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# CEA R&D ACTIVITIES RELATED TO EX-VESSEL CORIUM BEHAVIOUR IN A PWR

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IAEA TM meeting - « Phenomenology and technologies relevant to IVMR and EVCC »
October 17-21, 2016 - Shanghai, China

# Outline

1. Context of CEA severe accident studies
2. Main Severe Accident R&D corium issues for LWRs
3. Overview of CEA experimental facilities
4. Description of CEA R&D activities on the various issues
   1. Fuel coolant interaction
   2. Ex-vessel corium spreading, coolability and molten core concrete interaction
   3. Corium properties
   4. SA instrumentation
   5. Post-Fukushima expertise
5. Future PLINIUS2 experimental Platform
6. Conclusion

# CEA SEVERE ACCIDENT STUDIES - CONTEXT

**The CEA severe accident program aims at providing tools and expertise for severe accident understanding and management.**

- **For commercial LWR power reactors**

  - For existing plants, in the frame of life extension: safety improvement: study of S.A. mitigation systems to bring Gen II safety close to Gen III.

  - To contribute to studies of Gen III reactors S.A. mitigation options:

Core catcher scheme

- ex-vessel retention with larger spreading surface (core catcher) and/or water injection after vessel failure and corium flow (EPR, VVER);
- in-vessel retention (IVR) with reactor pit flooding (KERENA, AP-1000, …).

