PLINIUS 2
(formerly ARIANE - FOURNAISE)

Future Large mass Prototypic Corium Facility at CEA Cadarache

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Outline

1. Major Severe Accident issues for LWRs and for Gen IV SFRs
2. World panorama of existing facilities
3. Description of the Multi-technology PLINIUS 2 platform
4. Conclusions and perspectives
Severe Accident R&D

- Safety case
- Reactor study
  - Experiment, Validation Qualification
  - Separate Effet Tests
  - Physical models
    - Validation
  - Phenomelogical experiments
    - Property measurements

- Reactor design
  - Prototypic materials
  - Simulant materials

- Known materials?
  - yes
  - no

- Material References

- S.A. scenarios

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Main issues for Gen II and III

Gen II context in France
- Life extension
  - Adaptation of safety rules towards mitigation

Gen III context
- Ex-Vessel retention: EPR, ATMEA,…
- In-Vessel retention: KERENA, AP-1000,…

New step in R&D program
- IVR (In-Vessel Retention)
  - Oxide metal stratification and focusing effect
    - Kinetic effects
  ➔ Up to 500 kg of prototypic corium
- IVR Failure
  - FCI with large jet diameter.
  ➔ Up to 250 kg of prototypic corium
  ➔ Need for larger masses indicated in OECD/SERENA2 conclusions
- Ex Vessel Retention:
  - MCCI with water and other retention devices
  ➔ Up to 500 kg of prototypic corium
Main Issues for Gen IV (ASTRID)

French SFR Demonstrator ASTRID:
3 issues
- Confinement, Cooling and subcriticality of corium
- Minimization of energetic events
- In-vessel Core catcher

Specific R&D actions
- Study of mitigation devices
  - Dilution, dispersion, retention of corium
- Fuel Coolant (sodium) Interaction
  - Jet fragmentation
  - Vapor explosion
- Corium-sacrificial material interaction (core catcher)
  - Thermal ablation
  - Physico-chemistry
  - Coolability
  - Phase stratification

Need for experiments in simulant and prototypic (with depleted U) materials with large masses (between 200 and 500 kg) in Na environment for qualification of codes and mitigation devices
Issues for new fuel element materials, e.g. Gas-cooled Reactors

In gas cooled reactors, such as e.g. the GFR prototype project ALLEGRO, fuel and cladding are made of unusual materials:

- Carbides (UC, SiC…)
- Graphite

The behavior of these materials in a severe accident sequence must be thoroughly analyzed prior to implementation in a reactor.

- Small scale material tests
- Separate Effect tests
- Larger scale integral tests

This would apply also if new cladding or fuel materials were to be installed in a LWR.
## Which corium for Severe Accidents Experiments?

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>In pile</td>
<td>Neutronic effects&lt;br&gt;Heating representativity</td>
<td>Complexity (costs, time)&lt;br&gt;Size limited to a bundle</td>
</tr>
<tr>
<td>Irradiated fuel or MOX (Pu + FPs)</td>
<td>Presence of Pu.&lt;br&gt;Less complex than in pile tests&lt;br&gt;Radioactive FPs easier to detect and measure than prototypes.</td>
<td>Complexity (hot lab)&lt;br&gt;Small scale</td>
</tr>
<tr>
<td>Prototypic materials (depleted U)</td>
<td>Corium representativity&lt;br&gt;• Chemistry&lt;br&gt;• Physical properties&lt;br&gt;Relatively easy to handle (glove box/mask)&lt;br&gt;Possibility of large scale tests (100-1000 kg)</td>
<td>No Pu&lt;br&gt;Operational constraint (depleted uranium + high temperatures)</td>
</tr>
<tr>
<td>High Temperature simulants</td>
<td>Non radioactive&lt;br&gt;Cheaper operation&lt;br&gt;Possibility of Separate Effect Tests</td>
<td>Need for similitude law&lt;br&gt;Impossibility to verify scaling for all dimensionless groups&lt;br&gt;Different physicochemistry&lt;br&gt;Difficulties of high temperature experiments</td>
</tr>
<tr>
<td>Low temperature simulants</td>
<td>Dedicate to Separate Effect Test&lt;br&gt;Easier, more precise measurements&lt;br&gt;Possibility to run many tests. May enable large scales.</td>
<td>Little coupling between phenomena&lt;br&gt;Limited similitudes (1 or 2 phenomena)&lt;br&gt;Difficulty of establishing scaling (similitude) laws&lt;br&gt;Peu de couplage entre phénomènes</td>
</tr>
</tbody>
</table>
FARO tests (40-150 kg)
- Steady state reached after 50 kg poured at 9 cm dia. Jet
- Steady state requires significant period after melt bottom contact.
- Linear dependence of pressure to time (mass poured) in steady state

Jet break-up correlations have been extrapolated from available data
- To reach break-up length (60 cm at 3 cm dia.- 2.5 m at 10 cm dia.) up to 400 kg of corium must be poured

This provides order of magnitude of corium mass
Order of the mass of 1 ASTRID subassembly, used for PLINIUS2-SFR dimensioning.
Simulants?
Different chemistry, Different physical properties...

