Hydride embrittlement of Zircaloy-4 fuel cladding

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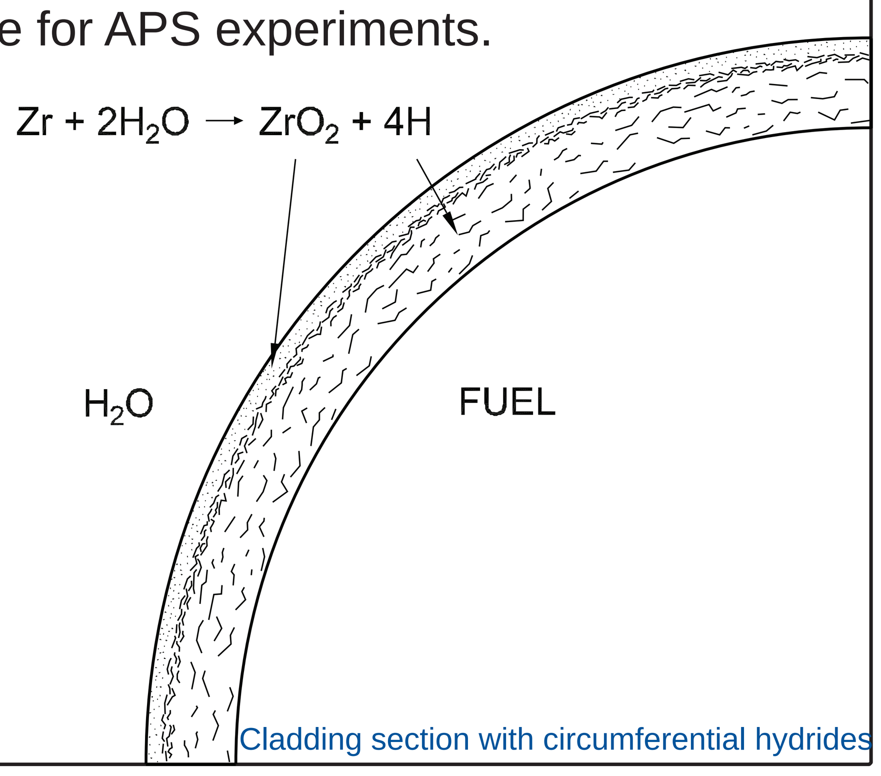
MOTIVATION AND OBJECTIVE

- In a nuclear reactor, Zr alloy fuel cladding is embrittled by the formation of circumferential zirconium hydride platelets. In dry storage of spent fuel, zirconium hydrides may undergo **reorientation** into radial hydrides which further embrittles the cladding.
- Using the Advanced Photon Source (APS) at Argonne National Laboratory, we can learn more about hydride behavior by observing the circumferential-to-radial reorientation of hydrides as it occurs (in-situ).
- Objective of this work: to determine a procedure that ensures the complete reorientation of hydrides in order to prepare for APS experiments.

Advanced Photon Source at ANL



Cladding section with circumferential hydrides

RESULTS AND IMPLICATIONS

- We have reoriented previously circumferential hydrides from an RHC of **4.5%** to a range of RHC varying from **6.7%** to **28.7%**.
- Main result: RHC for different loadings, thermal cycles, and the presence or absence of a 300 ºC cooling temperature plateau.
- **Applied loading** is most important: RHC doubles between the $0.85\sigma_y$ and $0.75\sigma_y$ cases.
- The duration of the **cooling plateau** does not affect RHC.
- To achieve further reorientation, will investigate more cycles at lower temperature, higher hydrogen concentration, and stronger materials.

