Overview of CEA Analytical Studies on PWR Nuclear Fuel cladding subjected to RIA Loading Conditions

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• **Design safety studies for Reactivity Initiated Accident**
  - Studies underway to raise the average burn-up of fuel assembly (ex: 1998, EDF, 47 to 52GWd/tU and 62 GWd/tU expected in the future)
  - Strong need for investigations of the fuel behavior under design basis reactivity accidents such as control rod ejection (failure of the control rod drive mechanism)

• **Assumption: Accidental ejection of a control rod**
  - Rapid increase of the local power (~ 50ms)
  - Increase of temperature ($10^3$ to $10^4$ K.s$^{-1}$)
  - Fuel swelling
  - Clad deformations (a few %)
  - Potential for crack initiation and growth (failure criterion required)
  - Fuel dispersal in the coolant, boiling crisis, etc ...
Reactivity Initiated Accident Problematic

Control rod ejection ⇒ Rapid local power increase (~50 ms)

Fast fuel temperature rise (10^4 °C/s)

Fuel thermal expansion

Accumulated fission gas expansion

Fuel expansion

Pellet-cladding gap closing

Fuel grain decohesion

Fission gas release

Pellet-Coolant Interaction (PCMI) loading

Internal pressure increase

Loss of cladding ductility due to a dense hydride thickness

First phase pre DNB failure

Crack initiation on outer diameter

Transient PCMI failure

Departure from Nucleate Boiling (DNB)

Fast cladding temperature increase (T<800°C)

Drop of the mechanical strength

Post-DNB failure by local ballooning

Nakamura et al., 2002

Last phase post DNB failure

Fuel fragmentation

Fuel dispersal and coolant interaction

Mechanical energy production

Post failure events

REP-Na 8 (Papin et al., 2003)

Waeckel., 1997

Nakamura et al., 2002
1992 : IRSN (formerly IPSN) initiated, in partnership with EDF, a research program, the CABRI REP-Na dedicated to:

- Study the behavior of highly irradiated fuel (UO₂ and MOX) under RIAs
- Verify the adequacy of the present safety criteria with available experimental database (SPERT, PBF, early NSSR experiments) restricted to fresh or lightly irradiated
- Evolution of the criteria and evaluate safety margins

CABRI REP-Na experimental program launched in the sodium loop reactor in France: fast power transient applied to irradiated rods

Development of the SCANAIR code:

- Interpret the test results, perform sensitivity studies
- Extrapolate to reactor conditions
- Process closely coupled phenomena such as rod thermics and thermal hydraulics, fuel and clad mechanics, transient behavior of fission gases

1992 : Initiation of a separate effects test program for the study of transient clad mechanical behavior: PROMETRA
PROMETRA: transient mechanical testing program for high burn-up claddings in support to the interpretation of integral RIA tests

CEA Saclay ring test
CEA Saclay axial tensile test
CEA Saclay PSU - Plane strain
CEA Grenoble ring test

Axial tensile
Hoop tensile
Plane Stress
Plane Strain

High heating rates
With gage section
Without gage section

Load controlled
Displacement controlled

Cladding mechanical behavior during RIA transients

New Hot Cells at CEA Saclay

2005
2000
1996
1992
LHA

PROMETRA : transient mechanical testing program for high burn-up claddings in support to the interpretation of integral RIA tests
Oxide layer thickness < 130 μm, Burnup: 54 to 64 GWd/tU, Strain rate: 0.01 to 5 s⁻¹, Cladding temperature: 20 to 900°C.

Ductile-Brittle Transition

[ H ] content measurement

Metallography or fractography

High Burnup cladding mechanical behavior:

→ Oxide layer thickness < 130 μm,
→ Burnup 54 to 64 GWd/tU,
→ Strain rate: 0.01 to 5 s⁻¹,
→ Cladding temperature: 20 to 900°C.

(39) (33) (8) (2) (105) (36) (66) (8) (3)

Axial tensile Hoop tensile Burst Axial tensile Hoop tensile Burst
CEA Saclay specimen CEA Saclay specimen CEA Grenoble specimen

Ductile Brittle Ductile Brittle

Ductile-Brittle Transition

(39) (58) (8) (3)

(33) (43) (8) (2)

Standard Zircaloy-4
Fresh Irradiated

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A Reliable Material Database For Highly Irradiated Fuel Claddings 2/2

- **Plane Strain test**
- **Hoop tensile**
- **Burst**

**1.5% Sn Zircaloy**
- Plane Strain test
- Hoop tensile
- Burst

**ZIRLO™**
- Plane Strain test
- Hoop tensile
- Burst

**PROMETRA hoop tests on irradiated alloys**
- (planned)
- Plane Strain test
- Hoop tensile
- Burst

**M5™**
- Plane Strain test
- Hoop tensile
- Burst

- **54 - 64 GWd /tU**
- **~75 GWd /tU**
- **60 - 75 GWd /tU**

( ): number of valid tests
CEA testing technique for high temperature rings:
(induction heating, T > 480 °C up to 900 °C)

- Load control
- Displacement control
- Cooling: conduction + natural convection

- Test Temperature
- Room temperature
- Load control: dT/dt=200°C.s⁻¹
- Displacement control: 10 to 20s
- Load control: 5 ± 0.05
- Displacement control: R=1.5
- TC: welded to specimen

UTS, 0.2YS
PROMETRA hoop tensile test at high temperature

Test specifications: $800^\circ C$, $1 s^{-1}$  Test duration: 20s including induction heating @ $100^\circ C/s$
On going research: towards a better interpretation of the PROMETRA test data

