Severe Accident Research activities at the CEA: methodology and main insights related to Source-Term quantification and Fuel Behaviour

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Outline

- CEA ACTIVITIES IN THE FIELD OF LWR SEVERE ACCIDENT

- CEA SEVERE ACCIDENT STUDIES IN THE FIELD OF SOURCE TERM
  - The context of safety studies related to FP release and transport
  - How to simulate SA conditions in hot cell?
  - VERDON loop and the ISTP programme
  - VERDON-5 test
  - Highlights on VERDON-1

- Conclusion
CEA ACTIVITIES IN THE FIELD OF LWR SEVERE ACCIDENT
Goal: *provide tools (codes, facilities) and expertise for severe accident understanding and management.*

- **National frame: in support to EDF, AREVA, IRSN for French fleet**
  - 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** (ex-vessel reflooding, IVR)
  - To contribute to studies of **Gen III** reactors S.A. mitigation options:
    - **ex-vessel retention** by larger spreading surface (core catcher) and/or water injection after vessel failure and corium flow (EPR, VVER);
    - **in-vessel retention** (IVR) by reactor **pit flooding** (KERENA, AP-1000), …).

- **International frame: as technical advisor**
  - Better evaluation (reduction of uncertainties, enhanced validation database) of Severe Accident regarding diagnosis of its progression and its consequences
  - Feasibility, design and evaluation of mitigation system and option performances
  - Support to post-Fukushima
The following issues are addressed by CEA (code, facility):

**Consistently with international roadmaps (SARNET, NUGENIA, OECD…)**

- **Goal: source term**
  - FP release evaluation (VERDON, MERARG)

- **Goal: containment integrity**
  - $\text{H}_2$ behaviour (Europlexus, MISTRA)
  - Structure behaviour (Europlexus)

- **Goal: accident diagnosis/instrumentation**
  - FP measurements (DECAPF)
  - Corium progression (DISCOMS)

- **Goal: In-Vessel Retention success probability, design**
  - In-vessel heat flux: in-vessel corium behaviour (PROCOR, CORDEB)
  - External vessel cooling (CATHARE, SULTAN, RESCUE, CALO, ANUBIS)

- **Goal: evaluation of basement melt-through/mitigation**
  - Spreading (THEMA, VULCANO)
  - MCCI dry conditions (TOLBIAC-ICB, VULCANO)
  - MCCI - reflooding (TOLBIAC-ICB, MERELAVA)

- **Goal: core degradation**
  - Prevention: accident tolerant fuel

- **Goal: Fuel Coolant Interaction**
  - More realistic conditions for loading of the structures
    - Fragmentation & steam explosion (MC3D, KROTOS)

- **Goal: containment integrity**
  - $\text{H}_2$ behaviour (Europlexus, MISTRA)
  - Structure behaviour (Europlexus)

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- **Goal: basic knowledge**
  - Physico-chemical corium properties (VITI)
  - Thermodynamic (NUCLEA, Fuelbase, DPC facilities)

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**PSA2 are not carried out by CEA**
CEA SEVERE ACCIDENT STUDIES IN THE FIELD OF SOURCE TERM
The objectives are as follows:

- **Create a realistic data base** for computing FP behaviour
- **Improve and validate models used in codes** describing the FP release to the environment during a severe accident sequence,

**Analytical experiments:**
- VERDON - VERCORS
- HI/VI - CRL
- VEGA

**Integral experiments:**
- PHEBUS FP

**FP release and transport models:**
- ELSA – MFPR
- SOPHAEROS

**Scenarios codes:**
- ASTEC
- MELCOR
- MAAP

**Data base on FP release and transport in SA conditions**

**PSA studies, level 2 Source term evaluations**
FP Behaviour in SA conditions: How to simulate SA conditions in hot cell?

- High Temperature Inductive furnace based on refractory ceramic materials (CEA design)
  - Temperature up to fuel melting
  - Swept by steam/hydrogen/air ...

- Fuel sample
  - Extracted from EDF’s PWR rod
    - 2-3 pellets in their original cladding
  - Re-irradiation at low power in OSIRIS
    - Rebuild short half-life FP inventory

- Fission Product measurements
  - On-line (and post test) gamma spectrometry at high counting rate (Kinetics release and FP balance)

- Post-test analysis (fuel sample): µ-analysis

H₂O, H₂, air injection
FP Behaviour in SA conditions: How to simulate SA conditions in hot cell?

