Hydride Effect on Cladding Behaviour for Spent Fuel Storage and Transport Conditions

IAEA- International Conference on Management of Spent Fuel
Vienna, Austria , 15 – 19 June 2015

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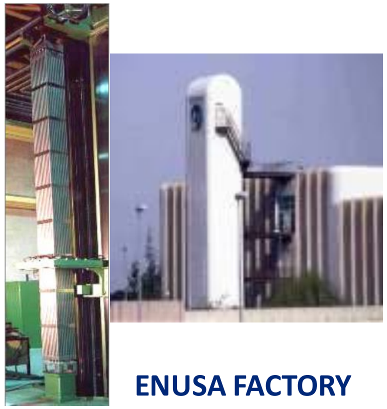
Spanish Fuel Cycle Strategy - Open Cycle

URANIUM



ENUSA FACTORY

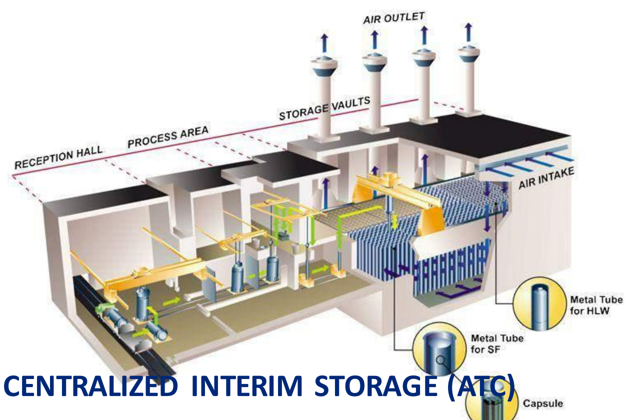
REACTOR

SPENT FUEL POOL
(re-racking)

INDEPENDENT SPENT FUEL STORAGE INSTALLATION (ISFSI)

3 ISFSI in operation

TRANSPORT



CENTRALIZED INTERIM STORAGE (ATC)

Designed in detail
Being licensed
Operation in 2018

Dry Spent Fuel Storage and Transport

SAFETY FUNCTIONS
Subcriticality
Confinement
Retrievability
Heat Removal
Shielding

Requirements in standards

10CFR 71 / 10 CFR 72

No gross cladding rupture

Geometric form not altered

Key Parameter

Cladding Integrity

Cladding Failure mechanism

Creep

Hydride embrittlement

…

Good behaviour Analyzed in other R&D projects (1)

Objective of the R&D project presented today

(1) M. Quecedo et al. "Results of Thermal Creep Test on Highly Irradiated ZIRLO". WRFPM 2008. Korea
M. Lloret et al. "Results of thermal creep tests on irradiated Zry-2", TopFuel meeting, Manchester, UK, 2012

R&D Project

Objective: Effect of hydrides in cladding behaviour during dry storage and transport

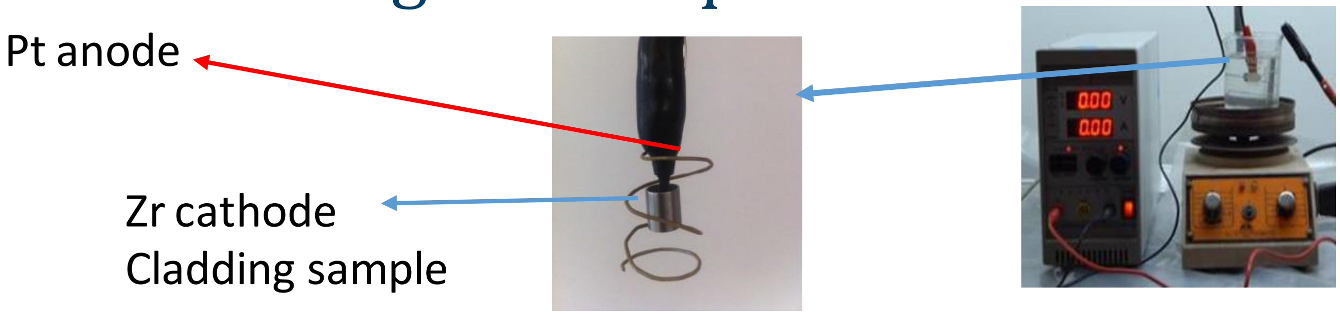
Material: Prehidrurated/ Non irradiated ZIRLO Cold Work Stress Relieved (CWSR)

