DE LA RECHERCHE À L'INDUSTRIE

A EUROPEAN CORIUM EXPERIMENTAL RESEARCH ROADMAP

Christophe Journeau, Viviane Bouyer, Nathalie Cassiaut-Louis, Pascal Fouquart, Pascal Piluso, Gérard Ducros (CEA Cadarache, France), Stéphane Gossé, Christine Guéneau, Andrea Quaini (CEA Saclay, France),

Beatrix Fluhrer, Alexei Miassoedov, Juri Stuckert, Martin Steinbrück (KIT Karlsruhe, Germany),

Sevostian Bechta, Pavel Kudinov (KTH Stockholm, Sweden),

Zoltan Hozer, Attila Guba (MTA EK Budapest, Hungary), Dario Manara, David Bottomley (JRC/ITU Karlsruhe, European Union),

Manfred Fischer, Gert Langrock, Holger Schmidt (AREVA GmbH Erlangen, Germany),

Monika Kiselova, Jiri Ždarek (ÚJV Řež, Czech Republic)

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OUTLINE

- Context – The SAFEST Project
- Issues
- Experimental Facilities
- Gaps / Needs
- Conclusions

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

- inform ourselves of the best state of knowledge on severe accident phenomenology, ~~and~~ qualified computer tools and appropriate methodology
- take into account notably the inevitable evolutions in reactor operations (new type of fuel, higher burn-up, extension of plant life, new generations of reactors)

DE LA RECHERCHE À L'INDUSTRIE

PROJECT BACKGROUND

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

SAFEST PROJECT MAIN GOALS

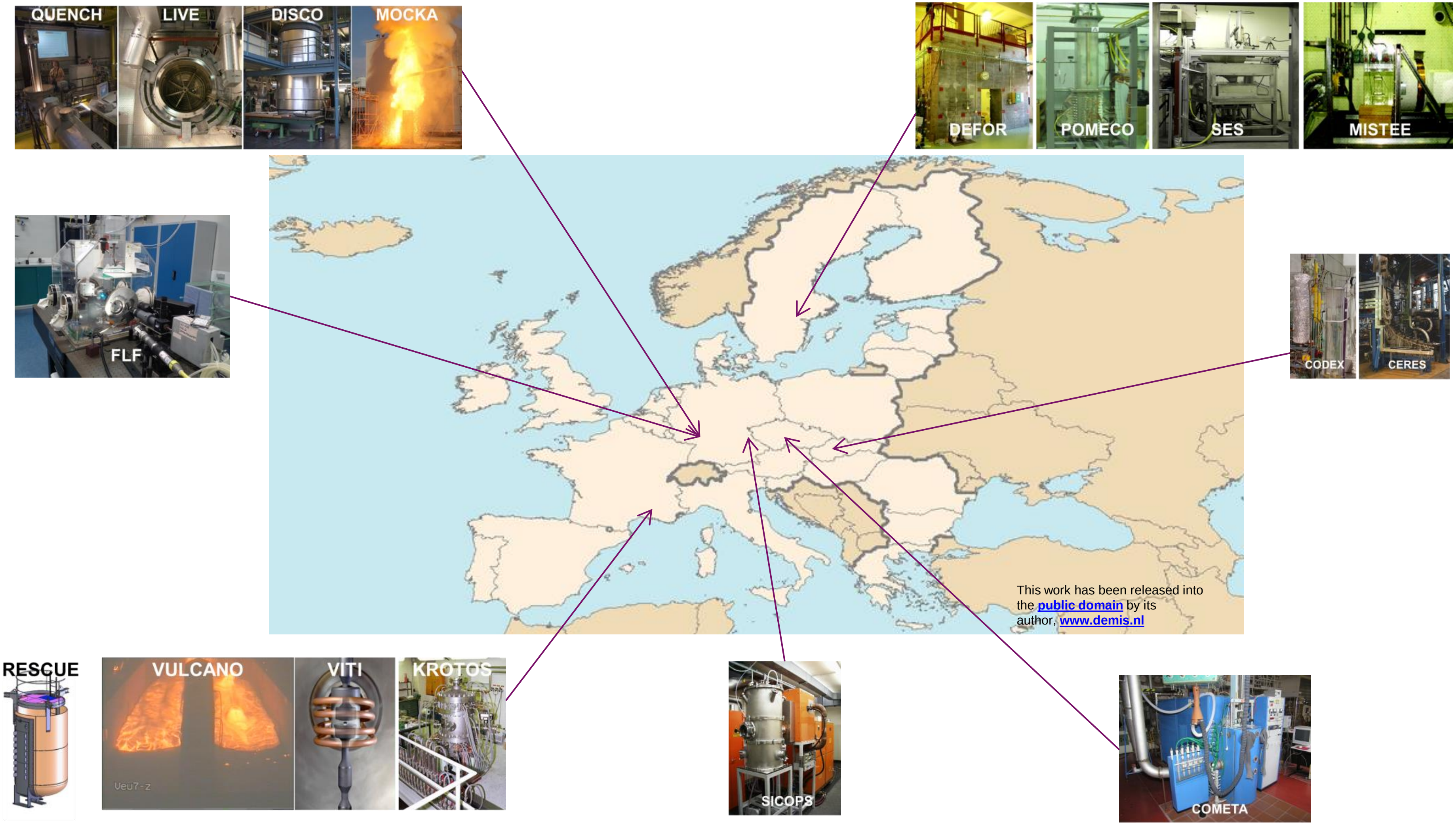
SAFEST (Severe Accident Facilities for European Safety Targets) is a 48 month EU-supported pan-European Integrated Research Infrastructure Initiative for increased safety of nuclear systems at EU level with 8 partners from 6 European countries.

