Challenges and outcomes from prototypic corium experiments within the safest european consortium

C. Journeau, V. Bouyer, N Cassiaut-Louis, P. Fouquart, N. Chikhi, P. Piluso, D. Manara, D. Bottomley, M. Kiselova, I. Pozniak, et al.

▶ To cite this version:

C. Journeau, V. Bouyer, N Cassiaut-Louis, P. Fouquart, N. Chikhi, et al.. Challenges and outcomes from prototypic corium experiments within the safest european consortium. The Nuclear Materials Conference (NuMat 2016), Nov 2016, Montpellier, France. cea-02437047

NuMat 2016
The Nuclear Materials Conference
7-10 NOVEMBER, 2016
MONTPELLIER, FRANCE

DE LA RECHERCHE À L'INDUSTRIE

cea den

CHALLENGES AND OUTCOMES FROM PROTOTYPIC CORIUM EXPERIMENTS WITHIN THE SAFEST EUROPEAN CONSORTIUM

Christophe Journeau, Viviane Bouyer,

Nathalie Cassiaut-Louis, Pascal Fouquart, Nourdine Chikhi,

Pascal Piluso, (CEA Cadarache, France),

Dario Manara, David Bottomley (JRC Karlsruhe),

Monika Kiselova (UJV Řež), Igor Pozniak (CVR Řež),

Gert Langrock (AREVA NP Erlangen),

Zoltán Hózer (MTA EK Budapest)

ROYAL INSTITUTE OF TECHNOLOGY

European Commission

AREVA
forward-looking energy

OUTLINE

- Context – The SAFEST Project
- Importance of *prototypic* corium to study severe accident phenomena
- Experimental Facilities
- Challenges and Outcomes

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

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)

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

EIGHT PROJECT 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 (EK, Hungary)
- Joint Research Centre (JRC, Karlsruhe)
- UJV Řež, a.s. (UJV, Czech Republic)
- AREVA NP GmbH (ANP, Germany)
- Belgian Nuclear Research Centre (SCK, Belgium)

SAFEST PROJECT MAIN GOALS

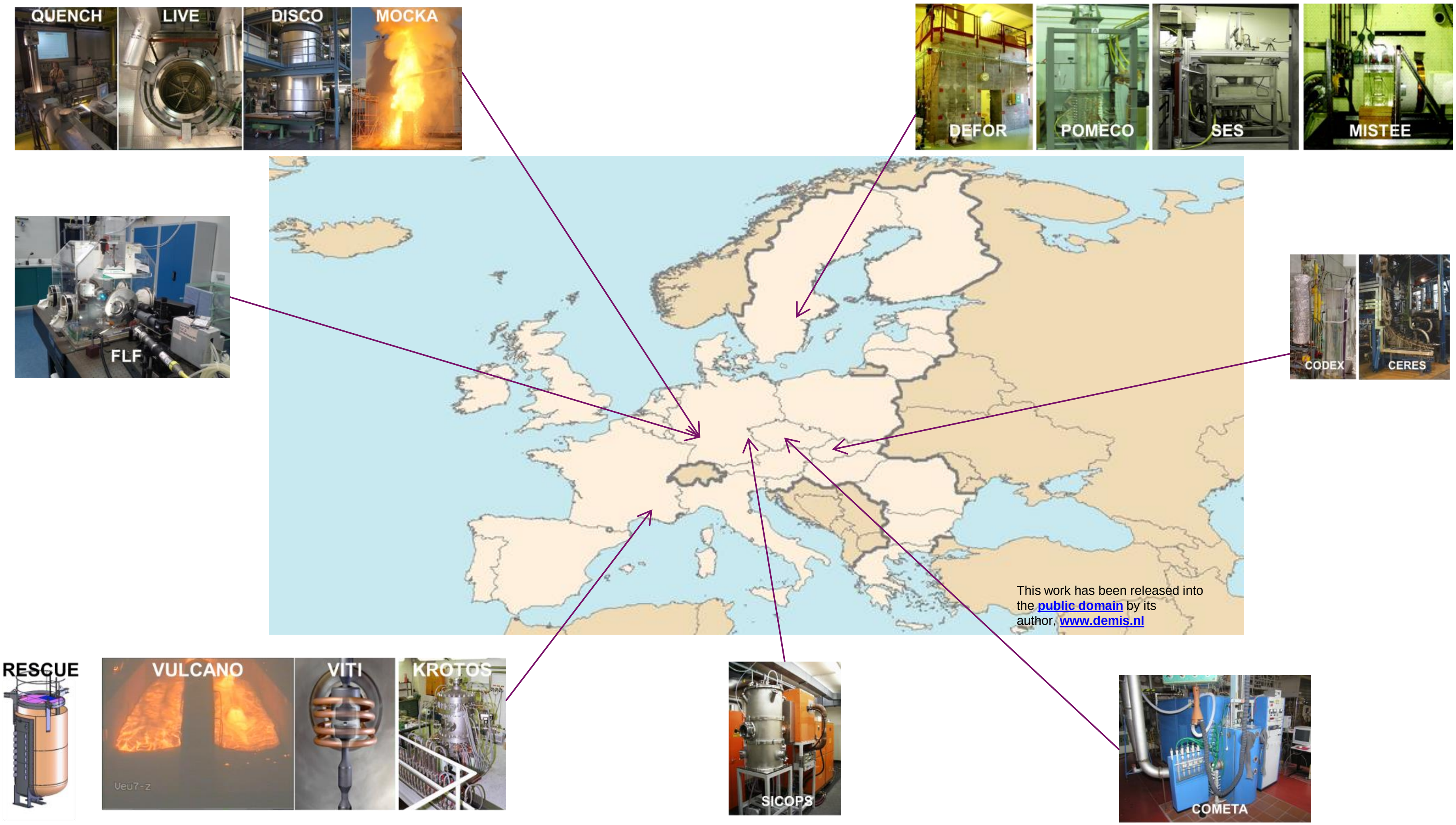
SAFEST (*Severe Accident Facilities for European Safety Targets*) is a 48 month EU-supported pan-European Integrated Research Infrastructure Initiative for increased safety of nuclear systems at EU level with 8 partners from 6 European countries.

