knowledge and expertise obtained for existing reactors as well as on specific safety characteristics of considered Gen IV designs.

- 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.

- November 2018

- The roadmap led to the proposal of a follow-up Horizon 2020 project dedicated to GENIV issues (SAFEST-GENIV).
WP 3- Distributed Research infrastructure

To integrate major European research facilities into a pan-European laboratory for severe accident and corium studies and to open it for interested organisations.

- **In-vessel corium and debris behaviour**
  - Reduce the remaining uncertainties or possibly solve the issues in corium behaviour during the in-vessel phase of severe accidents.
  - QUENCH, LIVE, RESCUE, POMECO-FL, POMECO-HT, CODEX, CERES

- **Ex-vessel corium and debris behaviour**
  - Provide new data and understanding of ex-vessel fuel-coolant interaction, debris bed formation, coolability and corium-concrete interaction.
  - DISCO, MOCKA, VULCANO, KROTOS, DEFOR, SES, MISTEE, SICOPS

- **Corium properties**
  - Improve the existing corium properties database; provide validated data for severe accident codes.
  - VITI, FLF, COMETA
WP 3 - SAFEST experimental facilities at KIT

- **QUENCH**: Early and late in-vessel phases of core degradation for different reactor types.
- **LIVE**: Evolution of the late in-vessel phase of a severe accident, incl. formation and behaviour of molten pool in the lower head.
- **MOCKA**: Corium-concrete interaction with stratified oxide and metal melts with and without rebars.
- **DISCO**: Integral DCH investigations to simulate melt ejection from the RPV to the reactor cavity after the RPV failure.
- **RESCUE**: Investigation of in-vessel retention capabilities for small and medium reactors.

- **VULCANO**: Study of corium spreading, interaction with concrete, solidification, etc. at temperatures of up to 3000 °C.

- **VITI**: Viscosity and surface tension measurements of different corium compositions by aerodynamic levitation.

- **KROTOS**: Steam explosion phenomena studies with about 5 kg of corium at more than 2850 °C.
WP 3 - SAFEST experimental facilities at KTH

- **DEFOR**: Study of melt jet fragmentation in water and formation of solid debris with up to 80 kg of simulant corium melt.
- **POMECO-FL**: Study of two-phase flows in a porous media.
- **POMECO-HT**: Study of the debris coolability and dryout heat flux.
- **SES**: Investigation of fuel coolant interaction in stratified melt coolant configuration.
- **MISTEE**: Study of steam explosion under well-controlled conditions.
SAFEST facilities at MTA EK

- **CODEX**: Study of the early phase of core degradation with electrically heated fuel bundles at high temperatures.
- **CERES**: Investigation of cooling of the flooded outer surface of reactor vessel in large scale for a wide range of thermal-hydraulic parameters.

SAFEST facility at JRC

- **FLF**: Laser heating/melting and fast pyrometry facility to study the melting behaviour of pure compounds and binary systems.
SAFEST facility at UJV

- **COMETA (IS-160):** Cold crucible induction furnace designed for several kilograms of corium that can be melted and analysed including melt sampling, aerosol and melt composition analysis.

SAFEST facility at Framatome GmbH

- **SICOPS:** Study of different phenomena of molten corium interaction with concrete or other sacrificial material in a cold crucible with sustained heating and with material mass of up to 20 kg.
Transnational access to SAFEST infrastructure

- Two calls for proposals were announced in 2015 and 2016.
- 19 proposals from 9 countries for experiments in 13 SAFEST facilities have been received during the first call for proposals.
- User Selection Panel with help of independent experts evaluated the submitted proposals and recommended the experiments to be performed in SAFEST.
- As a result of the evaluation during the 1st User Selection Panel Meeting, 11 experiments were selected for realization.
- 3 new proposals for experiments in three SAFEST facilities were received in the 2nd call for proposals and 4 proposals were moved from the 1st call.
- The proposals were discussed at the 2nd User Selection Panel Meeting and 5 experiments were selected for SAFEST support.
- Altogether 16 experiments or experimental series in several cases have been performed in the SAFEST project with participation of users from 15 organisations located in 8 countries.
# Objectives of the SAFEST experiments (1/3)