- 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 project results ~~of the project~~ to the European light water 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)
- Institute for Transuranium Elements (ITU, Karlsruhe)
- UJV Řež, a.s. (UJV, Czech Republic)
- AREVA NP GmbH (ANP, Germany)
- Belgian Nuclear Research Centre (SCK, Belgium)

17 CORIUM EXPERIMENTAL FACILITIES



EUROPEAN CORIUM EXPERIMENTAL RESEARCH ROADMAP

- Objectives:

  Develop a dedicated roadmap for EU experimental R&D on LWR severe accident~~s~~ issues and corium studies for the next 15 years .

  - based on the research priorities determined by SARNET SARP group as well as those from the newly formed NUGENIA Area 2 group (?) on severe accidents.
  - take into account issues identified in the ~~analysis of the~~ European stress tests and from the interpretation of the Fukushima accident.
  - will take advantage of the current and developing European corium infrastructures.
  - define general objectives and specify research needs to reinforce further the safety of NPPs with regard to severe accident~~s~~ management,
  - detail 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,

RANKINGS OF CORIUM ISSUES
PROPOSED APPROACH

- European ranking of Severe Accidnet Research Priorities
  - SARNET SARP presented at ERMSAR 2013 conference and in Ann. Nucl. Energ., Dec 2014 issue
  - SNE-TP Report « Identification of Research Areas in response to Fukushima Daiichi Accident »
  - NUGENIA TA2 Severe accidents
    - In NUGENIA Roadmap 2012 and 2015 editions

- Selection of high and medium priorities related to Corium issues

FROM SARNET SEVERE ACCIDENT RANKING (1/2)

High priorities

1) Core and debris coolability and thermal-hydraulics within particulate debris during re-flooding
2) Corium behaviour in a lower head
3) Keeping the RPV integrity by external reactor vessel cooling (ERVC)
4) 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.
5) Mixing of hydrogen in the containment (and reactor building) atmosphere, possible hydrogen combustion/detonation processes and the influence of countermeasures like Passive Autocatalytic Recombiners (PARs)or ~~the effect of~~ spray systems.
6) Ex-vessel fuel coolant interaction (FCI) including steam explosion (SE)
7) Molten Core Concrete Interaction (oxide-metal configurations; top-flooding)
8) Characterisation and quantification of the fission product (FP) release under oxidising conditions and in particular air ingress for High Burn-Up (HBU) and Mixed Oxide (MOX) fuel.
High temperature chemistry in the RCS and its impact on the source term, mainly iodine species, ~~as well as the~~ including iodine chemistry ~~of iodine~~ in the containment and ~~its impact on the~~ the resulting source term.
10) Fuel Assembly (FA) behaviour in spent fuel pool severe accident scenarios
11) Development and qualification of specific instrumentation for SA conditions.

