Fracture properties characterization of nuclear fuel using micro-cantilever bending

R. Henry, I. Zacharie-Aubrun, Jm. Gatt, T. Blay, S. Meille, C. Langlois

NuMat 2018 The Nuclear Materials Conference
14–18 OCTOBER 2018 • SEATTLE, WA, USA
materialstoday

16/10/2018

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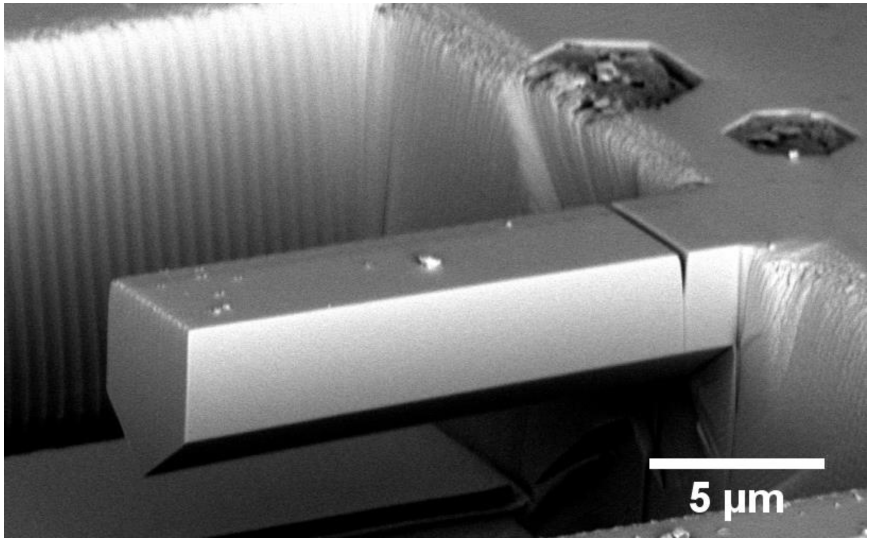


Notched micro-cantilever milled in irradiated nuclear fuel (UO_2)

R. HENRY [1], T. BLAY [2], I. ZACHARIE-AUBRUN [2], J.M. GATT [2], C. LANGLOIS [1], S. MEILLE [1]

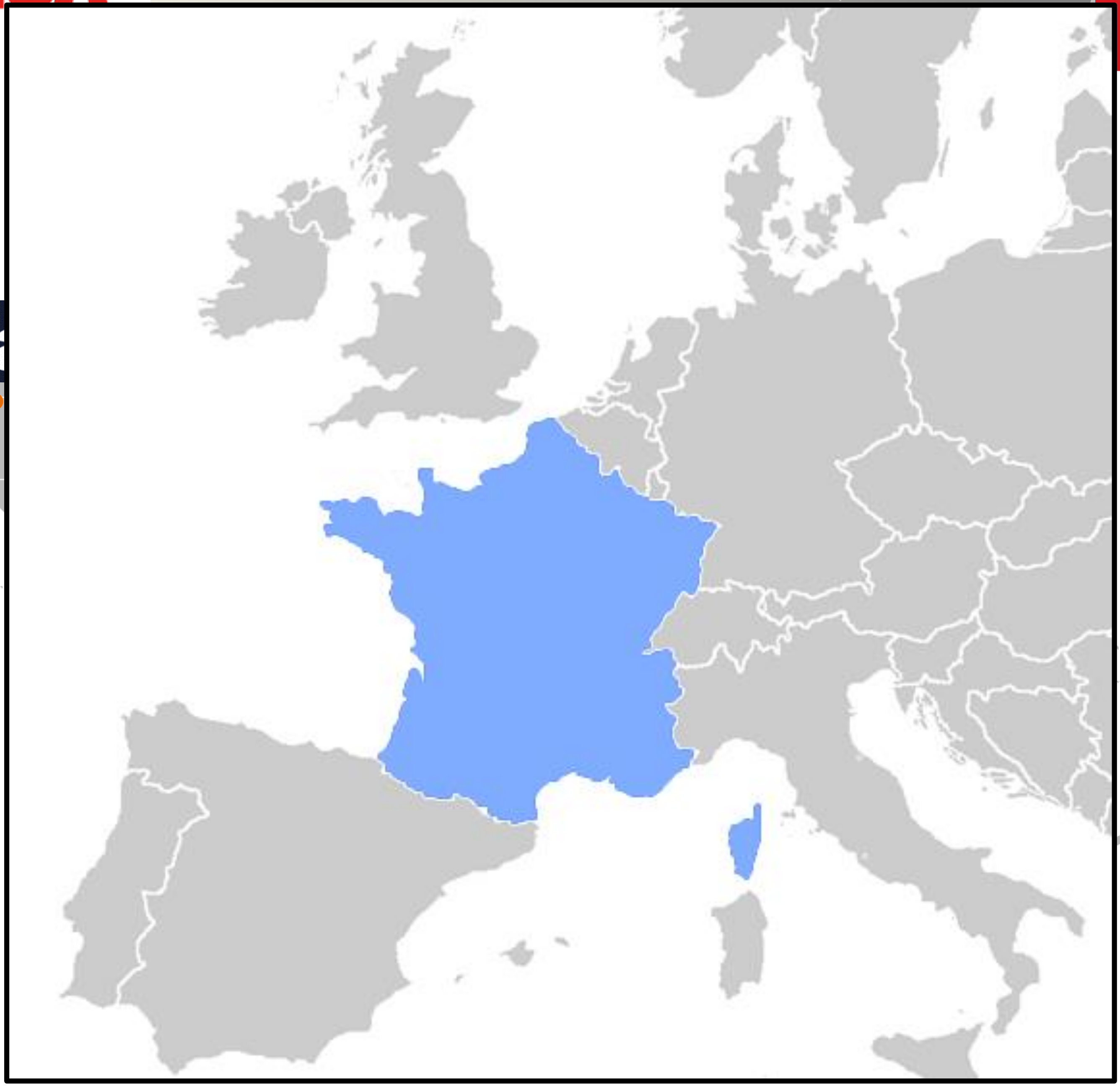
[1] Université de Lyon, INSA-Lyon, MATEIS UMR CNRS 5510, 69621 Villeurbanne, France

