R&D Insights and Perspectives on Storage and Transportation of High Burnup Fuel

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Potential Used Fuel Degradation Mechanisms Under Inert, Dry Storage Conditions

- Pre-1999
  - Diffusion-controlled Cavity Growth (DCCG)
- Post-1999
  - Thermal Creep
  - (Stress Corrosion Cracking)
  - (Delayed Hydride Cracking)
  - Hydride Re-orientation
- Regulatory Guidance Milestones
  - Associated with revisions of Interim Staff Guidance 11

K. A. Gruss et al.: "U.S. Nuclear Regulatory Commission Acceptance Criteria and Cladding Considerations for the Dry Storage of Spent Fuel" TOPFUEL Meeting, Wurzburg , Germany (2003)

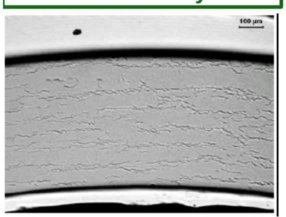
- ***"**... Based on these conclusions, the NRC staff has reasonable assurance that creep under normal conditions of storage will not cause gross rupture of the cladding and that the geometric configuration of the spent fuel will be preserved, provided that the maximum cladding temperature does not exceed 400°C (752°F). As discussed below, **this temperature will also limit the amount of radially oriented hydrides that may form under normal conditions of storage ..."***

ISG-11, Rev. 3 (November 2003)

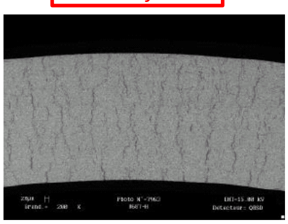
- Based on understanding of hydride re-orientation phenomena circa 2000
  - Storage
    - Burnup covered by commercial fuel license (up to 62 GWd/MTU rod average)
  - Transportation
    - Not addressed
    - Uncertain impact of hydride re-orientation
- Motivation for R&D Projects conducted to this day
  - ANL, JNES, NFIR
    - Better understanding of re-orientation phenomena

Hydride Re-orientation

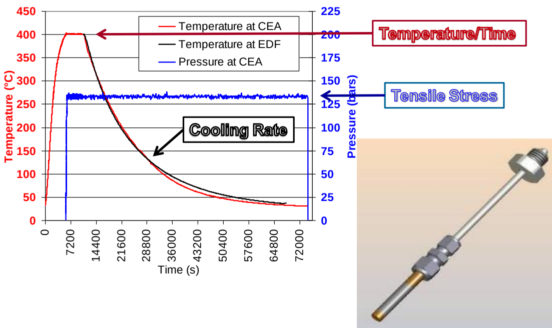
Circumferential Hydrides



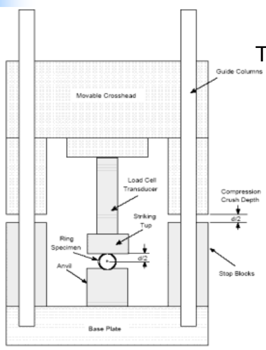
Radial Hydrides



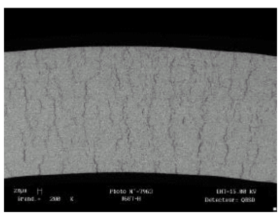
Laboratory Conditions



Laboratory Testing



Testing in the pinching mode



Ring Tensile Testing

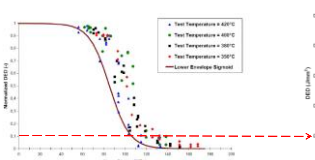


Figure 12 : Ductile to brittle transition observed on unirradiated hydrided Zirlo™ ring tensile specimens tested at ambient temperature as function of the treatment stress and temperature [14]. Normalized DED is the ratio between post treatment DED and initial DED, which is around 0.6 J/mm²