Bold characters: *corium related*

FROM SARNET SEVERE ACCIDENT RANKING (2/2)

Medium priorities

a. Hydrogen generation during re-flooding of strongly degraded cores
b. Integrity of RCS, especially integrity of Steam Generator tubes in High Pressure scenarios
c. Direct Containment Heating (DCH)
d. Long term loss of heat removal from wetwell in a BWR
e. Dry Molten Core Concrete Interaction (with single oxidic phase)
f. Dynamic and static behaviour of containment, crack formation
g. Core re-flooding impact on source term during late phases of core degradation (with highly degraded core/ loss of geometry)
h. Effect of impurities in water on corium behaviour
i. Data(bases) on corium thermodynamic and thermophysical properties

Bold characters: *corium related*

THE 19 CORIUM ISSUES (FROM THESE RANKINGS)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; liquid source term)**

Bold characters: *High priority*

THE 19 CORIUM ISSUES (FROM THESE RANKINGS)2/2

11) 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 thermophysical properties
18) Accident Tolerant Fuels
19) Analyses of Fukushima Daiichi corium samples

Bold characters: *High priority*

EXAMPLE: ISSUE 4
CORIUM BEHAVIOUR IN A LOWER HEAD

- Two main risks when corium relocates to the lower head:
  - when hot corium comes into contact with residual water, the steam produced will cause a pressure spike, or even an in-vessel steam explosion;
    - Issue closed thanks to OECD/NEA SERENA 1 project
    - Stress < Resistance of an intact RPV
  - upon contact with corium, the vessel will undergo heat fluxes, which may be of considerable magnitude locally, potentially resulting in vessel rupture;
- Main phenomena to study:
  - corium jet fragmentation and debris formation;
  - *debris bed dry-out and re-flooding possibilities (issue 12)*;
  - formation of molten pool;
  - natural convection in the molten pool;
  - focusing effect with convection in thin metallic layer;
  - corium oxidation including H_2 production;
  - metal/oxide stratification in the molten pool;
  - dissolution of reactor vessel steel at sub-melting point temperatures.
  - *knowledge of critical heat flux on the RPV external side is issue 5*
- *Link to IVMR European project (HORIZON2020)*

EXAMPLE: ISSUE 7
EX-VESSEL FUEL COOLANT INTERACTION (FCI) INCLUDING STEAM EXPLOSION (SE)

- Large scatter in the steam explosion loads predicted by different codes (MC3D, JASMINE, TEXAS, IDEMO etc.) and by different code users.
  - For instance, OECD/NEA SERENA2 PWR-2D exercise calculations of steam explosion impulse at the cavity bottom center and cavity wall produced values which encompassed typical containment resistances.
- Risk associated with steam explosion in stratified melt-coolant configuration might have been underestimated in previous studies.
  - Discovered development of self-sustainable premixing layer during underwater liquid melt spreading is in direct contradiction with earlier assumption.
- New release conditions to be studied
  - Experiments are mostly in “TMI2 configuration”: release above water surface
  - Case of failed IVR: release underwater, confined geometry

The most relevant issues in the field of FCI modelling that still require attention could be identified as:

1. Void fraction due to combined film boiling and thermal radiation as well as non-condensable gas. (Christophe I thought water depth was also a factor - maybe not fundamental. Sevostian would probably know more) – either way your list is already long enough!! -david)
2. Thermophysical properties of melt.
3. Dominant mechanism(s) of primary fragmentation
4. Key phenomena in “stratified” melt–coolant configuration.

EXAMPLE: ISSUE 19
ANALYSES OF FUKUSHIMA DAIICHI CORIUM SAMPLES

- Fukushima fuel debris have a number of features that make them of great importance for investigation and understanding of severe accident mechanisms.
- Fukushima Daiichi is a BWR reactor site
  - Possible formation of actinide boride and carbide that could be particularly difficult to break up and remove during dismantling
  - greater presence of Zr metal in the core;
    - this indicates lower U/Zr ratios,
    - lower oxidation index of the corium
    - and lower steel fraction.
  - use of untreated/unfiltered sea-water
- In preparation of dismantling work, corium facilities can be useful to provide prototypes of the corium which is expected to be found at various locations of the damaged plants.
  - prototypes can be used to test debris sampling/cutting techniques and debris chemical analysis techniques and processing methods with lower radiation doses before actual Fukushima debris samples are available.
- When Fukushima Daiichi samples are available from the site, European laboratories can use the acquired experience from corium and irradiated fuel experiments to analyse and interpret the corium samples.
  - The SAFEST round-robin exercise on the analyses of a MCCI prototypic corium sample in 4 European analysis laboratories can be ~~enlarged~~ extended to international partners in view of preparing the analysis of Fukushima Daiichi samples.