[2] CEA, DEN, DEC, Cadarache, 13108 St Paul Lez Durance, France

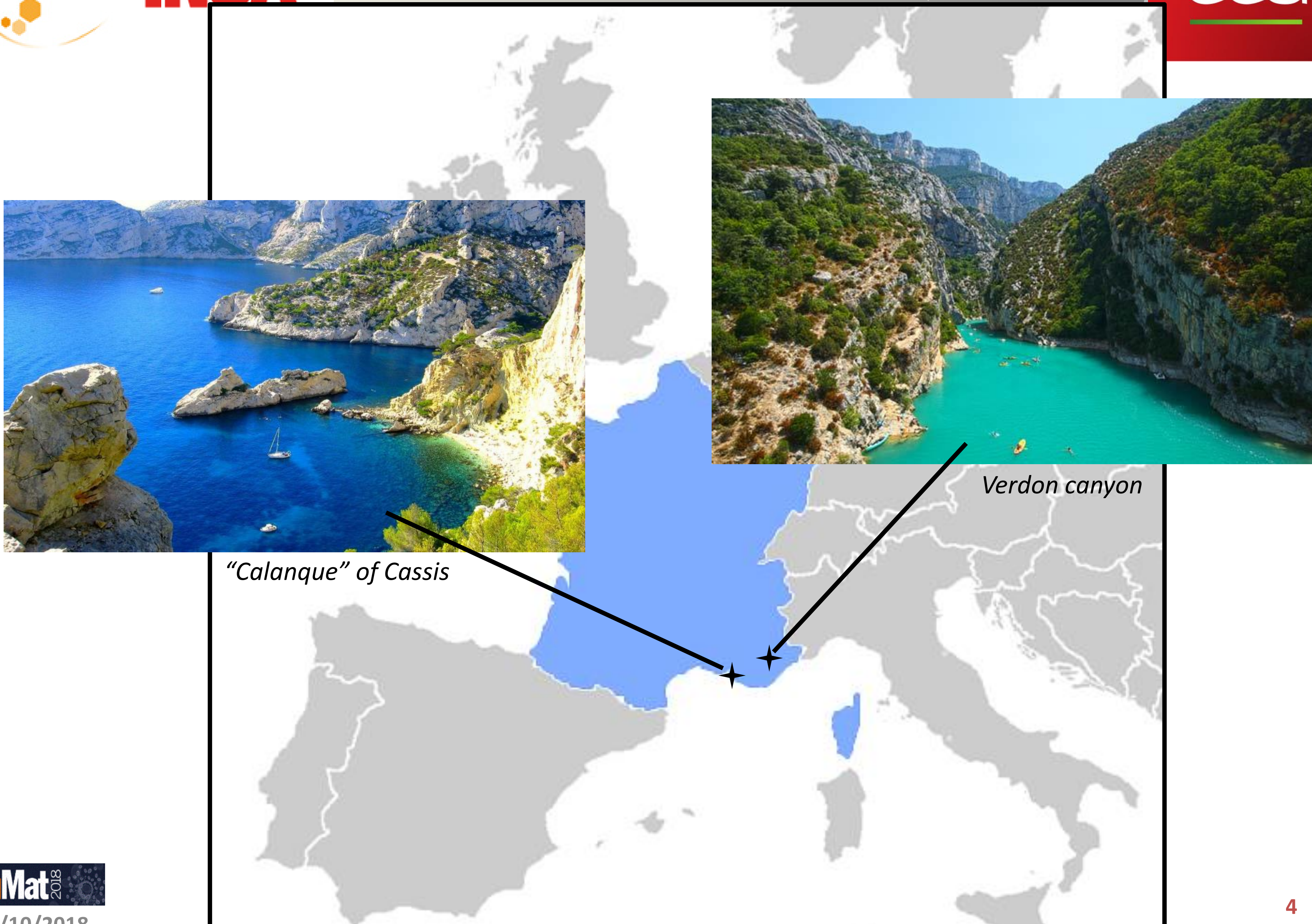
With the support of :