Many type of real corium already obtained

H₂O, H₂, air injection

Vercors 4:
UO₂, 38 GW/j/T, H₂
Close to fuel collapse

Vercors 5:
UO₂, 38 GW/j/T, H₂O
Close to fuel collapse

Vercors 6:
UO₂, 60 GW/j/T, Mixed H₂O/H₂
Fuel collapse after 20 min.

UO₂ highly porous
UO₂ split up
Open clad
Low fuel-clad interaction
Open high porosity in the RIM

UO₂ highly porous
Sintering of cracks
Open clad
Strong fuel-clad interaction
Open high porosity in the RIM

VERCORS RT1: Reference Test

Bottom
Middle
Top
FP Behaviour in SA conditions: How to simulate SA conditions in hot cell? The VERDON laboratory

**VERDON: a Severe Accident laboratory**

Follow-up of the previous VERCORS laboratory (CEA Grenoble) with improved instrumentation

- 2 Specific hot cells and 1 glove box (operational since 2011)

**C4 cell**
- Sample preparation & gamma spectrometry bench for quantitative analysis

**C5 cell: 2 experimental circuits**
- Dedicated to FP (fission product) release (→ 3 VERDON-ISTP tests)
- Dedicated to FP release and transport (→ 1 VERDON-ISTP test, VERDON-5 test)

*Worldwide unique facility to simulate SA conditions with irradiated fuel in a semi-integral way*
FP Behaviour in SA conditions: NUCLEAR FUEL CHARACTERIZATIONS LABORATORY (1/3) - LECA/STAR: a nuclear facility dedicated to irradiated fuel examination

T up to 2800°C, atm P

Complementary annealing

T up to 1600°C, 1600 bars

VERDON Laboratory

MERARG

LECA-STAR, CEA Cadarache centre

Irradiated Nuclear Fuels Characterization Laboratory

MEXIICO

LECA

Complementary annealing test loops

Others Laboratories (CEA Marcoule, …) for chemical analysis and specific analytical development on prototypic corium samples (coll. CEA/JAEA)
FP Behaviour in SA conditions: NUCLEAR FUEL CHARACTERIZATIONS
LABORATORY (2/3)

Microanalytical complementarity technics

Outside the hot cells

Inside the hot cells

Elemental analyses
(quantitative & distribution)

Morphology
Image analyses

Isotopic analyses
(FP)

Structure analyses

TEM (2018)

Structural and FP distribution characterizations
**Electron beam**

**Ion beam**

**In-situ nano-indenter**

**FIB tomography of nano-indent**

- **Indent**
  - Bottom view

- **Evidenced lateral cracks**

**Mechanical Properties**

- **Notched µ-cantilever for fracture toughness**

- **µ-Mechanical tests**

- **Compression Tests and Results on micropillars**

- **Pillar rupture**

- **Pillar strain**
VERDON and the ISTP programme

- **International Source Term Programme**
  - *Separate effect tests aimed at reducing uncertainties on source term assessment*
  - *Cooperative programme*
    - French part: CEA, EDF, IRSN
    - Cooperative partners: EC, US NRC, Suez, PSI, EACL, KAERI
  - *Composed of Separate Effect Tests covering 4 topics*
    - Iodine chemistry
    - Impact of boron carbide
    - Air ingress
    - Fission products release

- **VERDON compared to VERCORS**
  - *Two complementary loops* (CER and CET) similar to RT and HT loops
    - But CET will use multiple TGTs instead of one
  - More detailed *micro-analysis* of the fuel sample
    - in hot cells at the CEA Cadarache: optical microscopy, SEM, EPMA, SIMS, µ-XRD
  - PhD in support of the FP behavior understanding
## VERDON and the ISTP programme: Experimental grid

<table>
<thead>
<tr>
<th>Test</th>
<th>Performed</th>
<th>Fuel</th>
<th>Circuit</th>
<th>Atm</th>
<th>Temperature (°C)</th>
<th>Main Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERDON-1</td>
<td>2011</td>
<td>UO2, 72 GWd/t</td>
<td>Release</td>
<td>Reducing, H₂/H₂O molar ratio = 10</td>
<td>2600</td>
<td>High burn up effect on FP release kinetics / High temperature behaviour</td>
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<tr>
<td></td>
<td></td>
<td><strong>Re-irradiated</strong> (OSIRIS)</td>
<td></td>
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<tr>
<td>VERDON-2</td>
<td>2012</td>
<td>MOX, 60 GWd/t</td>
<td>Transport</td>
<td>Mixed steam-air conditions: 50-50%</td>
<td>2100</td>
<td>Air ingress / Ru release / Iodine revolatilisation</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td>VERDON-3</td>
<td>2013</td>
<td></td>
<td>Release</td>
<td>Oxidising</td>
<td></td>
<td>Complementary tests / FP behaviour under steam-hydrogen atm</td>
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<tr>
<td>VERDON-4</td>
<td><strong>2014</strong></td>
<td></td>
<td>Release</td>
<td>Reducing</td>
<td></td>
<td></td>
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</tbody>
</table>
The VERDON-5 test has been defined and performed in continuity with the International Source Term Program (ISTP).

