Radial Hydrides

Hydride Re-Orientation

- Only hydride that is dissolved and then re-precipitated can potentially “re-orient”
  - Cladding temperature will determine how much hydrogen goes back in solid solution in the Zircaloy matrix (~200 ppm at 400°C)
  - Upon cooling, re-precipitation will begin at a substantially lower temperature (~335°C for 200 ppm)
    - Reference: Hydride dissolution solvus versus hydrogen precipitation solvus [Kammenzind et al., ASTM STP 1295 (1996) pp. 338-370]
  - The potential for re-orientation greatly increases under thermal cycling conditions
    - Slight dependence of hydride dissolution solvus on applied stress and/or preferential dissolution of hydrides

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Hydrogen Solvus as a Function of T

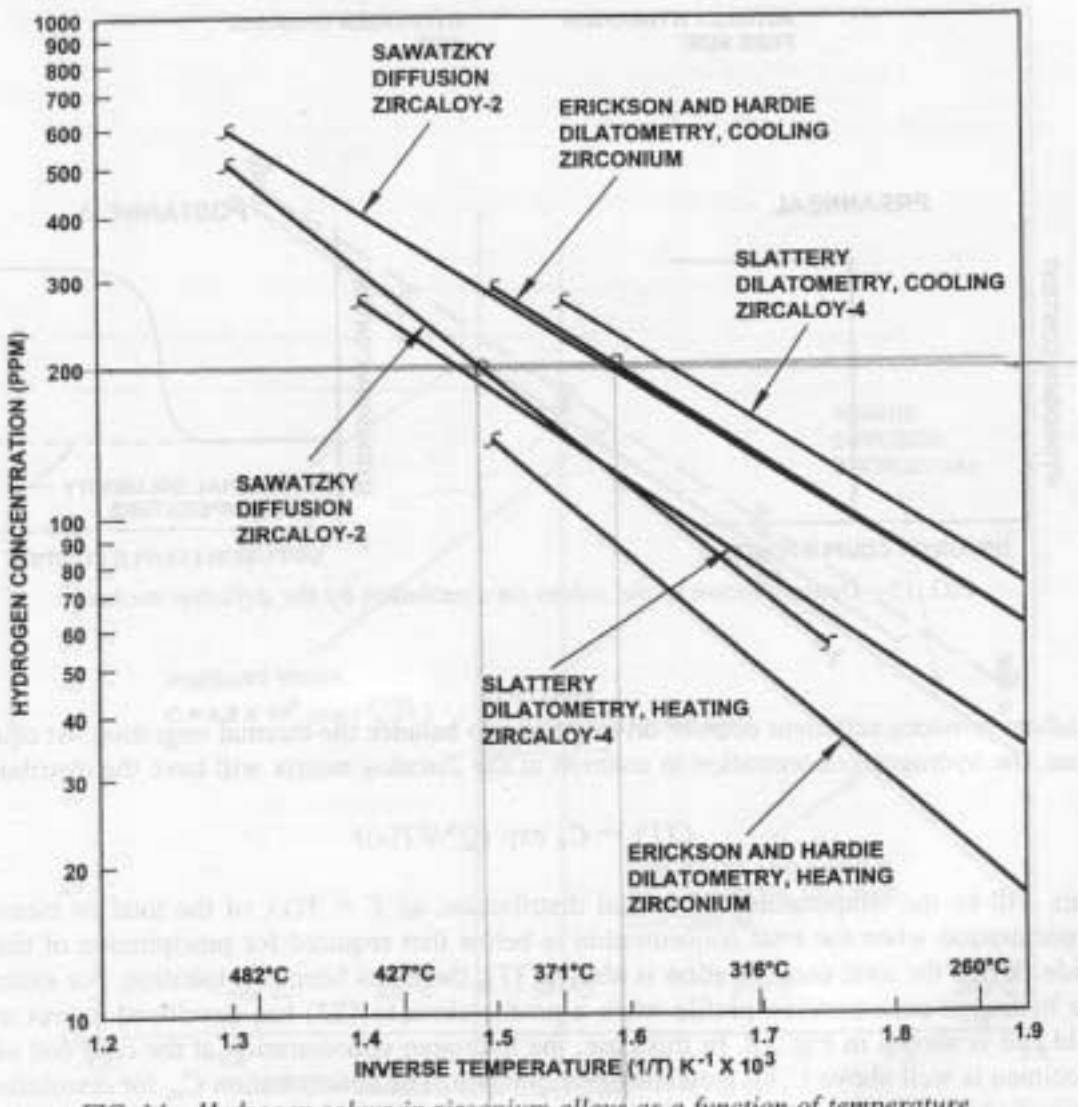

FIG. 14—*Hydrogen solvus in zirconium alloys as a function of temperature.*

Hydride Dissolution Solvus

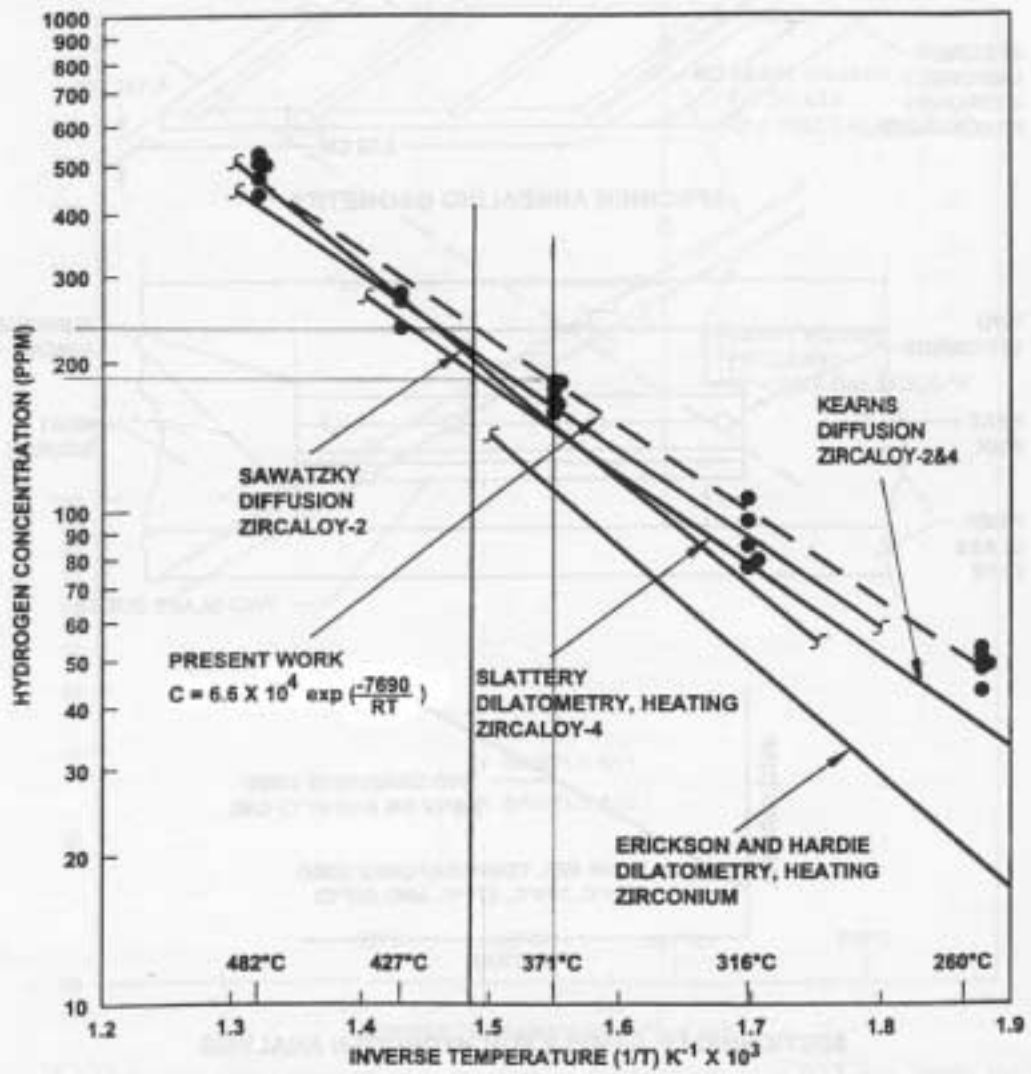

FIG. 16—*Hydride dissolution solvus of zirconium alloys as a function of temperature.*