R&D mainly conducted in the frame of partnership with EDF, AREVA and IRSN

- **For non power reactor:** nuclear propulsion, experimental reactors

- **Post-Fukushima expertise**

  - Expertise to estimate the state of reactors

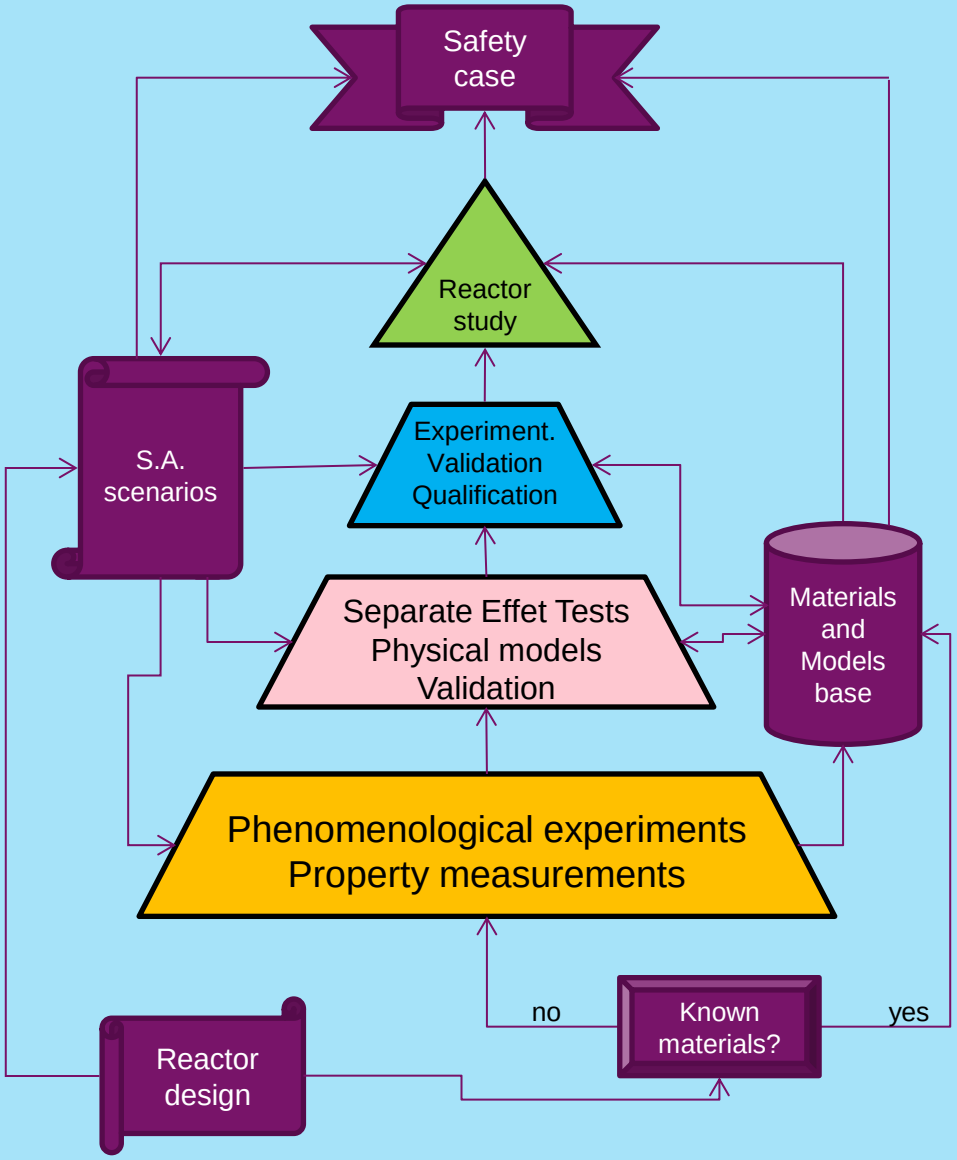
  - Support for decommissioning

# CEA SEVERE ACCIDENT STUDIES - APPROACH

**The corium behaviour R&D program consists of:**

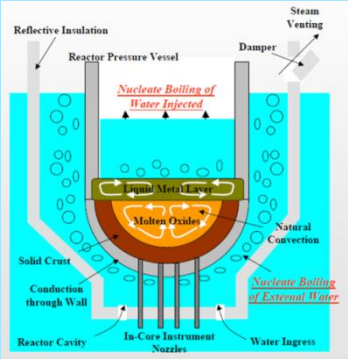
- The achievement of simulant and prototypical materials experiments to improve the knowledge of main relevant phenomena;
- The establishment of qualified physico-chemical properties and thermodynamical corium databases;
- The development and the qualification of both scenario and mechanistic codes for reactor calculations.

$H_2$ distribution in the containment, fission products release, mechanical aspects are not discussed here.

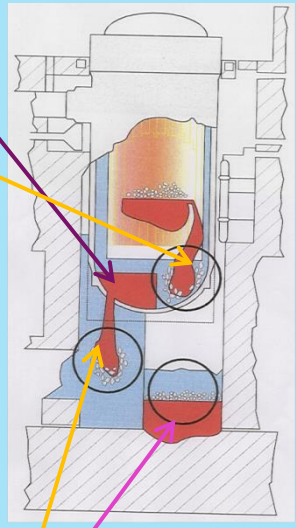


# Main Severe Accident R&D corium issues

## In-Vessel Retention strategy




- Corium formation and relocation in the vessel lower head
- **Corium stratification and vessel thermal loading** (focusing effect issue)
- External vessel cooling
- **Fuel Coolant Interaction**: leading to core melt fragmentation upon contact with water, steam production, dynamic loading of structures in case of steam explosion

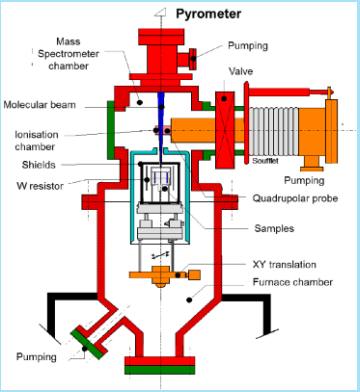


## Ex-vessel retention strategy

- **Ex-Vessel Corium Retention** in the reactor pit
  - Corium spreading : dry or under water conditions
  - Debris bed coolability
  - Molten Core Concrete Interaction under dry or water conditions
- **Fuel Coolant Interaction**: fragmentation and steam explosion

# OVERVIEW OF CEA FACILITIES FOR S.A. R&D

- Current experimental CEA platforms to support the ex-vessel corium R&D




**ATTILHA**

**KROTOS (5 – 8 kg)**
**corium-water interactions**

**Vulcano (50-80 kg)**
**MCCI**

**VITI (5 g)**
**Corium physical properties**

**PLINIUS platform with prototypic corium (depleted Uranium)**

- CEA has identified the need for a new platform to achieve tests with up to 500 kg of prototypic corium

  ⟶ **The PLINIUS-2 project**

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# FUEL COOLANT INTERACTION

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# FUEL COOLANT INTERACTION (1/3)