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

DE LA RECHERCHE À L'INDUSTRIE

cea den

17 CORIUM EXPERIMENTAL FACILITIES



7 PROTOTYPIC CORIUM FACILITIES

WHY PROTOTYPIC CORIUM ?

WHY PROTOTYPIC CORIUM ? SPECIFICITIES OF URANIUM OXIDE

Element	U	Al	Zr	Hf	Ce
Electronic structure	$5f^3$-$6d^1$-$7s^2$	$7s^2$-$6d^1$	$4d^2$-$5s^2$	$4f^{14}$-$5d^2$-$6s^2$	$4f^1$-5d1-$6s^2$
Oxidation state	0,+3,+4, +5, + 6	0, +3	0,+1,+4	0,+4	0,+1,+3,+4
Effective Ionic radius r (pm)	3+, r= 102.5 4+, r = 89 5+, r= 76 6+, r= 73	3+, r=53.5	+4, r=72	+4, r=71	3+, r=101 4+, r= 87

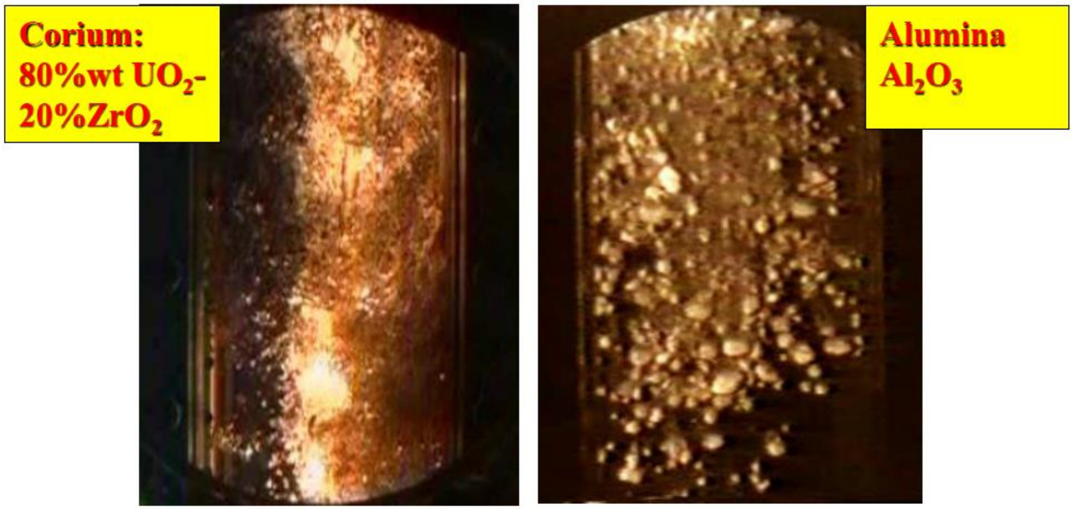
Uranium has 4 oxidation states (all of which may exist during severe accident scenarios) leading to many species in the U-O system:

