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# High-Burnup – 10 Years Later

**Albert Machiels**
Senior Technical Executive

**Used Fuel and HLW Management Technical Advisory Committee**
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# Contents

- Introduction
  - 10 Years Ago: ISG-11, Rev. 2
  - 1 Year Ago: November 1, 2011 Technical Exchange
- R&D and Other Topics
  - De-fueled Cladding Testing (Hydride Re-orientation)
  - Fuel-Cladding Bonding
  - Inner Liner (Zircaloy-2)
  - Internal Rod Pressure (PWR)
  - Plenum Temperature
- Dry Storage
- Transportation
  - Accident conditions
  - Normal Conditions
- Conclusion
  - Where should we invest in R&D?



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# Introduction

# 10 Years Ago

- July 31, 2002: Publication of Spent Fuel Project Office Interim Staff Guidance - 11, Revision 2 *Cladding Considerations for the Transportation and Storage of Spent Fuel*
  - Acceptance criteria
    - Peak cladding temperatures ≤ 400°C
    - Thermal cycling: $\Delta T \leq 65°C$
    - No 1% limit on thermal creep strain
    - Limited to dry storage (not transportation)
- *Dry Storage of High-burnup Spent Fuel – Responses to Nuclear Regulatory Commission Requests for Additional Information and Clarification,* Report 1009276 (November 2003) http://mydocs.epri.com/docs/public/000000000001009276.pdf
  - Documentation of NRC-Industry Interactions (RAIs, presentations, letter)

## From: K. A. Gruss, C. L. Brown, M. W. Hodges, U.S. Nuclear Regulatory Commission Acceptance Criteria and Cladding Considerations for the Dry Storage of Spent Fuel, TOPFUEL Meeting, Wurzburg , Germany (2003)

- *"In general, these data and analyses support the conclusions that: (1) deformation caused by creep will proceed slowly over time and will decrease the rod pressure; (2) the decreasing cladding temperature also decreases the hoop stress, and this too will slow the creep rate so that during later stages of dry storage, further creep deformation will become exceedingly small; and (3) in the unlikely event that a breach of the cladding due to creep occurs, it is believed that this will not result in gross rupture. 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."*