<table>
<thead>
<tr>
<th>Element</th>
<th>U</th>
<th>Ac</th>
<th>Zr</th>
<th>Hf</th>
<th>Ce</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic structure</td>
<td>5f³-6d¹-7s²</td>
<td>7s²-6d¹</td>
<td>4d²-5s²</td>
<td>4f¹⁴-5d²-6s²</td>
<td>4f¹-5d¹-6s²</td>
<td>3s²-3p¹</td>
</tr>
<tr>
<td>Ionization states</td>
<td>0,+3,+4, +5, +6</td>
<td>0, +3</td>
<td>0,+4</td>
<td>0,+4</td>
<td>0+3,+4</td>
<td>0, +3</td>
</tr>
<tr>
<td>Coordination</td>
<td>4, 6, 8</td>
<td>6</td>
<td>4, 6, 8</td>
<td>4, 6, 8</td>
<td>6, 8</td>
<td>4, 6</td>
</tr>
</tbody>
</table>
| Ionic radii (pm) | +3, r= 116  
+/4, r = 103  
+5, r = 90  
+/6, r = 66¹ | +3, r=126 | +4  
Coo 4: 73  
Coo 6: 86  
Coo 8: 98 | +4  
Coo 4: 72  
Coo 6: 85  
Coo 8: 97 | +3,  
Coo 6: 115  
Coo 8, 128  
+4,  
Coo 6: 101  
Coo 8, 111 | 3+  
Coo 4: 0.053  
Coo 6: 0.067 |

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Fusion point (K)</th>
<th>Density (g.cm⁻³ à 293K)</th>
<th>Thermal conductivity (W.m⁻¹.K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO₂</td>
<td>3 120 ± 30</td>
<td>10.96</td>
<td>8.9 (2 @ 2000 K)</td>
</tr>
<tr>
<td>CeO₂</td>
<td>3 073</td>
<td>7.10</td>
<td>12.8 (0.9 @ 1600 K)</td>
</tr>
<tr>
<td>HfO₂</td>
<td>3 031 ± 25</td>
<td>9.68</td>
<td>1.55 (2.37 @ 2000 K)</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>2 973</td>
<td>5.68</td>
<td>1.66 (2.99 @ 2000 K)</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>2 327</td>
<td>3.99</td>
<td>36.2 (7 @ 2000 K)</td>
</tr>
</tbody>
</table>
Differences in FCI between corium and alumina jets
KROTOS facility (at JRC Ispra)

- **Corium**: jet with small globules (size about 1 mm, some globules have an hole inside)
- **Alumina**: separate jet with coarse globules and chips (size about 12 mm, some globules have an hole inside)

Similar discrepancies can be found on other aspects of severe accidents
Current Prototypic Corium facilities

- SICOPS (AREVA) (Gen3)
- COMETA (UJV) (Gen3)
- LS-RMT (ANL) (Gen2&3)
- PLINIUS (Gen2, 3, 4)
- RASPLAV-3 (NITI) (Gen3)
- EAGLE (IPPE) (Gen4)
- TROI, VESTA (KAERI) (Gen3)
- PLUTON (IPPE) (Gen4)
- LAVA (Gen 2)
- SOFI (Gen4)
<table>
<thead>
<tr>
<th>Name</th>
<th>Org.</th>
<th>Country</th>
<th>Type of Corium</th>
<th>Heating technol.</th>
<th>Masse</th>
<th>Sodium</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS-RMT (ACE, MACE, CCI)</td>
<td>ANL</td>
<td>USA</td>
<td>Oxide</td>
<td>Thermite + DEH</td>
<td>2 000kg</td>
<td>No</td>
</tr>
<tr>
<td>VESTA</td>
<td>KAERI</td>
<td>Korea</td>
<td>Oxide + metal</td>
<td>Cold crucible Induction</td>
<td>400 kg</td>
<td>No</td>
</tr>
<tr>
<td>PLINIUS</td>
<td>CEA</td>
<td>France</td>
<td>Oxide + metal + concrete</td>
<td>Plasma arc Resistor Induction</td>
<td>70 kg 5 kg 5 g</td>
<td>No</td>
</tr>
<tr>
<td>LAVA EAGLE</td>
<td>NNC - JAEA</td>
<td>Kazakhstan (for Japanese)</td>
<td>UO2, ZrO2, Zr, Al2O3</td>
<td>Cold crucible Induction</td>
<td>60 kg 20 kg</td>
<td>No Yes</td>
</tr>
<tr>
<td>TROI</td>
<td>KAERI</td>
<td>Korea</td>
<td>Oxide + metal</td>
<td>Cold crucible Induction</td>
<td>30 kg</td>
<td>No</td>
</tr>
<tr>
<td>SICOPS</td>
<td>AREVA</td>
<td>Germany</td>
<td>Oxide + metal</td>
<td>Cold crucible Induction</td>
<td>5 to 20 kg</td>
<td>No</td>
</tr>
<tr>
<td>SOFI</td>
<td>IGCAR</td>
<td>India</td>
<td>Oxide + metal</td>
<td>Cold crucible Induction</td>
<td>5 to 20 kg</td>
<td>Yes</td>
</tr>
<tr>
<td>RASPLAV-3</td>
<td>NITI</td>
<td>Russia</td>
<td>Oxide + metal</td>
<td>Cold crucible Induction</td>
<td>2 kg</td>
<td>No</td>
</tr>
<tr>
<td>PLUTON</td>
<td>IPPE</td>
<td>Russia</td>
<td>Oxide + metal</td>
<td>Thermite</td>
<td>150 g</td>
<td>Yes</td>
</tr>
<tr>
<td>COMETA</td>
<td>UJV</td>
<td>Czech Republic</td>
<td>Oxide</td>
<td>Cold crucible Induction</td>
<td>1 kg</td>
<td>No</td>
</tr>
</tbody>
</table>
Synthesis on Prototypic Corium facilities