Hydrogen Precipitation Solvus

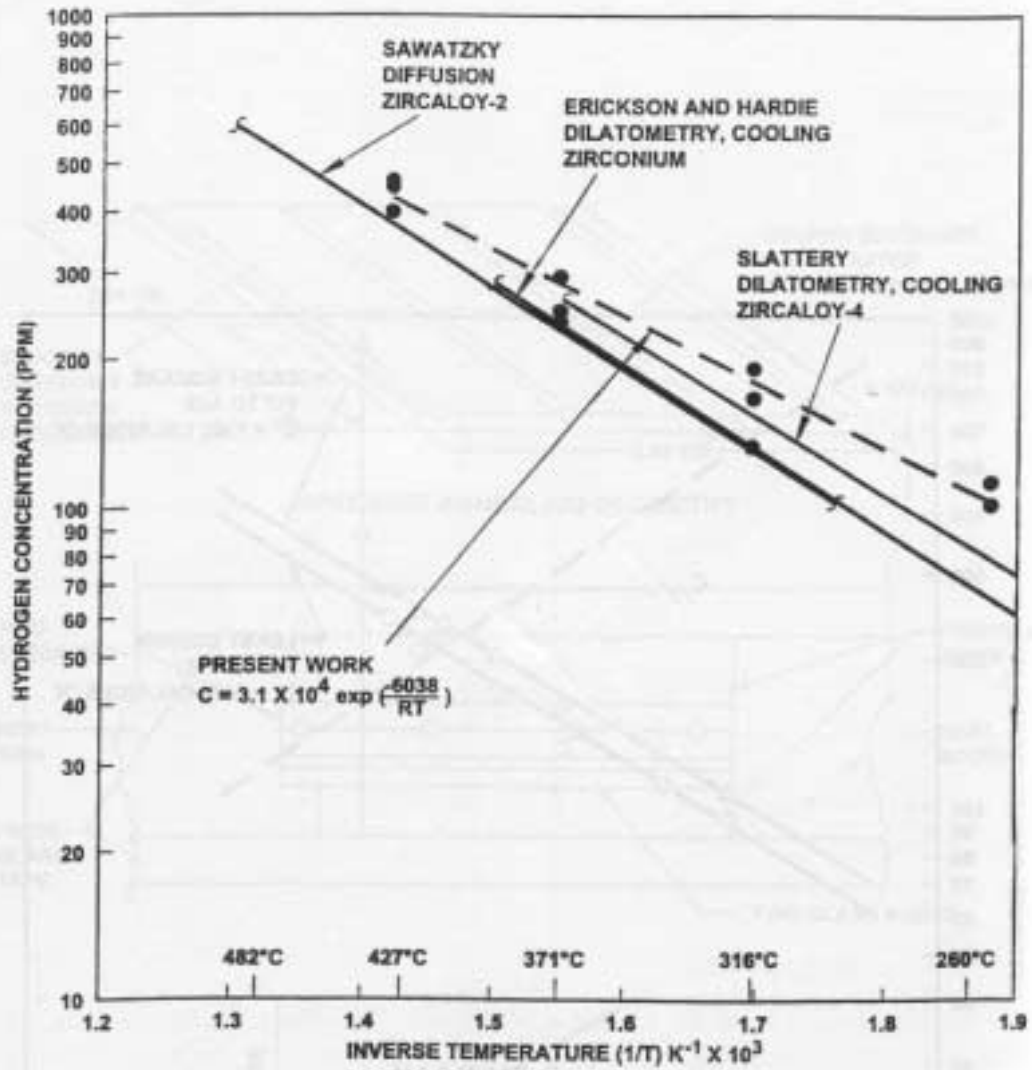

FIG. 19—*Hydrogen precipitation solvus of zirconium alloys as a function of temperature.*

Hydride Re-precipitation

1. Assume heating of fuel cladding to 400°C leading to ~210 ppm of hydrogen going back in solid solution in the Zircaloy matrix

- What is the amount of hydrogen re-precipitated upon cooling?

At 340°C	0 ppm
At 320°C	26 ppm
At 300°C	56 ppm
At 280°C	83 ppm
At 260°C	106 ppm
At 240°C	127 ppm
At 220°C	145 ppm
At 200°C	160 ppm

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Hydride Re-orientation Observations

- The actual extent of re-orientation upon precipitation and the morphology of the re-oriented hydrides are a function of temperature, stress conditions, and material microstructure (texture and grain morphology); cooling rate; and possibly other factors (thermal cycling, complete re-dissolution of hydrides, …)
  - Relative orientation of basal poles (texture) and applied stress
    - Essential criterion for re-orientation: high concentration of basal poles in the directions in which specimens are stressed [D. Hardie and M.W. Shanahan, J. Nuc. Mat. 55 (1975) 1-13]
    - Applied stress at which re-orientation starts to occur (the “threshold stress”) increases with decreasing basal pole concentrations in the applied stress direction
  - Applied stress at which re-orientation starts to occur (the “threshold stress”) increases with decreasing temperature

