The SAFEST project: severe accident facilities for European safety targets

A. Miassoedov, B. Fluhrer (KIT); C. Journeau (CEA) S. Bechta (KTH); Z. Hózer (MTA-EK) D. Manara, P.D. Bottomley (JRC); M. Kiselova (UJV) T. Keim, G. Langrock (AREVA GmbH) F. Belloni, M. Schyns (SCK-CEN)
SAFEST
Severe Accident Facilities for European Safety Targets

EU-supported pan-European Integrated Research Infrastructure Initiative for increased safety of nuclear systems at EU level

Duration: 4 years starting on 1 July 2014

www.safest.eu
Project background

- 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

- Integration of 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
Eight European partners, 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)

UJV Řež, a.s. (UJV, Czech Republic)

AREVA GmbH (ANP, Germany)

Belgian Nuclear Research Centre (SCK CEN, Belgium)

Collaborative Laboratories for Advanced Decommissioning Science (CLADS, Japan)

CLADS plans joining SAFEST as a partner in 2017
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 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

- **Applications of the results** of the project to the European light water reactors
Development of research roadmaps

- **European corium experimental research roadmap**
  - Focusing of future European R&D on providing evaluation of the stabilisation and termination of severe accidents in Gen II PWRs and BWRs taking into account the results of European stress tests

- **Joint experimental research roadmap with Japan**
  - Assessment of long-term goals and proposals for experimental support needed for proper understanding and interpretation of Fukushima accident, analysis of collected debris in European and Japanese laboratories and even processing of molten cores

- **Joint experimental research roadmap with U.S.A.**
  - Development of a joint research roadmap between European and USA organisations to identify the relevant activities for joint projects that would address severe accident issues important for both Europe and USA

- **European safety research roadmap for next generation plants**
  - Development of safety research roadmap for next generation plant safety taking advantage of the knowledge and expertise obtained for existing reactors as well as specific safety characteristics of considered Gen IV designs
European corium experimental research roadmap

Development of a roadmap for EU experimental R&D on LWR severe accidents issues and corium studies for the next 15 years:

- based on the research priorities determined by SARNET SARP group, SNE-TP Report «Identification of Research Areas in response to Fukushima Daichi Accident» and NUGENIA Topical Area 2 on severe accidents

- takes into account issues identified in the analysis of the European stress tests and from the interpretation of the Fukushima accident

- takes advantage of the current and developing European corium infrastructures

- defines general objectives and specify research needs to reinforce further the safety of NPPs with regard to severe accidents management

- details new R&D challenges and suggest topics to be further developed jointly by the SAFEST consortium, so as to arrive at a wider common vision

- selection of high and medium priorities related to corium behaviour in severe accidents
19 corium issues from the SARNET ranking (1/2)

1. Core and debris coolability and thermal-hydraulics within particulate debris during re-flooding

2. Hydrogen generation during re-flooding of strongly degraded cores

3. Core re-flooding impact on source term during late phases of core degradation (with highly degraded core, loss of geometry)

4. Corium behaviour in a lower head

5. Keeping the RPV integrity by external reactor vessel cooling (ERVC)

6. RPV vessel failure mode and the following corium release from the failed vessel, in the case of vessels with lower head penetrations such as BWRs

7. Ex-vessel fuel coolant interaction (FCI) including steam explosion (SE)

8. Direct containment heating (DCH)

9. Dry molten core concrete interaction (with single oxidic phase)

10. Molten core concrete interaction (oxide-metal configurations; top-flooding)

Bold: High priority
19 corium issues from the SARNET ranking (2/2)

11. Core and debris coolability and thermal-hydraulics within particulate debris during ex-vessel core catchers

12. **Debris formation and coolability (in and ex-vessel)**

13. **Effect of impurities in water on corium behaviour**

14. Recriticality in severe accident conditions

15. Spent fuel pool scenarios in case of loss of cooling system

16. **Development and qualification of specific instrumentation for SA conditions**

17. Databases on corium thermodynamic and thermo-physical properties

18. Accident tolerant fuels

19. **Analyses of Fukushima Daiichi corium samples**

*Bold: High priority*
Identified gaps and needs

- Two issues are not addressed experimentally
  - Core late re-flooding impact on source term
  - RPV vessel failure mode and corium release (role of penetrations)

There are needs to prepare experimental programs, either in EU or through experimental international collaboration, to provide data to the on-going and future R&D activities.

In some cases, as RPV failure and corium release, there are important experimental and analytical challenges preventing realization of R&D programs tackling the issues.

