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EXTENSIVE INVESTIGATION OF THE MECHANICAL PROPERTIES OF A CHOOZ A INTERNAL COMPONENT

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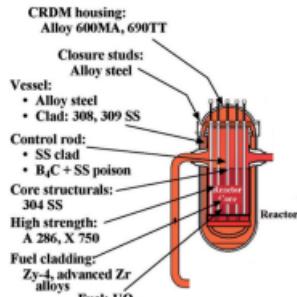
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^c EDF Lab

Fontevraud 9, September 17th - 20th, Avignon, France

Contribution of Materials Investigations and Operating Experience to Light Water NPP's Safety, Performance and Reliability

Internal Structures of Pressurized Water Reactors (PWR's)



(Allen et al., 2010)

- 300 series Austenitic stainless steels :
 - SA304(L) for baffle plates
 - CW316 for bolts
 - 308 for welds

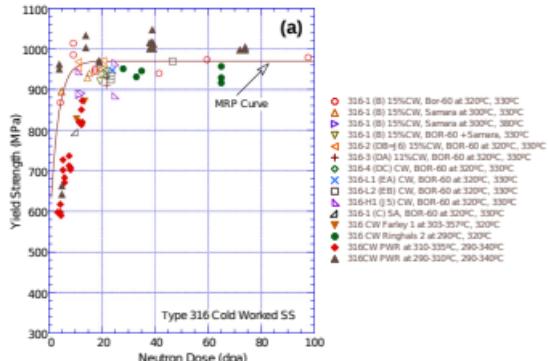
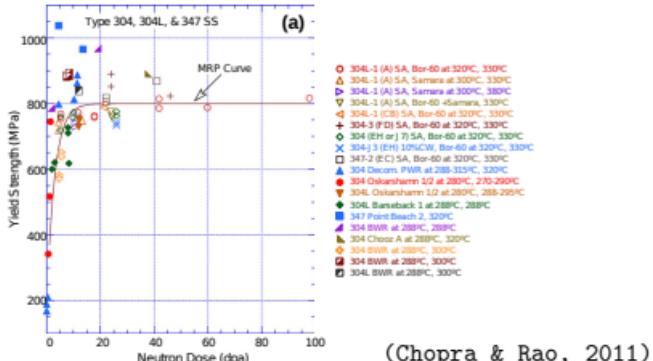
Evolution of mechanical properties with irradiation

- Increase of yield stress
- Decrease of strain-hardening capability
- Decrease of fracture toughness

} As a consequence of nanoscale irradiation defects

BACKGROUND

Evolution of yield stress with irradiation

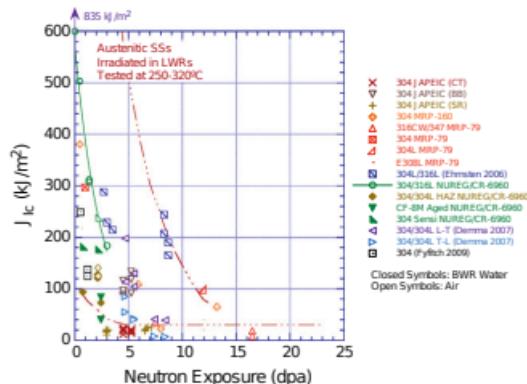
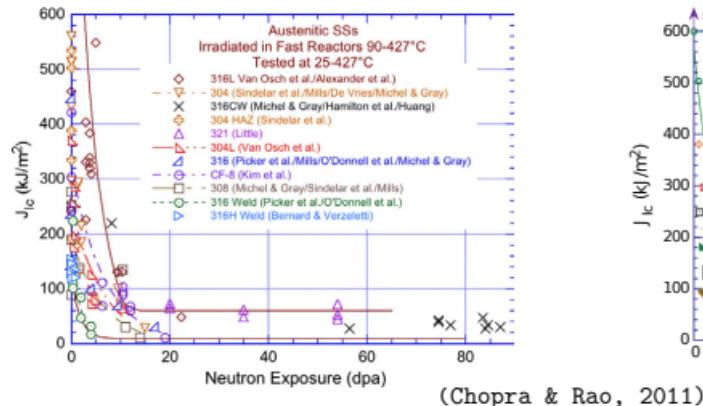


Well documented for doses up to 100dpa:

- Saturation for doses higher than ~20dpa
 - Higher saturation for CW316 compared to SA304
 - Consistent results between LWR and Fast reactors irradiation conditions
 - but few points from LWRs retrieved materials are higher

BACKGROUND

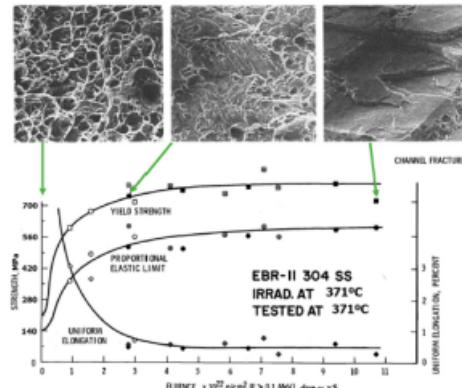
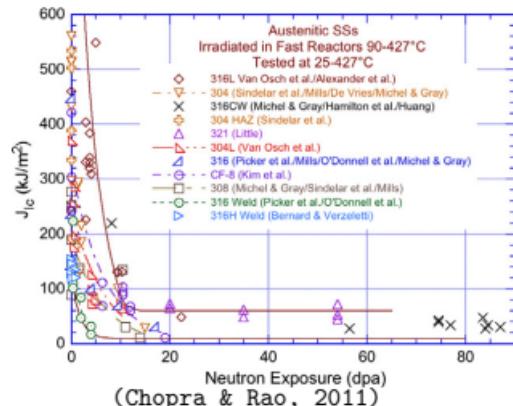
Evolution of fracture toughness with irradiation



- Saturation for doses higher than ~20dpa
 - But large variability
- Consistent trends between LWR and Fast reactors irradiation conditions
 - Limited data from LWRs retrieved materials at high doses
 - Similar fracture mechanisms ?

BACKGROUND

Evolution of fracture toughness with irradiation



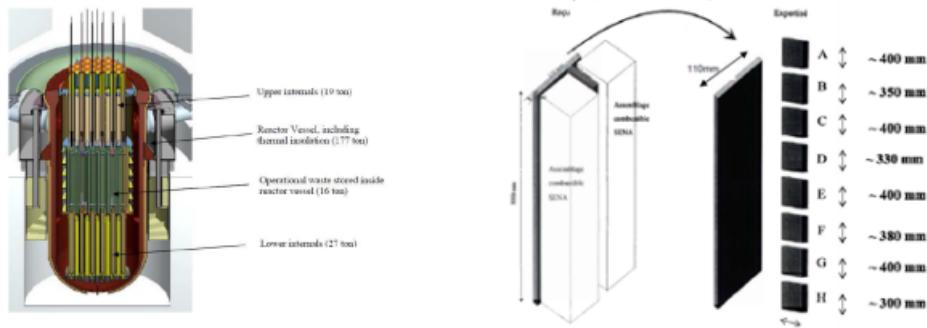
(Hojna, 2017)

- Saturation for doses higher than ~20dpa
 - But large variability
- Consistent trends between LWR and Fast reactors irradiation conditions
 - Limited data from LWRs retrieved materials at high doses
 - Similar fracture mechanisms ?

Main objective of this study

MATERIAL

Decommissionned PWR Chooz A reactor (operating between 1967 and 1991)



Retrieved baffle separating fuel assemblies

- 304 austenitic stainless steel

C	S	P	B	Mo	Co	Si	Mn	Cr	Ni	V	Nb	Cu	Ti
0.06	0.003	0.011	<0.0005	0.02	0.034	0.78	0.96	18.6	9.3	0.099	<0.02	0.089	<0.003

Characterization of sub-blocks in blocks A, C, H

- Different irradiation temperatures ($\sim 300^\circ\text{C}$ / $\sim 330^\circ\text{C}$)
- Different irradiation doses (between ~ 1 and ~ 30 dpa)