Results presented:

- ✓ Cladding Hidruration
- ✓ Hydride reorientation
- ✓ Ring Compression Tests
- ✓ Effect of Circumferential vs Radial Hydrides
- ✓ Fractographic analysis
- ✓ Failure criteria

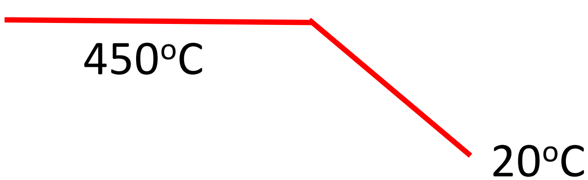
Cladding hidruration

- Cathodic Charge technique in KOH solution



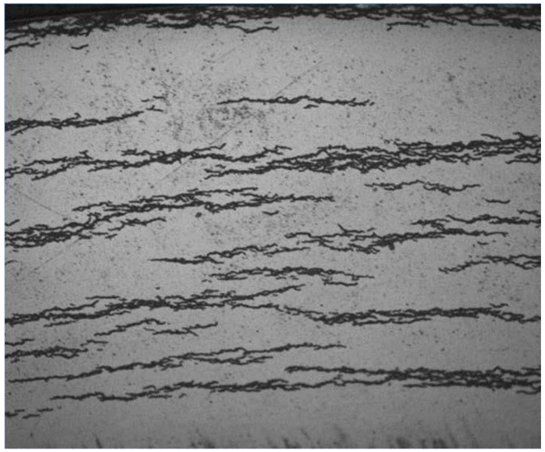
  - ✓ Parameters can be adjusted to obtain different H concentrations