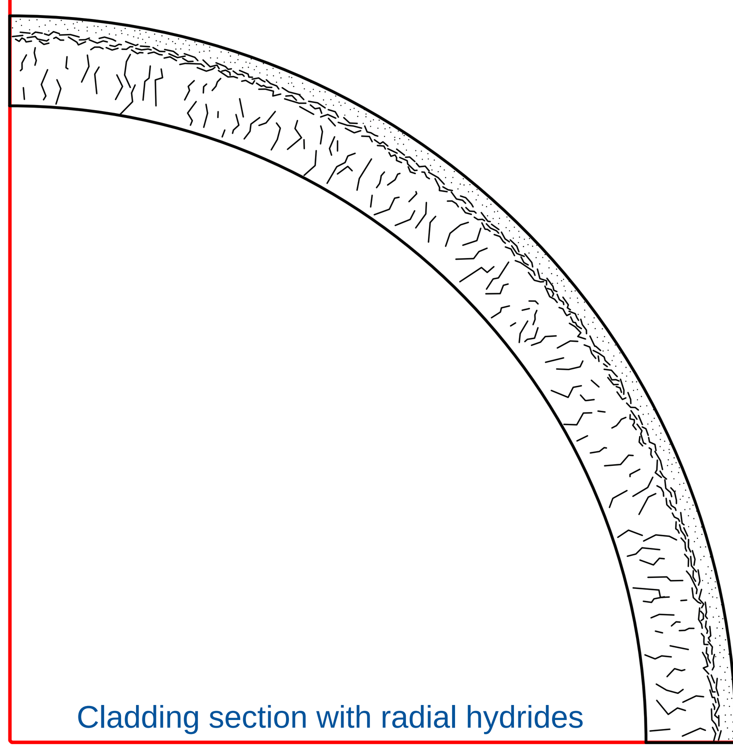
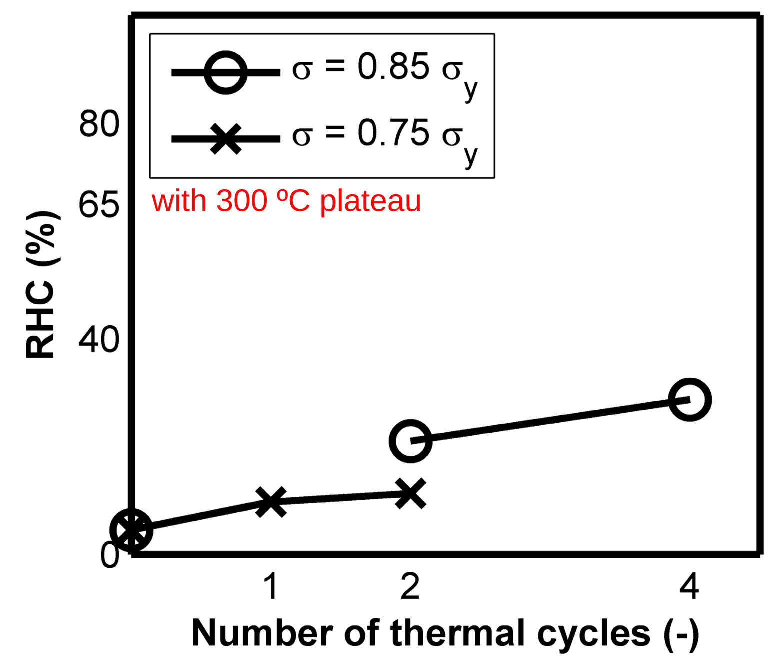

Cladding section with radial hydrides

Fig. 10: RHC vs Loading, Cycling



METHODS AND SAMPLE PREPARATION

Zircaloy-4 sheet samples (recrystallized) are provided by Westinghouse.

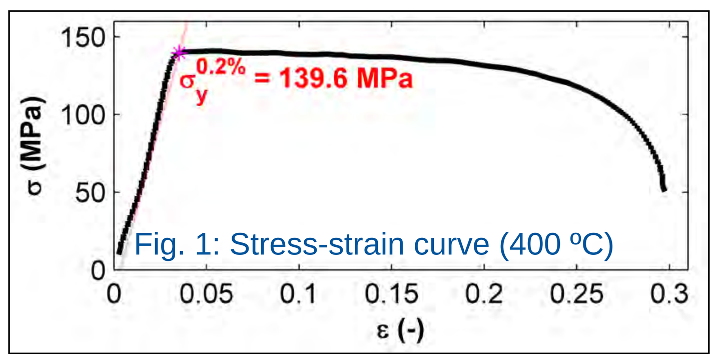


Fig. 1: Stress-strain curve (400 ºC)

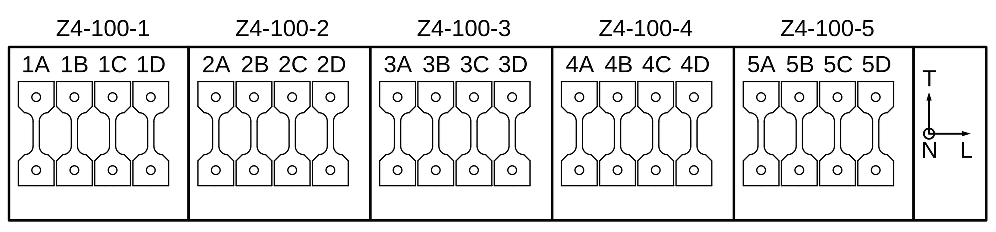


Fig. 2: Zircaloy-4 stock (thickness ≈ 0.5 mm)