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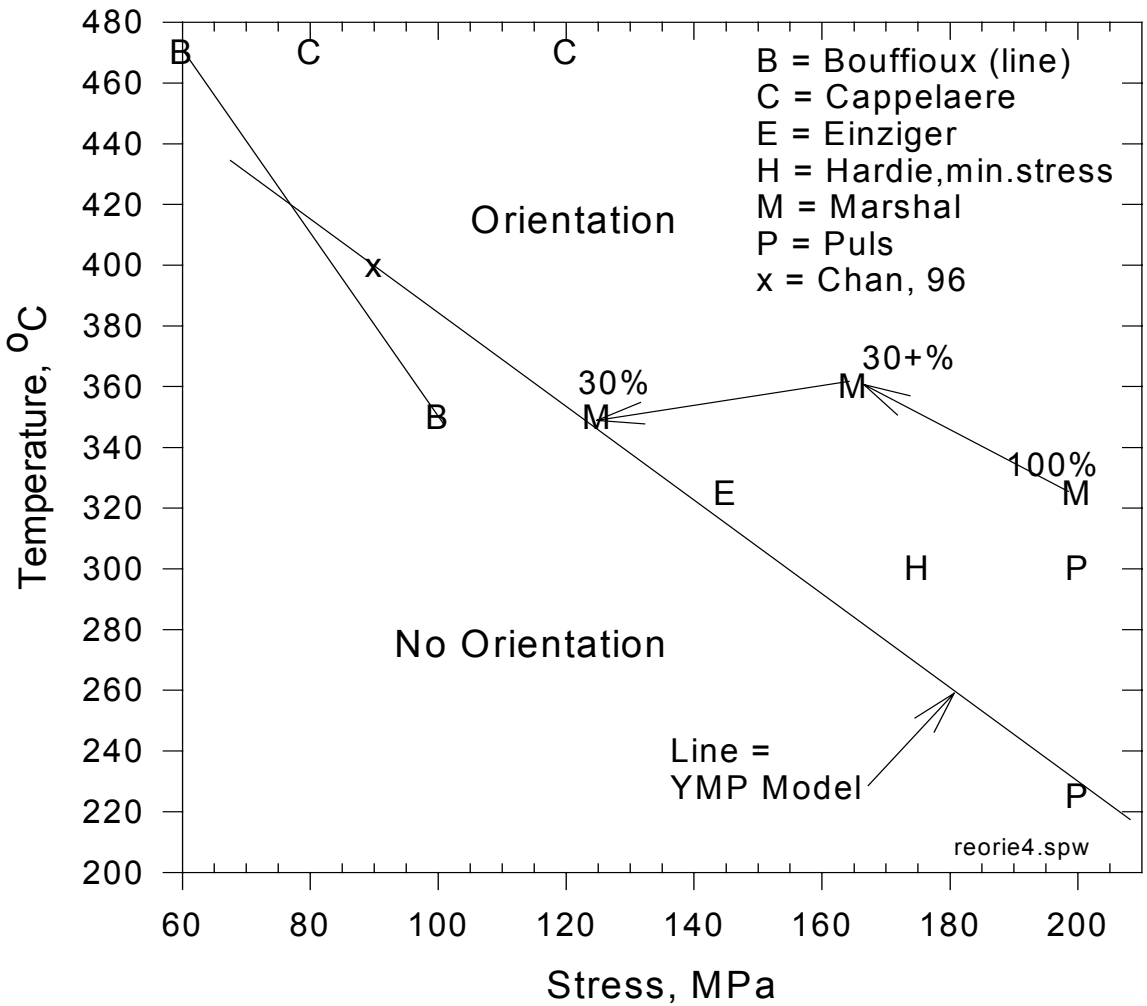
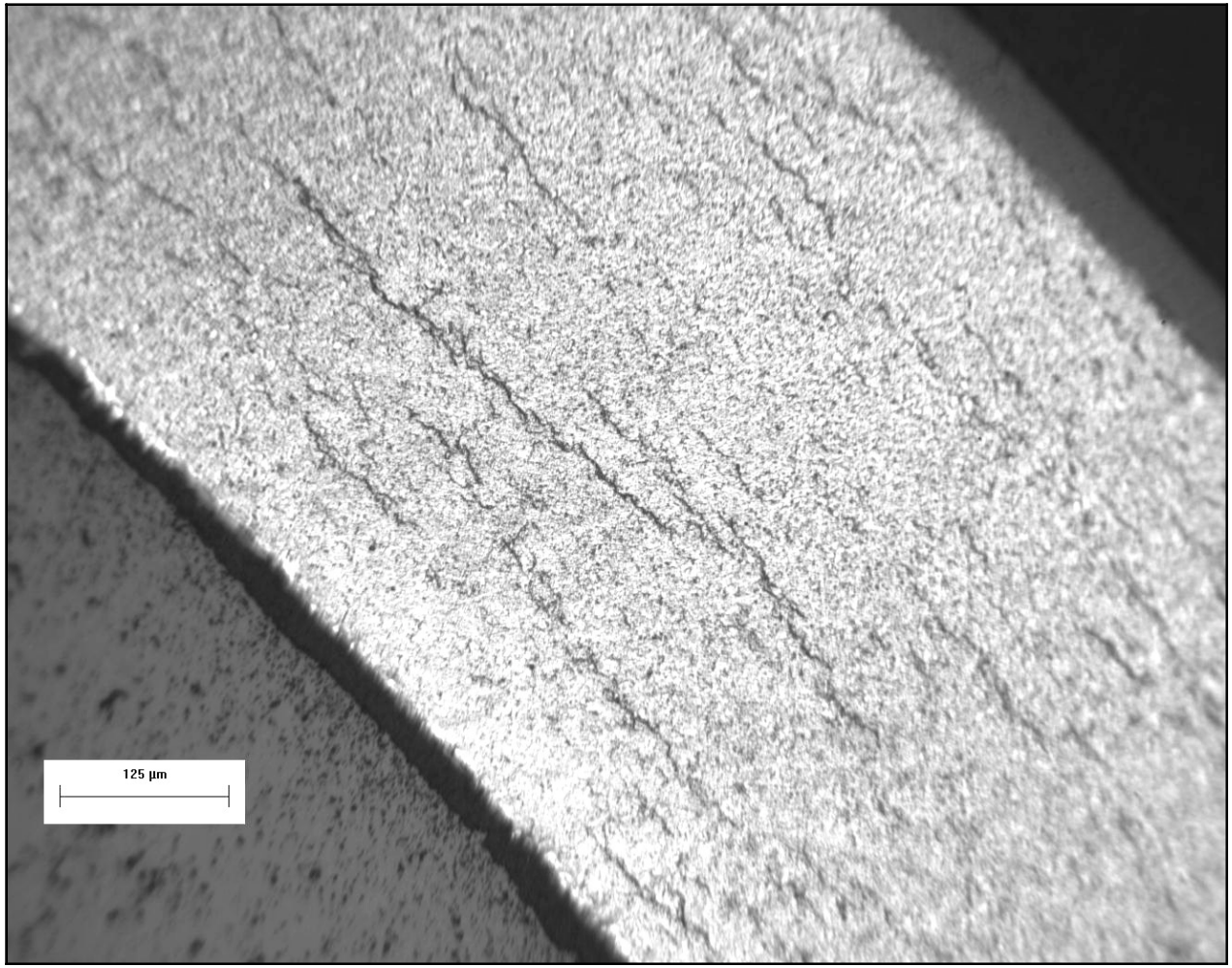
Data for YMP Reorientation Model