- Thermal treatment
  - ✓ Homogeneous distribution along hoop direction

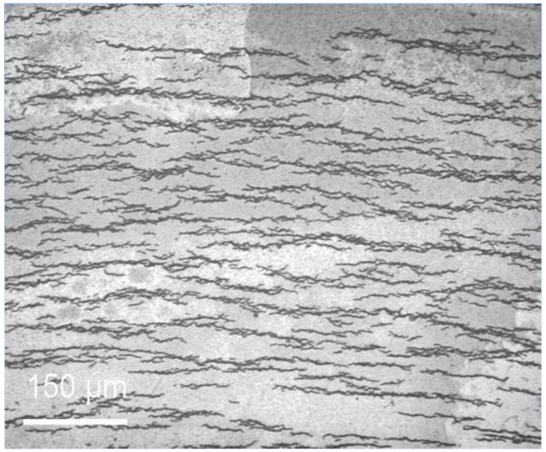


Cladding hidruration

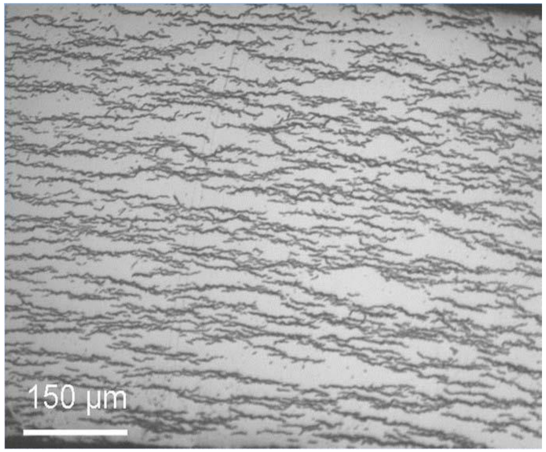
- 150 – 500-1200-2000 ppm hydrogen



150 ppm

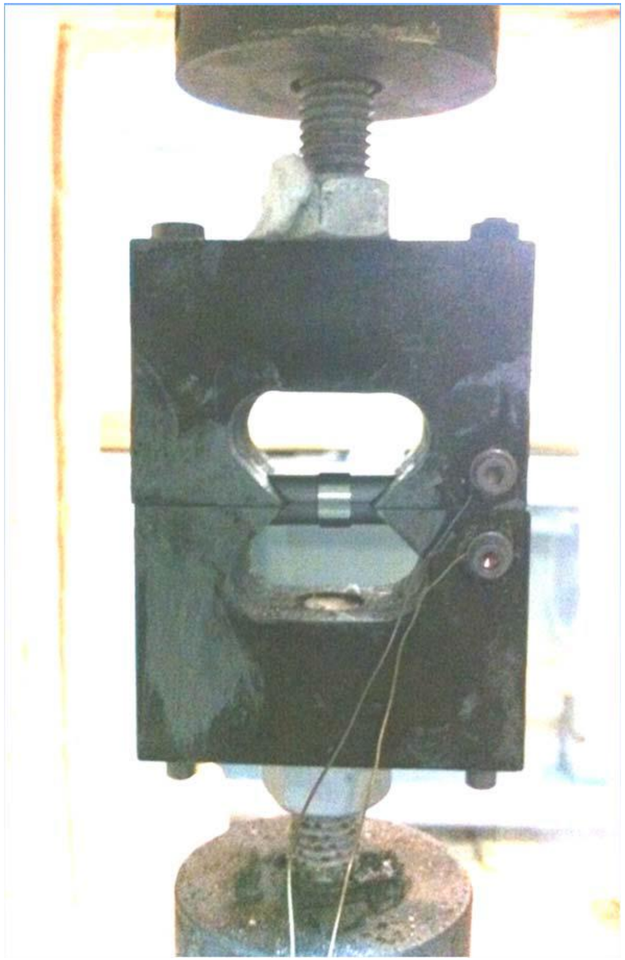


500 ppm



1200 ppm

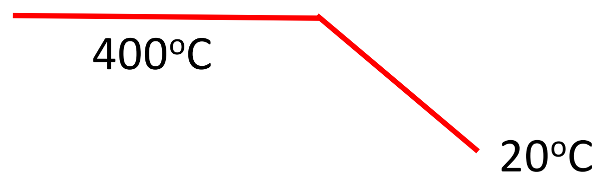
Hydride reorientation along radial direction



Circumferential stress

0-60-90-120-140 MPa

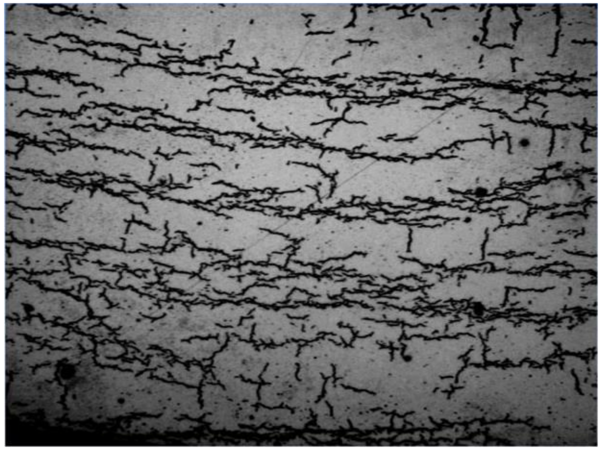
Termomechanical treatment

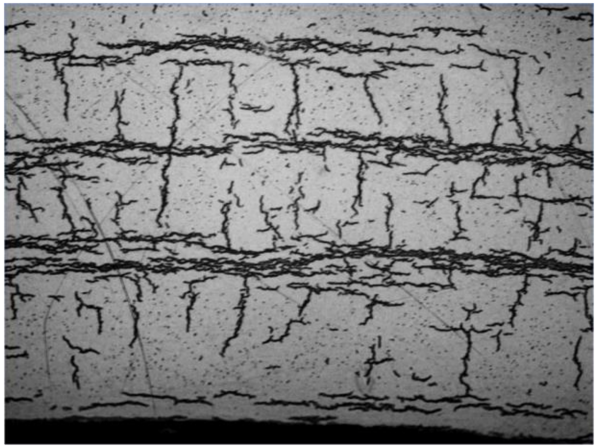


Constant hoop stress during cooling down: Thermal dilatation considered and load decreases as temperature decreases