- Solid state: U, UO_2 (actually may vary from $UO_{1.70}$ to $UO_{2.25}$), U_4O_9, U_3O_7, U_3O_8.
- Liquid state: Metallic liquid: U with dissolved oxygen; oxidic liquid: $UO_{2\pm x}$
- Gaseous state: U, UO, UO_2, and UO_3
  - UO and UO_3 vaporize at relatively low temperature
  - Their release modify oxygen stoichiometry of the liquid phase.

Oxides	Melting point (K)	Density (293K) ($g.cm^{-3}$)	Specific heat ($J.K^{-1}.kg^{-1}$)	Latent heat fusion ($kJ.kg^{-1}$)
UO_2	Tm = 3120 ± 30	10.956	~300	260
CeO_2	3073	7.10	~300	465
HfO_2	3031 ± 25	9.68 (monocl.)	~300	457
ZrO_2	2973	5.68 (monocl.)	~300	810
Al_2O_3	2072	3.95	~700	1140

WHY PROTOTYPIC CORIUM ?

PAST SIMULANT/PROTOTYPIC CORIUM-WATER EXPERIMENTS



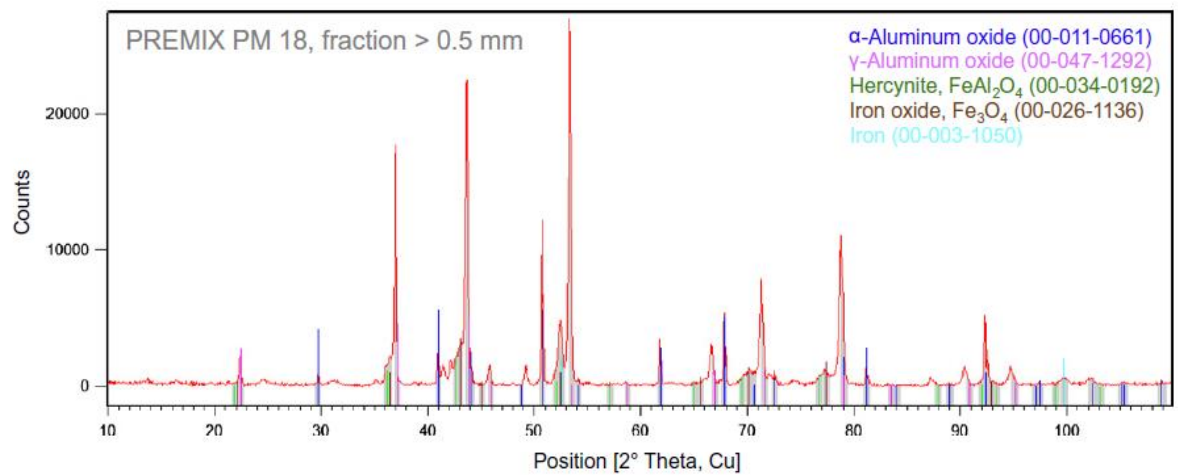
KROTOS experiments, Huhtiniemi & Magallon, Nucl. Eng. Des., 2001

- Comparisons of debris morphology, show that the debris resulting from the alumina pours is significantly different from the finely fragmented corium debris with a Mass Mean Diameter of about 1.7 mm (e.g. KROTOS 45) compared to larger alumina debris (e.g. 17 mm MMD in KROTOS 41);
- The more coherent corium jet pour tends to penetrate deeper into the water pool than an alumina jets;
- Different droplet solidification patterns are expected between opaque corium droplets and semi-transparent alumina particles (Dombrowski & Dinh, NED 238:1421-1429, 2008) while «the mitigating effect of solidification appeared quite clearly in […] experiments» (Meignien et al., Ann. Nucl. Energ. 74 (2014) 125-133)
- The oxidation of UO_2 by steam produces incondensable gases that may blanket the droplets and prevent explosions, but these exothermal oxidation reactions may also increase the explosion yield….