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Objectives of the SAFEST experiments (3/3)

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WP4: Upgrading the capacity of facilities and increasing the quality of R&D (1/2)

- Since most research topics in the past were focused on PWR design, there were clear needs for improvement and upgrading of SAFEST facilities towards BWR-specific features. Following activities have been considered in SAFEST:
  - QUENCH: high temperature degradation of BWR mock-up assembly containing the fuel rod simulators, the channel box and the absorber blade.
  - DISCO: Interaction of corium melt jet with water in a deep pool, focusing on jet fragmentation.
  - DEFOR: Influence of BWR control rod and instrumentation guide tubes on melt jet fragmentation in water in the reactor cavity and debris bed formation.
  - SICOPS: MCCI for prototypic Nordic BWR corium melt and concrete compositions.
  - MOCKA: 2-dimensional large scale MCCI for prototypic Nordic BWR concrete with and without rebars.
  - FLF: Study of melting and crystallization behaviour of BWR specific corium compositions.

- For the medium and longterm the roadmaps will serve as a basis for the directions of upgrading the facilities to meet the future needs.
WP4: Upgrading the capacity of facilities and increasing the quality of R&D (2/2)

- Besides the upgrading of SAFEST facilities towards BWR-specific features, following important work has been performed within WP4:
  - 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).
  - 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 are compared.
WP4.1: Guidelines for selecting simulant materials and scaling approaches (1/2)

- Compare the strategies for selection of simulant materials and scaling approaches
- Identify the properties of simulant materials to represent, to the greatest extent possible, the important physical properties of the real core materials (depending on phenomena to be studied)
- Provides a guideline of scaling methodology developed by a Technical Program Group (TPG) that was established by the USNRC in 1989, which involves 10 steps for a new phenomenon or process:
- Step 2 “perform scaling analysis” is the central step in the whole process, which is a hierarchical, two-tired approach (top-down or system approach and the bottom-up or process approach).
- Some top-down systematic approaches are presented: in-vessel core melt heat transfer, DCH, debris coolability and the criteria of prototypical corium mass for different in-vessel and ex-vessel corium behaviour.
WP4.1: Guidelines for selecting simulant materials and scaling approaches (2/2)

- The bottom-up process is practiced in most of the experimental facilities.
- Each facility owner has provided either their own scaling criteria or the insight of the most important scaling-relevant parameters on his studied topic.
- The document SAFEST-UCF-D4.1 has been finalized with inputs from KIT, CEA, KTH, Framatome and MTA-EK.

In summary

→ Comprehensive studies on scaling analysis of a broad spectrum of phenomena in the severe accident research were systematically performed in the SAFEST project.
→ The individual impacts of facility size, mass and the properties of corium or its simulant can be identified.
→ The outcome of the scaling analysis highlights the importance of synthesis of experimental results of different concept and emphasis.
The objective of this WP was to provide the necessary supporting and coordination activities for preserving, increasing, keeping updated and disseminating the knowledge obtained in the SAFEST project.

- 3 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 (CEA, KTH, MTA EK).

- During the 2nd workshop, it has been possible to organise 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.

- A mobility programme has been established within the SAFEST project where researchers could be delegated to other consortium laboratories for education and training in order to share expertise and to increase their level of competence. 2 researchers/students could use this possibility.
SAFEST was a very successful European project combining 8 European partners and Japan.

Thanks to the networking between the 16 European corium facilities, there has been significant improvements in the experimental capabilities.

Establishment of a forum for in-depth discussions between the technical staff in charge of the facilities on topics of common interest (heating, instrumentation, uncertainties…).

A lot of very important joint work has been performed and valuable reports have been developed → all the work has been presented at the SAFEST Final Seminar on the 10th and 11th December 2018.

In order to continue the work started in SAFEST, a new proposal SAFEST-GENIV has been submitted to the EU in the last HORIZON 2020 call → recently rejected by the EU.

The partners would appreciate it to continue the work in a follow-up project SAFEST-2.

But it seems that there is no room for a SAFEST2 project in the next calls of the EU?
Acknowledgments

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Thank you for your attention!