Hydride reorientation along radial direction

Cladding samples

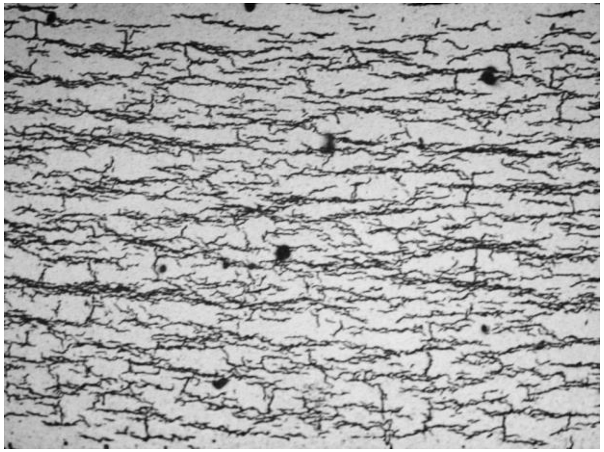


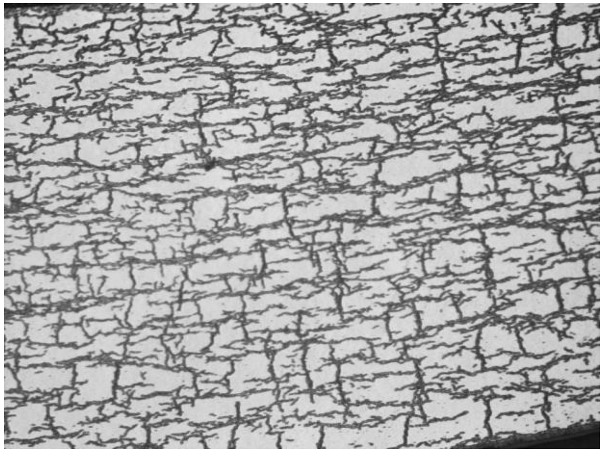


150 ppm

90 MPa

140 MPa

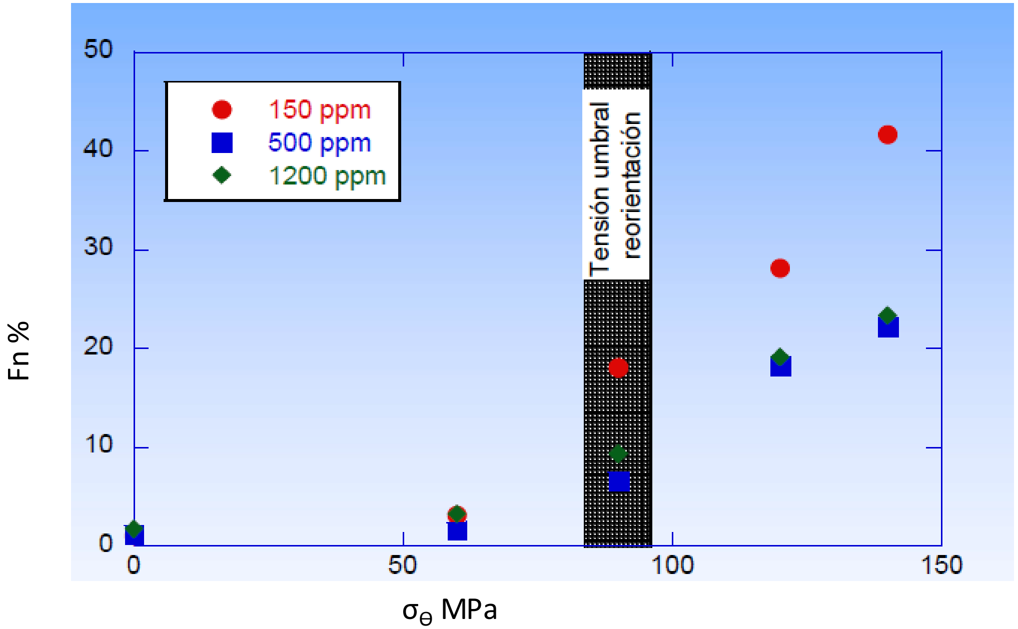




1200 ppm

Hydride reorientation

- Fn factor (reoriented hydride percentage) has been calculated for de 3 hydrogen concentration
- It has been calculated following ASTM B811