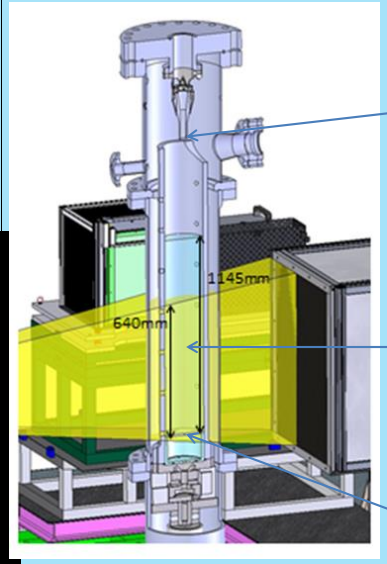
- **Goal: to assess the main relevant uncertain parameters and phenomena to improve fragmentation and steam explosion energetics evaluation**
- **Past and current experiments**
  - Experiments with prototypic corium: FARO (JRC-EU), TROI (KAERI) and KROTOS (CEA) with an advanced instrumentation (X-ray to observe on-line corium/liquid water/steam distribution)
  - Experiments with simulant materials (Lorraine University, KTH…)

**KROTOS facility**

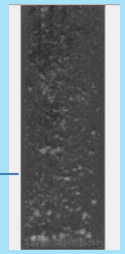
- Experiments with prototypic corium
- Resistive Furnace allowing to heat 8kg of corium up to 3000K
- Release tube
- Test section

**Measurements**

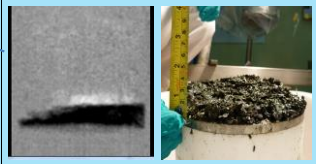
- High speed video
- X-ray radioscopy system
- TC, pyrometer
- Water level (void fraction)
- Dynamic pressure transducer
- Gas analysis



**High speed video of the melt corium jet**



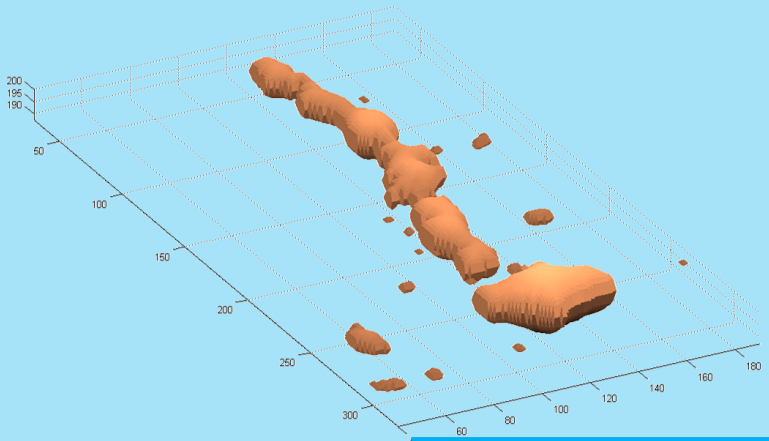
**X-ray image of the fragmentation**



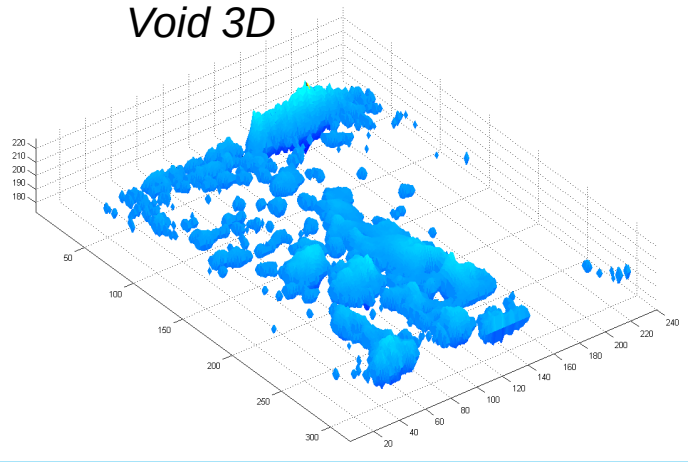
# FUEL COOLANT INTERACTION (2/3)

