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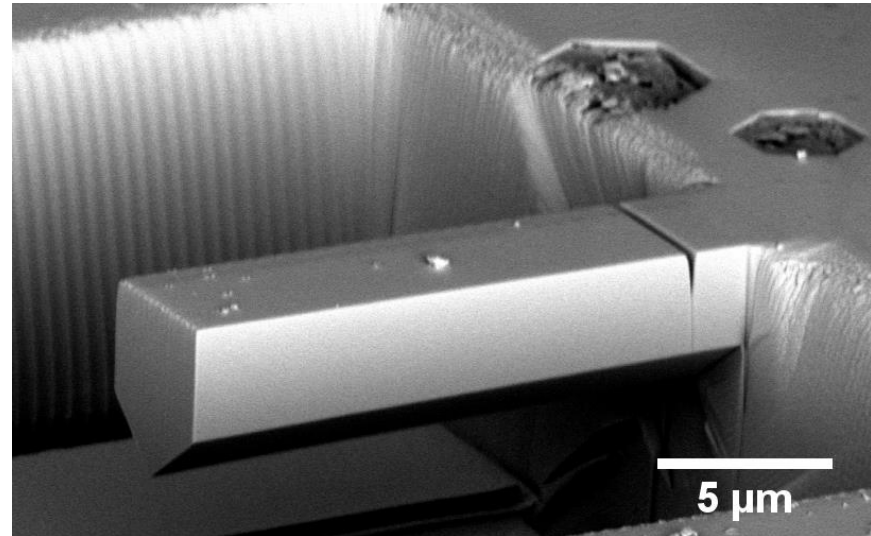
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16/10/2018

Fracture properties characterization of nuclear fuel using micro-cantilever bending



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

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DE LA RECHERCHE À L'INDUSTRIE

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Introduction

I. Context

- 1. PWR fuel's behavior under irradiation*
- 2. Mechanical properties at the micro-scale*

II. Experimental approach

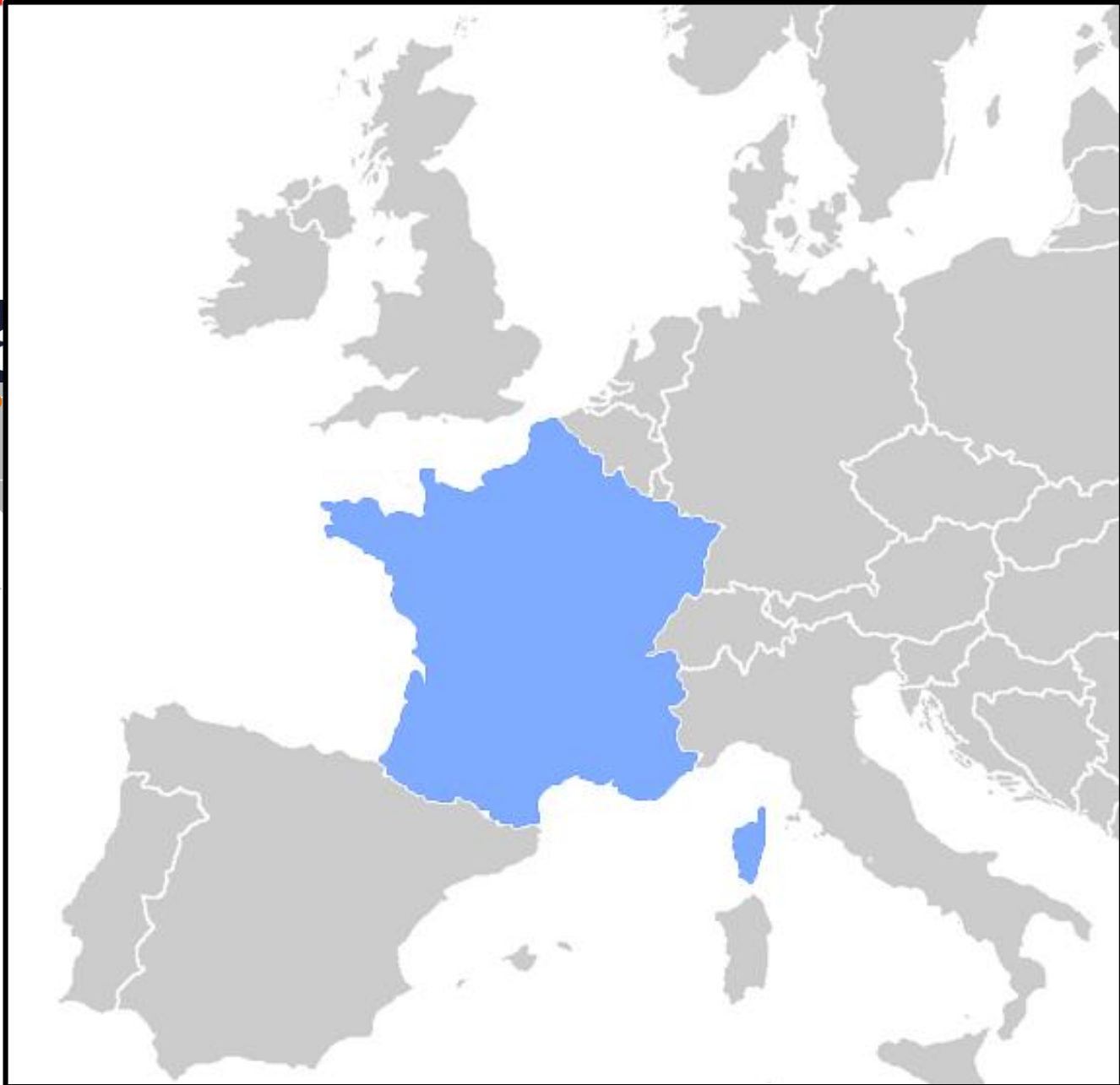
- 1. Validation on ZrO_2*
- 2. Preparation of μ -cantilevers*
- 3. Mechanical test performed with a nano-indenter*
- 4. Calculation of fracture properties*