- **Conventional** and **true stress-strain** interpretation of the PROMETRA data is made:
  - To derive validated mechanical transient mechanical properties usable in SCANAIR
  - To develop failure criteria

YS and UTS for irradiated Zry4, M5 and Zirlo, Cazalis et al., SMIRT 18, 2005
On going research: towards a better interpretation of the PROMETRA test data

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![Graph showing total elongation vs. test temperature](image)

**TE for irradiated M5 and Zirlo, visual view of M5™ broken leg, tested 816°C**

*Cazalis et al., SMIRT18, 2005*
On going research: towards a better interpretation of the PROMETRA test data

- FE modeling is achieved to deeply understand the tests data and insure that experimental artifacts, geometry (strain and stress gradients), boundary conditions (contacts and friction) do not invalidate the data.

![Graph showing force-displacement data with different friction coefficients.](image-url)
On going research: towards a better interpretation of the PROMETRA test data

- **GPL constitutive law (Goguel Poussard Limon) (Goguel et al., 2005):**
  - For a better use of the PROMETRA data, a validated constitutive equation applicable to the whole temperature, strain rate and loading conditions RIA domain, compatible with structural mechanics computations codes (CAST3M, SCANAIR, ...) has been identified.

  Jean Lemaitre formalism:
  \[ \dot{\varepsilon} = \frac{3}{2} \dot{\varepsilon}^p + \frac{\Sigma_0}{\Sigma} \]

  with
  \[ \dot{\varepsilon}^p = \dot{\varepsilon}_0 \left( \frac{\Sigma}{\Sigma_0} \right) \]

  and
  \[ \Sigma = \sqrt{\frac{1}{2} M : \dot{\varepsilon}^T = \sqrt{H_\rho (\Sigma_\rho - \Sigma_{\rho})^2 + H_\phi (\Sigma_\phi - \Sigma_{\phi})^2 + H_\theta (\Sigma_\theta - \Sigma_{\theta})^2} } \]

  70 tests available, 20 to 800°C
  80 tests available, 20 to 900°C
  5 tests available, 20 to 350°C

  \[ \Rightarrow \text{Domain of application:} \]
  - Burnup up to 64 GWd/tU,
  - Temperature (200 up to 800°C),
  - Strain rate (3.10^{-4} \text{ up to } 5 \text{ s}^{-1})
  - Material anisotropy (temperature and neutron flux dependant ... the anisotropy decreases when the irradiation increase)

  \[ \Rightarrow \text{The GPL law, available in } \sqrt{ } \text{ and CAST3M can now be used to model structures} \]
On going research: towards a better interpretation of the PROMETRA test data

- International collaboration with ANL and Penn State University (USA), JAEA (Japan) and Studsvik (Sweden) underway since 2001:
  - Experimental and analytical Round Robin to exchange and validate experimental practice and test interpretation

1 Gage ring tensile specimen
2 gauges and dog bone ring tensile specimen
2 gauges ring tensile specimen
On going research: towards a better interpretation of the PROMETRA test data

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![Graph showing comparison of different labs and conditions](image)
On going research: measurement of local strains

- Measurement of local strain at failure from Penn State University specimens with a zero strain biaxiality between the notches

Room temperature tests

- Speckle Painting + Image analysis

V direction

U direction

U Cast3m (mm)

Image analysis (mm)
On going research: measurement of local strains

Example of local strain measurements for a ring specimen at $350^\circ$C through the window of the furnace available in M04 hot cell:

movie
Towards a representative RIA analytical test...

- Actual available experiments do not fully represent the biaxiality expected during an RIA:

\[
\varepsilon_{zz}^p / \varepsilon_{00}^p
\]

\[
\sigma_{zz} / \sigma_{00}
\]

CABRI REP Na tests, IRSN

A. Motta et al., ASTM 2004
Towards a representative RIA analytical test...

- PhD thesis (Matthieu Le Saux) underway to develop further an EDC test with a controlled biaxility

Mechanical properties:
- Media: inverse identification
- Cladding: GPL law

Inverse identification of friction coefficients (media vs. jack and media vs. cladding)

### Table

<table>
<thead>
<tr>
<th>Modeling</th>
<th>Computation vs. experiment</th>
<th>Biaxiality</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Modeling Diagram" /></td>
<td><img src="image2.png" alt="Computation vs. Experiment" /></td>
<td><img src="image3.png" alt="Biaxiality Diagram" /></td>
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</tbody>
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**Aluminium, \( T = 300^\circ C, \mu_{PM} = 0, \mu_{TM} = 0.2 \)**

**EDC ~ pure circumferential loading**: ⇒ It is necessary to control the axial deformation
Summary and closing points

- PROMETRA represents an extensive material database with:
  - over 250 validated tests results for fresh and high burnup Zircaloys, M5 and Zirlo subjected to thermomechanical transients
  - various geometries tested with high heating rates systems and dynamic testing machines
  - supported by full 3D modeling, indispensable for a correct interpretation of the data
  - over 15 publications worldwide with our colleagues of EDF and IRSN

- On-going research within PROMETRA:
  - new measuring techniques developed in hot cells (image analysis, acoustic emission, ...)
  - new mechanical tests prototypical of reactor biaxial loading
  - constitutive equations for a better representation of the material database
  - development of constitutive equation coupled with damage
PROMETRA axial tensile test at high temperature

Test specifications: 800°C, 5s⁻¹  Test duration: 18s including Joule effect heating @ 100°C/s

Thank you for your attention!
Any questions?

movie