- **Instrumentation**
  - Specific Instrumentation of KROTOS test section : X-Ray Linatron (50-200 frames/second)- KIWI software developed by CEA
  - Qualitative and quantitative data

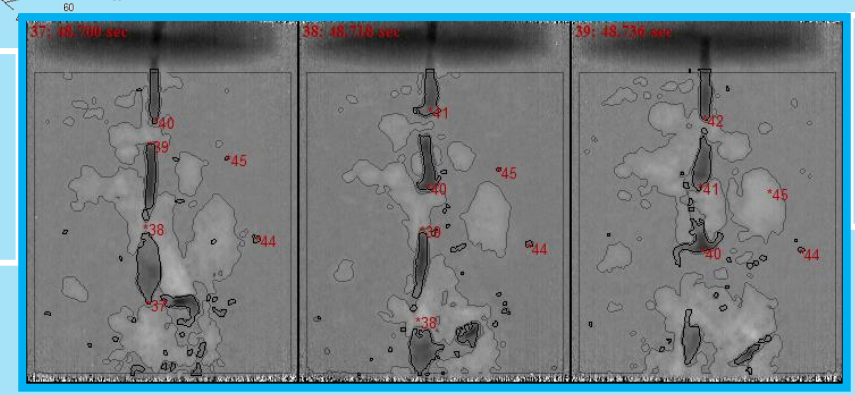
*Corium 3D*



*Void 3D*



- Corium volume
- Corium surface area



- Void volume
- Void surface area

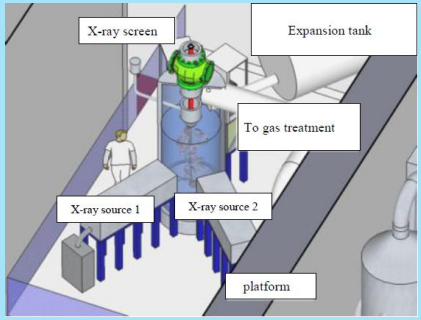
# FUEL COOLANT INTERACTION (3/3)

- **Development of codes**
  - Capitalization of the state of the art in the MC3D numerical simulation code for premixing and steam explosion calculations - developed by IRSN with CEA support and EDF fundings
- **Experimental needs to improve and qualify models and codes**
  - OECD/SERENA2 project (2007-2012) concludes that for ex-vessel steam explosions, margins were small with respect to acceptable loads
  - IVR strategy specificity (flooded reactor pit) : inclined corium jet flow under water + confined environment, metallic jet (in case of vessel failure due to F.E attributed to thin metallic layer)
- **Current work and perspectives**
  - ICE French national program : 5 experiments in KROTOS, corium thermophysical and thermodynamic properties measurements and MC3D improvements
  - The future CEA PLINIUS-2 facility will include a hall dedicated to FCI (with and without steam explosion) with several test sections:

    - metallic jet for IVR strategy

    - high oxide corium mass (>200 kg) to be representative of reactor case

    - intermediate oxide corium masses (~ 100kg) with X-ray imaging



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# EX-VESSEL CORIUM SPREADING, INTERACTION WITH CONCRETE, AND COOLABILITY

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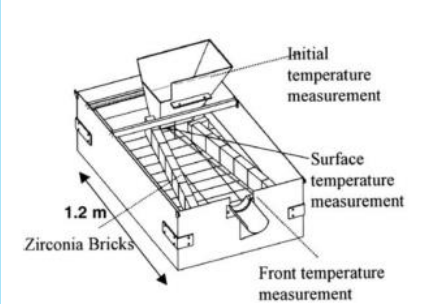
# EX-VESSEL CORIUM SPREADING

- **Goal: evaluation of the corium spreading giving input data for MCCI**
- **Context:**
  - Initially dry pit (over concrete) or Pit flooded after 1st pour followed by a second pour underwater (over corium)
  - Simulant materials tests with shallow water (PULIMS, SES) indicate energetic explosion possibility
  - Driving forces :
    - Dry: spreading mainly controlled by bulk solidification and inertial and viscous forces
    - Underwater: spreading controlled by the yield stress in crust at the flow front (crust mechanical strength) →Necessity of large scale tests : ~ 500 kg (for 10 cm thickness)
- **Past and current experimentations**
  - Under dry conditions:
    - experimentations with prototypic corium: VULCANO facility (CEA), FARO (JRC-EU)
    - experimentations with simulant materials: CORINE (CEA), KATS (FZK)…
  - Under water: only experimentations with simulant materials: CORINE (CEA), PULIMS (KTH)