III. Results : Fracture properties of fresh and irradiated nuclear fuels UO_2

- 1. Fracture stress of nuclear fuels UO_2*
- 2. Fracture toughness of nuclear fuels UO_2*

Conclusion and perspectives

NuMat

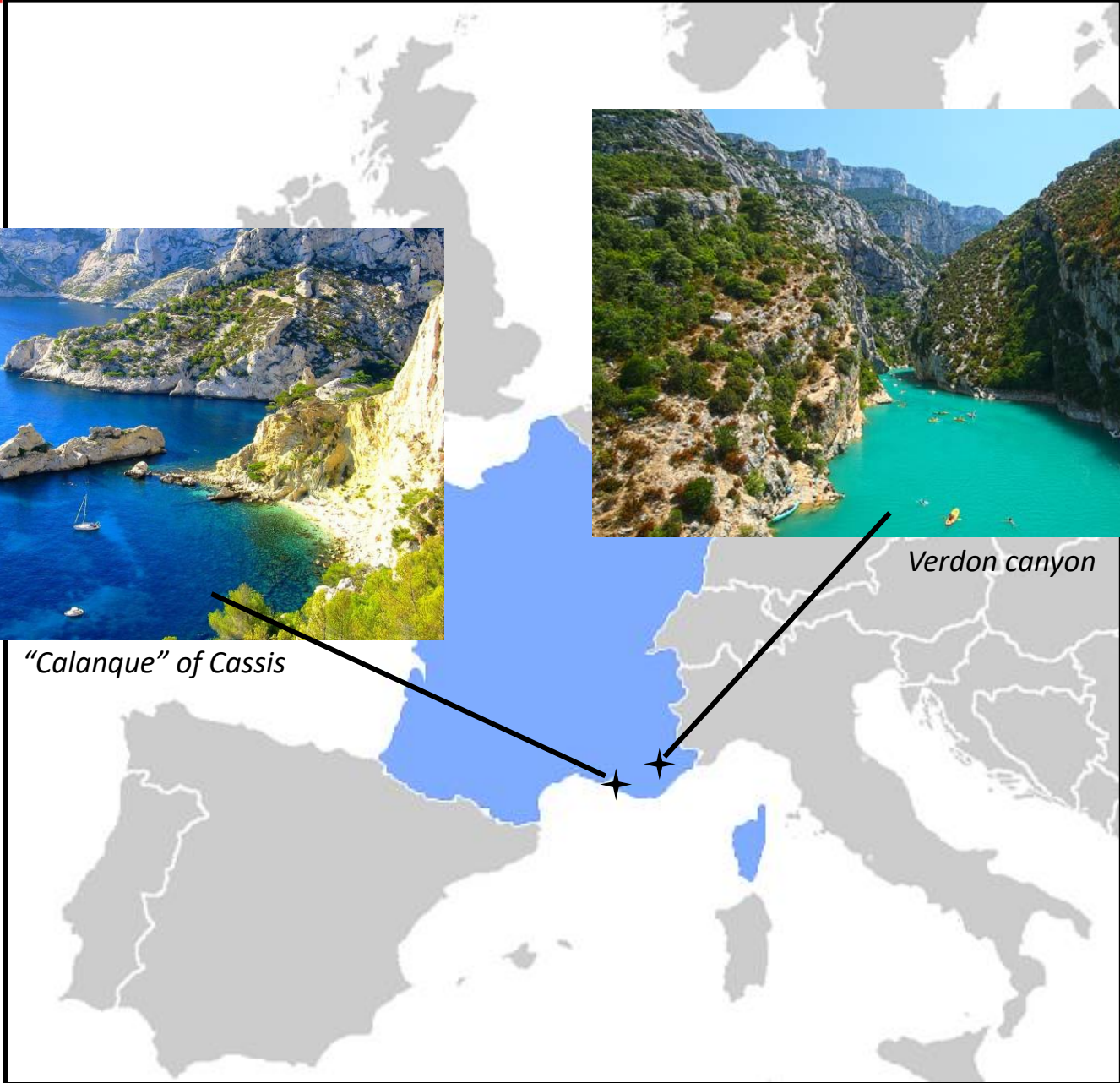




"Calanque" of Cassis



Verdon canyon





CEA

(French) Alternative Energies and Atomic Energy Commission

Cadarache Center

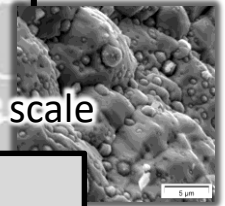
Research center for energy :

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

LECA/STAR

A nuclear facility dedicated to the irradiated fuel examination

From the whole rod to the microscopic scale



Fuel treatment
(before storage)

Non-destructive examinations
MEGAFOX
(full-length LWR rods)

CORALIE :
Fuel rod re-fabrication
& instrumentation

Non-destructive examinations
VENDAUM (experimental pins)
PLACIDE (fuel plates)

DUNCAN :
Fuel rod cutting
and machining

Fission gas release