Same blocks used in (Renault-Labonne), (Fukuya) and (Miyahara) presentations

Available data not sufficient for a purely numerical estimation of dpa

Simplifying assumptions

Calibration

Coupled Experimental / Numerical strategy

Sampling of material

at well-defined locations along the blocks

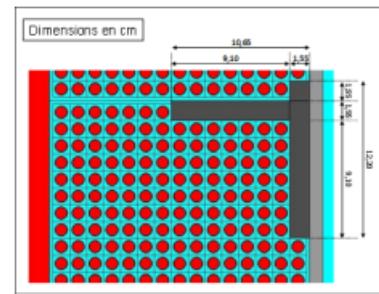
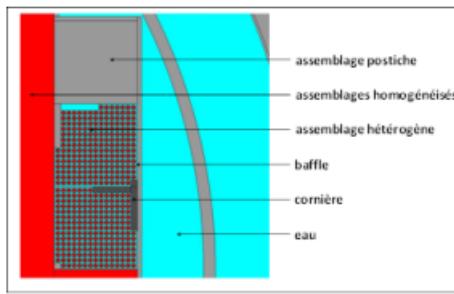
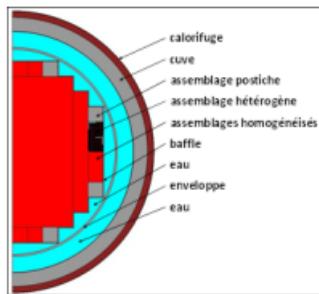
Measurements of Residual ^{59}Co and ^{60}Co activity

TRIPOLI-4 Monte-Carlo transport code
JEFF 3.1.1 Nuclear DataBase

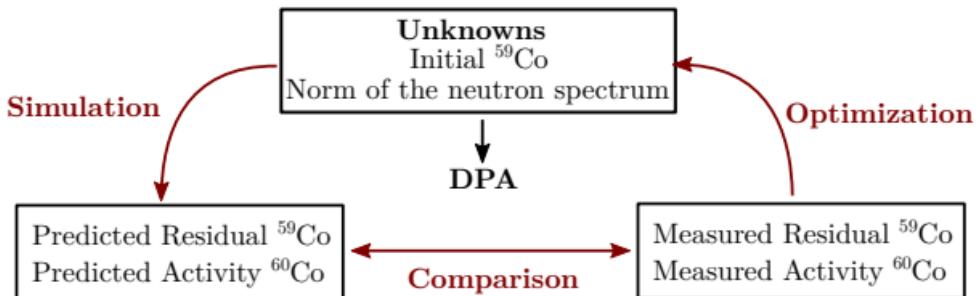
- DPA, neutron spectrum

DARWIN/PEPIN2 evolution code

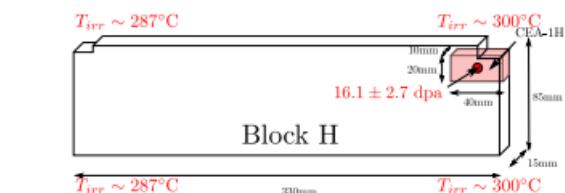
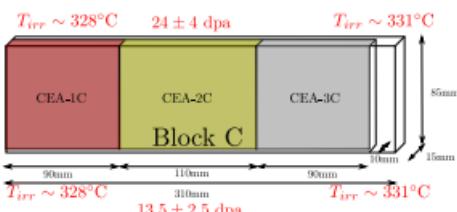
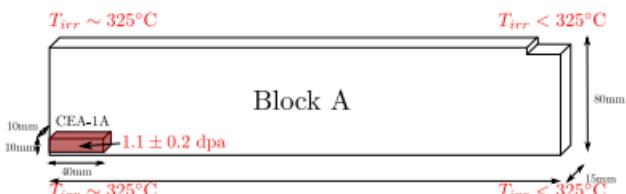
- ^{60}Co and ^{59}Co



EVALUATION OF IRRADIATION DOSES



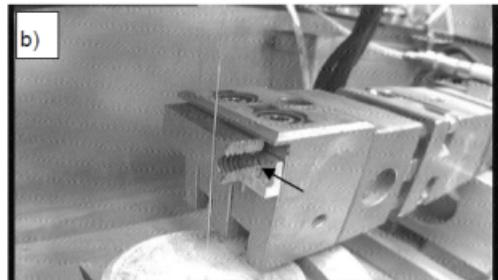
Results: Dose estimation (at block locations)



New doses \lesssim Older estimations
(used in previous studies)

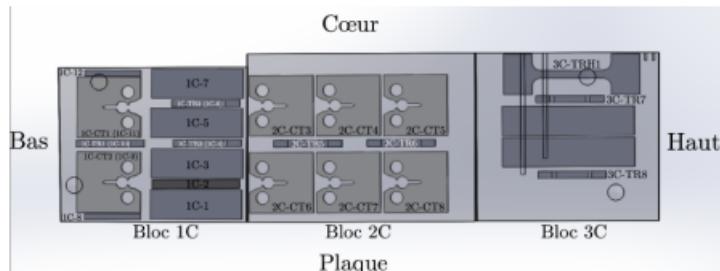
Machining of samples (CEA Saclay Hot Cells)