# Conclusion from November 1, 2011 Technical Information Exchange [Topic: "Cladding"]

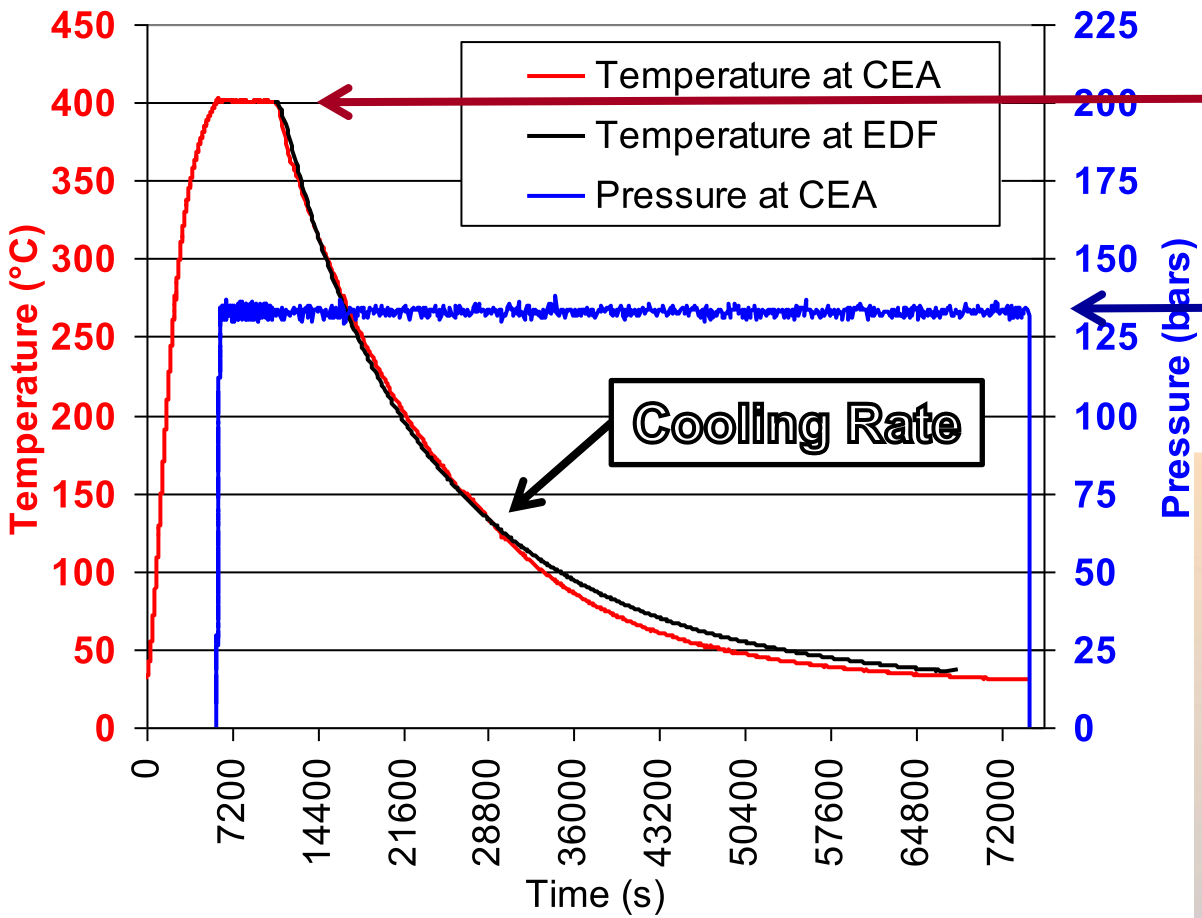
- Dry storage and especially transportation are drivers for extending the scope of work associated with high-burnup fuel, particularly with regard to cladding performance
  - Effects of neutron fluence and hydrogen/hydride contents
- Much R&D work has been performed over the past decade, especially with regard to:
  - Thermal creep
  - Hydride re-orientation
- R&D work will continue especially in concert with introduction of new cladding materials
- *Key question: Given what we learned, how does that knowledge support existing –or coming up with new– regulatory guidance?*