Rods cuttings

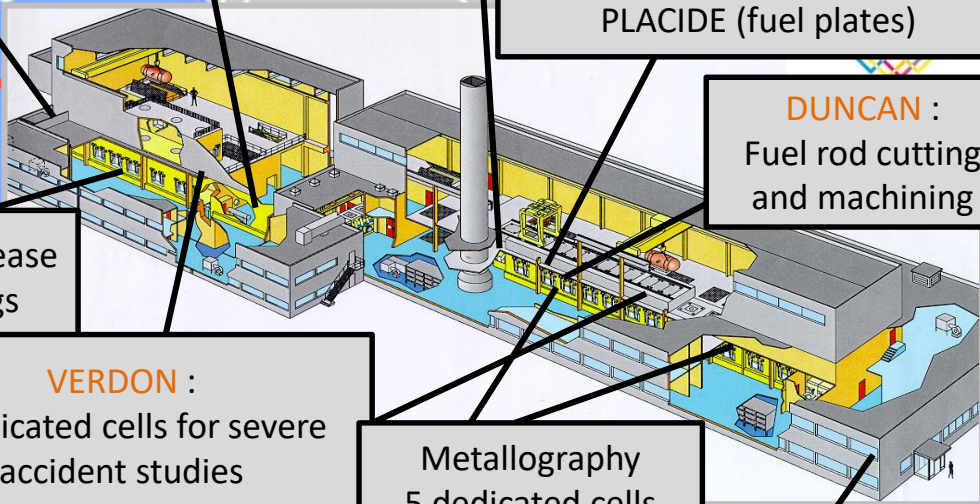
VERDON :
2 dedicated cells for severe
accident studies

Metallography
5 dedicated cells

MEYRARG :
Furnace (gas analysis)
CROCODILE
Furnace (oxidizing conditions)

MEXICOO :
Very high pressure
furnace

Micro-analysis laboratory
FIB/SEM, EPMA, SIMS, XRD, TEM





The front shielded wall

The glove box

FIB / SEM

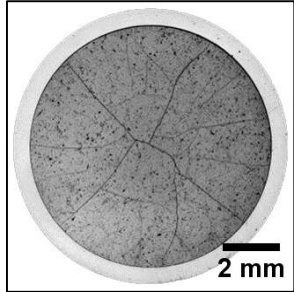
FIB / SEM

TEM

FEI

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

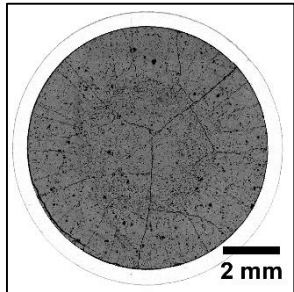
Normal operations



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

Irradiated in PWR

Power ramps

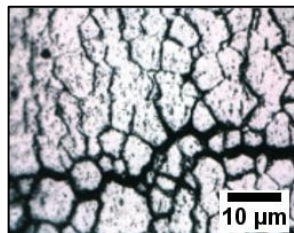


→ PCI (Pellet-Cladding Interaction)

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

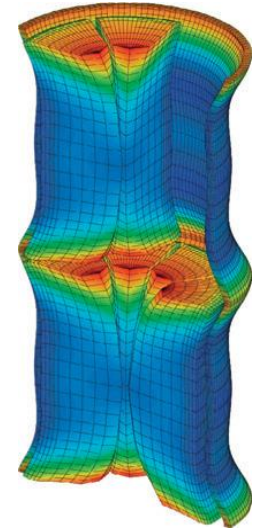
Irradiated in PWR + RIA test

→ Take it into account in numerical simulations

Fuel modelling :