- Electric Discharge Machining
 - Conventional Milling
- Unexpected screws / holes



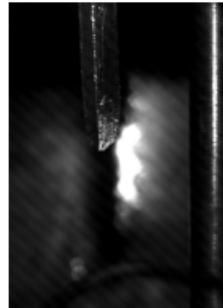
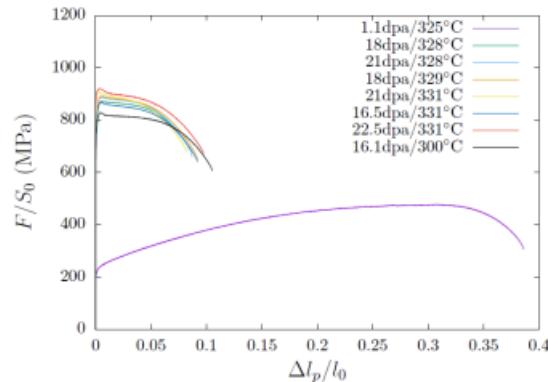
Available samples

- 10 flat tensile specimens (one homothetic x2)
- 7 Compact Tension (CT12.5) fracture toughness specimens



Mechanical tests performed at CEA Saclay Hot Cells

Conventional tensile curves (330°C)



Overall saturation of mechanical properties for doses higher than 16dpa

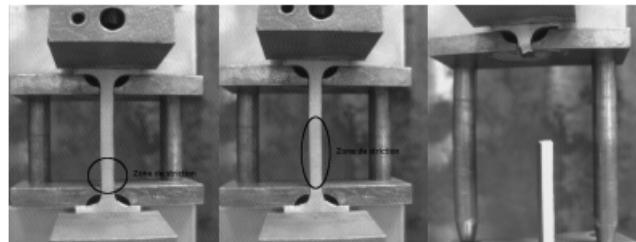
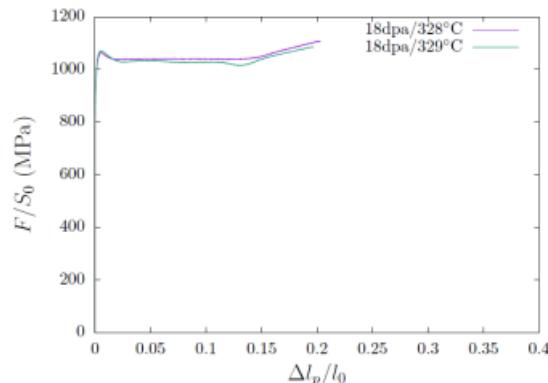
- Yield stress ~850MPa
- Ultimate tensile strength stress ~900MPa

No significant effect of tensile sample geometry $S_0 = 7\text{mm}^2$ vs. 28mm^2

(Unexpected ?) effect of irradiation temperature $T_{irr} \searrow \sigma_{ys} \searrow$

Significant local ductility, followed by shear band failure

Conventional tensile curves (20°C)



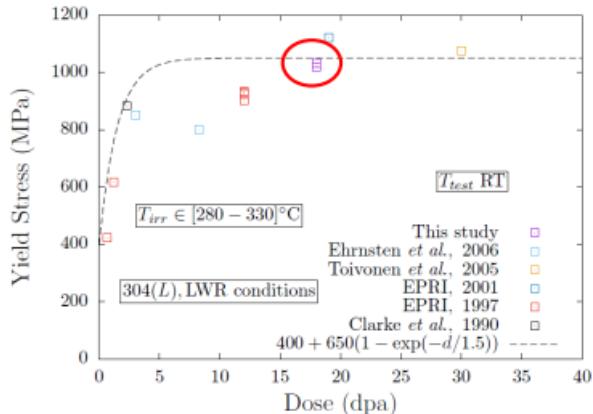
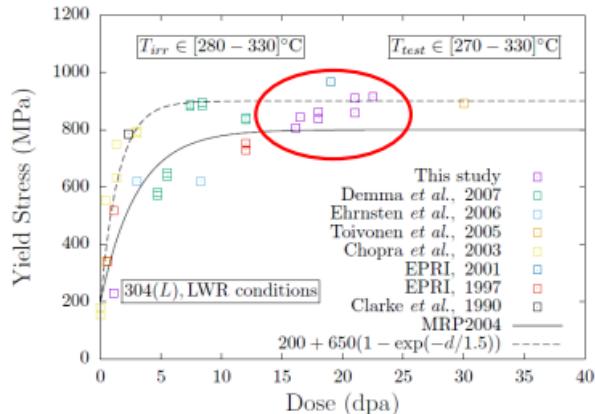
Reproducible stress-strain curves at 18dpa: **Stress plateau and re-hardening**