# Conclusion from November 1, 2011 Technical Information Exchange [Topic: “Reconfiguration”]

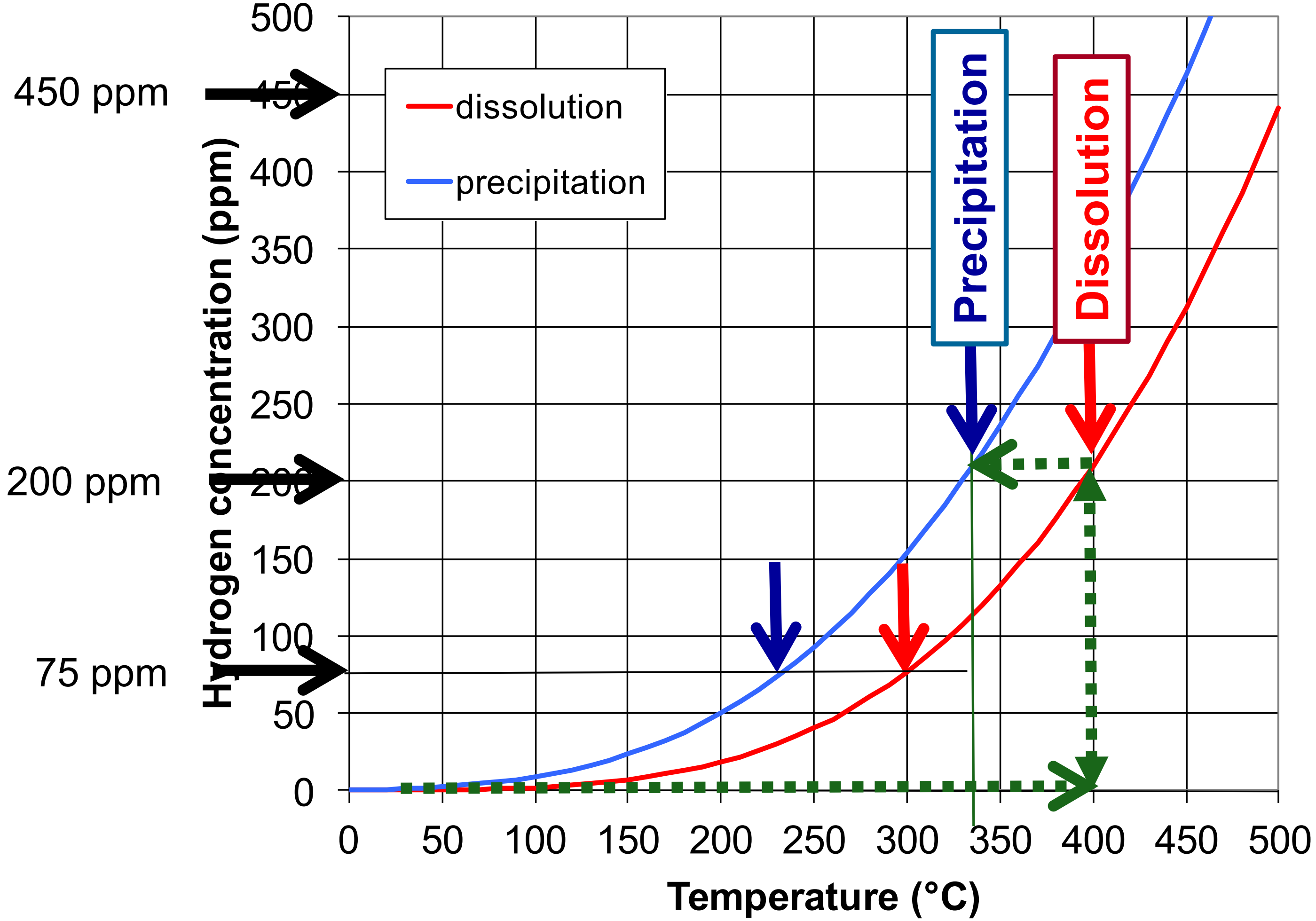
- *Key question: Given what we learned, how does that knowledge support existing –or coming up with new– regulatory guidance?*
  - Storage → *no change!*
  - Transportation accident conditions
    - Holistic approach [risk information/moderator exclusion and burnup credit (defense-in-depth)/impact of fuel relocation (worst cases and best-estimate cases)] → *non-issue!*
  - Normal conditions of transport
    - *May have to account the impact of low fuel temperature!*
    - But instrumentation of initial shipments (together with potential feedback of international experience) can provide straightforward resolution path