Courtesy of Eric Siegmann (YMP)

Hydride Orientation (ANL Program)



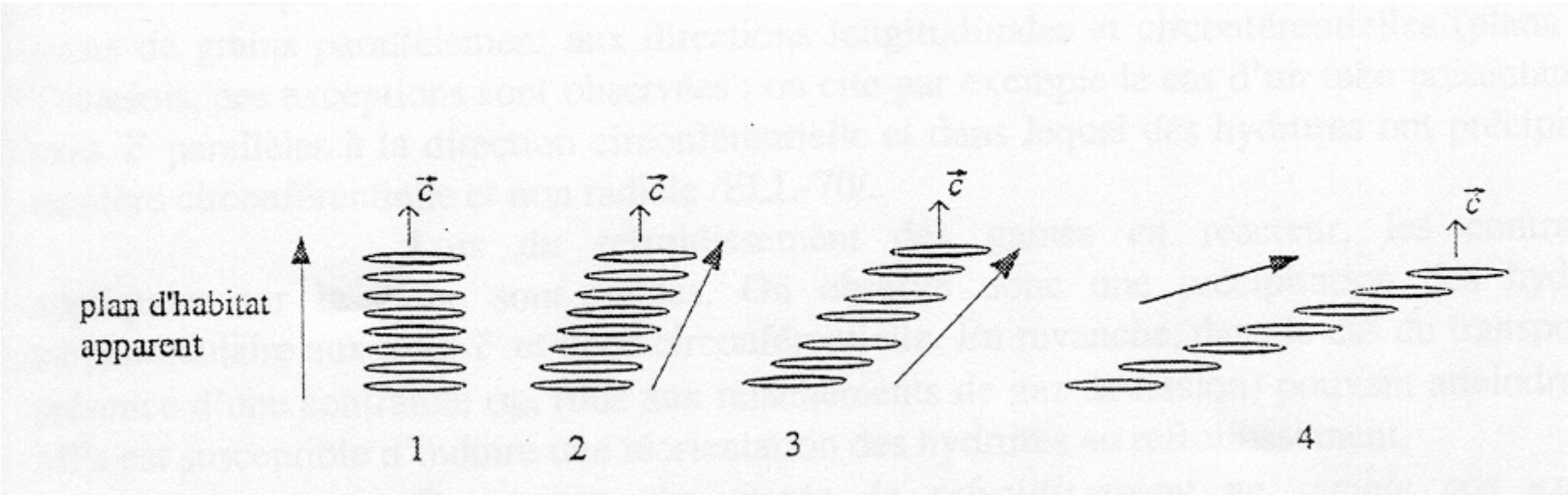
Hydrogen content:

248±35 ppm

T_{max}: ~415°C

Initial Hoop Stress:
~63 MPa

Microscopic Vs. Macroscopic Hydrides



Effect of "Q" Ratio on Texture

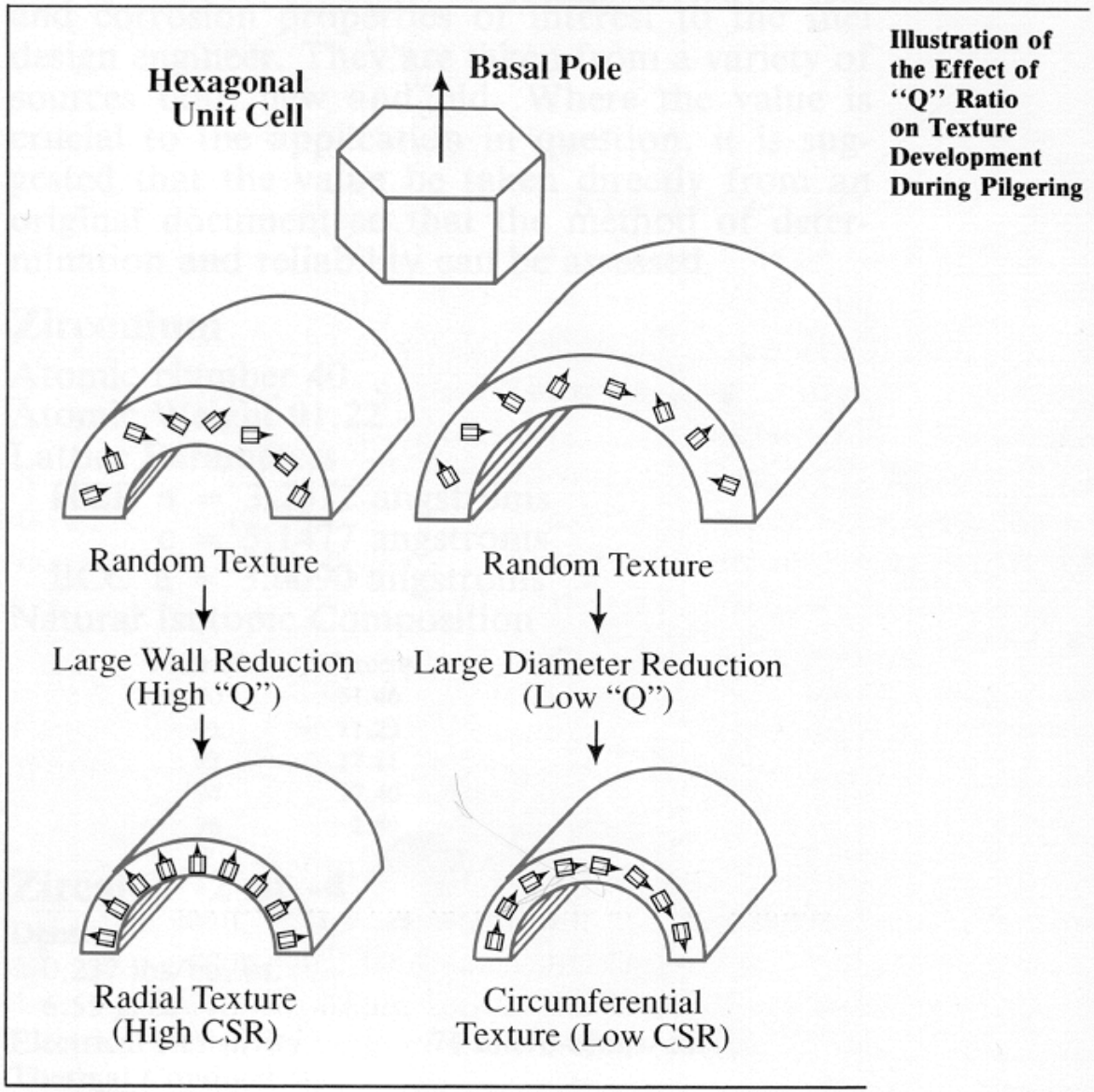
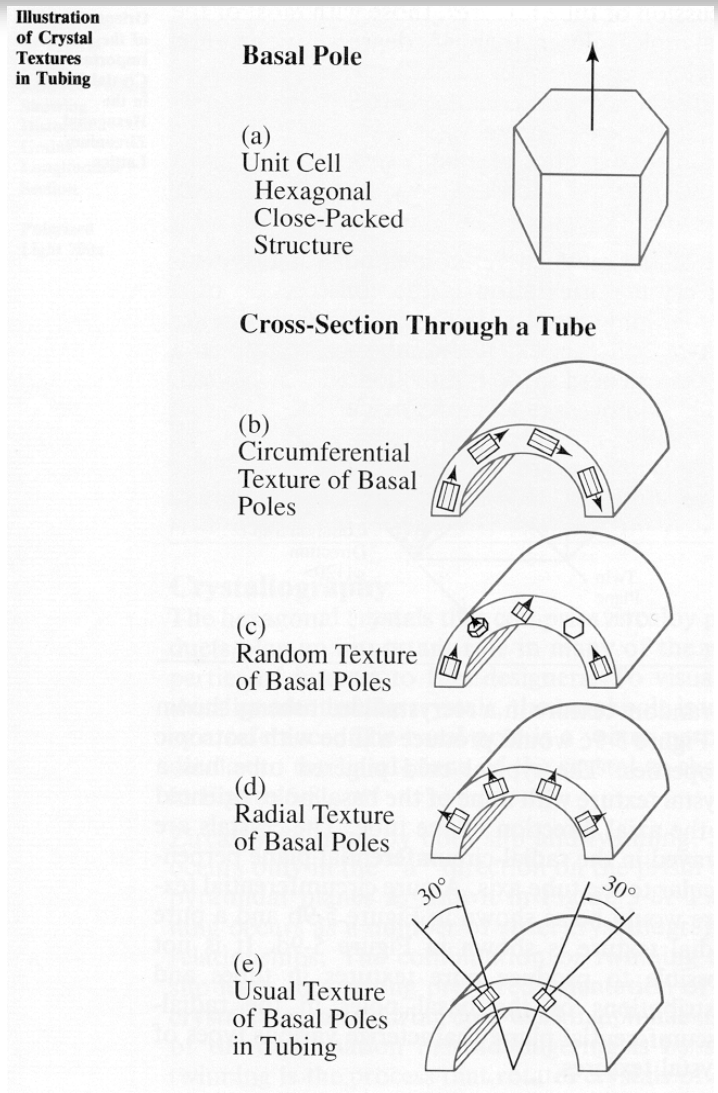
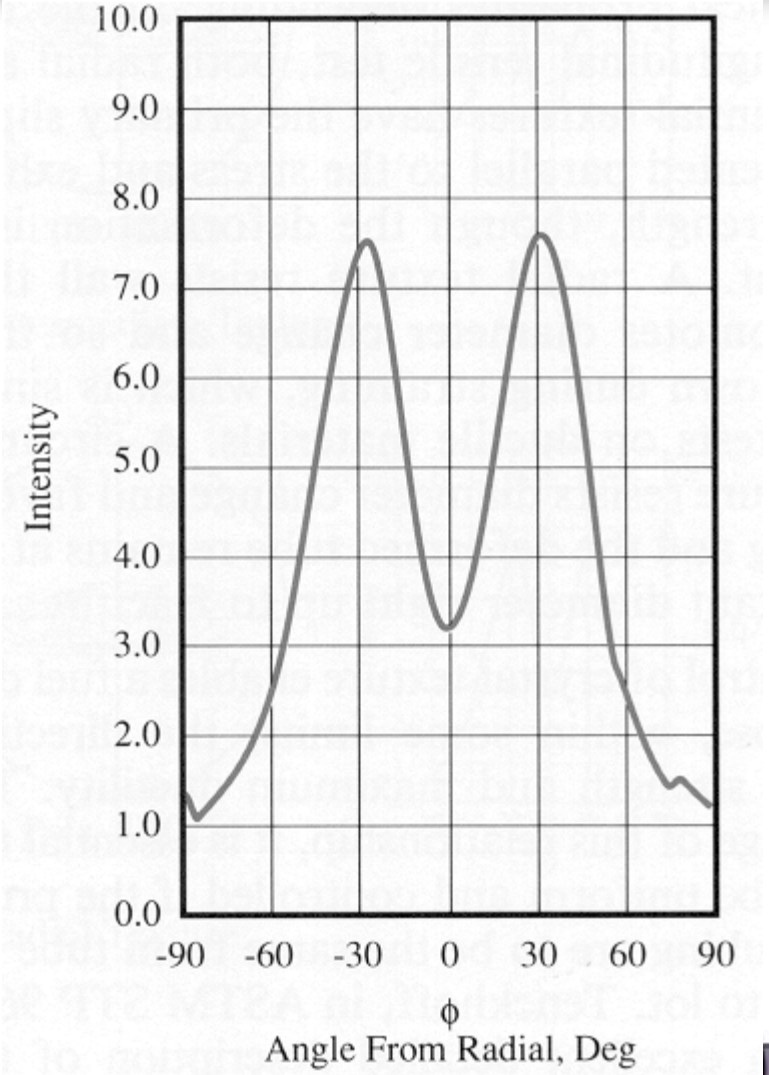