- **Yield stress** ~1000MPa
- **Ultimate tensile strength stress** ~1100MPa

Stable neck propagation (along the gage length) during the stress plateau

Quasi-brittle fracture (perpendicular to loading)

TENSILE PROPERTIES : COMPARISON WITH LITERATURE DATA



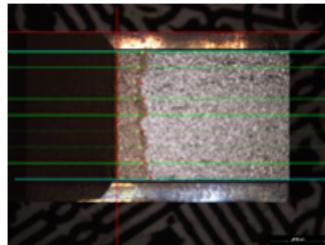
Consistent with previously published data

High doses values higher than MRP2004 curve at $\sim 300^\circ\text{C}$

- **Saturation value** for MRP curve based on Fast Reactor data

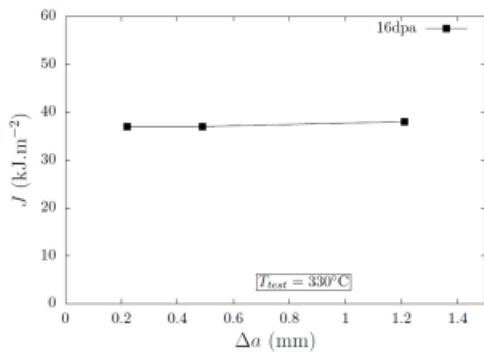
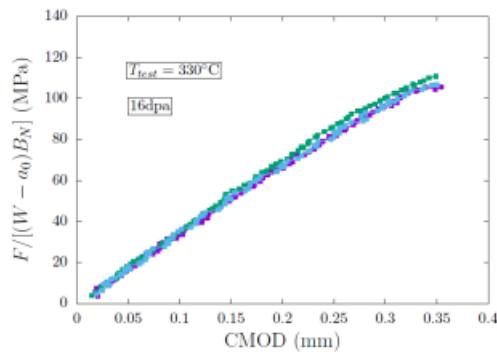
Similar observations for ultimate tensile strength

Methodology



- Precracking in fatigue at 20°C
- Interrupted tests at 330°C (for a given Δa)
- Final fracture at 20°C
- Post-mortem measurements of :
 - Initial crack length
 - Crack propagation

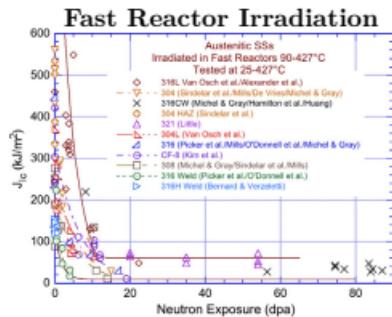
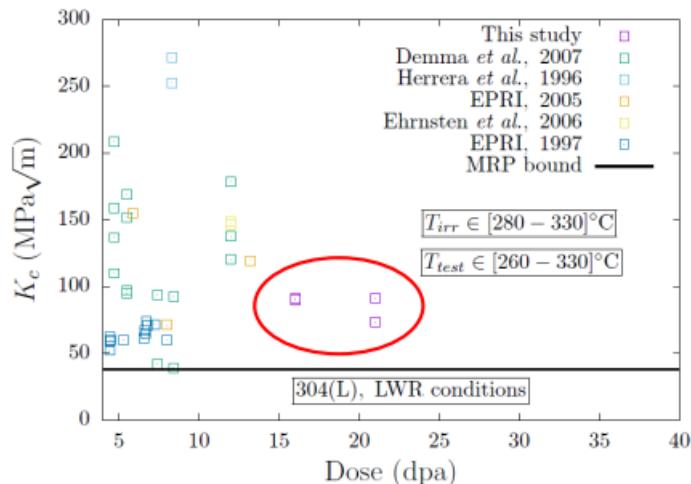
Typical results (at a given dose)