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

→ **Experimental data needed**



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

Cracks in the fuel

→ **Values of :**

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

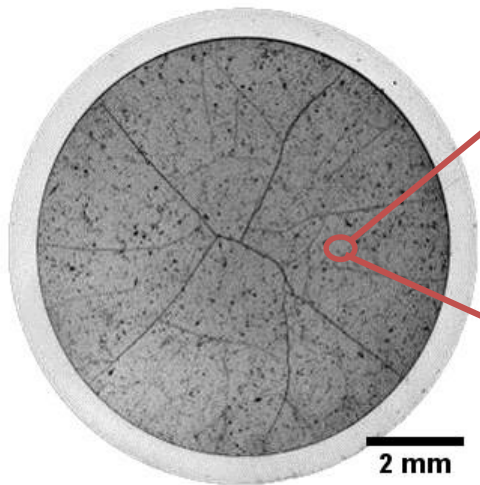
⇒ **Fresh nuclear fuel** ⇒ **Irradiated nuclear fuel**

➤ OK

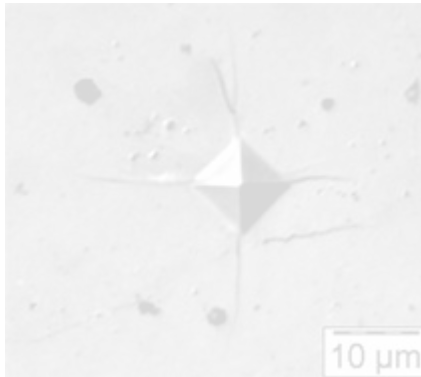
➤ Impossible to machine macroscopic specimens for mechanical testing

μ -mechanical tests :

- To avoid cracks (and porosities)
- To measure “intrinsic” properties



Optical micrograph of an irradiated pellet section



Vickers indentation on irradiated fuel

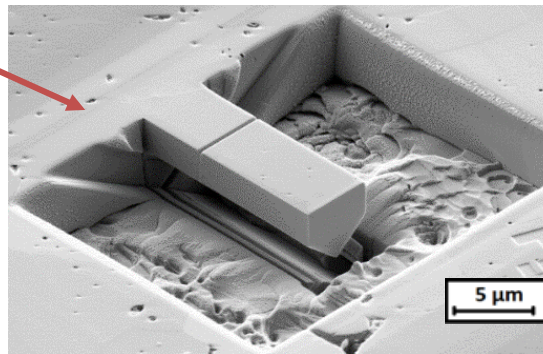
Indentation

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

Today's topic :

μ -cantilever bending :

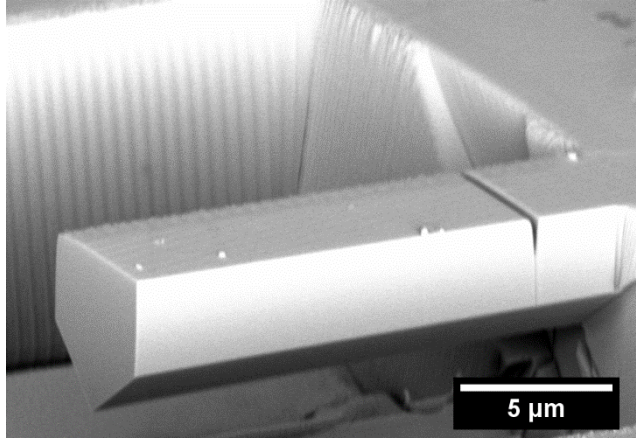
- Closer to bending test
- Preparation with FIB/SEM(Ga beam)
- Mechanical testing with a nano-indenter
- Numerical modeling



Notched μ -cantilever for fracture toughness measurement (ZrO_2)

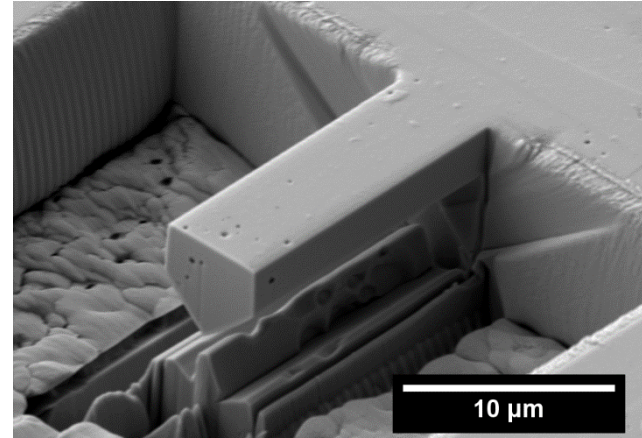
Notched cantilever

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

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

→ Good agreement with literature
(macroscopic tests on single crystals)