Illustration of the Effect of "Q" Ratio on Texture Development During Pilgering

Courtesy of J.Schemel

Tubing Texture

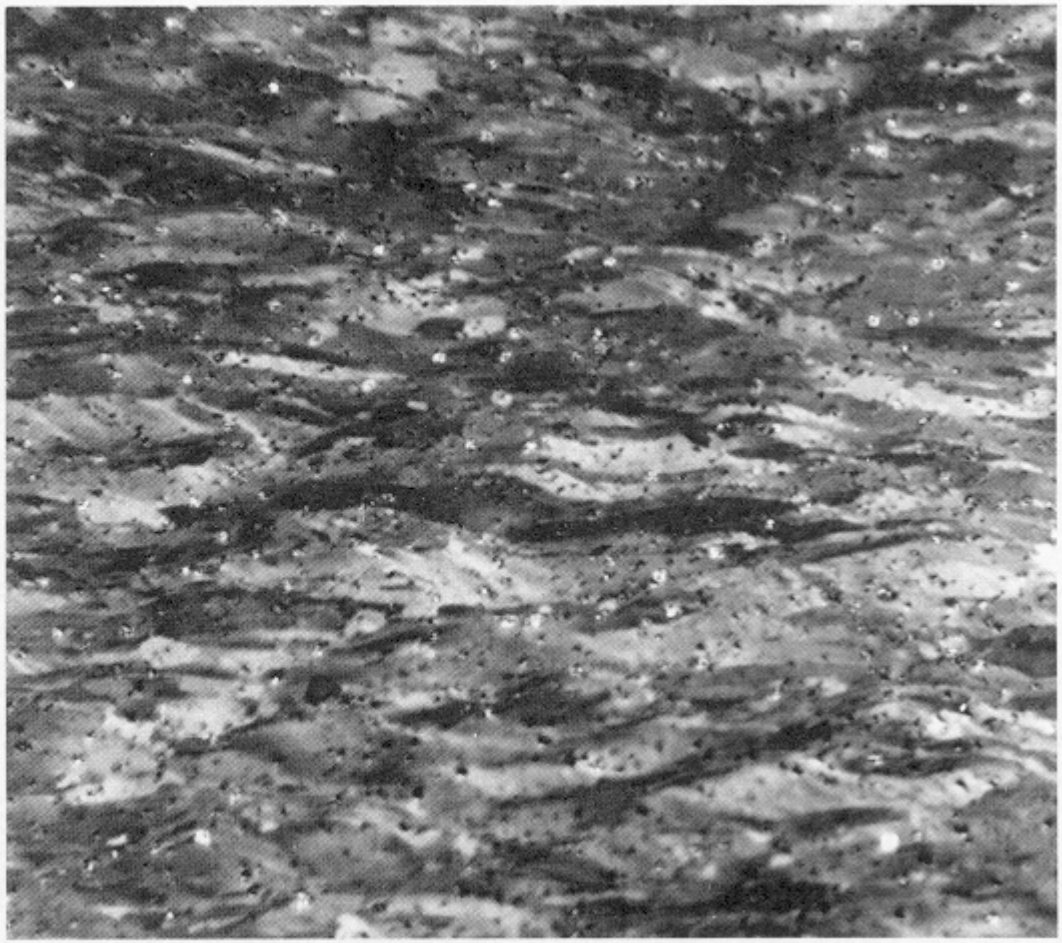




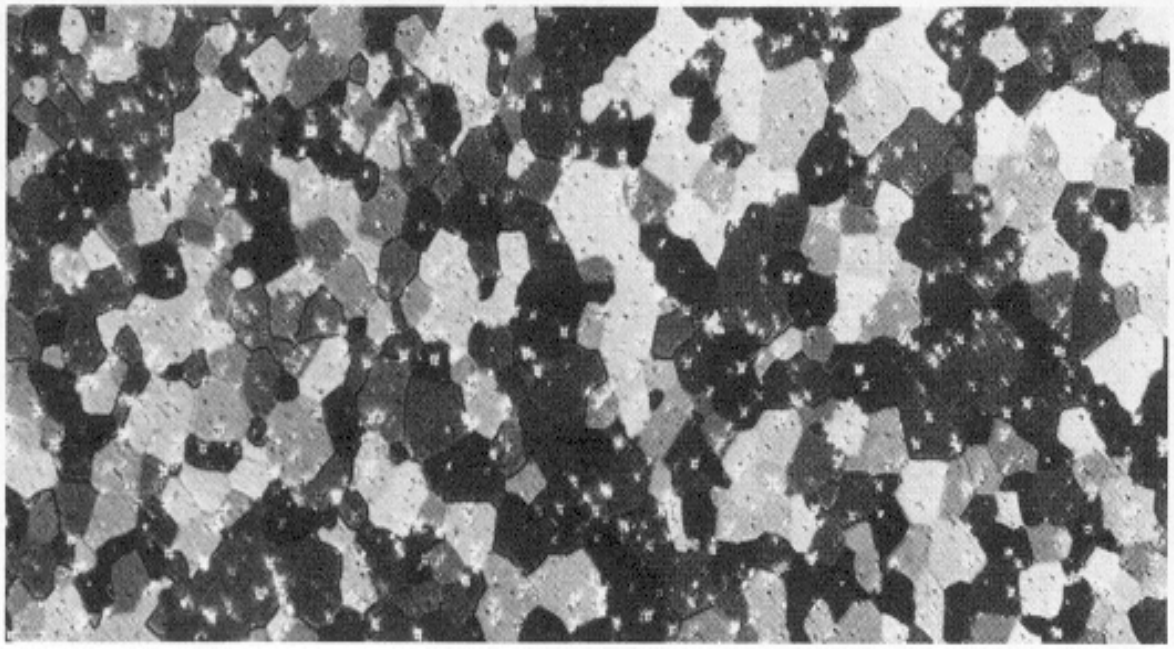
Stress Relieved Tubing

Micrograph of Typical Stress Relieved Tubing Showing Distorted Grains Longitudinal Section

Polarized Light 700x



Recrystallized Tubing



Micrograph of Typical Recrystallized Tubing Showing Equiaxed Grain Structure and Uniform Distribution of Intermetallic Compound Particles

Polarized Light 700x

PWR Spent Fuel Characteristics

- Favorable texture and grain morphology to start with:
  - Radial texture is dominant
  - Elongated grain size in stress-relieved tubing and residual fabrication stresses favor hydride platelets nucleation and formation in the circumferential direction
- To minimize potential[&] for hydride re-orientation:
  - Limit peak temperature to minimize hoop stress and amount of hydrogen available to re-orientation
  - Preserve original microstructure as much as possible by maintaining short-term peak cladding temperatures below temperature range where residual cold work recovery and recrystallization start to occur (For example, 470°C/with ~250-ppm hydrogen according to French work]
  - Avoid repeated thermal cycling (ΔT >>~65°C)

[&] Does not prejudge how much re-orientation is acceptable

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Regulatory Requirements

Regulatory Requirements

- The RAI states "… ability of the storage system *to meet the regulatory requirements* …" during hypothetical accidents
- In the preamble to the questions, reference is made to:
  - §72.124 (nuclear criticality safety); $72.128(a) (general criteria for ensuring adequate safety)
  - §72.104, §72.122(h)(1), §72.122 (l), and §72.236(m)
  - §72.106 (maximum dose to any individual located on the nearest boundary of the controlled area from a design basis accident)