LIST OF EXISTING/PLANNED FACILITIES

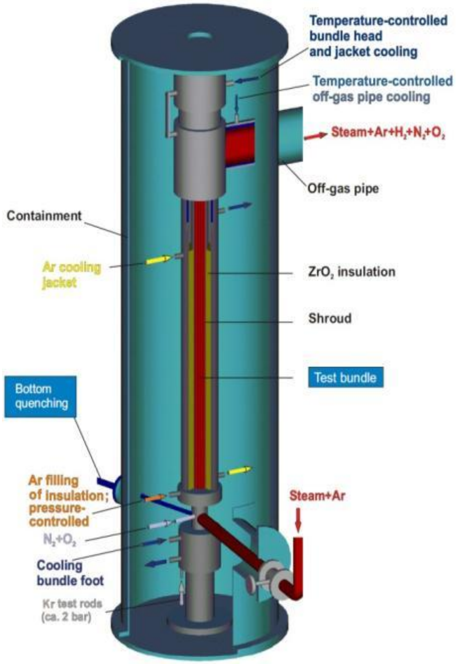
- *QUENCH*
- *CODEX*
- *DEFOR*
- *PLELUDE*
- *PEARL*
- *DEBRIS*
- *COOLOCE*
- *POMECO*
- *LIVE*
- *RASPLAV*
- *VITI*
- *RESCUE*
- *CERES*
- *IVR (UJV)*
- *IVR (CNPRI)*
- *IVR (SJTU)*
- *REPEC*
- *KROTOS*
- *SES*
- *DISCO*
- *VULCANO*
- *PLINIUS 2*
- *SICOPS*
- *HECLA*
- *CCI - SSWICS*
- *MOCKA*
- *CLARA*
- *BENSON*
- *COMETA*
- *ATTILHA*
- *FLF*
- *ITU Thermophysical facilities*
- *LECA-STAR Corium Analysis Lab*
- *MARCOULE corium Analysis Lab*
- *LIPC Corium Analysis Lab*

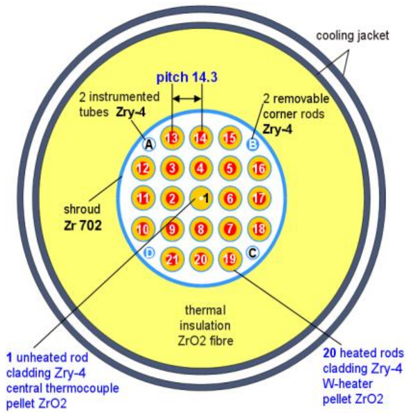
E.U. facilities + International facilities to which European organizations have some access

EXAMPLE: QUENCH FACILITY AT KIT

- Test bundle made of 20+ Zr-clad ZrO_2 rods
- Heated rods simulating decay heat
- Various atmospheres
- Possibility to flood with water
- Precise on-line, off-gas analysis

- The QUENCH facility is mainly devoted to the study of
  - issue 1 (Core and debris coolability)
  - issue 2 (Hydrogen generation during late debris reflooding).
  - issue 12 (debris coolability).
  - issue 13 (effect of water impurities during core quenching).
  - issue 15 (SFP-LOCA scenarios).
  - issue 18 (testing of candidate Accident Tolerant Fuels).



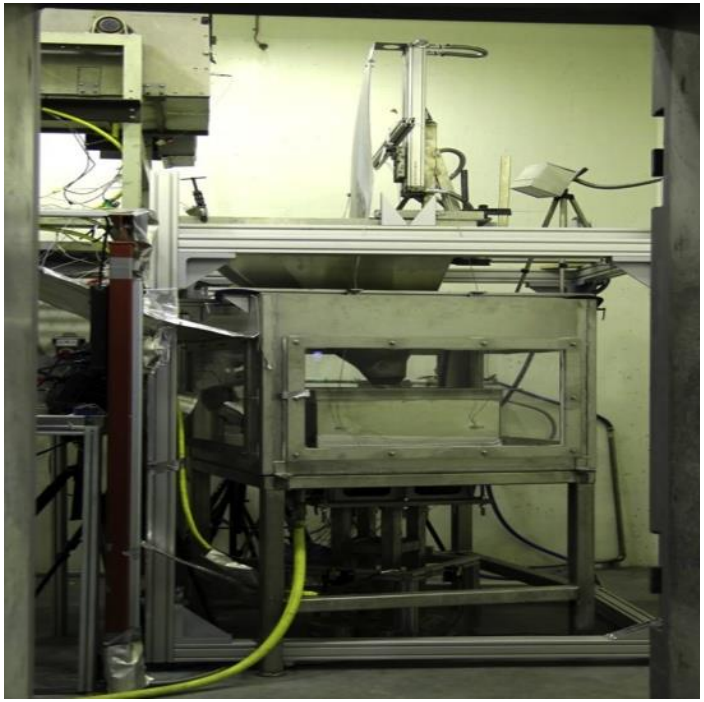


EXAMPLE: SES FACILITY AT KTH

- Recent tests with simulant corium material at KTH has shown that, although it had been previously thought to be excluded, there may be a risk of energetic steam explosion duing underwater spreading.
- This will have to be confirmed with prototypic material.