## VULCANO-Spreading facility

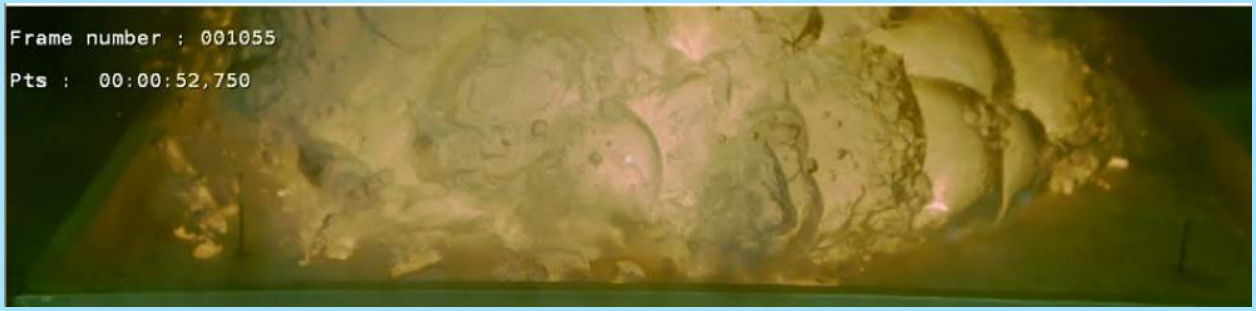
- Configuration for corium spreading experiments
- Spreading plane test section made of refractory bricks, steel plate or concrete



# EX-VESSEL CORIUM SPREADING

- **Development of codes:** THEMA
  - validated under dry conditions for EPR
  - development in progress under water layer

- **Current work and perspectives**
  - Development of models and code under water situations
  - Proposed in the current H2020 call : Project E²VR
  - CEA project to build a new facility (PLINIUS-2) to study spreading with higher mass (~500 kg) of prototypic corium and reflooding
  - Need to characterize the thermomechanic properties of the corium crust



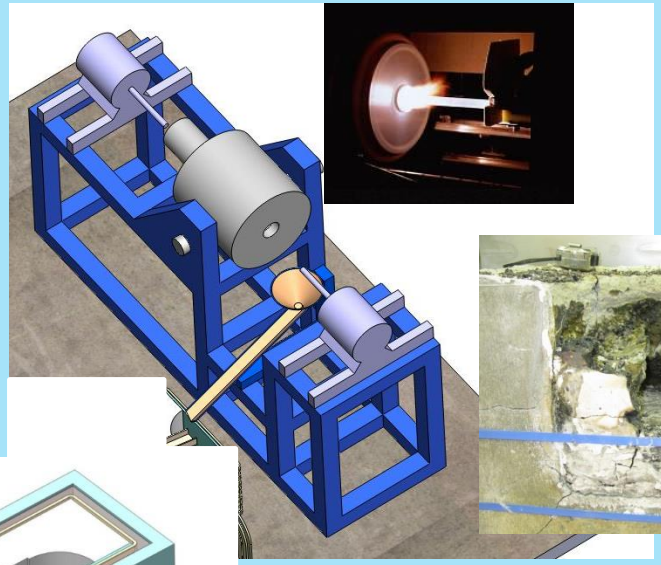
# MCCI AND EX-VESSEL CORIUM COOLABILITY (1/2)

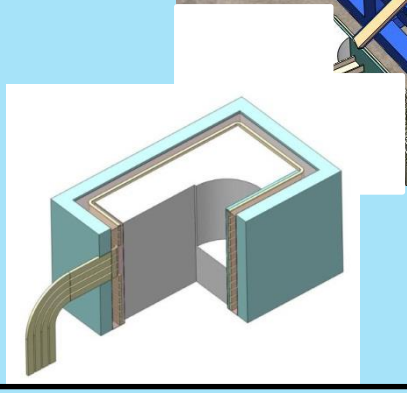
- **Context: evaluation of the MCCI kinetics**