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Regulatory Requirements (cont.'d)

- For normal and anticipated occurrences, the focus is on the "mechanical integrity" of the spent fuel elements during storage (including loading, drying, transfer to the pad), any subsequent handling, shipment, unloading, etc.
  - §72.104 (dose limits)
  - §72.122(h)(1) (prevention of gross degradation)
  - §72.122 (l) (retrievability)
  - §72.236(m) (compatibility with removal of the stored spent fuel from the reactor site, transportation, and disposal)

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Regulatory Requirements (cont.'d)

- For hypothetical accident conditions, the focus is on the "mechanical integrity" of the confinement boundary
- Spent fuel behavior is relevant only when fuel reconfiguration resulting from the accident could impact the integrity of the confinement boundary
- Therefore, if it can be determined that for a specific design, fuel reconfiguration does not represent a threat to the confinement boundary, there should be no regulatory-driven need for calculating spent fuel behavior during hypothetical accident conditions

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Regulatory Requirements (cont.'d)

- §72.106 (b)
  - "Any individual located on or beyond the nearest boundary of the controlled area may not receive from any design basis accident the more limiting of a total effective dose equivalent of 0.05 Sv, …"
- From ISG-3:
  - "The accident analysis chapters should be re-written to require that the Staff evaluate all credible accidents and focus the review on those accidents with potential consequences resulting in the failure of the confinement boundary. Upon identification, the event shall be evaluated against the requirements of 10 CFR 72.106 and 72.122(b)."

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