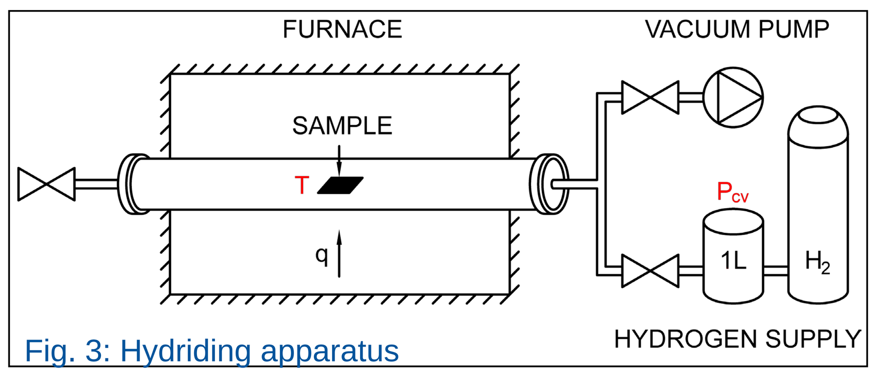


Fig. 3: Hydriding apparatus

Sheet samples are hydrided by gaseous hydriding in a tube furnace.

Hydride platelets are **initially in-plane** (circumferential).

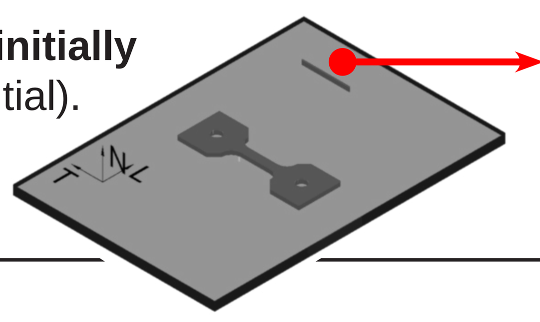
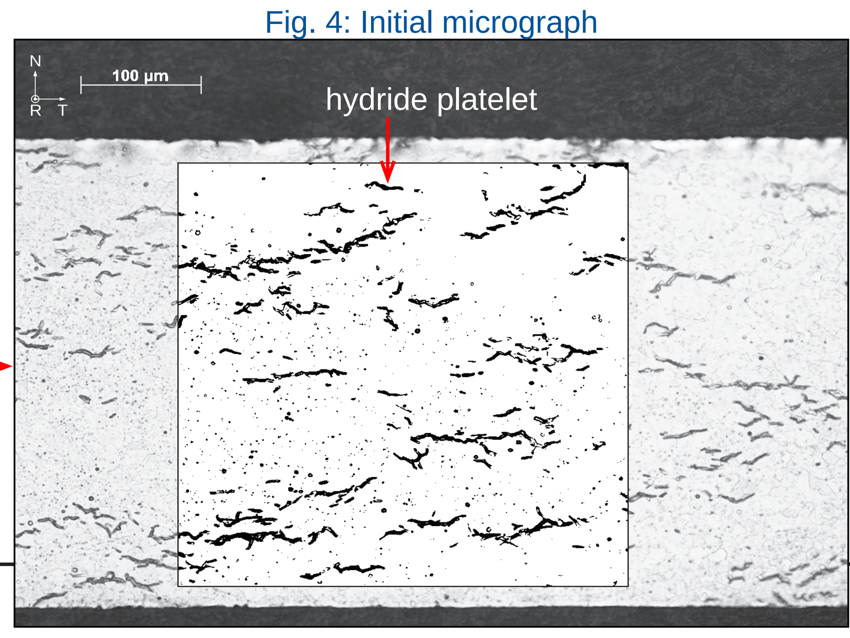