# R&D and Other Topics

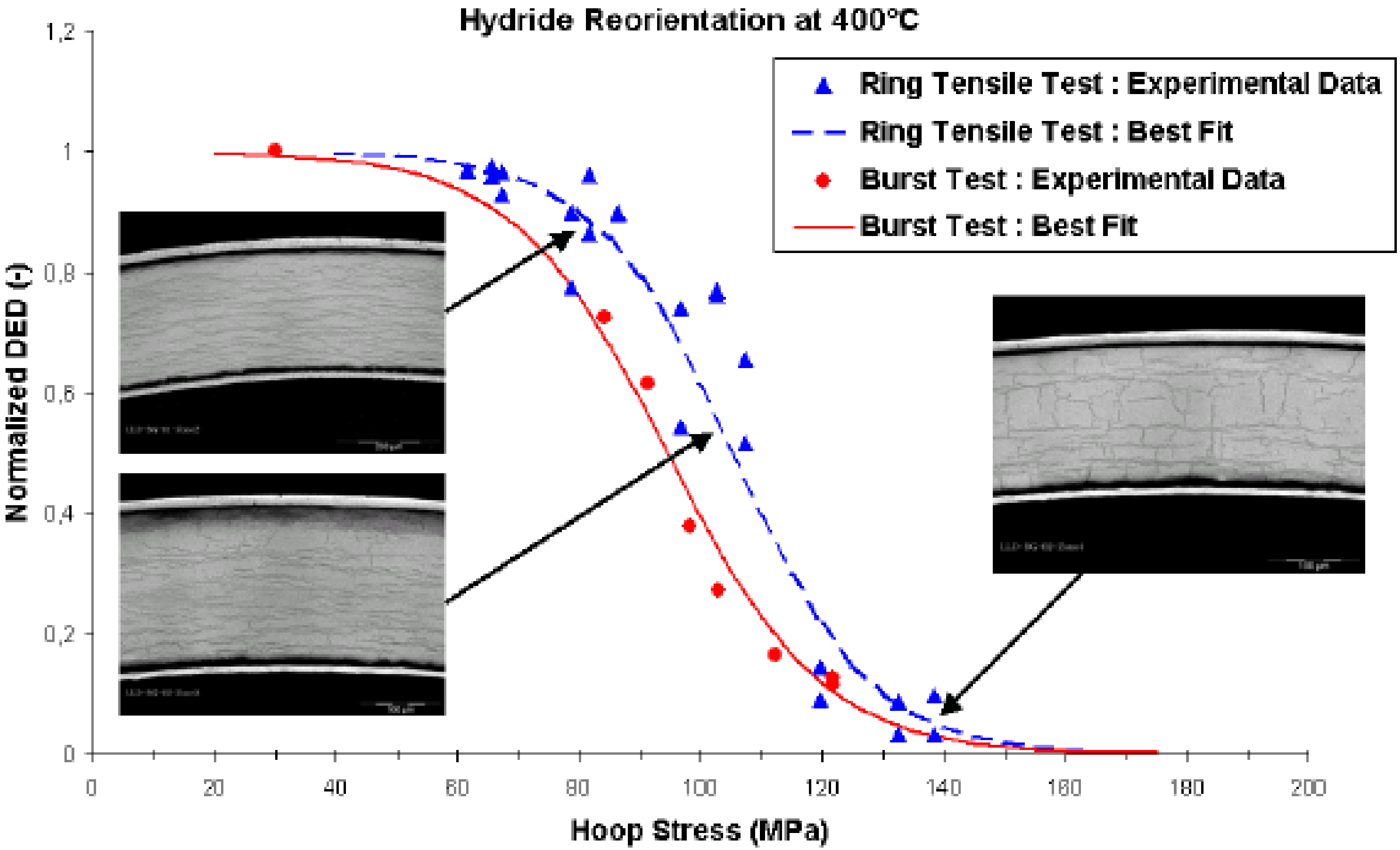
# Heating – Temperature Plateau – Cooling Cycle




# Dissolution and Precipitation of Hydrides



# Hydride Re-orientation – Room Temperature Ductile-to-Brittle Transition (Ring Tensile Testing)



# Ductility Recovery with Temperature (Ring Tensile Testing)

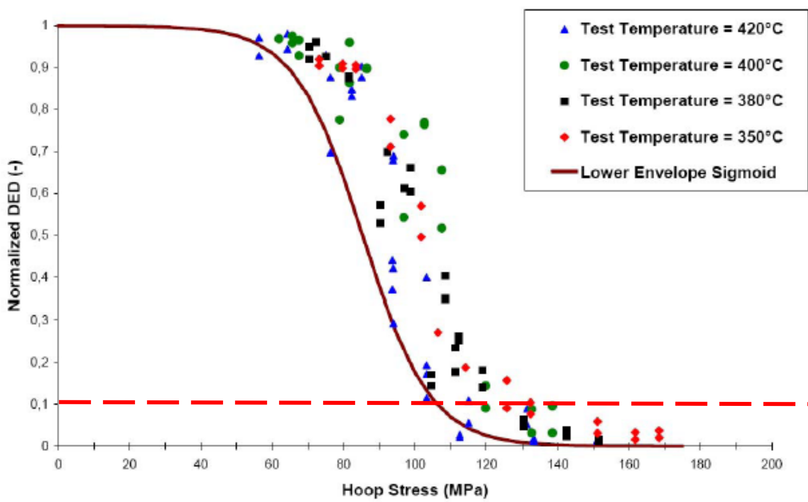



**Figure 12 :** Ductile to brittle transition observed on unirradiated hydrided Zirlo$^{TM}$ ring tensile specimens tested at ambient temperature as function of the treatment stress and temperature [14]. Normalized DED is the ratio between post treatment DED and initial DED, which is around 0.6 J/mm$^2$