GEN II&III facility capabilities

- PLINIAUS 70 kg oxide + metal
- CCI-ANL 1-2000 kg oxide
- RASPLAV (NITI, Russia), TROI (Korea) 20 kg oxide + metal

Large oxide + metal masses: non available

GEN IV facility capabilities

- EAGLE out of pile 20 kg alumina sodium
- PLUTON 0.15 kg oxide + metal sodium

Large oxide + metal masses: non available

Recent facilities:

- LWRs : TROI (30kg + water), VESTA (400kg),
- SFRs : SOFI (5kg + sodium)
NEED FOR A NEW CORIUM FACILITY AT CEA

There is a need for **simulant and prototypic** corium experiments. Test scale must vary **from small masses (<100 g)** to significant masses (~500 kg) for the understanding of **corium progression and interaction phenomena**, the **validation of mitigation devices** and the **qualification of Severe Accidents codes and materials**.

This need exists for all reactor technologies for which design projects are conducted.

- **GEN IV**: Support to ASTRID design (to be available by 2018)
  - Also for other technologies, e.g. ALEGRO GFR?
- **GEN II & III**: Support to utilities, vendors and regulators
  - Innovative designs
  - Current Fleet Life Extension

**Context:**
- **Globalized energy market**
- **Post Fukushima**
- **Convergence of standards for Gen II and Gen III**
- **Gen IV requirements**

**CEA/DEN** is preparing the building at Cadarache of a new large corium facility: **PLINIUS 2** (formerly called **FOURNAISE** for **GEN IV issues**).
Corium-Sodium Facility
- 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
- Ablation (core catcher material, ceramics, concrete)
- Corium mass: 50 to 500kg
- With/without cooling
- Size up to 3m x 3m x 1m
- Potentially X-ray imaging

Corium-Water Facility
- FCI up to Steam explosion
- Temp: ~80°C
- Mass: 50 to 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
Sketches of PLINIUS 2 Building

Material & Mitigation

Sodium

H₂O

2 200m² (walls excluded)

30m

50m
1st soil studies have been performed. 
Ecological impact study has been performed. 
*endangered species (bat) only far from point of interest*
Technological challenges

FURNACE
- Fusion of 600kg corium (500kg transferable)
- Temperature ~ 3 000 K
- Single phase of oxide + metal mixture
- Thermitic load and/or cold crucible
- Coolant ≠ water (Na/H₂O risk prevention)

Transfer Device
- Complex at high temperatures
- Bases on experience of past facilities
  - FARO, VESTA, LAVA…

Powder preparation workshop
- U, UO₂, U₃O₈ (depleted)
- Zr, Fe, Cr, Al₂O₃, Fe₂O₃, Cr₁O₃
- Automation for large batches
- Safety (pyrophoric, carcinogen, radioactive)
Technological challenges

Corium-Sodium facility
- $T^\circ$ sodium between 400$^\circ$C and 850$^\circ$C (Tsat)
- Jet dia. $\sim$ CRGT = 8 - 10 cm
- Modular design (liner, insulator, vessel)
- Instrumentation : developments needed (X-rays, US, …)
- Focus on waste management
- Lessons learnt from FARO TERMOS

Corium-Water facility
- Will take lessons from KROTOS, TROI, FARO
- Importance of corium quenching facility

Instrumentation
- Adaptation, improvement of PLINIUS 1
- High temperature measurements
- Phase visualization during FCI
Gains of a multi-technology 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
R&D needs for large scale corium platform
Positive outcome of feasibility study:
- Furnace
- Sodium Loop
- Building
- Site preselection

A PLINIUS 2 seminar is planned in 2014 near Cadarache
- Present PLINIUS 2
- Discuss potential collaborations
- External partners will be welcome
  - National partners
  - International collaborators

Commissioning is scheduled for 2018
- Long term R&D experimental program is expected to start around 2019 at PLINIUS-2
Thank you for your attention!