Very reproducible Load - Opening loading curves

Tearing modulus ($dJ/d\Delta a$) **close to zero**

FRACTURE TOUGHNESS PROPERTIES : COMPARISON WITH LITERATURE DATA



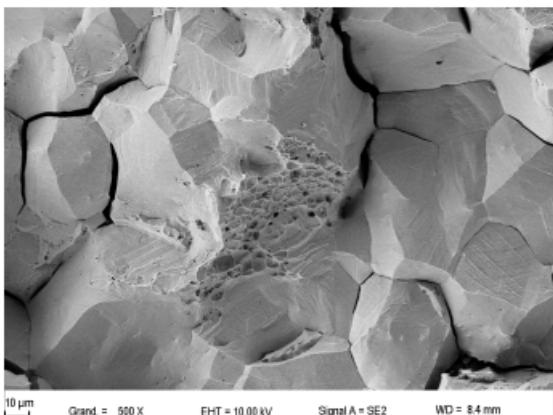
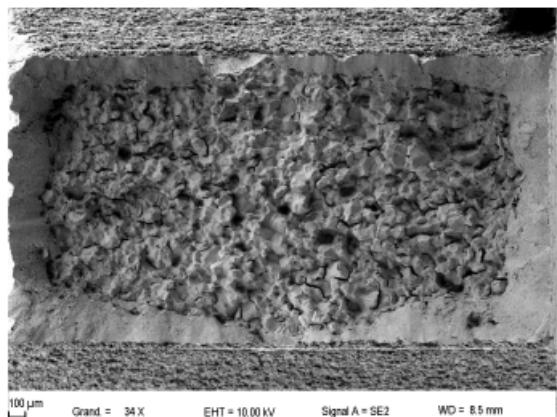
$$K_J = \sqrt{\frac{EJ}{1-\nu^2}}$$

New data lead to $K_{Jc} \approx 80 \text{ MPa}\sqrt{m}$ / $J_c \approx 30 \text{ kJ.m}^{-2}$ for dose $> 16 \text{ dpa}$

- **within the scatter** of previous results (at lower doses) for LWR conditions
- **consistent** with the saturation value from Fast reactors data
- **Significantly above** the MRP bounding line

Towards modelling: SEM Observations of fracture surfaces (high doses)

At 20°C (on tensile samples)



Fracture surfaces almost fully **intergranular**

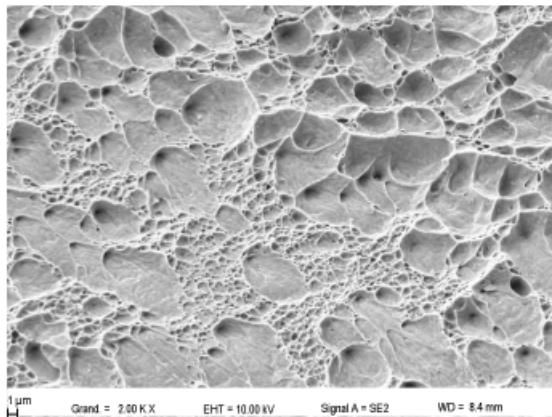
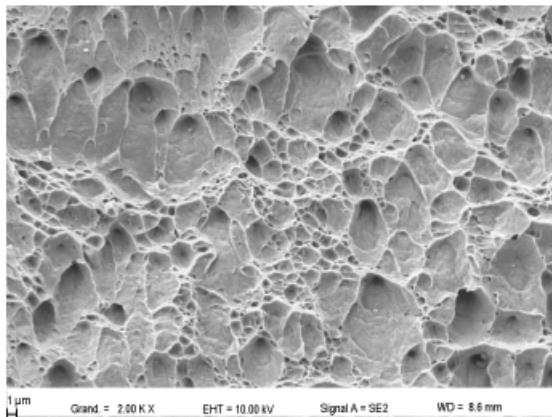
Local zones of **ductile fracture** through void growth to coalescence

Similar observations for fracture surfaces at 20°C on CT specimens

In addition : fatigue crack is also mostly intergranular

→ Related to **martensitic transformation** during straining ?