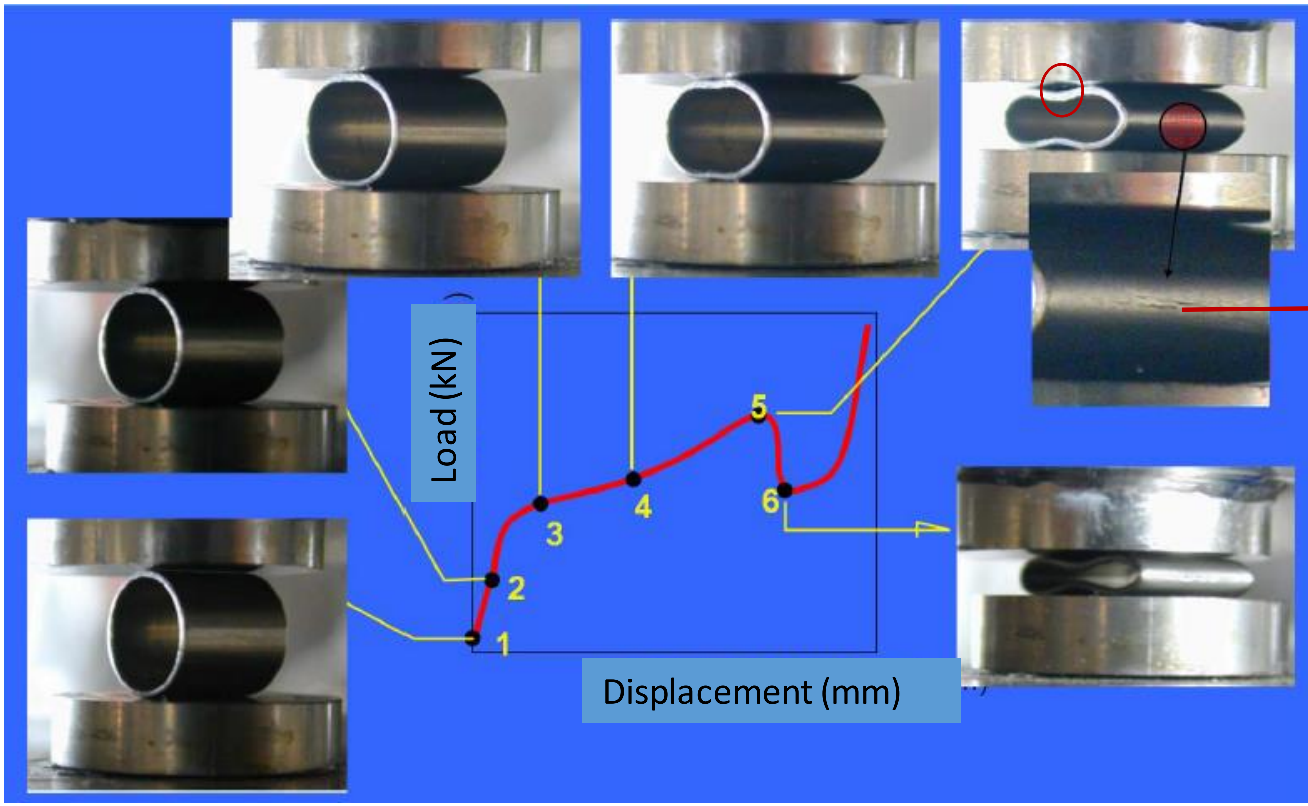
Highest reorientation factor for 150 ppm
Similar values and evolution for 500 and 1200 ppm

enusa enresa CSN

Ring Compression Tests

Mechanical tests has been performed on different hydrides morphologies samples to evaluate the cladding structural integrity