CONTENT

INTRODUCTION



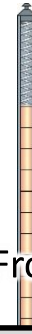
INTRODUCTION

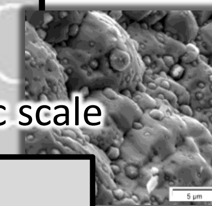


LECA/STAR

A nuclear facility dedicated to the irradiated fuel examination

From the whole rod to the microscopic scale





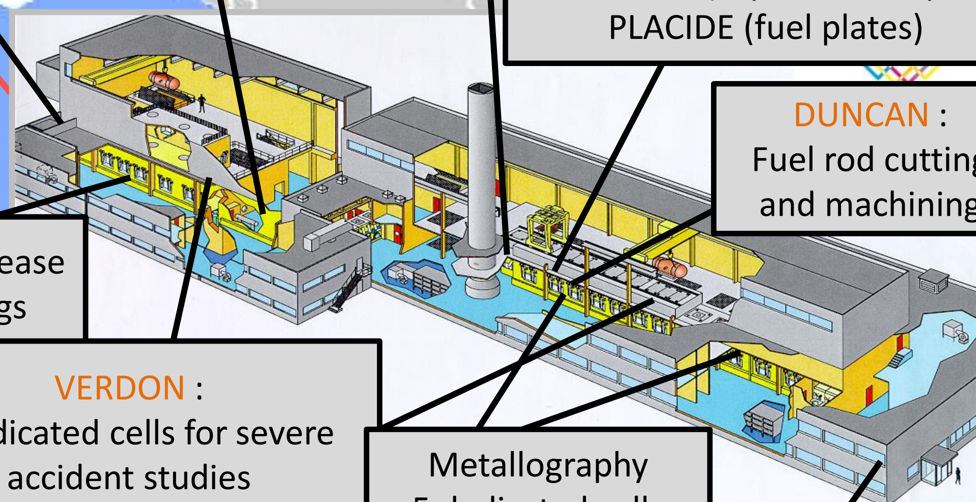
CEA

(French) Alternative Energies and Atomic Energy Commission

Cadarache Center

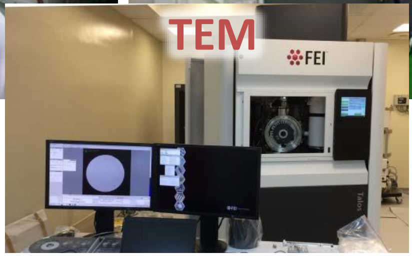
Research center for energy :

- Nuclear fission
- Nuclear fusion (ITER : (International Thermonuclear Experimental Reactor))
- Nuclear propulsion



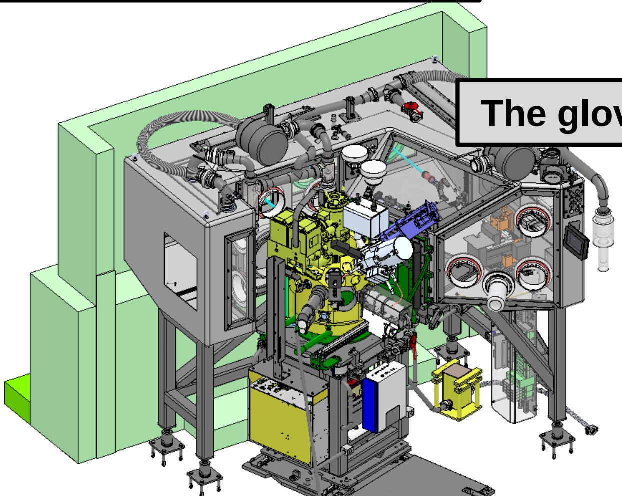
INTRODUCTION

Micro-analyses laboratory



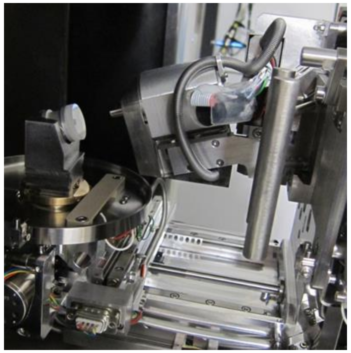
The front shielded wall

The glove box



FIB / SEM

FIB / SEM



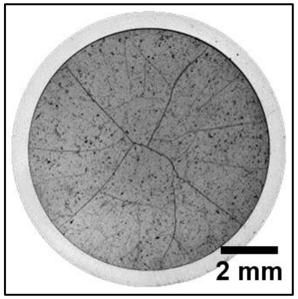
Nano-indenter *in situ* :
μ-mechanical tests

CONTEXT

PWR fuel's behavior under irradiation

PWR = Pressurized Water Reactor

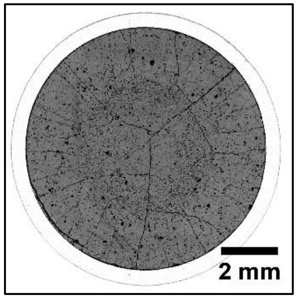
Normal operations



Optical micrograph of a sample section of UO_2 fuel and its cladding

Irradiated in PWR

Power ramps

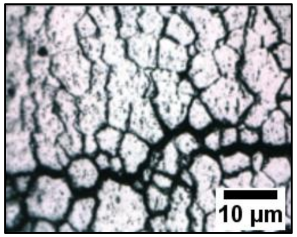


➔ *PCI (Pellet-Cladding Interaction)*

Optical micrograph of a sample section of UO_2 fuel and its cladding

Irradiated in PWR + power ramp test

Accidental situations



➔ *RIA (Reactivity Insertion Accident)*
➔ *LOCA (Loss Of Coolant Accident)*

Optical micrograph of a UO_2 fuel in the pellet's periphery

Irradiated in PWR + RIA test

Cracks in the fuel

➔ **Take it into account in numerical simulations**

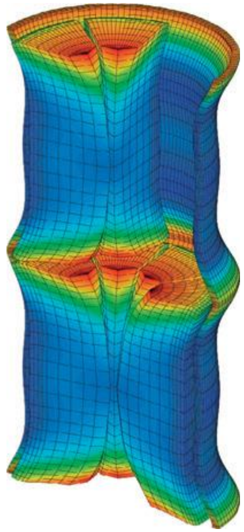
Fuel modelling :