The main objectives of the VERDON-5 test were to:

- Complete the Source Term database for high burn-up UO₂ fuel under air-ingress conditions in a semi-integral way, including fission product (FP) transport and possible interactions between FP deposits;
  - characterize the Ru behavior on a similar thermal-hydraulic sequence to VERDON-2, but using a high burn-up UO₂ fuel.

- allow studying Boron injection (vapor) impact onto the iodine speciation

Funded by JAEA, NRC, ENGIE, EDF, IRSN and CEA

Performed on November 19, 2015
Highlight - VERDON-1: beginning of fuel collapse at 2880 K

Slight decrease of the $^{140}\text{La}$ signal at the end of the test

Impact of reducing conditions? → later confirmation by post-test examination of the fuel sample

VERDON-1
No relocation at the end of the test (T=2880 K)

VERCORS Data base: Systematic collapse Between 2400-2600 K
Highlight - VERDON-1: beginning of fuel collapse at 2880 K

Elevated porosity
Moderate porosity
Low porosity

Melting due to eutectic $\text{UO}_2$-$\text{ZrO}_2$
Highlight - VERDON-1: Mo behavior during the high temperature plateau

Mo and Ru always together

SIMS Ion maps – Centre, BEFORE Experiment

V1 Experiment

Low porosity

Moderate porosity

Elevated porosity
Highlight - VERDON-1: Mo behavior during the test?

Mo behavior during the temperature ramp?

11 FP stables oxides milled with natural UO$_2$ powder, followed by a sintering stage + dedicated annealing tests

SIMFUEL

XAS, Synchrotron

Allows to determine the oxidation state and local environment (R ~ 6 Å) of an element

Mo spectra Linear Combination Fit

Mo$^0$ 39%
MoO$_2$ 24%
MoO$_3$ 10%
(MoO$_4$)$_{2+}$ 27%

$^{\text{Thermodynamic calculation}}$

FP Chemistry during the test

Cs, Ba, RE, … identical approach

Methodology available soon on irradiated fuels (MARS beam Line)
Current and Potential Future activities
VERDON chemical post test analysis and leaching

“Leaching experiments” to obtain leaching rate data of FP and/or actinides

- Current leaching experiments\(^1\) on COLIMA samples (in-vessel and ex-vessel simulant debris elaborated in the Plinius platform with depleted U and inactive simulant of FP)
- Possibility to perform leaching on Irradiated corium debris representative of Fukushima: either with VERDON existing samples or specific corium samples elaborated in the VERDON furnace, focusing in particular on Cs, Sr, Pu and other radionuclides of interest in Fukushima debris at the time of corium recovery
- Possibility to perform leaching on VERDON coupons representative of the primary circuit either with existing VERDON samples or specific ones elaborated in the VERDON loop

Determine chemical speciation of FP deposited on primary circuit

- On existing VERDON samples or specific ones elaborated in the VERDON loop to be representative of Fukushima

\(^1\) : S. Perrin, A. Nakayoshi, C. Jegou, ”Fuel debris leaching experiments under oxidizing conditions”
CONCLUSION
CEA has a large expertise on Severe Accident Source Term quantification and Fuel Behaviour Characterization

In the frame of Fukushima decommissioning, CEA expertise may be useful for:

- Determining needs for fuel debris analysis
- Developing fuel debris properties characterization method
- Estimating properties of fuel debris
- Providing advices on experimental/analytical techniques and demands in hot-testing facilities
- Performing experiments on VERDON existing samples or Fukushima dedicated ones

→ CEA participation in OECD projects in support to Fukushima: BSAF, TCOFF, Pre-ADES
Thank you for your attention
VERDON: Two Experimental Circuits

Release loop

Transport loop

4 rotating thermal gradient tubes to simulate the FP deposition