Solidification of fine debris with alumina ? Metastable low-melting point γ-Al_2O_3

- Post test XRD of alumina samples (from KROTOS and PREMIX facilities) have shown that, in case of vapour explosion, a significant part of the smaller debris is γ-Al2O3.
- γ-Al2O3 is a metastable phase
  - Solidifies several 100s K below solidification point of α-Al2O3 (2050°C)
  - No similar metastable phase observed in $(U,Zr)O_2$ system

- Role of subcooling has been reported by numerous authors for FCI
  - Difficult to reproduce/scale from one material to the other…



Tyrpekl & Piluso, Annals Nucl. Energ. 46 (2012) 197-203

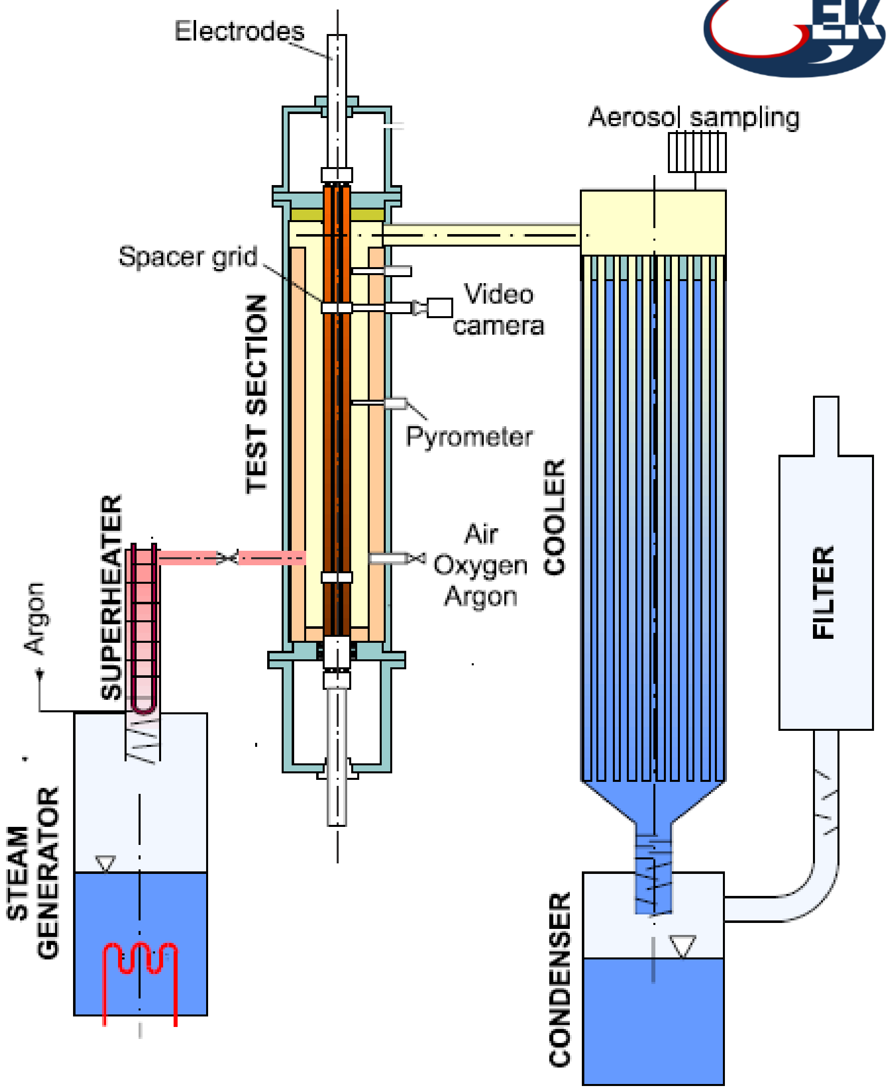
WHY PROTOTYPIC CORIUM ?

