International Experts' Meeting on Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant
IAEA, Vienna 16 – 20 February 2015

FROM RESEARCH TO INDUSTRY

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IAEA
International Atomic Energy Agency
Atoms for Peace

CEA post-Fukushima R&D programmes on PWR Severe Accidents

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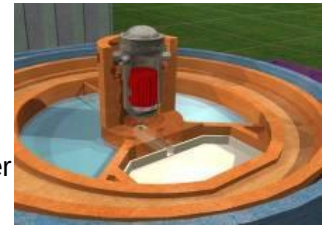
Outline

- ➔ Overview of LWR Severe Accident Program
- ➔ CEA Assets
  - Codes
  - Experimental Facilities
- ➔ Some R&D Issues
  - Source Term
  - Fuel Coolant Interactions
  - Spreading
  - Molten Core Concrete Interaction
  - Fukushima NPP related R&D
- ➔ Conclusions

CEA SEVERE ACCIDENT STUDIES

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

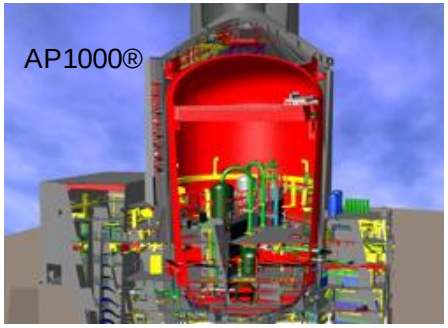
- For commercial LWR power reactors
  - For existing plants, in the frame of life extension : demand to bring Gen II safety close to Gen III (i.e WENRA rules): study of S.A. mitigation systems.
  - To contribute to studies of Gen III reactors S.A. mitigation options:
    - ex-vessel retention with larger 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, …).



Core catcher scheme

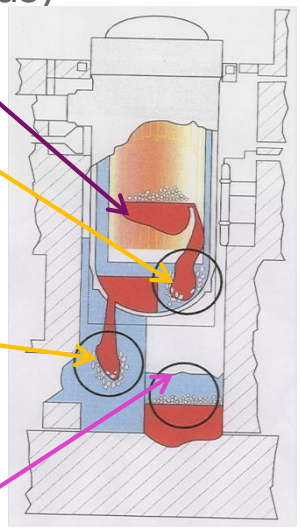
R&D mainly conducted in the frame of partnership with AREVA, EDF and IRSN

- For non power reactor: nuclear propulsion, experimental reactors



Main Severe Accident R&D issues

- **Source Term Issues**
  - Effect of air ingress on Fission Product release and transports
  - Effect of high burnup and MOX fuel
- **In-Vessel Retention**
  - Corium formation and relocation in the vessel lower head
  - **Corium stratification and vessel thermal loading** (focusing effect issue)
  - **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 phenomena**
  - **Fuel Coolant Interaction**: fragmentation and steam explosion
  - **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
- **Hydrogen**
  - Thermalhydraulics in containment
  - Mitigation systems

French National Research Call on Nuclear Safety and Radioprotection

Fukushima accident showed the need to increase the expertise and deepen the R&D in safety and radioprotection.

The French government launched a 50 M€ call in summer 2011.

- Funded by “Investment for the Future » general commission
- Operated by ANR (French National Research Agency)

- Announcement of the list of selected project on May 17, 2013 by 3 Ministers and General Commissioner for Investment
  - The 22 selected projects shall
    - provide insights on the conditions that led to major accidents, in particular Fukushima,
    - study accident management measures both for operators and public authorities,
    - Analyse the impact of these accidents in term of radioactive material releases and impact on health and environment.

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Some CEA participations related to Severe Accident R&D

SINAPS
- ✓ Explore uncertainties on knowledge of seismic risks and structure vulnerability.
- ✓ Identify, quantify seismic margins.

DECA-PF
- ✓ Assessment of FP release in the environment and Diagnosis of Damaged Core state by measurement of Fission Products

DISCOMS
- ✓ Aiming at improving the surveillance of the 3rd barrier during a severe accident thanks to the use of distributed optical fiber measurements and of self powered neutron (and gamma) detectors.

ICE
- ✓ Improvement of knowledge on the Corium-Water Interaction phenomena and major uncertainties:
  - Primary fragmentation of molten fuel
  - Corium oxidation and fragmentation
  - Fine modeling of vaporization and pressurization during steam explosion.