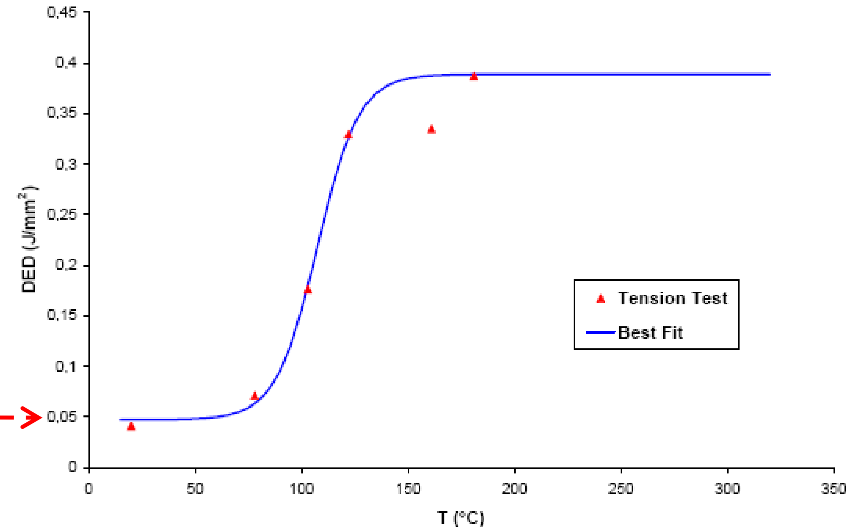
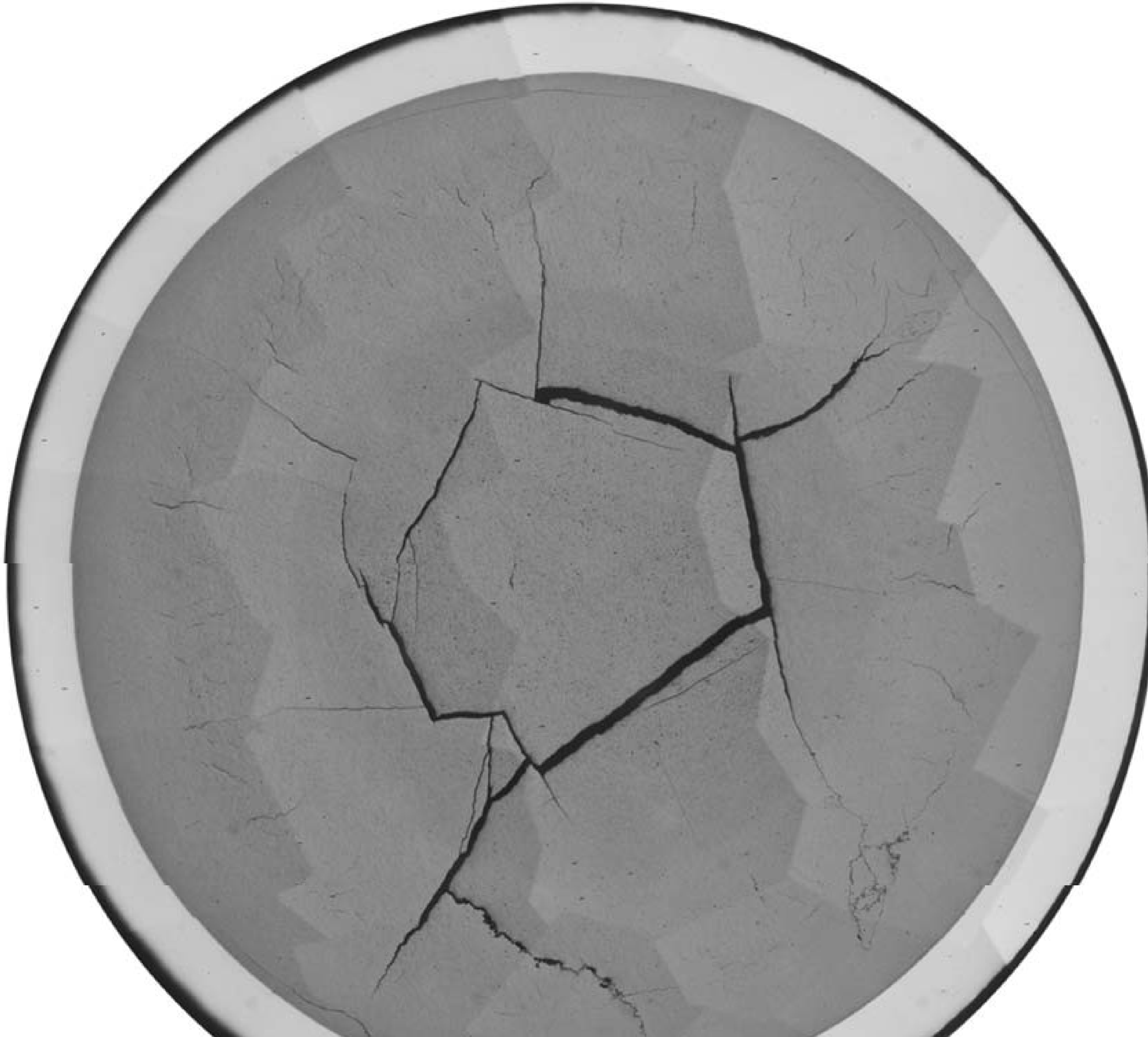