- Differences between corium and alumina in FCI tests

  Zirconia also behaved differently from corium in some TROI FCI tests
- Similar issues clearly arises for experiments where mass transfers between oxide and metal phases is important:
  - crust formation and solidification
  - stratification both in-vessel and ex-vessel
  - evolution of metallic layer during Molten Core Concrete Interaction
- Impossible simulation of phenomena which are mainly controlled by corium crust strength, such as underwater spreading
- In the absence of reliable thermophysical properties for corium, it is anyhow difficult to find a satisfactory scaling.
- Solutions (in complement to simulant material experiments):
  - In pile experiments (e.g. Phebus FP)
  - Experiments with irradiated fuel (e.g. VERCORS/VERDON)
  - **Prototypic corium experiments**

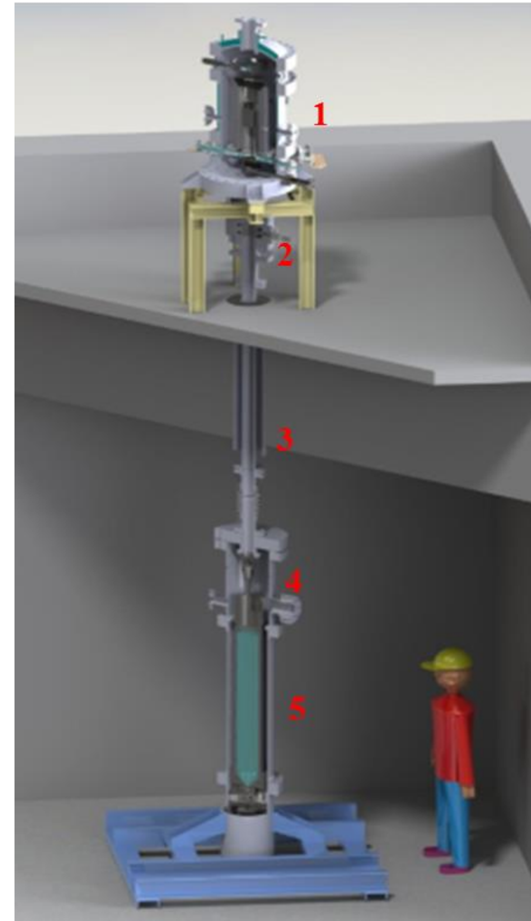
SAFEST FACILITIES– CODEX (MTA EK)

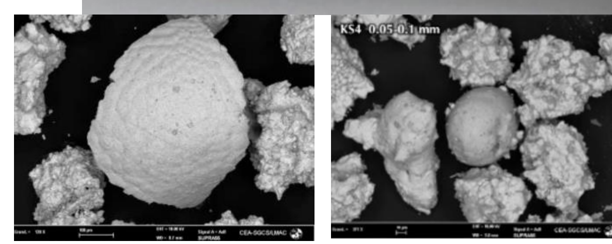
- The CODEX (Core Degradation Experiment) test facility investigates the early phase severe accident phenomena with small electrically heated bundles.
- 7-rod VVER geometry and 9-rod PWR bundle geometries were used for experiments.
- CODEX-COOL: coolability tests with 19 rods.
- Pellets are applied for the simulation of LOCA scenarios (up to 1200 °C).
  - Formerly UO_2
  - Presently Al_2O_3
- Heated length of the test bundle is 600 mm.



SAFEST FACILITIES– KROTOS (CEA)

- The KROTOS facility is dedicated to fuel coolant interaction (jet fragmentation, debris formation, steam explosion).
- ~5 kg of corium at more than 2850 °C are dropped in water.
- The facility consists of four main parts:
  - The furnace (1) is a water cooled stainless steel container designed to withstand 4 MPa pressure and is equipped with a three-phase cylindrical heating resistor.
  - The transfer channel (3) is a vertical tube, connecting the furnace and the test section. After corium transfer, the valve (2) is closed.
  - The test section consists of a pressure vessel (4) with a test tube inside (5). The test tube is a free standing cylinder filled with water.
  - The X-Ray radioscopy system can trace the fragmentation of the melt.