MIT3BAR
- ✓ Mitigation of the risk of breaching the 3rd barrier (containment) in view of possible reinforcement of Gen 2 plants safety with comparison to Gen 3.
- ✓ Top flooding of corium pool interacting with corium
- ✓ Bottom flooding through dedicated porous concrete layer.

MACENA
- ✓ Mastering Containment Leaktightness during Accidents
- ✓ Models and Predictive tools

MITHYGENE
- ✓ Improve the knowledge on hydrogen distribution and combustion inside containment and its effects on structures.

CEA ASSETS FOR SEVERE ACCIDENT R&D

Major Corium Codes at CEA

- Late In-Vessel Progression: **PROCOR** platform
  - ✓ takes into account the complexity of the different models and their coupling used in the scenario analysis and must deal with transitory phenomena;
  - ✓ could be used to perform statistical analysis of those parameters using Monte Carlo method (URANIE framework which is a CEA statistical tools, Monte Carlo = black box so easy and fast);
  - ✓ Each model could be analyzed stand alone (sensitivity analysis) and could be replaced by a more accurate model (model evolution/reduction/….);
  - ✓ Robust numerical schemes;
  - ✓ Models coupling/assembly will evolve during the live cycle of the application, driven by sensitivity analysis and scenario analysis.
- Fuel Coolant Interaction: **MC3D**
  - ✓ Contribution to the qualification and upgrade of this IRSN tool
- Mechanical Response to explosions: **EUROPLEXUS**
- Corium (dry) spreading: **THEMA**
  - ✓ Validated on CEA (VULCANO, CORINE) and European (CSC, ECOSTAR) experimental programmes
- Molten Core Concrete Interaction: **TOLBIAC-ICB**
  - ✓ Joint CEA-EDF programme. Dry MCCI and Coolability
  - ✓ Validated on VULCANO (CEA) and International (CCI, etc.) experiments

CEA EXPERIMENTAL ASSETS: THE VERDON FACILITY

- Furnace to study the release of Fission products from (re-)irriadated UOX or MOX fuels
  - Fuel can be re-irradiated in MTR and tested less than 70 hrs after irradiation.
- Induction furnace (up to fuel melting 2600°C)
  Possibility to control atmosphere
  - Oxidizing: steam, air
  - Reducing: H2

- FP Release
- FP Transport
- Dedicated instrumentation + expertise on the interpretation of FP γ–spectra.

- Provide useful data in complement to integral in-pile tests
- Open to international collaborations

VERDON-5 TEST PLANNED IN 2015

"Air ingress" on UO_2 fuel (same high Burn-Up fuel as VERDON-1), using the same conditions than VERDON-2