Higher fracture stress

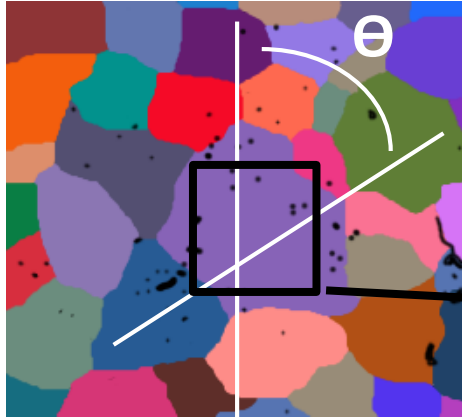
$$\sigma_c \approx 2 \text{ GPa (against } \approx 200 \text{ MPa for macro)}$$

→ Scale effect : less defects in a μ -sample

R. Henry¹, T. Blay², T. Douillard¹, I. Zacharie-Aubrun², J-M Gatt², C. Langlois¹, S. Meille¹: To be published.

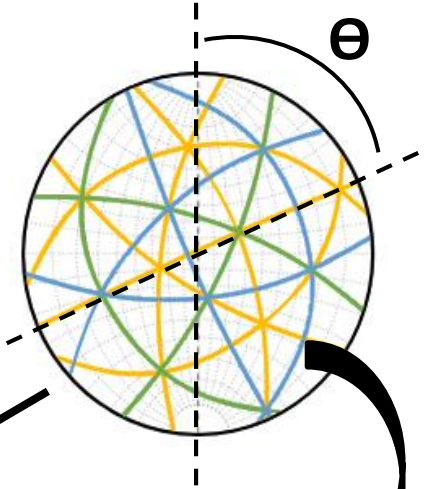
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² CEA, DEN, DEC, Cadarache, 13108 St Paul Lez Durance, France

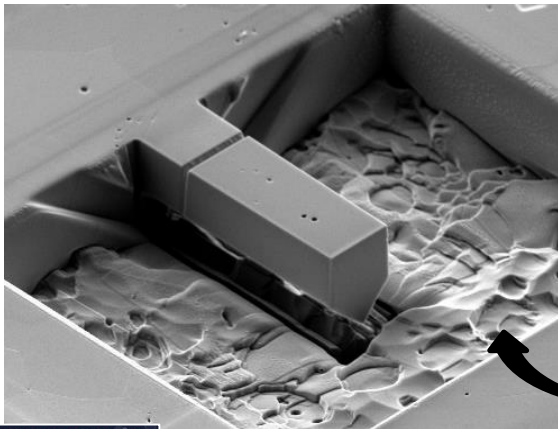


EBSD orientation map
 Grain's choice : large enough to contain a whole cantilever

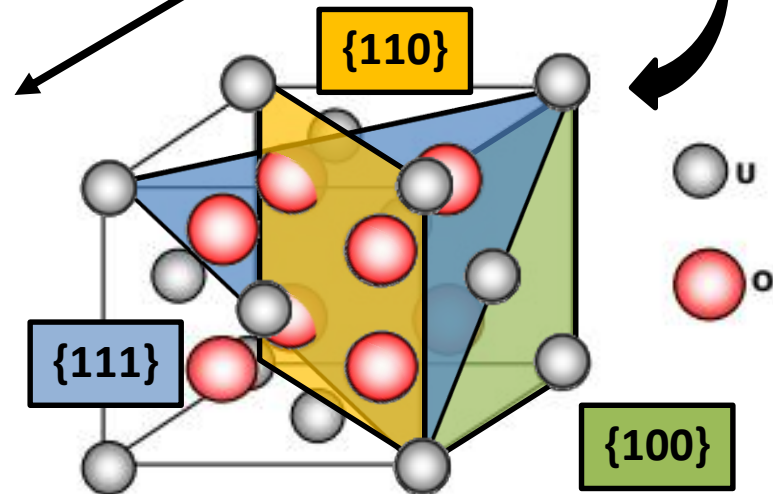
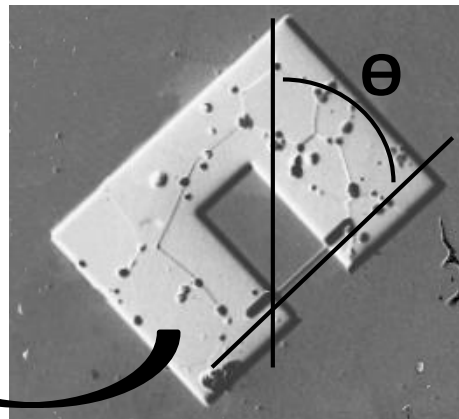
Stereographic projection
 The targeted crystallographic plane is normal to the sample surface