- **Past and current experiments**
  - Experiments with prototypic corium: VULCANO facility (CEA), CCI and SSWICS (USA)…
  - Experiments with simulant materials: ARTEMIS, ABI, BALISE, CLARA, CORINE (CEA), MOCKA (KIT), KATS (FZK)…

## MCCI VULCANO facility

- Concrete test section with over 150 TCs to follow concrete ablation front
- Induction simulation of decay heat
- Half cylindrical cavity (for better induction coupling) + refractory wall
- Post-test examinations and analyses





# EX-VESSEL CORIUM COOLABILITY AND MCCI (2/2)

- **Development of codes :** TOLBIAC-ICB funded by EDF

- **Current work and perspectives**

To carry out additional R&D program for more realistic situations including mitigation approach:

- to understand non isotropic ablation origin as a function of concrete type (siliceous)
- to study mitigation by water cooling (top or bottom flooding) through tests with prototypic corium (oxide + oxide/metal)

➢ MIT3BAR French national program (Mitigation of the risk of breaching the 3rd barrier ) with 4 tests in the MERELAVA facility

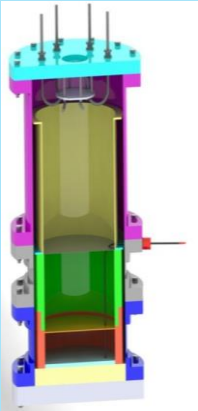
➢ Contribution to experimental programme at ANL-US with high oxidic corium mass tests (mainly funded by French partners)

➢ Proposed in the current H2020 call : Project E²VR

➢ The future CEA PLINIUS-2 facility will include a room dedicated to MCCI with metal-oxide corium (~500 kg), possibility of reflooding for mitigation studies and induction heating to simulate decay heat

**MCCI MERELAVA facility (New facility being built to study water cooling)**

- Close to SSWICS but with oxide + steel
- Thermitic melt generation
- Possibility of induction heating
- Study of cooling by top or bottom flooding
- Measurement of generated steam rate (condenser line) for cooling power
- Management of hot flammable gases



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# CORIUM PROPERTIES

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# CORIUM PROPERTIES

- **Goal:** to measure corium properties at high temperature

## VITI (PLINIUS platform)

**Principle:** **high temperature (up to 3000°C) induction heating furnace to perform analytical studies with small quantities (several g) of prototypic corium (with $UO_2$):**

- Thermophysical properties measurements by aerodynamic levitation: density, surface tension, viscosity.
- Oxidation studies by steam or air
- Solidification process of corium oxide melt
- Interaction between corium and sacrificial materials.

**Conditions:** different atmospheres (reductive, neutral and oxidant) and configurations according to the goal

**Measurements:** on line gas spectroscopy, pyrometers, post-mortem analysis

## Saclay Lab

**ATTILHA:** **high temperature laser heating device (up to 3000°C) to measure phase diagram data on ex-vessel corium sub-systems (with $UO_2$):**

- Phase diagram transitions (solidus, liquidus, eutectic)
- Radiative properties (IR emissivity at 4 µm)
- Observation of solidification process of corium oxide melt
- Interaction between corium and core catcher materials

**HTMS:** **high temperature mass spectrometry coupled with Knudsen cells (up to 2150°C) to measure vapour pressure and gas release from a complex mixture:**

Measurement of both thermodynamic data or kinetic phenomena

**Conditions:** control of the atmosphere (Red/Ox)

**Measurements:** high speed camera, IR pyrometry and post-mortem analyses

## Database

Experimental data are used to improve NUCLEA and TAF-ID thermodynamic database

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# SEVERE ACCIDENTS INSTRUMENTAION

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# SEVERE ACCIDENTS INSTRUMENTATION

- **Goal: to improve the monitoring of the status/the evolution of the accident and then its management**

- **French national projects**

Following Fukushima accident, the French government launched National projects:

  - DECA-PF

  Diagnosis of degraded core state by measurement of released fission products

  - DISCOMS

  Improving the surveillance of the 3rd barrier during a severe accident thanks to the use of remotely operated instrumentation, even in case of Station Black-Out:

  - ✓ Distributed Optical Fiber sensors
  - ✓ Self Powered Neutron (and gamma) Detectors