Representative Load-Displacement curve



Higher stresses
Load decrease
Crack initiation

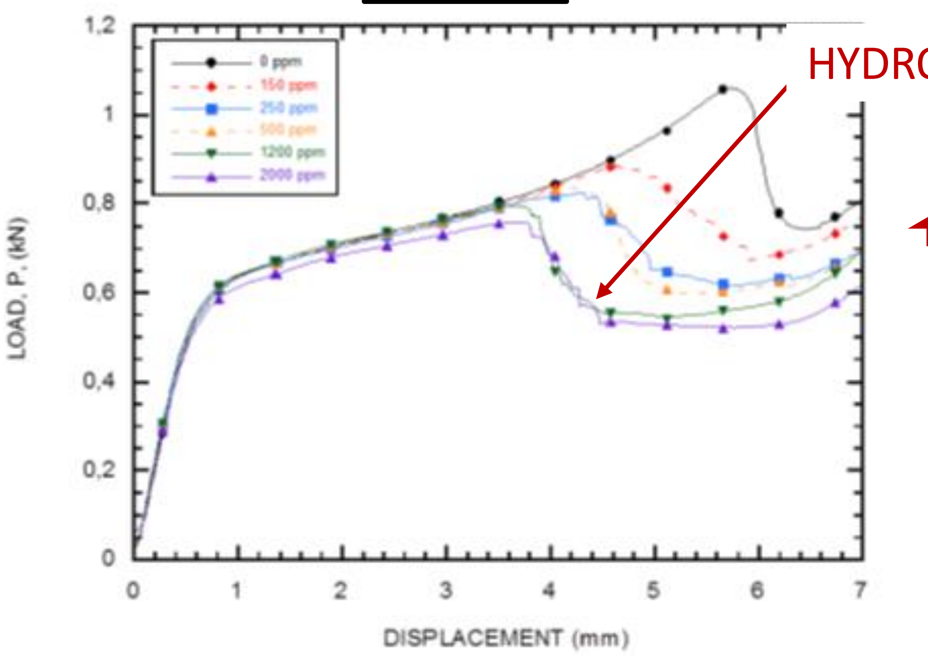
RCT - Circumferential Hydrides

Test Conditions

Temperature: 20, 135, 300 ºC

Hydrogen content: 150, 250, 500, 1200, 2000 ppm

20 ºC



HYDROGEN INCREASE

[H] displacement for crack initiation

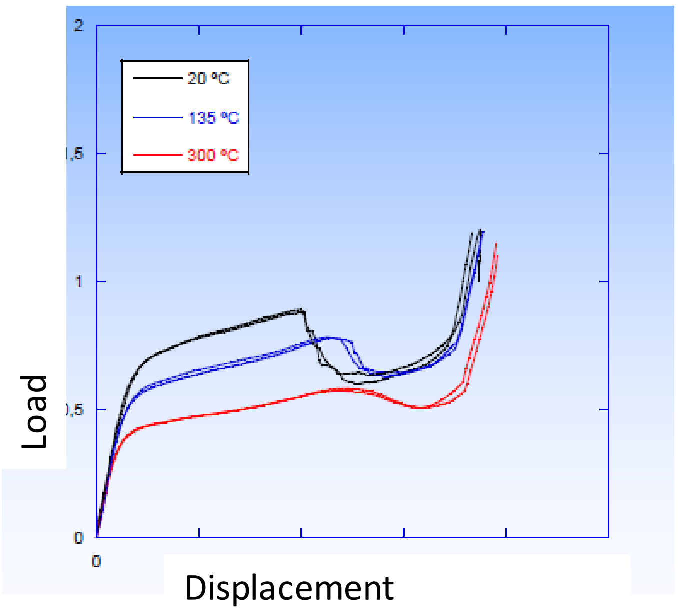
Displacement always higher than 3mm

Yield strength / Young Modulus

No dependence with [H]

RCT- Circumferential Hydrides

Similar results for 135 and 300 ºC



Results for the same hydrogen concentration (1200 ppm) and different temperature

Temperature effect as expected:

Same Young's Modulus

Lower Yield Stress at higher Temperature

Displacement for crack initiation always higher than 3 mm

Ductility is not a problem with circumferential hydrides

RCT- Radial Hydrides

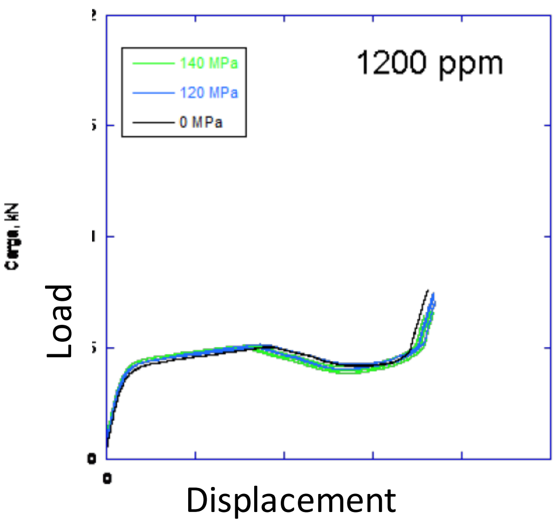
Test Conditions

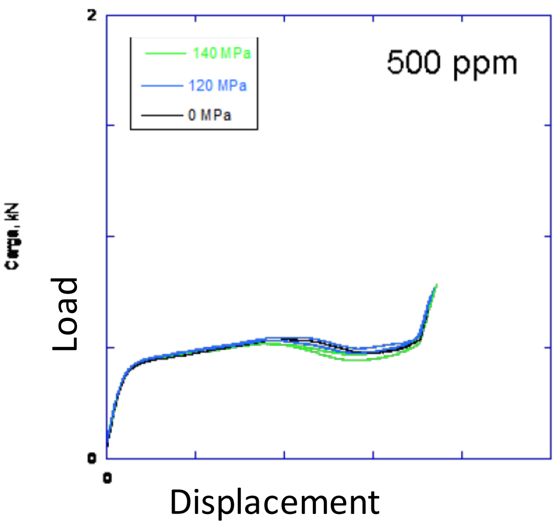
Temperature: 20, 135, 300 ºC

Hydrogen content: 150, 500, 1200 ppm

Reorientation Hoop Stress: 60, 90, 120, 140 MPa

300 ºC





No effect of reoriented hydrides

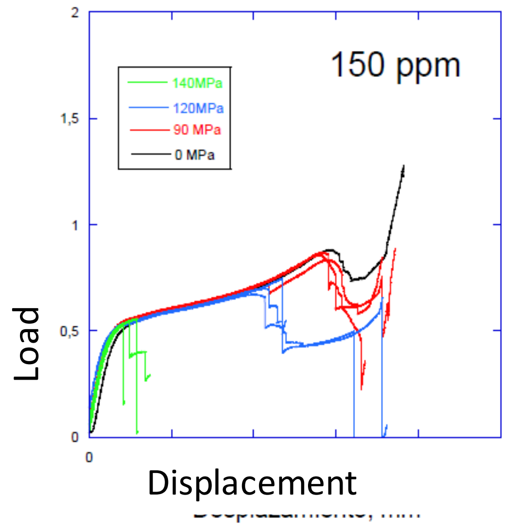
Enough ductility

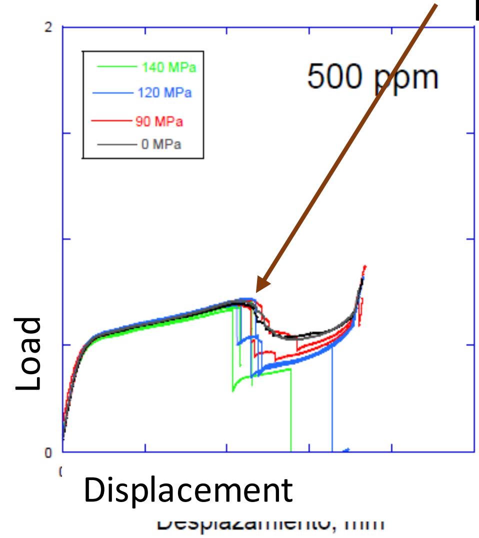
300ºC
DUCTILE BEHAVIOUR

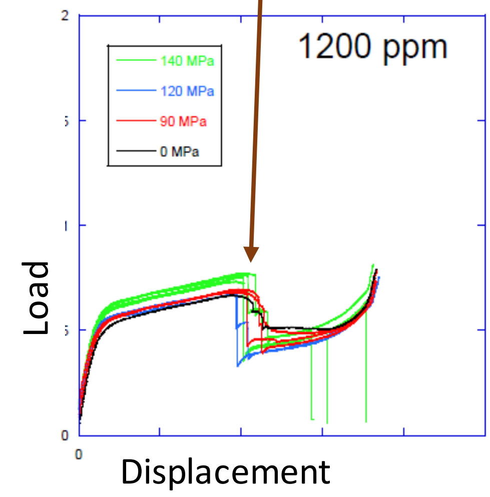
RCT- Radial Hydrides

135 ºC

Enough ductility
Rupture displacement
almost independent of
radial hydrides







150 ppm
Relevant effect of radial hydrides

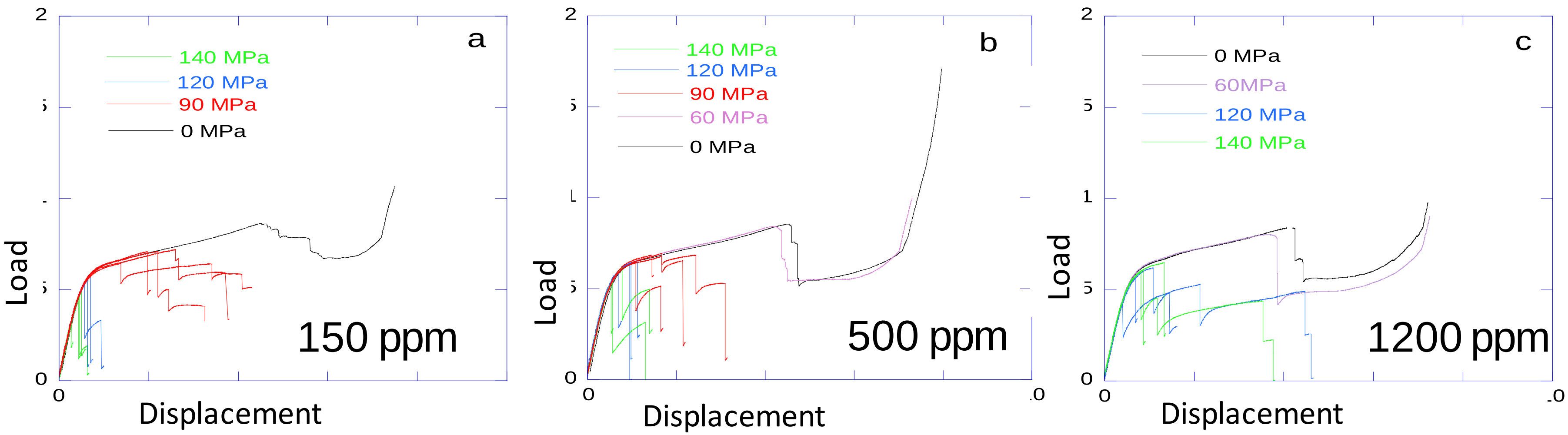
Higher radial effect for lower hydrogen content
Related with Radial-Hydride-Continuity Factor (RHCF) [(2)]

DUCTILE BEHAVIOUR EXCEPT FOR 150PPM AND 140 MPA

(2) M.C. Billone, T.A. Burtseva, R.E. Einzenger, JNM 433 (2013) 431-448

RCT- Radial Hydrides

20 ºC



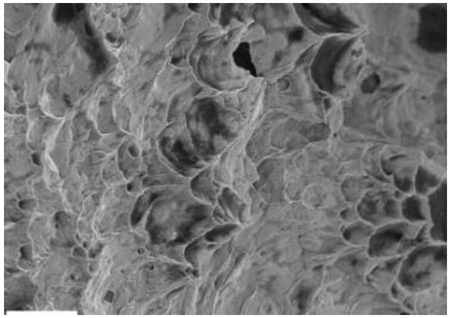
- Important effect of radial hydrides