Boron injection during the initial phase under steam

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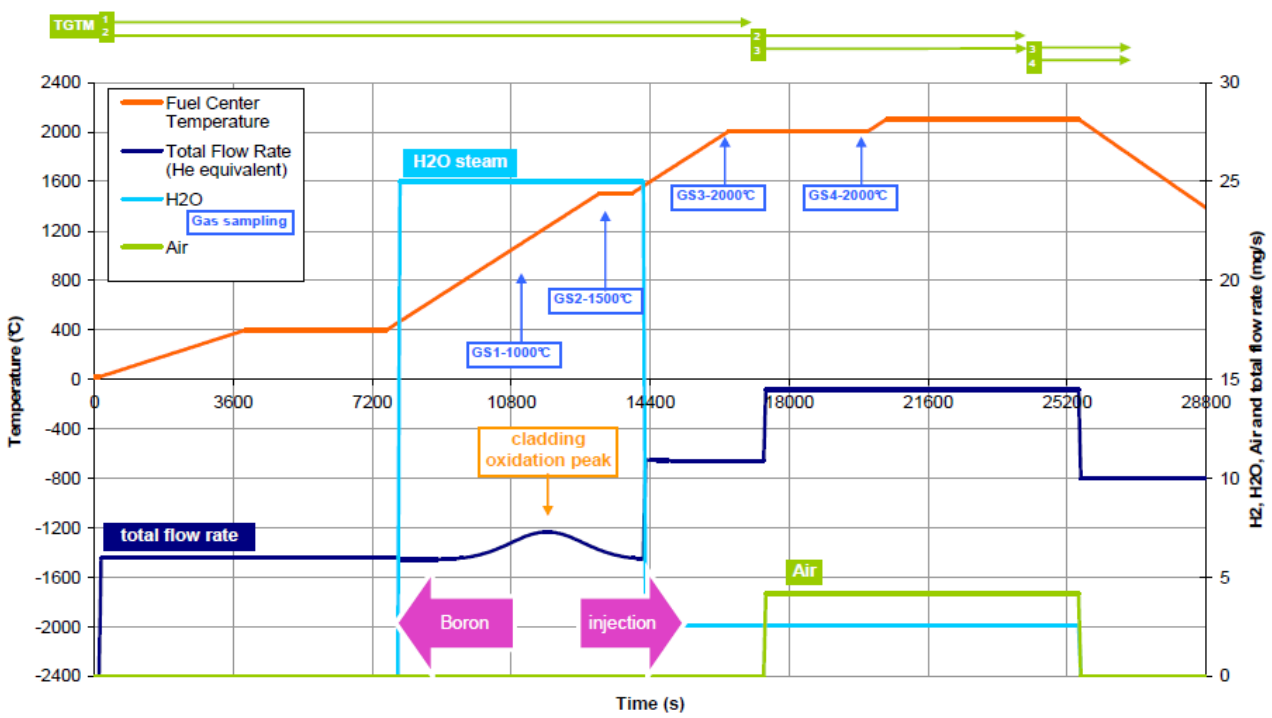


CEA EXPERIMENTAL ASSETS: THE MISTRA FACILITY

- Dedicated to Hydrogen risk and related containment thermalhydraulics issues
  - Direct link with code development and validation
    - Laser Doppler Velocimetry
    - Quantitative Mass Spectrometry sampling points,…
  - 3D effects distributed sources of gas/steam…
  - Qualification of mitigation approaches (aspersion, inerting, recombiners…)
- 1/10th scale model of PWR containment
- Thermalhydraulics of air, steam, nitrogen, hydrogen (simulated by helium)

CEA EXPERIMENTAL ASSETS
PLINIUS PLATFORM : 3 FACILITIES

VITI
(5g)
Basic Physical data

KROTOS
(5kg)
FCI (water)

VULCANO
(50kg)
Spreading - MCCI

Prototypic corium experiments with depleted uranium

SAFEST pan-European Distributed Laboratory for Corium Experimental R&D

SWECOR
KTH

SICOPS
AREVA NP

LACOMECO
KIT
FLF
JRC/ITU

COMETA
UJV

PLINIUS
CEA

CODEX,
CERES
EK

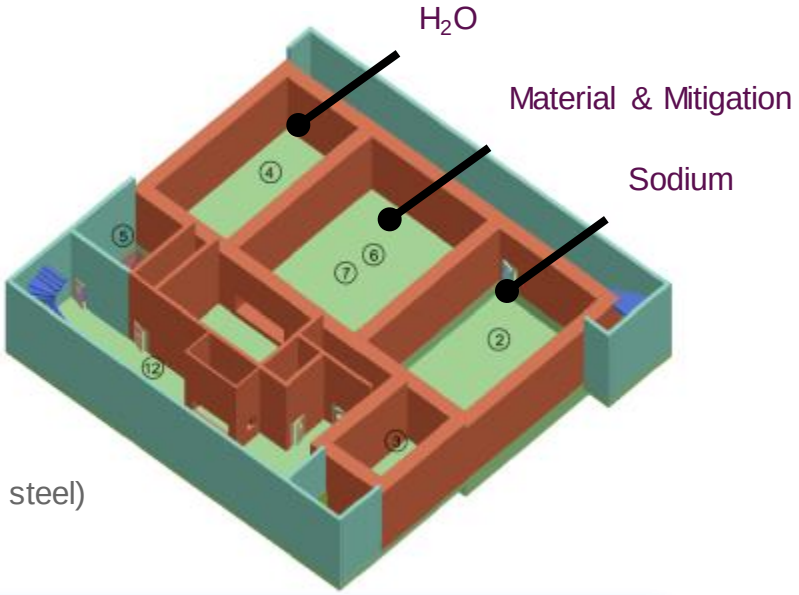
16 Experimental facilities
EURATOM FP7 Research Program 2014-2018