Fig. 4: Initial micrograph



HYDRIDE REORIENTATION

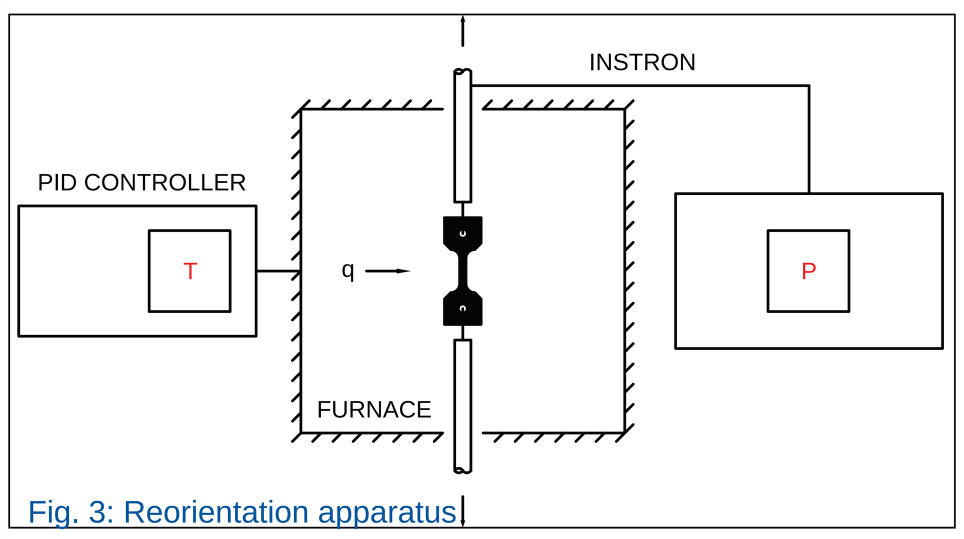


Fig. 3: Reorientation apparatus

Reorientation occurs by cooling under stress. Temperature **T** and axial load **P** can be controlled to reproduce conditions under which hydride reorientation occurs.

Many parameters are explored:
- Hydrogen concentration (approx. 100 wt. ppm)
- Hold temperature (400 ºC)
- Cooling rate (1 ºC/min)

Varied parameters:
- Loading (75% or 85% of σ_y)
- Cooling plateau (2 hrs at 300 ºC)
- Number of thermal cycles (1 to 4+)

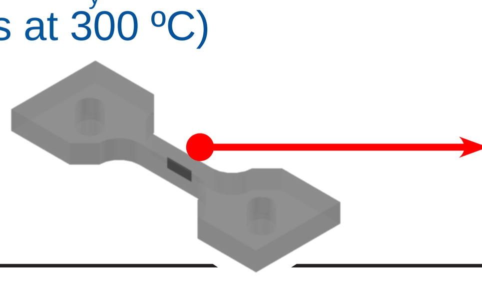
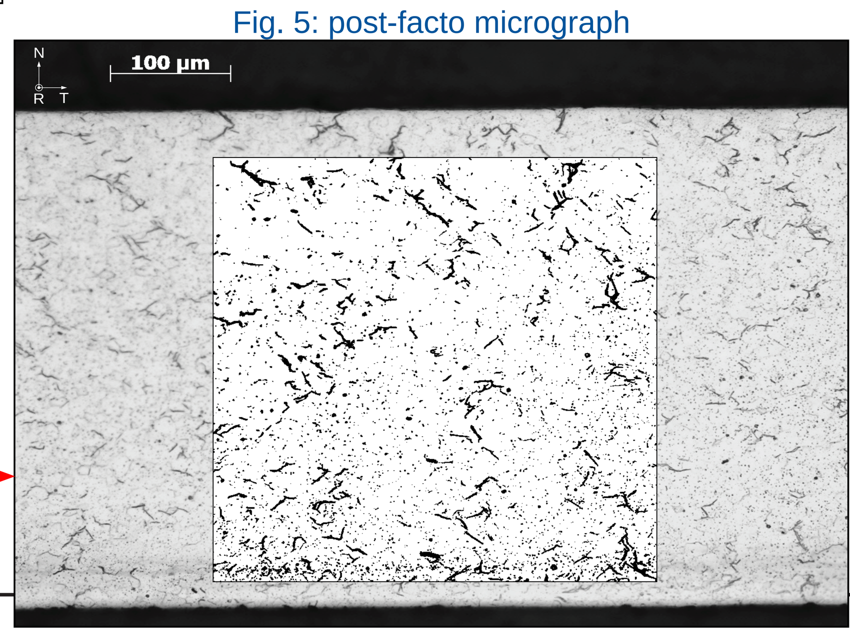


Fig. 5: post-facto micrograph



PROCEDURE DESIGN AND ANALYSIS

- Systematic investigation of the parameters considered is shown by the tree below.
- The orientation of hydrides is quantified by *Radial Hydride Content* (RHC) [1], determined from micrographs. RHC = 80% is desired.

$$RHC = \frac{\sum_i L_i f_i}{\sum_i L_i}$$

Where L_i is the length of hydride i and
f_i = 1 for hydrides between 75 and 90°,
f_i = 1/2 for hydrides between 40° and 65° and
f_i = 0 for hydrides between 0° and 40°.