Specimen
 Orientated into a chosen crystallographic plane

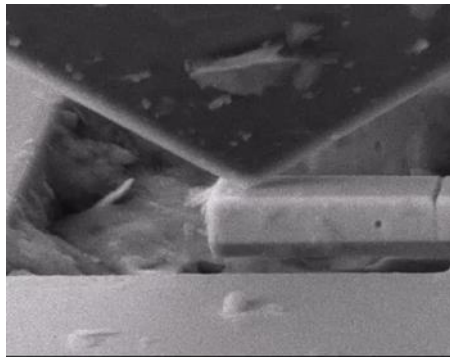


Positioning
 Use of θ angle for the milling

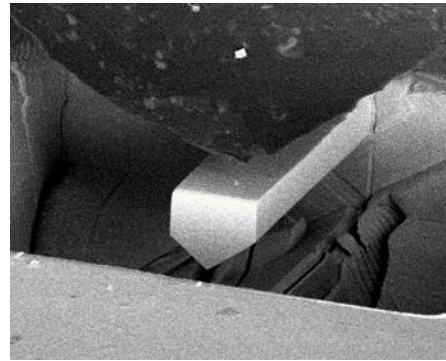


Cubic crystal of UO_2 and some of its crystallographic planes

Movies of in situ bending tests



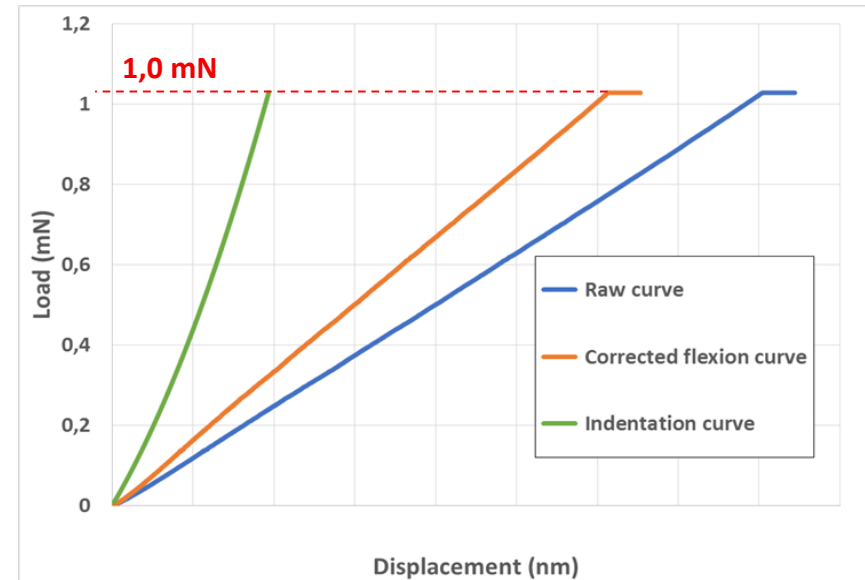
Fresh UO₂
 With the support of
 X. Iltis (CEA), N. Tarsien (CEA)



Irradiated UO₂
 With the support of
 S. Chalal (Carl Zeiss)

Linear load-displacement curve

Corrected from indentation
 → Fracture load

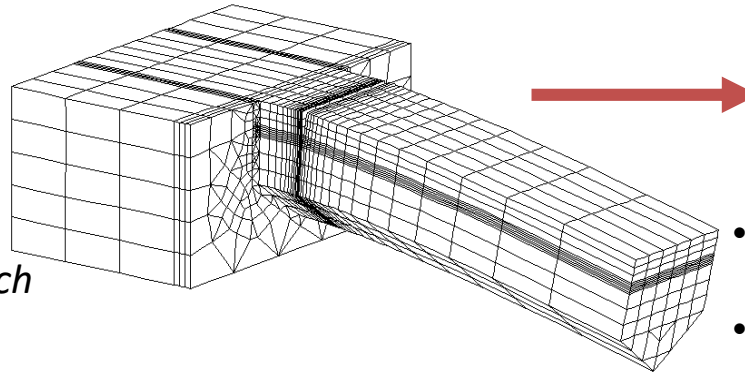


➔ No plasticity : brittle behavior (elastic up to fracture)

FEM modelling

Calculation inputs :

- Fracture load
- Dimensions of the beam and notch



FEM analysis (Cast3m® (CEA, France))

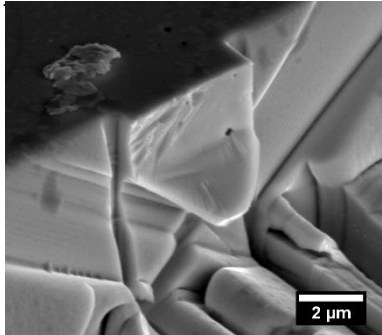
Calculation outputs :

- 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

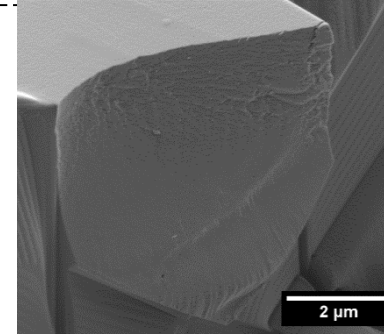
Standard UO_2 (grain size : $10 \mu m$)
Fresh fuel