- Viscoplasticity in the core
- **Brittle on the periphery**

➔ **Experimental data needed**

➔ **Values of :**

- **Fracture toughness (K_{IC})**
- **Fracture stress (σ_R)**



Modeling of strain location in Zircaloy cladding and fuel pellets (Pressurized Water Reactor)

⇨ **Fresh nuclear fuel**

➢ OK

⇨ **Irradiated nuclear fuel**

➢ Impossible to machine macroscopic specimens for mechanical testing

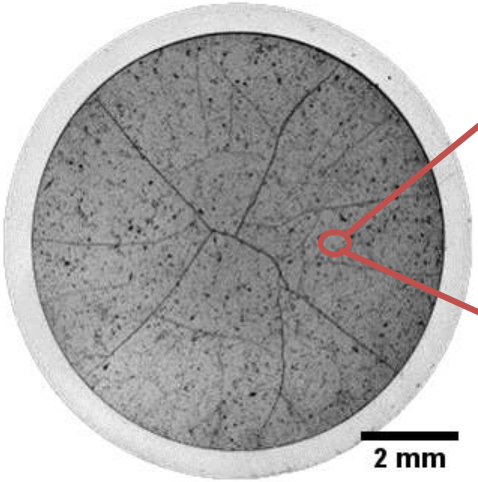
CONTEXT

Mechanical properties at the micro-scale

μ-mechanical tests :

➔ To avoid cracks (and porosities)

➔ To measure "intrinsic" properties



Optical micrograph of an irradiated pellet section

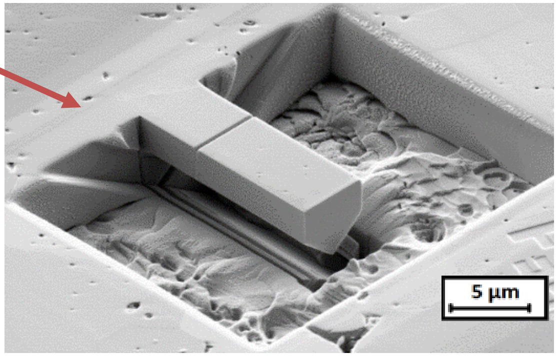
Vickers indentation on irradiated fuel

Indentation

- Handy solution
- Studied and used before
- Sometimes difficult to make a proper measurement

Today's topic :

μ-cantilever bending :



Notched μ-cantilever for fracture toughness measurement (ZrO_2)

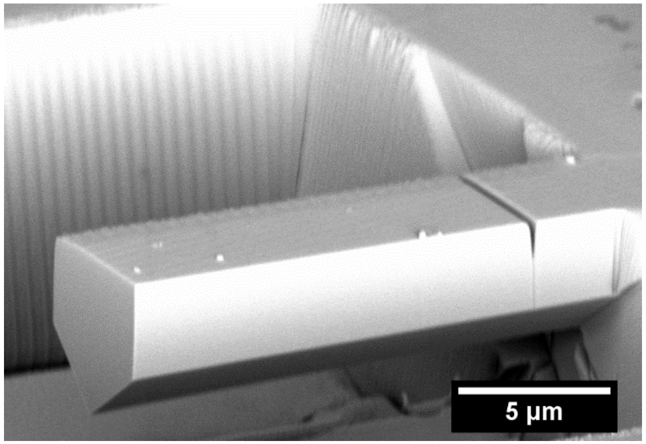
- Closer to bending test
- Preparation with FIB/SEM(Ga beam)
- Mechanical testing with a nano-indenter
- Numerical modeling

EXPERIMENTAL APPROACH

Validation on ZrO_2

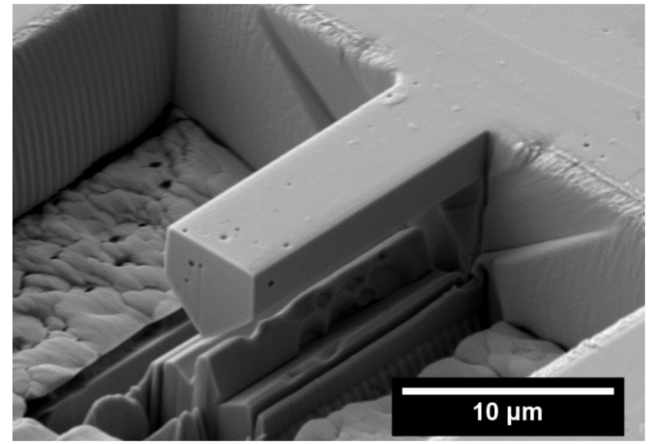
Notched cantilever

Fracture toughness (K_{IC}) measurement



Un-notched cantilever

Fracture stress (σ_c) measurement



Setting up the experimental method on cubic zirconia (ZrO_2) :

- Crystallographic characteristics close
- Mechanical properties similar (at the macroscopic scale)

Validation by comparison with literature data :

Similar fracture toughness

$K_{IC} \approx 1.5$ MPa.m$^{0.5}$

➔ *Good agreement with literature (macroscopic tests on single crystals)*

Higher fracture stress

$\boldsymbol{\sigma_c} \approx 2$ GPa *(against ≈200 MPa for macro)*

➔ *Scale effect : less defects in a µ-sample*

R. Henry [1], T. Blay [2], T. Douillard [1], I. Zacharie-Aubrun [2], J-M Gatt [2], C. Langlois [1], S. Meille [1]: To be published.
[1] *Université de Lyon, INSA-Lyon, MATEIS CNRS UMR 5510, 69621 Villeurbanne, France*
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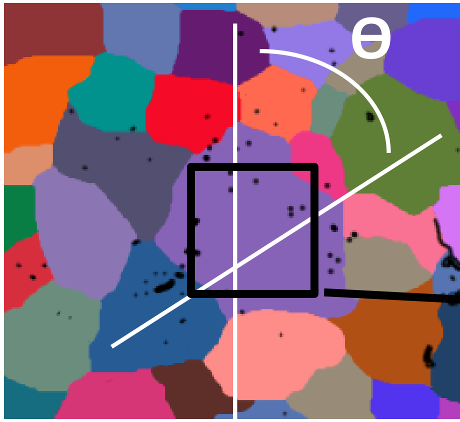
EXPERIMENTAL APPROACH