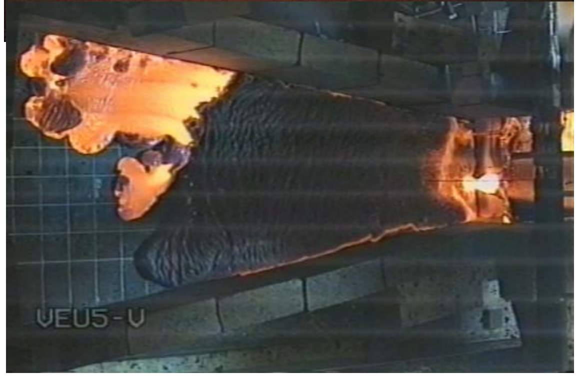




V. Tyrpekl PhD thesis 2012

SAFEST FACILITIES– VULCANO (CEA)

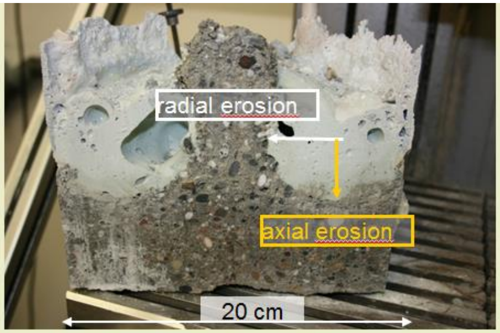
- VULCANO is a rotating plasma arc furnace able to melt ~80 kg of corium at temperatures of up to 3000 °C (in- or ex-vessel corium) and to pour the melt in a dedicated test section.
- Corium can be poured into a crucible in which the decay heat is simulated by a 150 kW inductor device.
- Experiments to study
  - Corium spreading over different types of substrates (ceramic, concrete…)
  - Corium solidification
  - Corium pool thermalhydraulics
  - Corium progression in debris bed
  - Long term interaction of corium with materials such as concrete or materials to be used in a core catcher
  - Validation of corium cooling strategies



DE LA RECHERCHE À L'INDUSTRIE

SAFEST FACILITIES– SICOPS (AREVA)

- The SICOPS (Simultaneous Interaction of Molten Corium with Protective and Sacrificial Material) test facility studies 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.
- Centerpiece of SICOPS is a high-frequency (1 – 4 MHz) furnace with a cold crucible (diameter of up to 20 cm).
- Tests with material masses of up to 20 kg molten material (simulant or prototypic, with temperatures up to 3000 °C) and with a generator power of max. 100 kW can be performed.



solidified melt on concrete

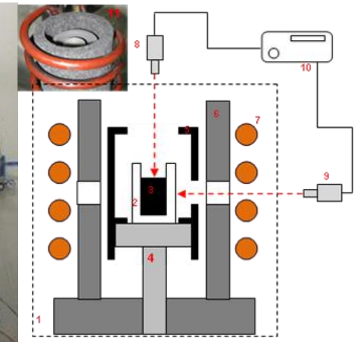
BMWi project, grant number 1501332

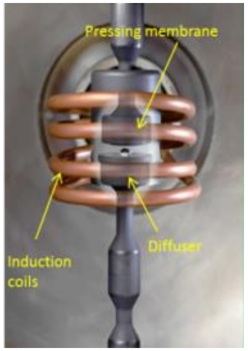
Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

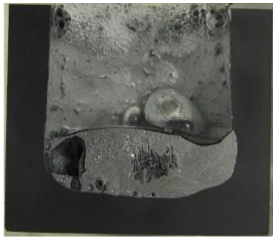
AREVA
forward-looking energy

SAFEST FACILITIES: VITI

- VITI (CEA Cadarache)
  - Induction heating of corium thanks to a graphite susceptor
  - Contactless levitation for thermophysical measurements
    - Droplet volume => Density
    - Droplet shape => Surface Tension
    - Droplet deformation => viscosity
  - Crucible tests for material interaction and transition temperatures.
  - Possibility to study oxidation in dedicated hafnia leaktight tube (CEA Patent).