- Another gap lies with the absence of large-scale prototypic corium facilities in Europe
  - Closure of COMAS, FARO in the late 1990s, early 2000s
  - Scaling effect and material effects
  - CEA is designing its new large scale facility PLINIUS-2
SAFEST 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 user groups*

- **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
SAFEST experimental facilities

- In-vessel and ex-vessel corium and debris behaviour
- Corium properties

QUENCH at KIT
VULCANO and VITI at CEA
DEFOR and SES at KTH
CODEX at EK
SICOPS at AREVA

MOCKA and LIVE at KIT

DISCO at KIT, RESCUE at CEA, MISTEE at KTH

KROTOS at CEA, POMECO at KTH, CERES at EK

COMETA at UJV

FLF at ITU
Experiments in SAFEST facilities

- Two calls for proposals were announced in 2015 and 2016
  - 22 proposals from 10 organisations
  - User Selection Panel with help of independent experts evaluated the submitted proposal and recommend the experiments to be performed in SAFEST
- Experiments in 16 facilities

- First tests performed in 2016, many tests are scheduled for 2017
## Objectives of the SAFEST experiments (1/3)

<table>
<thead>
<tr>
<th>Test facility</th>
<th>Proposing Organisation</th>
<th>Test objective</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISTEE-AL KTH</td>
<td>IRSN + others</td>
<td>Investigation of the ability of alumina melt to undergo thermal fragmentation as a mechanism for spontaneous steam explosions and determination of the void produced with high temperature drops</td>
<td>09/2015</td>
</tr>
<tr>
<td>COMETA UJV</td>
<td>CEA</td>
<td>Quantitative assessment of the kinetics of the reaction between UO$_2$ and B$_4$C</td>
<td>03/2016</td>
</tr>
<tr>
<td>SES KTH</td>
<td>EDF + others</td>
<td>Investigation of the energetics of spontaneous steam explosion and of the characteristics of the premixing zone in stratified melt under water configuration</td>
<td>04/2016</td>
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<tr>
<td>DEFOR KTH</td>
<td>KIT</td>
<td>Investigation of the influence of control rod and instrumentation guide tubes on melt fragmentation in water for BWRs</td>
<td>07/2016</td>
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<tr>
<td>SICOPS AREVA</td>
<td>SSM</td>
<td>Investigation of MCCI with BWR-specific corium composition (lower U/Zr ratio, lower oxidation fraction of Zr, reduced steel mass) and concrete composition (basaltic in Nordic BWRs)</td>
<td>2016/2017</td>
</tr>
</tbody>
</table>
## Objectives of the SAFEST experiments (2/3)

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<tr>
<td>FLF JRC</td>
<td>SSM</td>
<td>To receive experimental data and to improve understanding of the quasi-binary section of ternary U-Zr-O diagram in the composition domain of BWR specific corium composition, i.e. at U/Zr atomic ratio close to 0.9 and Zr oxidation index close to 20 - 30%</td>
<td>2016/2017</td>
</tr>
<tr>
<td>MISTEE-OX KTH</td>
<td>IRSN + others</td>
<td>To investigate the ability of pure zirconium melt to undergo thermal fragmentation while falling into water and thereby undergoing oxidation</td>
<td>2016/2017</td>
</tr>
<tr>
<td>CERES MTAEK</td>
<td>Bohunice NPP</td>
<td>Investigation of the effect of the elevated sump level on the in-vessel melt retention for VVER-440 reactors during the melt retention by flooding of the reactor cavity</td>
<td>2017</td>
</tr>
<tr>
<td>DISCO KIT</td>
<td>IRSN</td>
<td>Investigation of scaling effect during FCI premixing in the DISCO facility</td>
<td>2017</td>
</tr>
<tr>
<td>CODEX MTAEK</td>
<td>KIT + others</td>
<td>influence of nitrogen on oxidation and degradation of fuel rod claddings in the temperature range of 800-1200 °C in air-steam atmosphere</td>
<td>2017</td>
</tr>
</tbody>
</table>
## Objectives of the SAFEST experiments (3/3)

<table>
<thead>
<tr>
<th>Test facility</th>
<th>Proposing Organisation</th>
<th>Test objective</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOCKA KIT</td>
<td>SSM</td>
<td>Study of MCCI in 2D cylindrical crucibles made of concrete typical for Nordic BWRs</td>
<td>2017</td>
</tr>
<tr>
<td>QUENCH KIT</td>
<td>SSM</td>
<td>Study of BWR-specific important phenomena like influence of control rod blade on bundle degradation</td>
<td>2017</td>
</tr>
<tr>
<td>LIVE KIT</td>
<td>IRSN</td>
<td>Assessment of the characteristic time of convection development in a homogeneous melt pool in 3D after a rapid change in boundary conditions</td>
<td>2017</td>
</tr>
<tr>
<td>FLF JRC</td>
<td>EDF + others</td>
<td>Measurements of emissivity of U+Zr+steel alloys in different atmospheres</td>
<td>2017</td>
</tr>
<tr>
<td>VULCANO CEA</td>
<td>KIT + GRS</td>
<td>Influence of crusts on the melt-concrete interface during MCCI</td>
<td>2017</td>
</tr>
<tr>
<td>VITI CEA</td>
<td>SSM</td>
<td>To obtain thermophysical properties (density, surface tension and, if feasible, viscosity) of (U, Zr, Fe) metallic alloys representative of reactor compositions</td>
<td>2018</td>
</tr>
</tbody>
</table>
MISTEE–AL experiments on single drop steam explosion

- Facility has been upgraded with new furnace and additional pressure measurements
- 24 tests with Al$_2$O$_3$ melt drops FCI are completed
- Only one spontaneous steam explosion happened at very high melt superheat and high water subcooling
- Measured data were used by users for model validation and code development