Preparation of μ-cantilevers

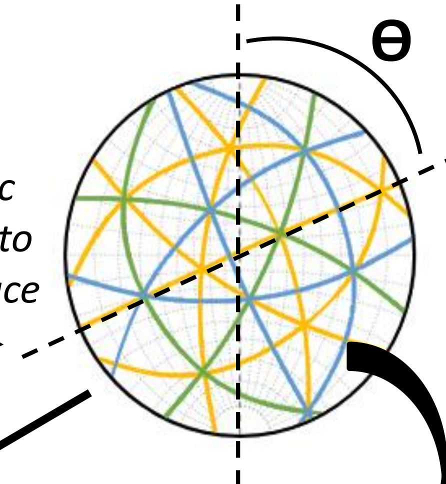


EBSD orientation map

Grain's choice : large enough to contain a whole cantilever

Stereographic projection

The targeted crystallographic plane is normal to the sample surface

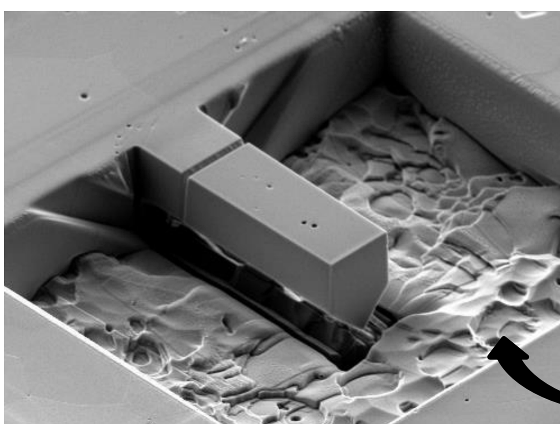


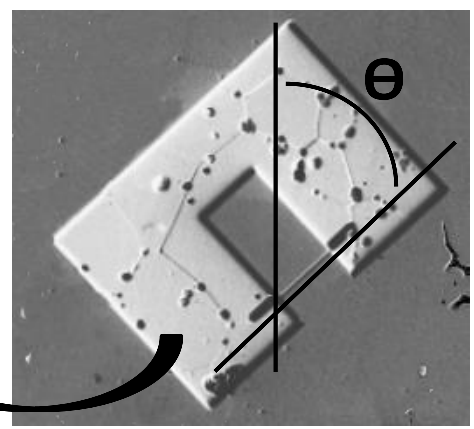
Specimen

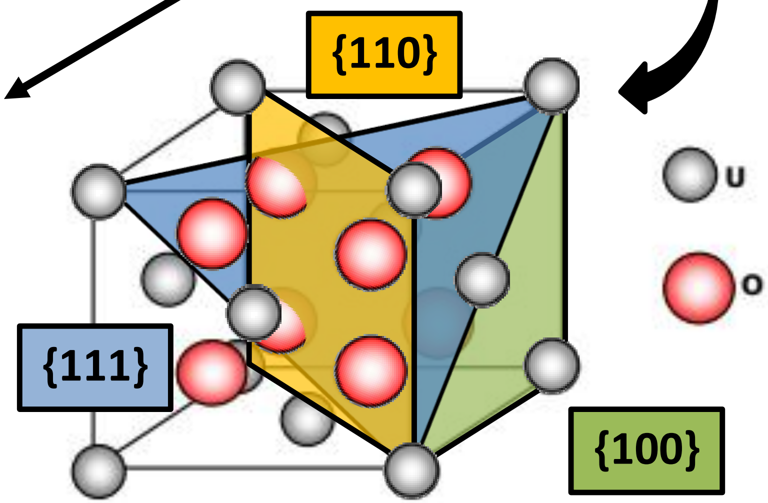
Orientated into a chosen crystallographic plane