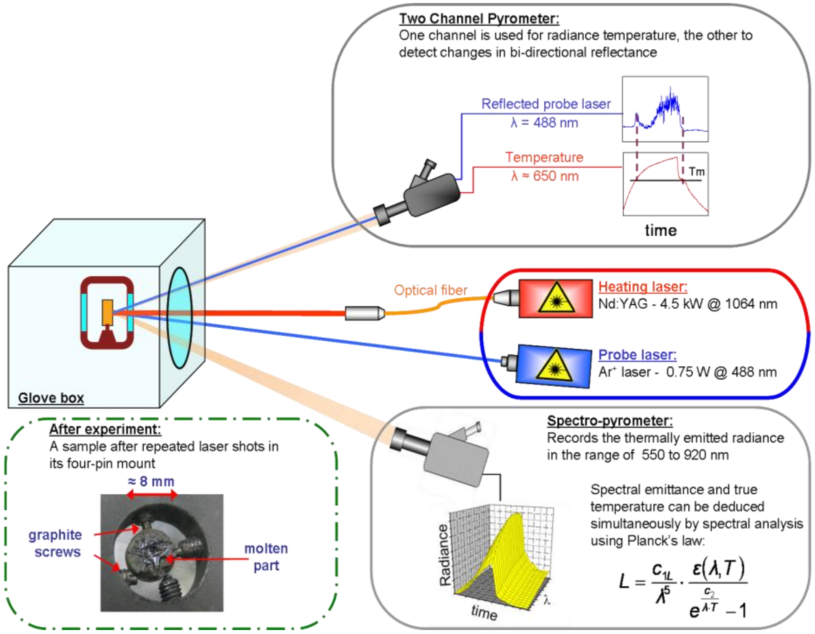


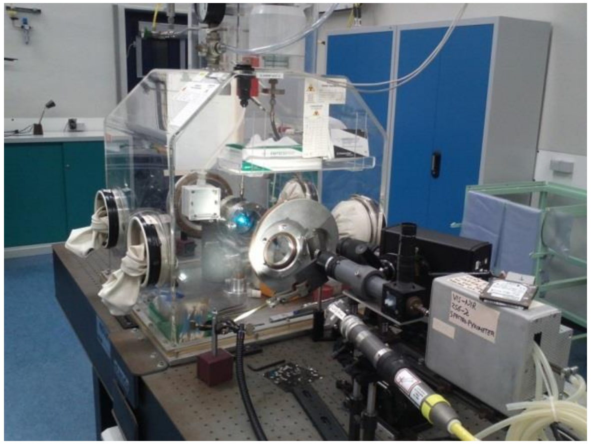


K. Plevacova et al., An Experimental Study of the Effect of Boron Carbide on the SFR Corium Composition, IYNC 2010, Capetown.

SAFEST FACILITIES– FLF (JRC)

- The FLF test facility is a laser heating/melting and fast pyrometry facility (to measure the temperature) to study the melting behaviour of pure compounds and binary systems.
- Experiments are carried out in an autoclave under medium to high pressure (from a few tenths up to a few hundreds 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.

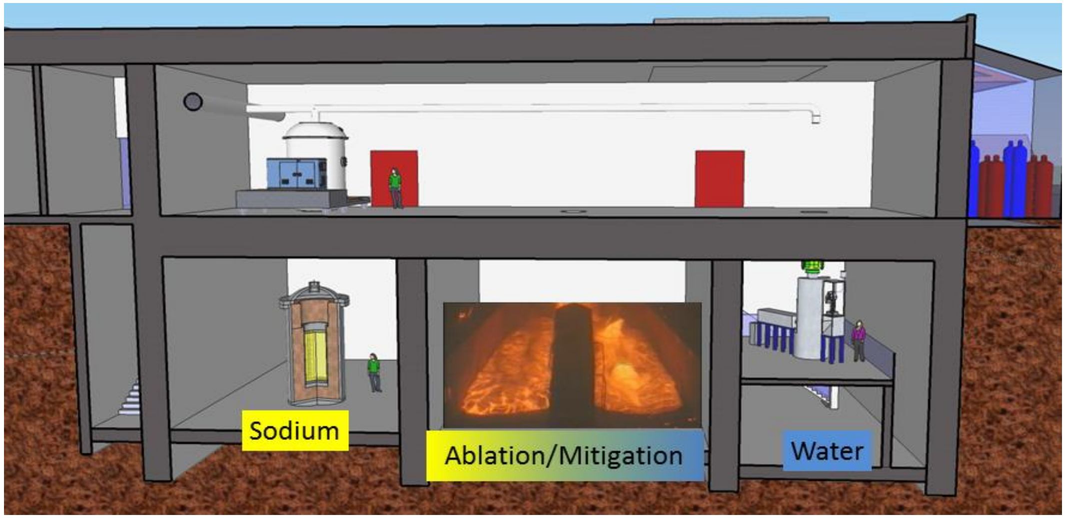




SAFEST FACILITIES– COMETA (UJV)