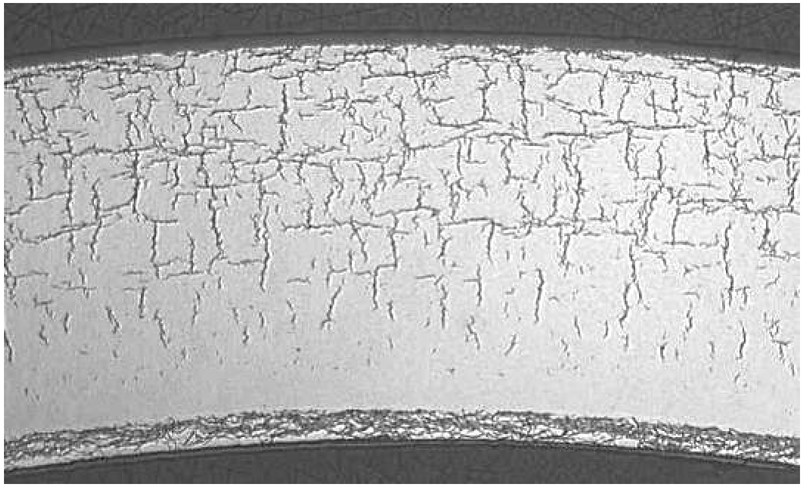