Positioning

Use of θ angle for the milling





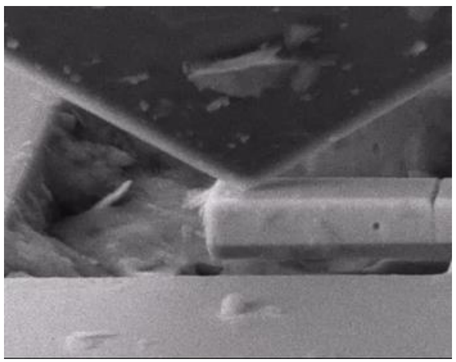


Cubic crystal of UO_2 and some of its crystallographic planes

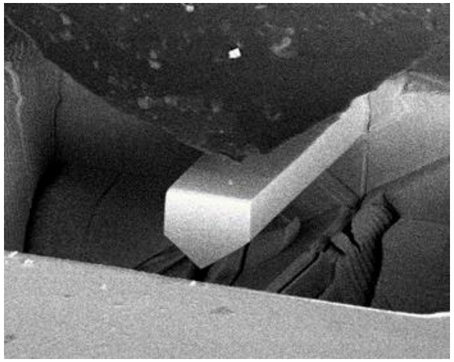
EXPERIMENTAL APPROACH

Mechanical test performed with a nano-indenter

Movies of in situ bending tests



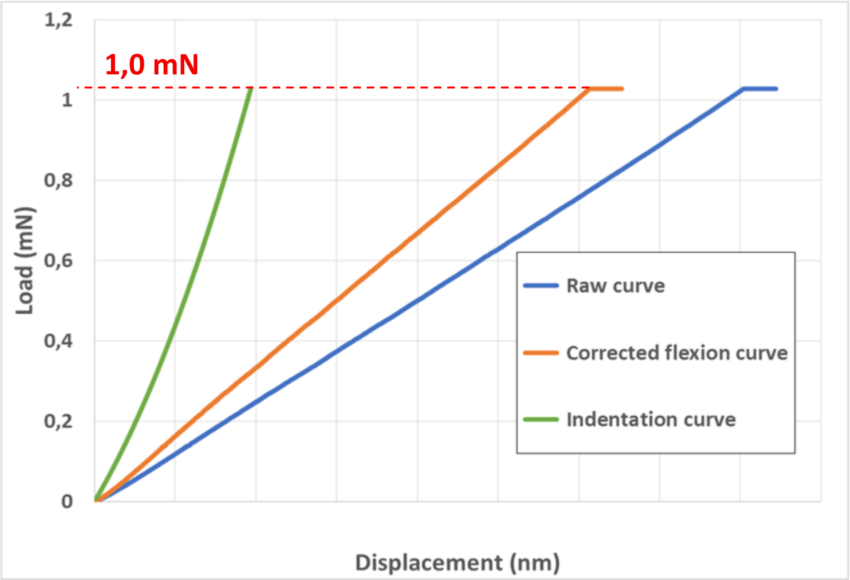
Fresh UO_2
With the support of
X. Iltis (CEA), N. Tarisien (CEA)



Irradiated UO_2
With the support of
S. Chalal (Carl Zeiss)

Linear load-displacement curve

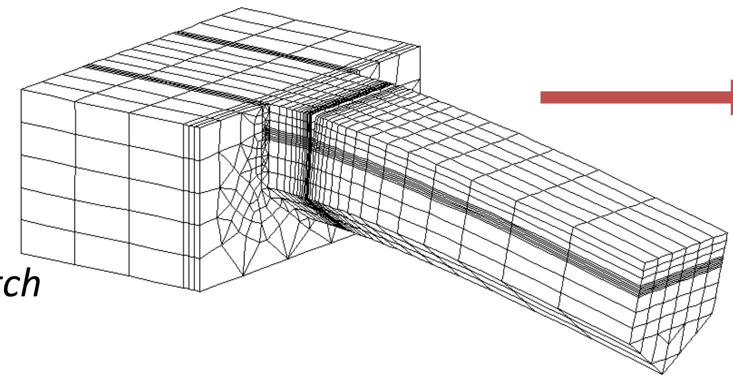
Corrected from indentation
➔ Fracture load



➔ **No plasticity : brittle behavior** (elastic up to fracture)

FEM modelling

Calculation inputs :
- *Fracture load*
- *Dimensions of the beam and notch*



FEM analysis (Cast3m® (CEA, France))

Calculation outputs :
- K_{IC} *(fracture toughness)*
  or
- σ_c *(fracture stress)*

Numerical parameter study :
- Optimization of the test
  ➔ *Dimensions, positioning, influence of different parameters*
- Study of the effect of anisotropic elasticity

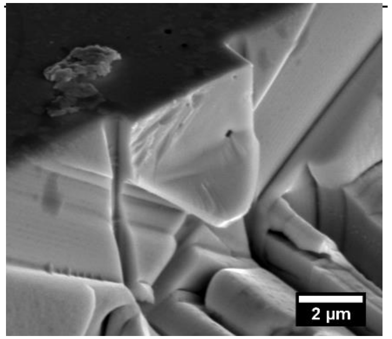
RESULTS

Fracture stress of nuclear fuels UO_2

Standard UO_2 (grain size : 10 µm)
Fresh fuel

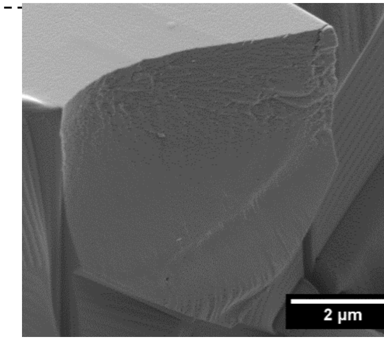
Large grain UO_2 (grain size : 60 µm)
Irradiated fuel (34 GWj/tM)

{100}



σ_R= 3.4 ± 0.7 GPa

σ_R= 3.6 ± 0.4 GPa



Fracture surface almost flat
Highest value of stress

{111} family plane seems weaker

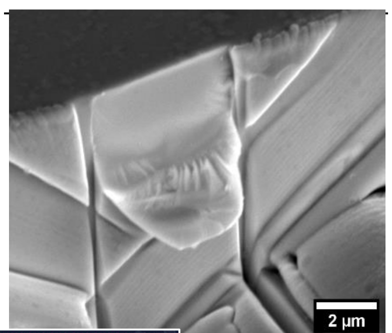
➔ *Coherent with numerical simulations at atomistic scale (MD and DFT)*

Y. Zhang et *al.*, "Crack tip plasticity in single crystal UO_2 : atomistic simulations, Journal of Nuclear Materials, 2012.