- The cold crucible induction furnace test facility COMETA is constructed for powder oxide materials melting with melt temperatures up to 3000 °C.
- The facility is adopted for the operation with radioactive materials (in particular with UO_2) and intended for simulating real corium melts.
- The capacity of the cold crucible is about 1 kg of initial corium batch (250 cm^3 volume of melt).
- The power supply is a high-frequency generator with max. 80 kW at 4.5 MHz frequency.
- Possible crucible shift: 0-50 mm/min
- Melt sampling, aerosol and melt composition analysis
- New larger facility under commissionning within SUSEN

PLINIUS-2



- CEA future platform for prototypic corium experimental R&D (commissioning ~2021)
  - For ASTRID SFR severe accidents
  - For LWR severe accidents

  - Will be the successor of current PLINIUS platform (VULCANO, VITI, KROTOS).
- One Furnace (Cold crucible induction - ~500 kg)
- 3 experimental halls
  - Corium/sodium
  - Ablation-Mitigation
  - Corium-Water
- Smaller scale / simulant material facilities.

CHALLENGES AND OUTCOMES

CHALLENGES OF PROTOTYPIC CORIUM EXPERIMENTAL RESEARCH

- High temperatures (1500-3000 K) depending to the materials which may have mixed with molten fuel
  - In vessel (U, Zr)O_2 melts ~3000 K
  - Ex vessel corium melts with large fraction of concretes → ~2000 K
- There is not ONE corium but a continuum of compositions depending on:
  - Scenarios
  - Time-evolution within a given scenario

  Physical properties are not well known and are evolving during experiment and from one test to another.
- Complex material for analyses:
  - A huge number of elements (~20 when FP prototypes are inserted)
  - A large number of major elements (U, Zr, O, Si, Ca, Fe, Cr, Ni for MCCI)
  - Large atomic mass contrast between Uranium and Oxygen (boron, carbon) affects techniques as EDX.
- Even if natural/depleted uranium oxides are usually used:
  - Nuclear accountability
  - Health and safety protection of workers
    - Protective devices
    - Nuclear ventilation, Very High Efficiency Filters….
  - Low-activity nuclear waste management

SOME MAJOR ACHIEVEMENTS

- Knowledge of the pellet-cladding interaction during early phases (to be extended to ATF)
- Evidence of redox reactions between in-vessel oxide and steel layer (MASCA project) leading to gravitational inversion [reduction of UO_2 into U leads to metallic density above that of oxidic melt whereas initially molten steel lighter than $(U,Zr)O_2$] and changing heat flux profiles.
- Larger energy of steam explosions with multicomponent mixtures having large solidification intervals (SERENA2: TROI/KROTOS)
- Validation of core catcher concepts
  - European projects CSC, COMAS, ECOSTAR proved the efficiency of spreading even below corium liquidus temperature
  - Validation of VVER1200 core catcher sacrificial material (RASPLAV2)
- Determination of MCCI melt cooling mechanisms and of maximum concrete fraction enabling efficient water ingression in corium crust (OECD MCCI projects)
- Discovery of MCCI anisotropic ablation of silica-rich concretes (CCI and VULCANO)
- Improvement of the corium thermodynamic databases needed to run the severe accident codes thanks to corium experiments (RASPLAV2, COMETA, FLF, VITI, VULCANO, ATTHILA,…)
- Study of interaction between corium melt and sea salt (JAEA for Fukushima)
- Corium samples fabricated and studied to qualify Fukushima debris cutting / retrieval / storage. (VULCANO, COMETA,…)
- Development of corium analysis techniques to be used to analyze Fukushima debris

Thank you for your attention

This activity is funded by
the SAFEST grant agreement
number 604771 (EURATOM FP7)

Christophe Journeau
CEA Cadarache
Direction de l'Energie Nucléaire
CEA Cadarache
Département de Technologie Nucléaire
Service de Mesure, Modélisation, Transferts et Accidents graves
Laboratoire de Physique et de Modélisation des Accidents graves