$\sigma_R = 3.4 \pm 0.7$ GPa

{100}

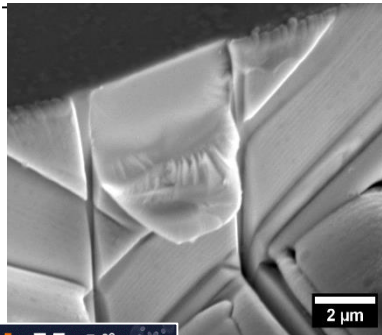
Large grain UO_2 (grain size : $60 \mu m$)
Irradiated fuel (34 GWj/tM)



$\sigma_R = 3.6 \pm 0.4$ GPa

Fracture surface almost flat
Highest value of stress

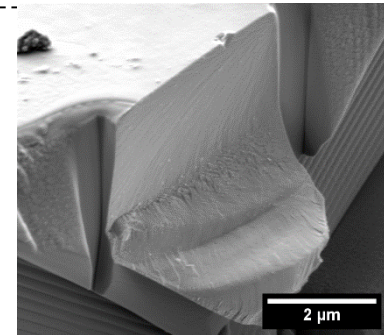
{111} family plane seems weaker
 → Coherent with numerical simulations at atomistic scale (MD and DFT)
 Y. Zhang et al., "Crack tip plasticity in single crystal UO_2 : atomistic simulations, Journal of Nuclear Materials, 2012."
Scale effect on fracture stress
 → ≈ 3 GPa (micro) against ≈ 150 MPa (macro)



$\sigma_R = 2.7 \pm 0.1$ GPa

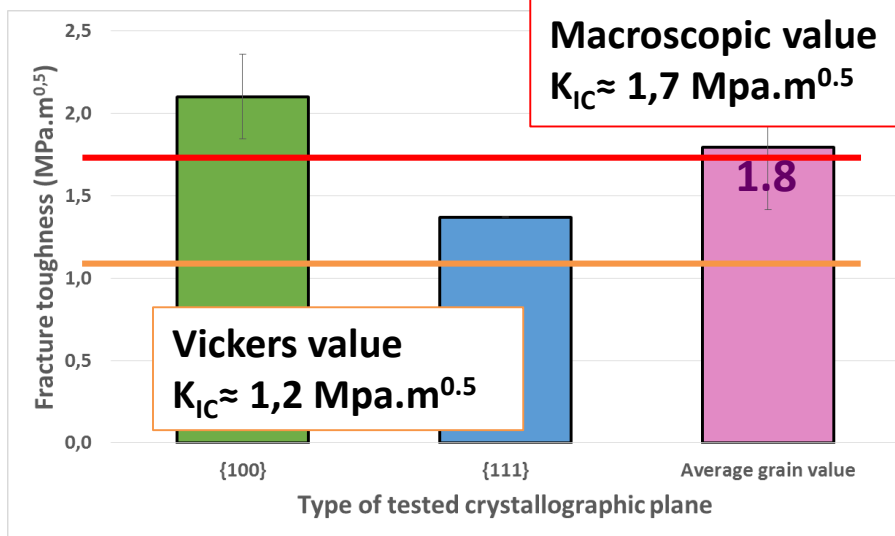
{111}

$\sigma_R = 2.2 \pm 0.4$ GPa

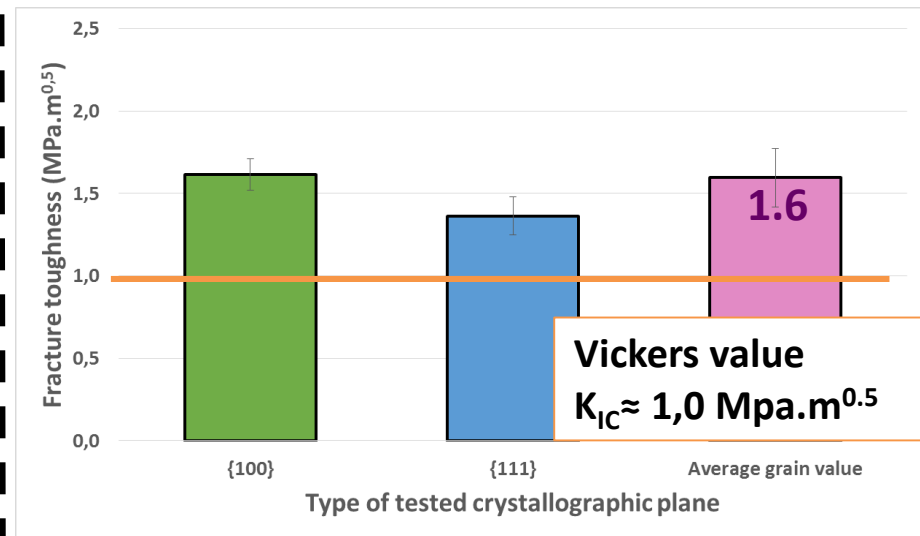


Fracture surface flat (higher part)
Lowest value of stress

Standard UO_2 (grain size : $10 \mu m$)
Fresh fuel



Large grain UO_2 (grain size : $60 \mu m$)
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*