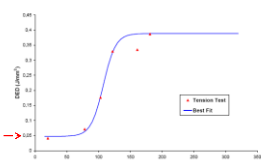


Figure 11 – Zirlo™ : DED best fit by sigmoid function

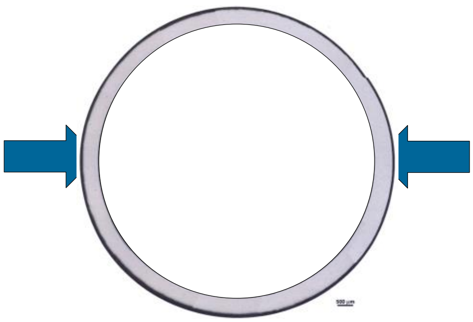
From "High ductility" to "Low Ductility" Room Temperature Testing

Back to "High ductility" By Increasing Testing Temperature

R&D Observations in the Context of Field Conditions

- R&D Results
  - Zirconium-based claddings do not behave identically
  - Hydride re-orientation is mitigated, or even completely prevented, due to field conditions:
    - End-of-Life internal rod pressures
    - Role of plenum temperature
    - Decreasing hoop stress due to decreasing temperature
  - Hydride re-orientation is enhanced by
    - Unusual wear (fretting) of defects (true cracks)
  - Testing on empty tubes likely represent a worst-case situation
    - Bonding between cladding and fuel → Composite mat'l

Fueled vs. Defueled Rods



Perspectives on Regulatory Treatment

- Storage: no change
  - Gross degradation can be ruled out
    - Stored mechanical energy is too low (~200 J)
  - Needed
    - Confirmatory demo project
- Transportation
  - From shutdown sites
    - Spent fuel stored in canisterized systems
    - Risk information
  - From operating plants
    - Spent fuel stored in pools
    - Emphasis on normal conditions of transport

Selected EPRI Publicly Available References

- *Transportation of Commercial Spent Nuclear Fuel – Regulatory Issues Resolution*, Report 1016637 (December 2010)
  - Also presented (and published) at the 16th Int'l Symposium on the Packaging and Transport of Radioactive Materials (3-8 October 2010)
- *Criticality Risks During Transportation of Spent Nuclear Fuel – Revision 1*, Report 1016635 (December 2008)
  - Also published in "Packaging, Transport, Storage & Security of Radioactive Material" Volume 21, No. 1, 2010, pp. 51-61
- *Spent Fuel Transport Applications – Assessment of Cladding Performance: A Synthesis Report,* Report 1015048 (December 2007)

Selected Publicly Available EPRI References
(continued)

- *Spent-fuel Transportation Applications – Modeling of Spent-fuel Rod Transverse Tearing and Rod Breakage Resulting from Transportation Accident*, Report 1013447 (October 2006)
- *Spent-fuel Transportation Applications – Longitudinal Tearing Resulting from Transportation Accidents*, Report 1013448 (December 2006)
- *Spent-fuel Transportation Applications – Assessment of Cladding Performance: A Synthesis Report*, Report 1015048 (December 2007)
- *The CASTOR-V/21 Spent-fuel Storage Cask: Testing and Analyses,* Report NP-4887 (November 1986)

Selected Publicly Available EPRI References
(continued)

- *Spent-fuel Transportation Applications – Normal Conditions of Transport*, Report 1015049 (June 2007)
  - Also presented (and published) at the IAEA International Conference on Spent Fuel Management (May 29-June 4, 2010)
- *Fuel Relocation Effects for Transportation Packages*, Report 1015050 (June 2007)
  - Also published in Nuclear Technology, Vol. 179, pp. 180-188 (August 2012)

These reports (as well as several others) can be downloaded free of charge from:
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001022909

in which "abcdefg" is the EPRI Report number

Restricted Distribution

- Technical Report 1019097 "*Hydride Reorientation Studies – Part 1: Unirradiated Zirconium Alloy Cladding*" (March 2010)
- Technical Report 1025199 "*Hydride Reorientation Studies – Part 2: Irradiated Zirconium Alloy Cladding*" (August 2012)

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