- **International level**

  - 7th PCRD-SAFEST: WP dedicated to the improvement of instrumentation at high temperature to be implemented in S.A experimentations

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# POST FUKUSHIMA EXPERTISE

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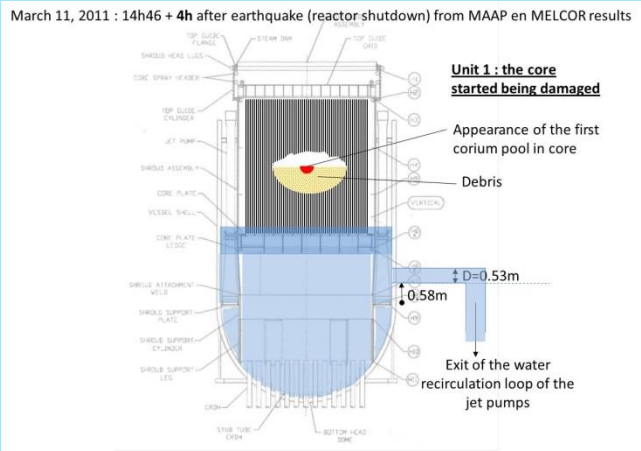
# POST-FUKUSHIMA CEA ACTIVITIES

- **Goal: estimation of the state of reactors and support for decomissionning**
- **Contribution to international projects**
  - OECD/BSAF (Phases 1 & 2)
    - ➢ Alternative scenario analysis for in-vessel progression
    - ➢ MCCI calculations with TOLBIAC-ICB
    - ➢ FP data analysis and interpretation of accident
  - OECD/SAREF (*Senior Expert Group on Safety Research Opportunities Post-Fukushima)*
  - OECD/TCOFF *(Thermodynamic Characterization of Fuel debris and Fission products)*




- **CEA - Japanese bilateral contracts**
  - To evaluate in-vessel debris composition
  - To evaluate physico-chemical and mechanical MCCI material properties
  - To develop laser cutting device
  - To evaluate in-vessel and ex-vessel debris leaching behaviour

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# FUTURE PLINIUS2 EXPERIMENTAL PLATFORM

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# THE FUTURE PLINIUS2 EXPERIMENTAL PLATFORM OBJECTIVES FOR LWR

## Two main issues

- Consolidation of corium behavior modelling, Model development, Code validation **with realistic corium**
- Support of the development of new mitigation concepts (Gen2 or Gen3 reactors) with **conditions as close as possible to the reactor case**

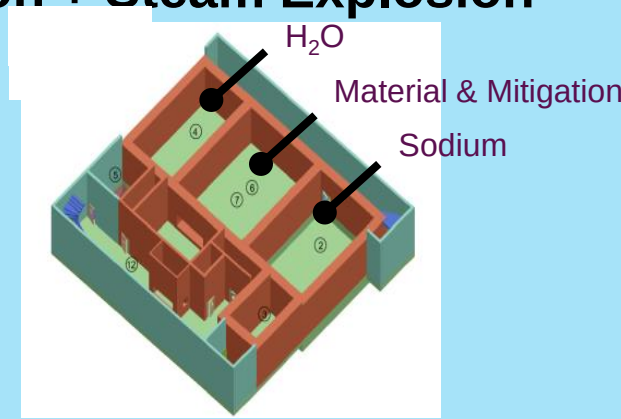
## Investigated issues / aimed test device performances

### IVR (In Vessel Retention) Oxide/metal stratification and focusing effect

➔ Mass between 50 and 250 kg ➔ metallic jet or oxide corium
➔ On-line instrumentation (X-ray imaging, ultrasonic methods) to catch kinetics

### FCI with water Fragmentation, Debris Bed formation + Steam Explosion

➔ Mass ~ 50 - 500 kg
➔ X-ray imaging




### Corium spreading with several 10 cms of water

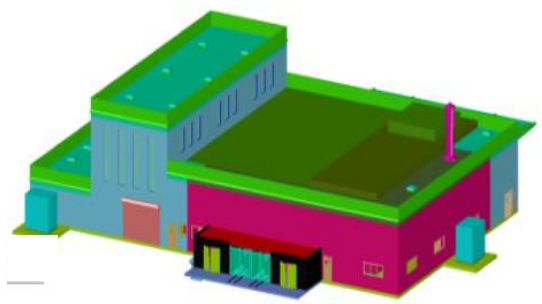
➔ Mass ~ 500 kg

### MCCI top flooding and other mitigation concepts

➔ Mass ~ 500 kg ➔ metal/oxide corium
➔ Possibility to maintain heating during ablation (to simulate residual power)