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)	✗	✗



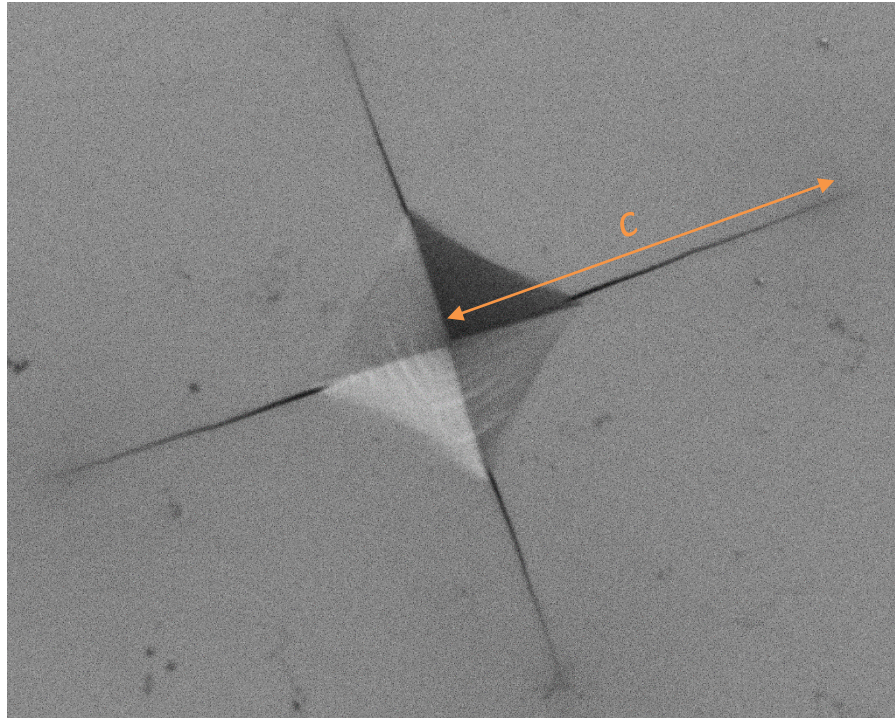
Avec le soutien de :



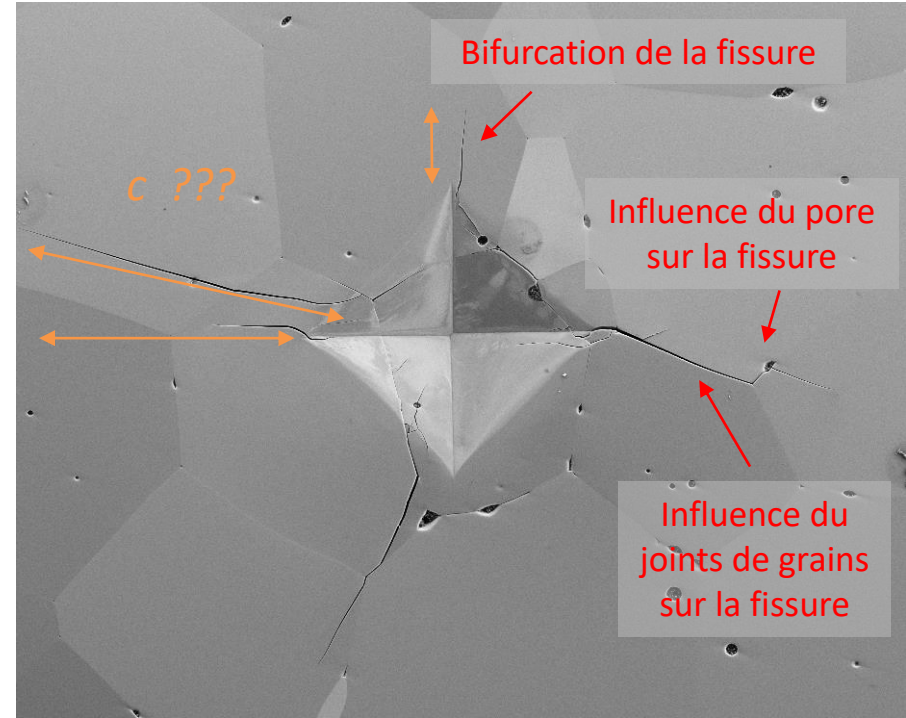
Thank you for your attention



ronan.henry@insa-lyon.fr



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



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