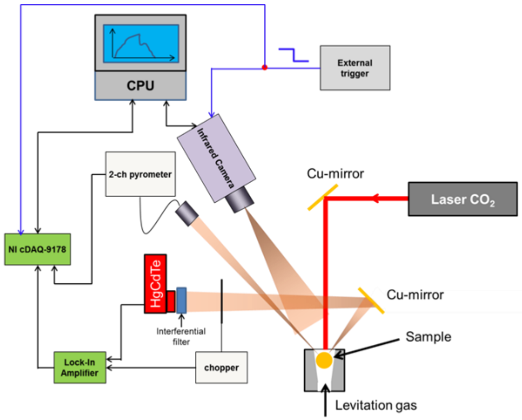
- molten binary oxidic melt mixtures at temperatures up to 1600°C
- masses up to 80 kg
- with large shallow water pool at temperatures up to 95°C

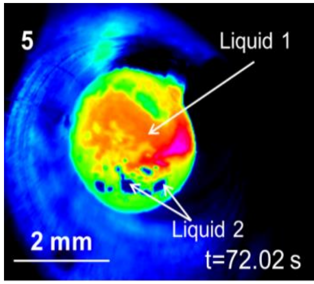
- Issue 7: Ex-vessel fuel coolant interaction (FCI) including steam explosion (SE)

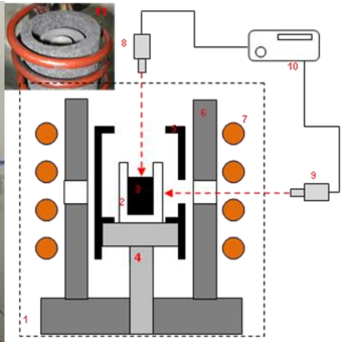


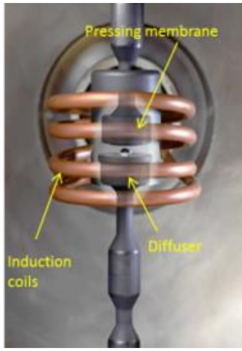
EXAMPLE: VITI AND ATTILHA

- Two CEA facilities dedicated to corium thermochemistry and thermophysical properties (Issue 17)
  - Uncertainties on corium data are now often larger than uncertainties on phenomenological modelling.
  - ATTILHA (CEA Saclay):
    - sample is heated by means of a 250 W CO_2 laser
    - Measurement of transition temperatures
    - Contactless setup with levitated droplet
  - VITI (CEA Cadarache)
    - Induction heating of corium
    - Contactless levitation for measurement of density, surface tension, viscosity
    - Crucible tests for material interaction and transition temperatures.









SYNTHESIS TABLE (1/2)

Issue Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	Core and debris Coolability	Hydrogen generation during late core re-flooding	Core late re-flooding impact on source term	Corium behaviour in a lower head	External Reactor Vessel Cooling	RPV vessel failure mode and corium release	DCH	Ex-vessel FCI	Dry oxidic-pool MCCI	Steel, Flooding MCCI	Core Catchers	Debris Formation and coolability	Effect of Water Impurities	Recriticality in Severe Accident conditions	SFP scenarios	SA Instrum.	Thermo-dynamic and thermos-physical databases	Accident Tolerant Fuels	**Fukushima corium samples**
QUENCH	X	X										X	X		X			X	
CODEX	X	X											X		X				
DEFOR								X				X	X	X					
PRELUDE	X											X	X						
PEARL	X											X	X						
DEBRIS	X											X	X						
COOLOCE	X											X	X						
POMECO	X											X	X						
LIVE				X		X						X							
CORDEB				X															
VITI				X					X	X			X				X	X	

SYNTHESIS TABLE (2/2)