Scale effect on fracture stress

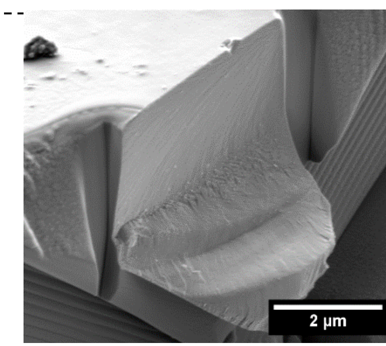
➔ *≈3 GPa (micro) against ≈ 150 MPa (macro)*

{111}



σ_R= 2.7 ± 0.1 GPa

σ_R= 2.2 ± 0.4 GPa

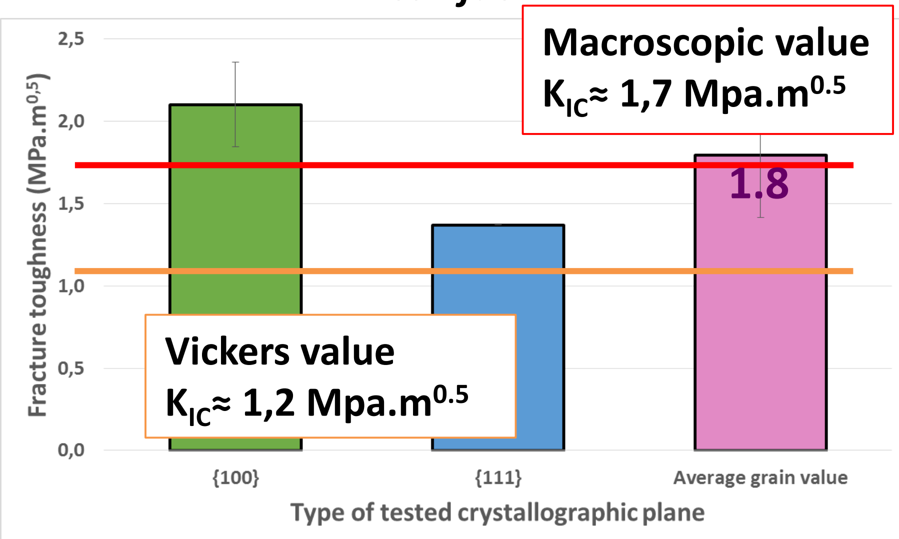


Fracture surface flat (higher part)
Lowest value of stress

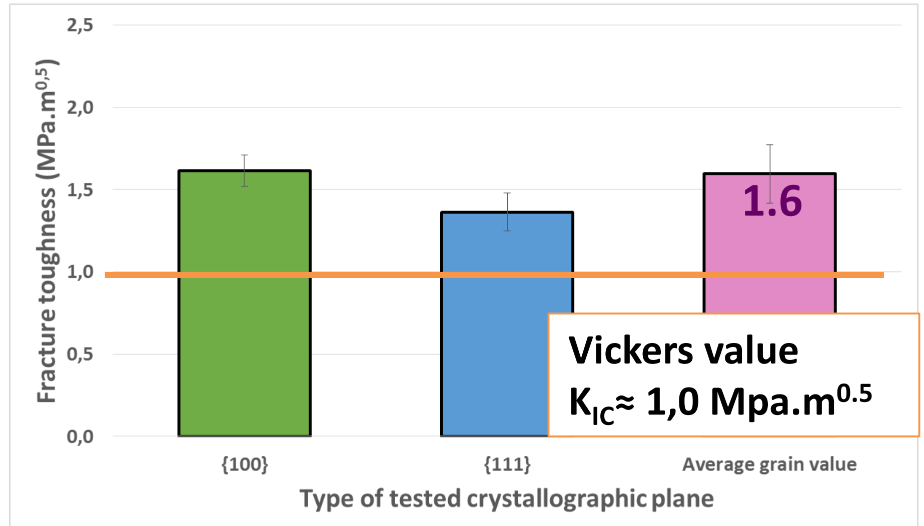
RESULTS

Fracture toughness of nuclear fuels UO_2

Standard UO_2 (grain size : 10 µm)
Fresh fuel



Large grain UO_2 (grain size : 60 µm)
Irradiated fuel (34 GWj/tM)



{111} family planes weaker

➔ *Cleavage of a fcc crystal*

No scale effect on fracture toughness

➔ ***Same value as bending tests on macroscopic samples***

Values higher than VIF (Vickers Indentation Fracture toughness test)

➔ *Same tendency but higher values*

➔ *Calibration of VIF will be considered*

CONCLUSION / PERSPECTIVES

Feasibility of the test showed *(despite hard constraints on irradiated fuel)*

➔ *Shielded FIB/SEM + glove box + manipulator*

- On irradiated fuel with large grains (60 µm)
  - ➔ *First mechanical tests on irradiated in PWR fuel*

First results :

- Results on individual grains
  - ➔ *Good complementarity with indentation tests*
- Resistance of crystallographic planes
  - ➔ *Complement to numerical simulations of surface energies (DFT and MD)*

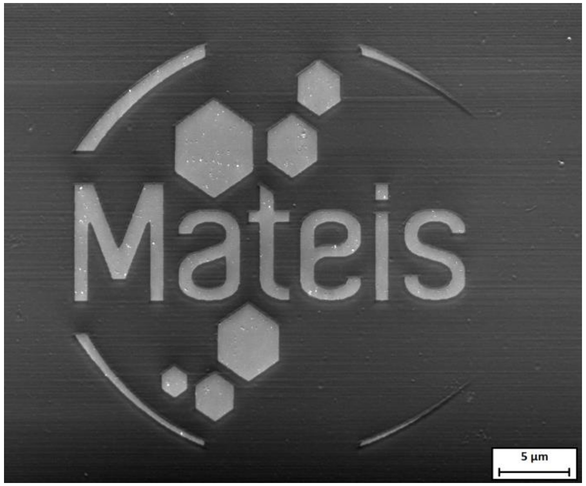
Perspectives :