OHC: out-of-plane, MHC: mixed, IHC: in-plane hydride content

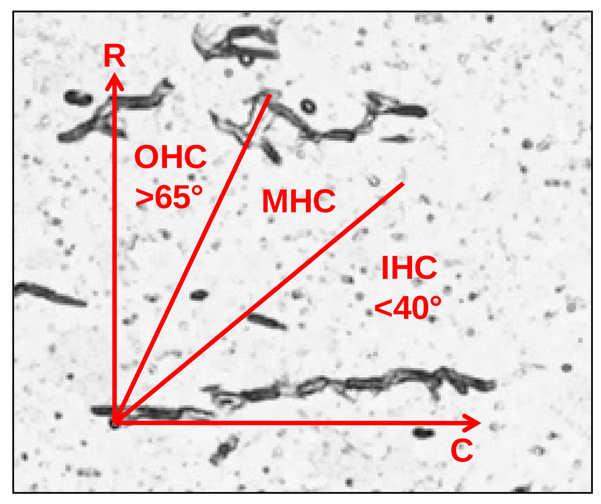
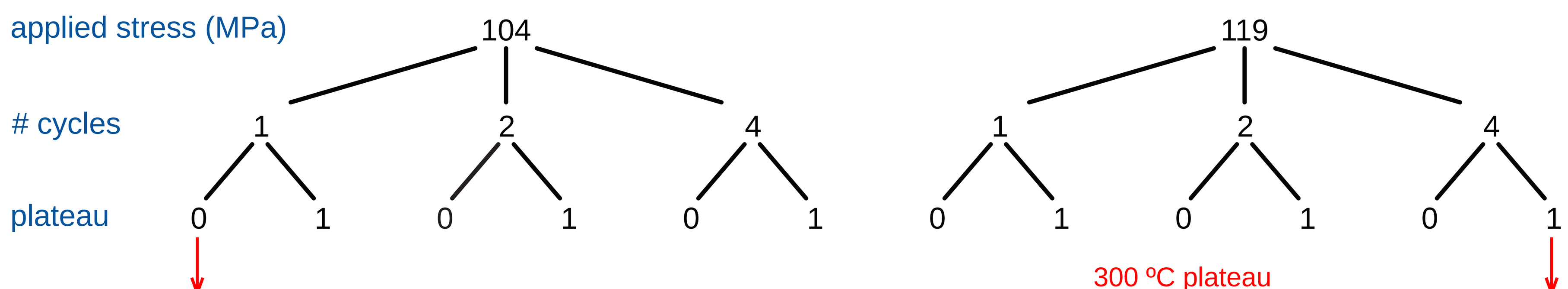


Fig. 6: Hydride classifications.