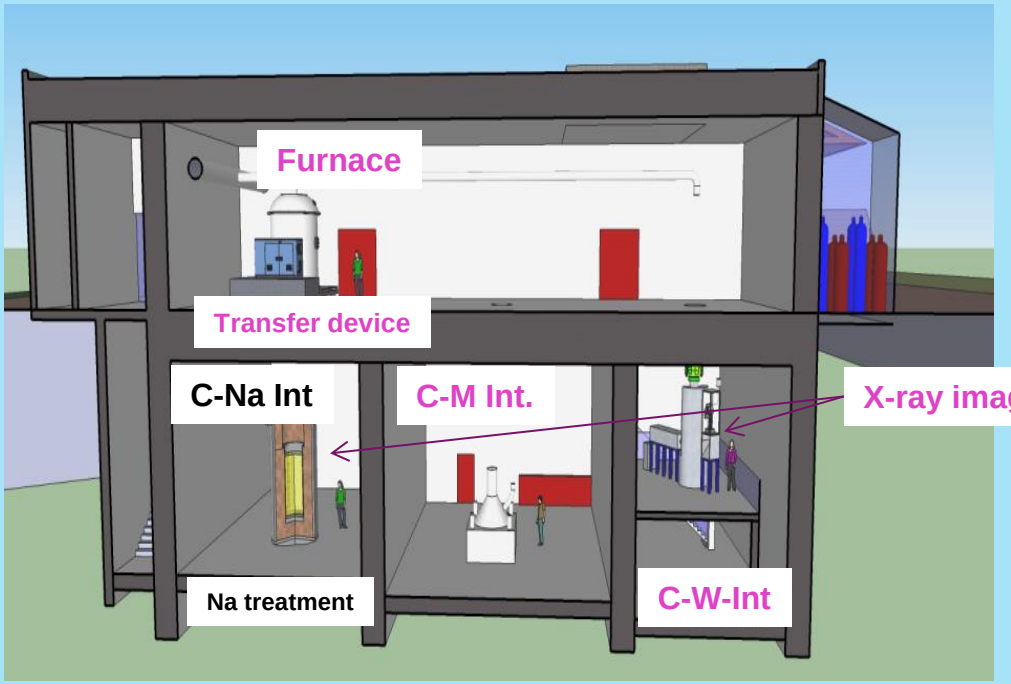
# THE PLINIUS2 PROJECT - OVERVIEW

## Building



- **Functions:**
  **Networks, nuclear ventilation, halls, radioprotection…**

## Processes

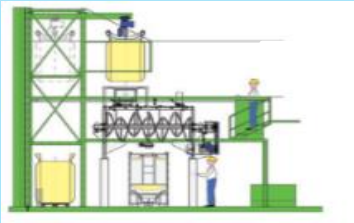



- **Processes :**

➔ **Shared: load preparation facility, Furnace, gas/$H_2$ extraction/treatment system, workshops, instrumentations, PTE…**

➔ **Specific to each type of interaction: Corium/sodium, corium/materials, corium/water**

**Load preparation hall**



# CONCLUSION

- **CEA has gained expertise (more than 20 years of R&D) in corium behaviour during a severe accident including:**
  - Design and Conduct experimental facility
  - Model and code development
  - Expertise for different kinds of reactors
- **CEA has decided to build a new large mass prototypic corium experimental platform, PLINIUS-2, to improve this knowledge – First test is planned in 2021**
- **This experience is shared thanks to several national (with EDF, AREVA and IRSN) and international collaborations in the frame of:**
  - The development of mitigation concepts to improve existing reactor safety
  - The design of the future reactors
  - The support to Fukushima decomissionning

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# Thank You for Your Attention

IAEA TM meeting - « phenomenology and technologies relevant to IVMR and EVCC » - October 17-21, 2016 - Shanghai, China

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