**Triggered SE** (Superheat $\approx$ 167K, Subcooling $\approx$ 82K)
- First cycle
- Second cycle
- Third cycle

**Spontaneous SE** (Subcooling $\approx$ 85$^\circ$K, superheat $\approx$ 215$^\circ$K)
MISTEE-AL experiments on Zr melt fragmentation

- To study oxidation behaviour of Zr melt drops
- Proposed by the user group from IRSN, CEA and JSI
- Facility has been upgraded for metal melts
- The measurements include:
  - High speed visualization of the Zirconium melt droplets and water interaction
  - Estimation of hydrogen production from the size of the bubbles in subcooled water
  - Post-test SEM/EDX analysis and oxygen determination in the quenched drops
- It is complicated to measure melt temperature in water: it will be estimated
- First performed experiments demonstrated:
  - Much larger lifetime of molten Zr drop in water in comparison with other materials which do not undergo oxidation
  - Significant hydrogen formation
  - Large final oxidation of quenched drop
- The tests and post-test examinations will be completed in 2017
Test objective was to estimate an influence of control rod and instrumentation guide tubes on melt fragmentation in water and debris bed formation and characteristics.

Eutectic mixture of Bi$_2$O$_3$–WO$_3$ to simulate corium melt.

The main test parameters were similar to the DEFOR-A4 test which was characterised by a relatively low melt temperature of 1221 K (melt superheat of 78 K).

Although, the measured porosity of debris bed is slightly higher in comparison with the reference tests without the rod, there is general agreement with data obtained in previous DEFOR tests.

Modification of test conditions is recommended for the future tests.

Cumulative particle size distribution

Agglomeration factor
Test objective was to measure the energetics of spontaneous steam explosion and investigate the characteristics of the premixing zone in stratified melt under water configuration.

The test resulted in a very early spontaneous steam explosion only 0.6 s after the beginning of melt spreading.

The explosion duration was approximately 4 ms, with a peak 175 kN load and a total impulse of 0.42 kN·s, which is comparable, though weaker, than previous explosive PULIMS/SES tests.

The total melt mass released when the explosion occurred was estimated between 0.8 and 1.7 kg.

Preliminary parametric analysis was performed with MC3D for two parameters characterizing the premixed layer - the melt volume fraction and the premixing layer radius.

Best-fit value of a total mass of melt in the premixed layer is around 0.24 kg, which correspond to 17-30% of the estimated total melt mass released before explosion.
FLF experiments on high-temperature behaviour of BWR corium compositions

- The objective is to improve understanding of the quasi-binary section of ternary U-Zr-O diagram in the composition domain of BWR-specific corium composition (U/Zr atomic ratio close to 0.9 and Zr oxidation index close to 20-30%)
- Laser melting/freezing experiments successfully carried out on eight compositions
- Thermal arrests identified
- Spectral emissivity of the surface determined in the visible range, revealing a more metallic behaviour in the liquid and a more oxidic one in the solid surface

<table>
<thead>
<tr>
<th>U/Zr (mol)</th>
<th>C=ZrO₂/(Zr+ZrO₂) (mol)</th>
<th>Mol%</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UO₂</td>
<td>ZrO₂</td>
<td>Zr</td>
</tr>
<tr>
<td>0.90</td>
<td>20</td>
<td>47.2</td>
<td>10.6</td>
</tr>
<tr>
<td>0.90</td>
<td>30</td>
<td>47.3</td>
<td>15.7</td>
</tr>
<tr>
<td>1.22</td>
<td>20</td>
<td>55.1</td>
<td>8.9</td>
</tr>
<tr>
<td>1.23</td>
<td>30</td>
<td>55.1</td>
<td>13.6</td>
</tr>
<tr>
<td>0.67</td>
<td>20</td>
<td>40.0</td>
<td>12.0</td>
</tr>
<tr>
<td>0.66</td>
<td>30</td>
<td>39.9</td>
<td>18.1</td>
</tr>
<tr>
<td>0.5</td>
<td>20</td>
<td>33.3</td>
<td>13.3</td>
</tr>
<tr>
<td>0.5</td>
<td>30</td>
<td>33.3</td>
<td>20</td>
</tr>
</tbody>
</table>

Compositions prepared and analysed in this work
KUBI tests at on assessment of the kinetics of the reaction between UO$_2$ and B$_4$C

- Cold crucible load composed of from 2 kg of pellets and powder of depleted UO$_2$ with 25 g of metallic uranium
- UO$_2$ melting with a crust on top was achieved under nitrogen flow after less than 20 minutes
- Five B$_4$C pellets (11 g) were dropped on the pool crust which has then been mechanically broken
- Significant gas release has been observed as interaction started
- After some short generator failures heating was disconnected and corium ingot was extracted from the furnace
- A large porosity was observed and attributed to gaseous releases (mainly CO$_2$ according to thermodynamic modelling)
- Samples were taken from various ingot locations and prepared for post-test SEM/EDX and XRD analyses
The authors gratefully acknowledge funding by Euratom to support the work within SAFEST project.

Thank you for your attention!