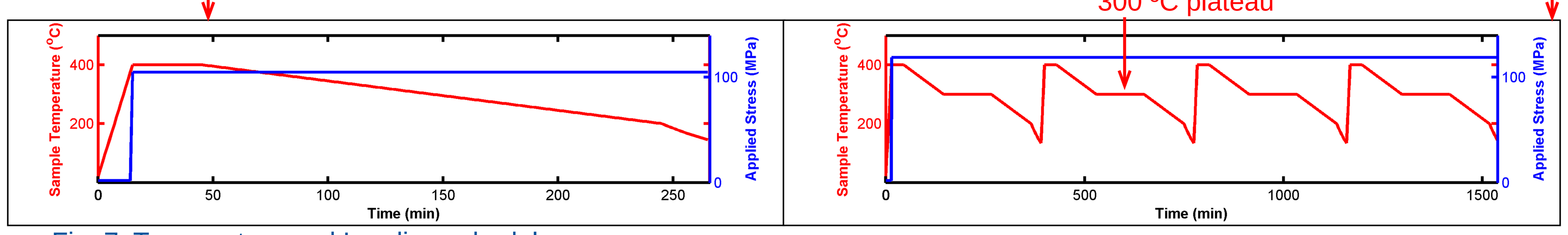


Fig. 7: Temperature and Loading schedules

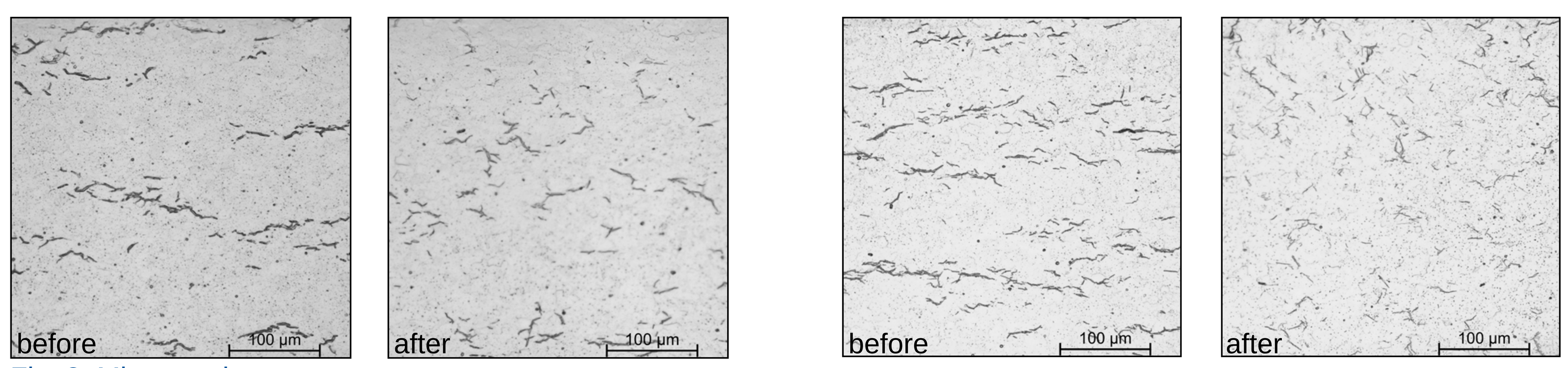


Fig. 8: Micrographs

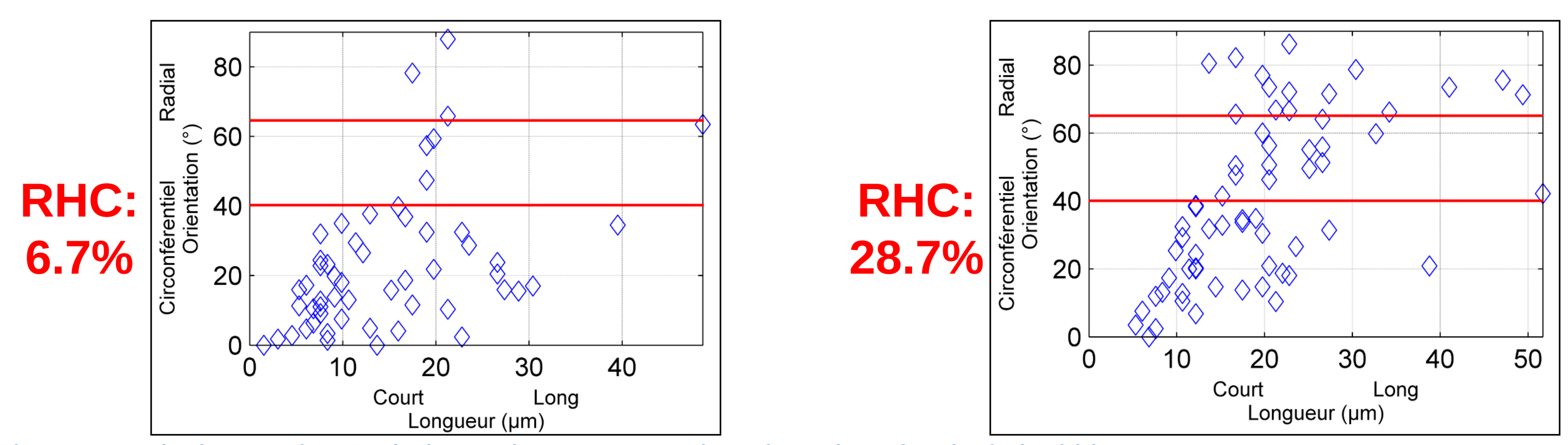


Fig. 9: Quantitative results. Each data point represents the orientation of a single hydride.

These plots of hydride orientation and length are generated by HYDROMORPH from CEA, France.

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[1] P. Raynaud, PhD Thesis, The Pennsylvania State University (2009)

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08 NOVEMBER 2010