- Application on irradiated fuel with standard grain size (10 µm) ✖
  - ➔ *Comparison with standard fresh UO_2 : irradiation effect*
  - ➔ *Evolution of the resistance with the burnup*
- Calculation of elastic properties
  - ➔ *Young Modulus of the cantilever*

		Effect of irradiation	
		Fresh fuel	Irradiated fuel (34 GWj/tM)
Effect of µ-structure	Large grain size (60 µm)		✖
	Standard grain size (10 µm)	✖	✖

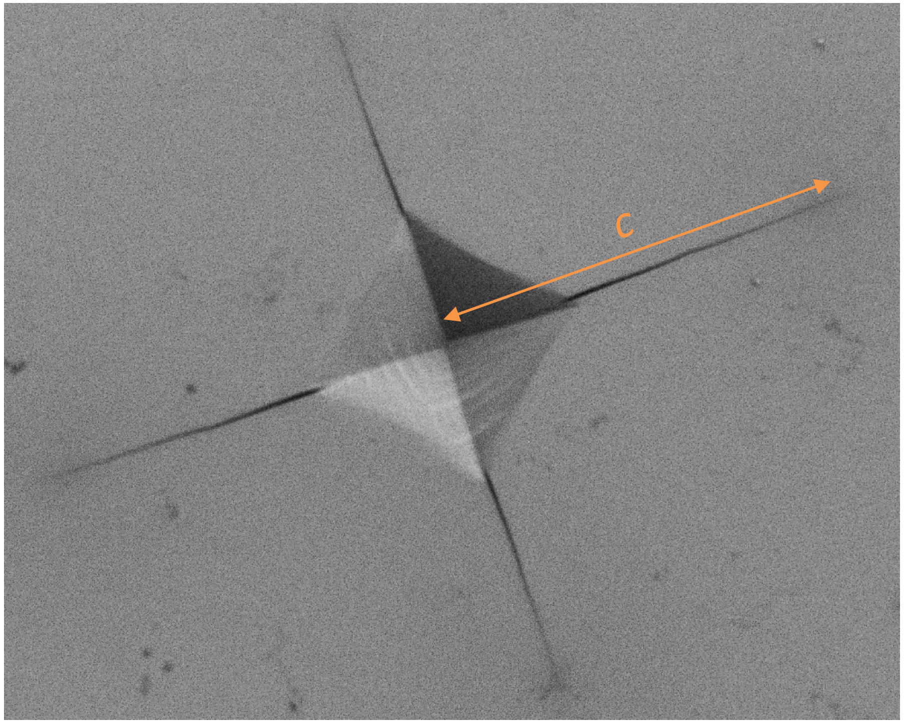
Avec le soutien de :

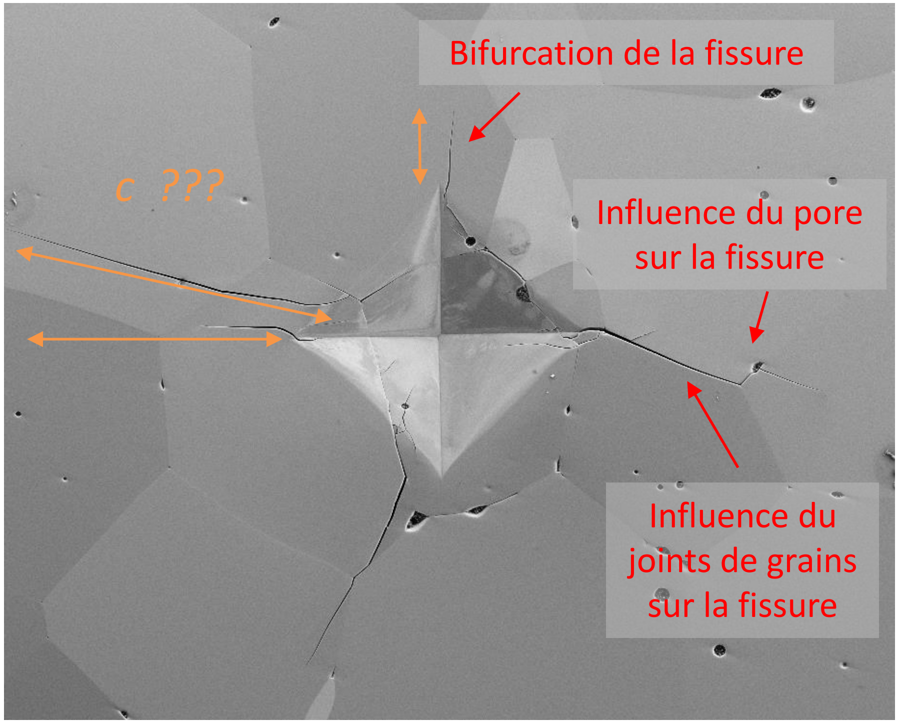
Thank you for your attention



ronan.henry@insa-lyon.fr

INDENTATION





Nano-indentation Vickers d'un monocristal de 8Y-FSZ (400 mN)

Nano-indentation Vickers d'un échantillon polycristallin de 8Y-FSZ (660 mN)