New Large Infrastructure for Prototypic Corium Research: PLINIUS 2

Corium-Sodium Facility

GEN4

- FCI up to vapor explosion
- Sodium temp.: 400 to 850°C
- Corium mass : 50 to 500kg
- Na test section + circuit ~2 tonnes
- X-ray imaging



Material interaction facility

GEN4
GEN2&3

- Ablation (core catcher material, ceramics, concrete, steel)
- Corium mass : 50 to 500kg
- With/without cooling
- Size upto 3m x 3m x 1m
- Potentially X-ray imaging

Corium-Water Facility

GEN2&3

- FCI up to Steam explosion
- Temp : ~80°C
- Mass: 50 à 500kg
- Steam quenching system
- X-ray imaging

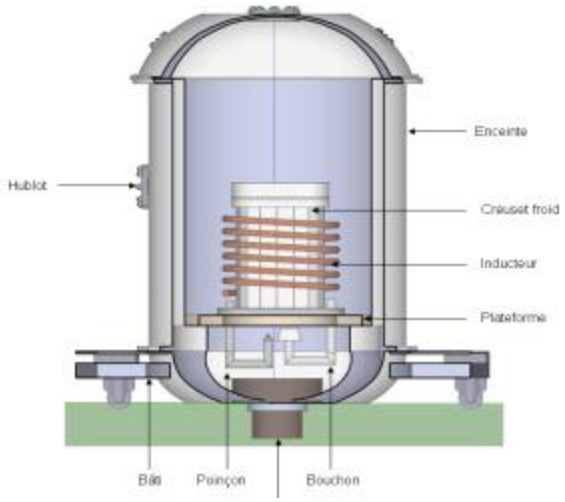
- ✓ **Corium temperature > 2850°C**
- ✓ **Separation Water/Sodium rooms**
- ✓ **Handling of large masses**
- ✓ **One furnace – 3 test facilities**
- ✓ **Electric power ~ 1 000 kVA**

+ Phenomenological tests (VITI)

+ Analytical tests (Low Temperature)

PLINIUS2:
Gains of a multi-technology (LWR, SFR…) platform

- ➔ Common infrastructure for cost sharing
  - Furnace, workshops, instrumentations, PTE…
- ➔ Operations, process, experimental expertise
  - Automation
  - Common support for security, safety, waste management, experimental expertise …
- ➔ Greater visibility and attractiveness
  - ➔ National and International collaborations



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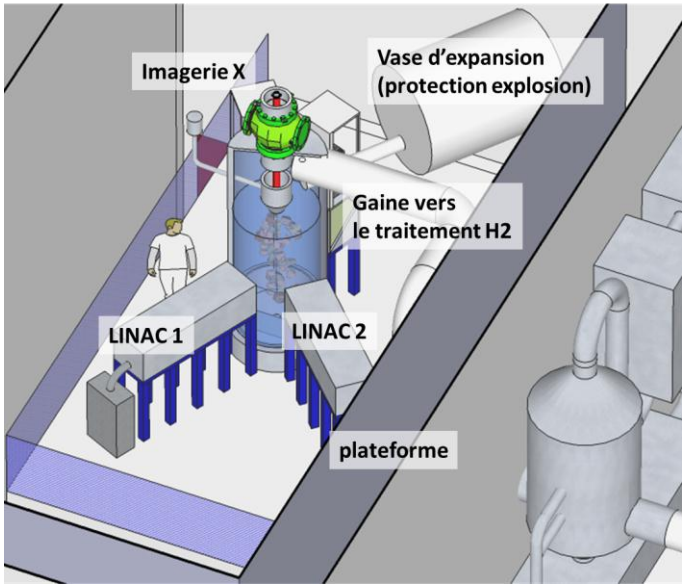