- Relevant decrease of displacement for failure when radial hydrides increase
- Rupture in elastic zone in some cases for reorientation stresses higher 90 MPa

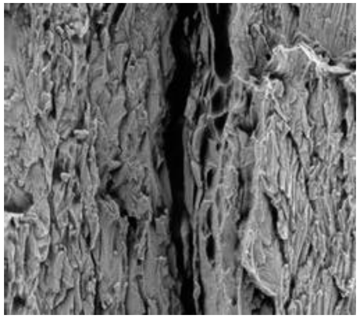
DUCTILE ONLY FOR REORIENTATION HOOP STRESS LOWER THAN 90 MPA

Fractographic analysis

- Scanning Electron Microscopy analysis of fracture surface to identify fracture micromechanism has been performed

ductile





brittle

Failure criteria

- Three different failure criteria based on strain, plastic deformation and Strain Energy Density has been considered.

Conclusions

- CSN, ENRESA & ENUSA have performed R&D projects regarding cladding material behaviour during dry storage and transport
- Samples with embrittlement states similar to irradiated material has obtained
- RCT at temperatures representative of storage and transport have been performed
- Circumferential hydrides: the material is ductile, even for 2000 ppm hydrogen and 20ºC
- For radial hydrides, hydrogen content, reoriented hydride percentage, and temperature are key parameters
- The results are coherent with other authors published data for non irradiated material

Thank you
for
your attention

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