At 330°C (on tensile samples)

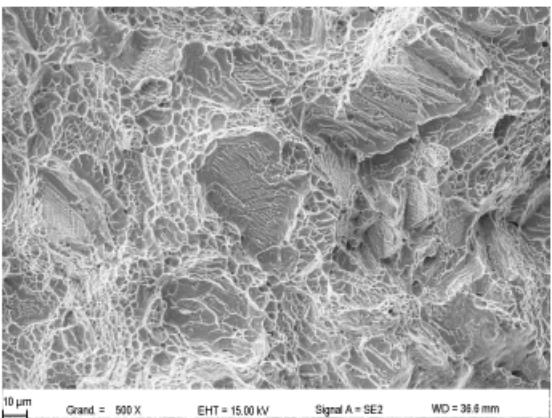
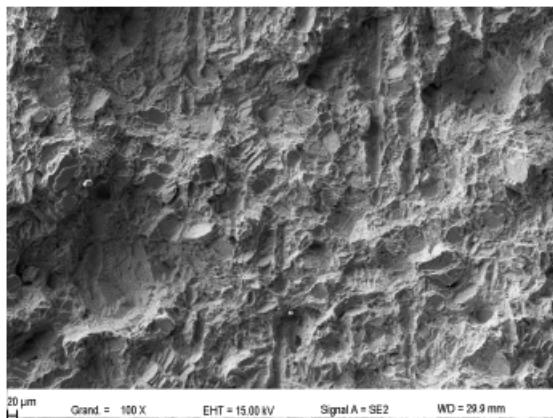


Fracture surfaces **fully transgranular with dimples**

- **Two dimple size populations** : ~10 microns and ~1 microns
- **Elongated dimples**: failure in a shear band

Typical of ductile fracture through void growth to coalescence

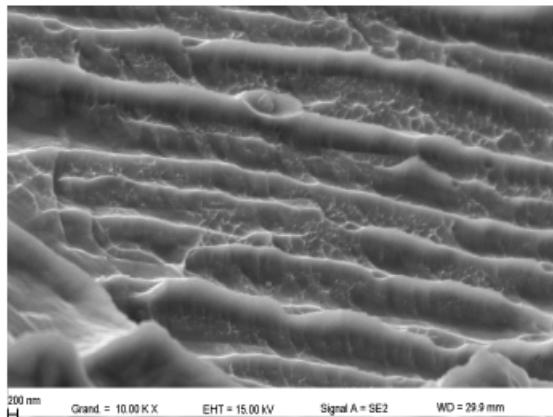
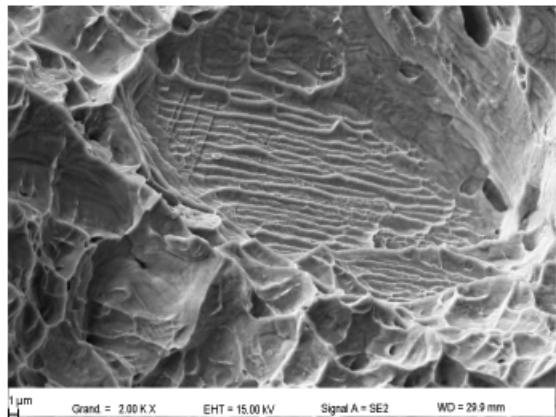
At 330°C (on fracture toughness samples)



Three main features on fracture surfaces

- **Presence of stringers** with MnS inclusions
- **Micron-scale classical ductile fracture** (transgranular dimples)
- **Planar facets** with ridges and nanoscale dimples

At 330°C (on fracture toughness samples)



3 main features on fracture surfaces

- **Presence of stringers** with MnS inclusions
- **Micron-scale classical ductile fracture** (transgranular dimples)
- **Planar facets** with ridges and nanoscale dimples
 - **Fracture mechanisms ?**

Investigation of the mechanical properties of a Chooz A internal component

- **Tensile properties** consistent with previous data
 - Void growth to coalescence fracture mechanisms at 330°C
 - Intergranular failure at 20°C
- **Fracture properties** supplement existing data for LWR conditions
 - Still significant at 20dpa/330°C: $K_{Jc} \approx 80 \text{ MPa}\sqrt{\text{m}} / J_c \approx 30 \text{ kJ.m}^{-2}$
 - Similar to Fast reactors data showing Channel fracture
 - Void growth to coalescence fracture mechanisms at 330°C
- **Open questions**
 - Mechanism and modelling of intergranular fracture
 - Nano-scale dimples on planar **inter/trans (?) facets**: Mechanism ?