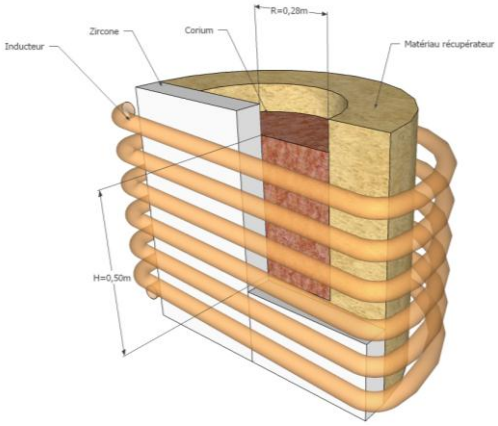

First tests expected for 2020

SOME R&D ISSUES

FUEL COOLANT INTERACTION

- **R&D needs: to assess the main relevant uncertain parameters and phenomena to improve fragmentation and steam explosion energetics evaluation**
  - SERENA 2 OECD project conclude that for ex-vessel steam explosions, margins were small with respect to acceptable loads
  - IVR strategy specificity: flooded reactor pit
- Need for experiments with representative geometry to characterize **fragmentation and associated steam explosion loading**: inclined corium jet flow under water + confined environment
- Need for data to improve and qualify models and codes

Experiments with and without explosion with prototypic corium (oxide and metal/oxide) + on-line imaging techniques

→ **with representative geometry: modified KROTOS facility (~5-8 kg) with inclined jet, and flooded pit (mid-term)**

→ **with large mass (>200 kg): possibilities given by PLINIUS-2 facility (longer-term)**

- **Flooded pit, inclined jet,…**
- **X Ray imaging**
- **~Water counterpart of Sodium test section**

UNDERWATER SPREADING

Context

- Ex Vessel Retention
  - Initially flooded pit (over concrete)
  - Pit flooded after 1st pour; second pour underwater (over corium)
- Simulant material tests (PULIMS, SES) indicate possibility of energetic explosion

Difference with dry spreading (VULCANO-E)

- Dry: controlled by bulk solidification, bulk viscosity increase
  - Possibility of medium scale tests
  - EPR: Corium-concrete mixture with large solidification range
  - EvR : Only one VULCANO Test (VE-U8) and 2 FARO-LS tests
- Underwater: controlled by crust mechanical strength
  - Necessity of large scale tests : > 150-200 kg (~FARO-LS)
  - Take into account SE risk and H2 risk (steel)

MOLTEN CORE CONCRETE INTERACTION

- A comprehensive R&D programme has been performed on dry MCCI to solve the issue of early basemat melt-through
  - After the thickenning of Fessenheim NPP basemat, risk of early melting of concrete basemat is practically eliminated.
  - Knowledge, and produced corium-concrete samples are currently used to contribute to R&D related to Fukushima dismantling of corium debris.
- New R&D focus on coolability issues (Mitigation)
  - How to prevent late melt-through ?
  - CEA programme is based on:
    - Improvement of TOLBIAC-ICB code
    - Contribution to experimental programme at ANL
    - New MIT3BAR experimental program (at CEA and KIT)
    - Future Large scale facility (PLINIUS-2) at CEA Cadarache

R&D RELATED TO FUKUSHIMA DAIICHI PLANTS

- CEA Expert group during March-May 2011
- Participation to BSAF (1 & 2) OECD project
  - Alternative scenarios for in-vessel progression
    - Sidewards progression of corium pool
  - Fission Product data analysis and interpretation of accidents
  - Molten Core Concrete Interaction
- Support to the decommissioning of 1F corium debris.
  - Selection of representative corium samples from PLINIUS corium bank
  - Analyses focused on mechanical and chemical properties relevant for corium cutting and treatment
  - Qualification of laser-cutting tool for corium debris

Conclusion - Perspectives

- CEA has gained expertise on severe accident thanks to the long term performance of severe accident R&D (experiments + modelling + codes) for more than 20 years.
  - ✓ CEA is a major actor of the European Research Area in Severe Accident (SARNET, NUGENIA and several EURATOM-sponsored projects) as well as OECD/NEA activities on the topic.
- Fukushima accident has launched a renewed interest in severe accident research
  - ✓ New projects are being started to improve the knowledge of severe accidents and to provide validated mitigation strategies.
  - ✓ New large prototypic corium facility is being designed.
  - ✓ CEA contribute to the international activities to understand the accident progression and to assist Japan for its decommissioning.
- CEA is currently conducting several international collaborations on Severe Accident Research and is open to new ones.

Thank you for your attention

We gratefully acknowledge support from:

- EDF, IRSN, AREVA
- CGI (Investments for the Future)
- EURATOM
- NUGENIA / SARNET
- OECD/NEA
- IRID, JAEA,…