Issue Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	Core and debris Coolability	Hydrogen generation during late core re-flooding	Core late re-flooding impact on source term	Corium behaviour in a lower head	External Reactor Vessel Cooling	RPV vessel failure mode and corium release	DCH	Ex-vessel FCI	Dry oxidic-pool MCCI	Steel, Flooding MCCI	Core Catchers	Debris Formation and coolability	Effect of Water Impurities	Recriticality in Severe Accident conditions	SFP scenarios	SA Instrum.	Thermo-dynamic and thermos-physical databases	Accident Tolerant Fuels	**Fukushima corium samples**
RESCUE					X								X						
CERES					X								X						
IVR (CNPRI)					X								X						
IVR (UJV)					X								X						
REPEC II					X								X						
KROTOS								X					X				X		
PLINIUS 2								X	X	X	X	X	X			X			**X**
SES								X					X						
DISCO							X	X											
VULCANO				X					X	X	X					X			**X**
SICOPS									X	X	X								
HECLA									X	X									
CCI-SSWICS									X	X									
MOCKA									X	X	X								
CLARA									X	X									
BENSON					X						X								
COMETA									X	X	X		X				X		
HTMS				X					X								X		
FLF													X	X			X	X	
ITU analysis lab																	X		**X**
LECA.STAR																			**X**
ATALANTE																			**X**
LIPC																	X		
Need for new facility			O			O									O				

GAPS - NEEDS

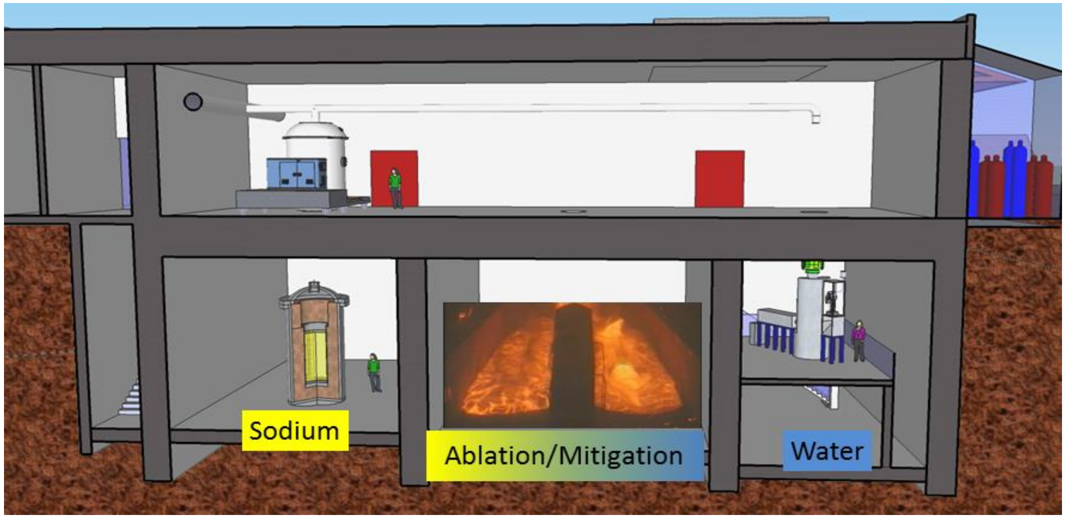
- 3 issues without dedicated experimental facilities
  - **Core late re-flooding impact on source term**
  - **RPV vessel failure mode and corium release**
  - **SFP scenarios**

  There are needs to prepare experimental programs, either in EU or through experimental collaboration, to provide data ~~to the~~ for 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~~ execution 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 (next slide)

PLINIUS-2



- CEA future platform for prototypic corium experimental R&D
  - 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.

OUTLINE OF THE 100+ PAGE ROADMAP

SUMMARY

- Thanks to SAFEST European project a roadmap is being issued that links research priorities to European and international experimental facilities in the corium domain
- After Fukushima Daiichi accident, the research priorities have been reevaluated in various European groups.
- 19 issues of high or medium importance have been listed and described
- 34 experimental facilities have been considered
    - 29 in the European Union
    - 5 international facilities
- Cross analysis between research needs and facilities
    - 3 domains lacking experimental facilities in Europe
    - Need for a large scale prototypic corium facility in Europe: PLINIUS-2
- This roadmap draft will soon be available to European stakeholders for comments/improvements.
    - Revised version to be issued by mid 2017.

- Within SAFEST other roadmaps are planned:
    - On Gen 4 severe accident experimental R&D
    - Post-Fukushima experimental research (with Japan)

Thank you for your attention

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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