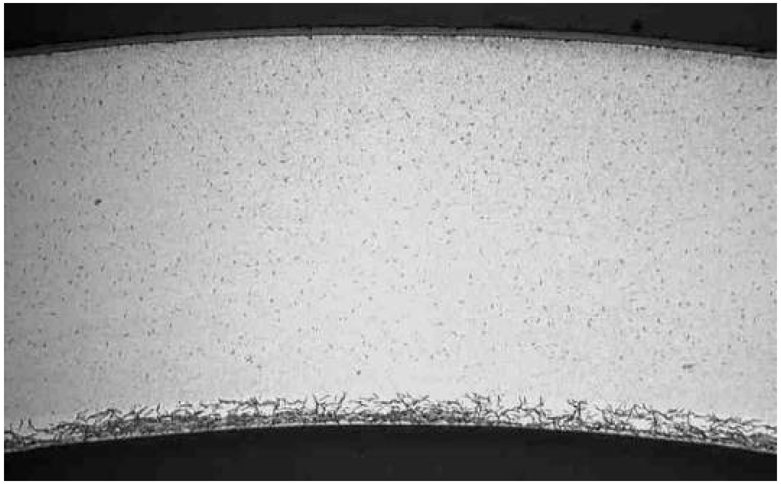

Figure 11 – Zirlo$^{TM}$ : DED best fit by sigmoid function



# Effect of Liner in Zircaloy-2

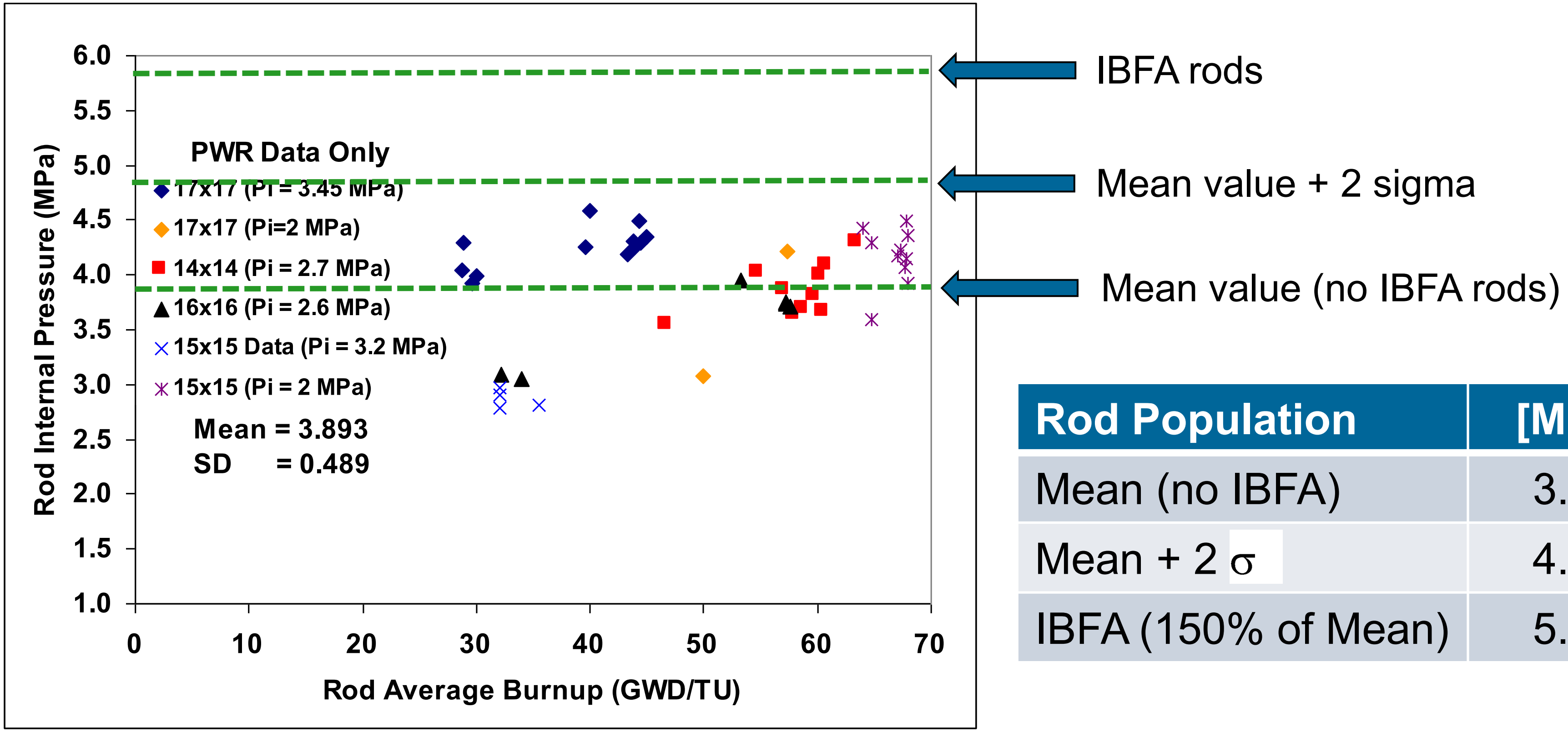


Cooling rate:
~50°C/hour



Cooling rate:
~0.5°C/hour

# End-of-Life PWR Rod Internal Pressure at 25ºC (Source: EPRI 1015048)




| Rod Population | [MPa] |
|---|---|
| Mean (no IBFA) | 3.89 |
| Mean + 2 σ | 4.87 |
| IBFA (150% of Mean) | 5.84 |

**Data**

***End-of-Life PWR rod internal pressure***

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# Effect of Plenum Temperature (Source: EPRI NP-4887)

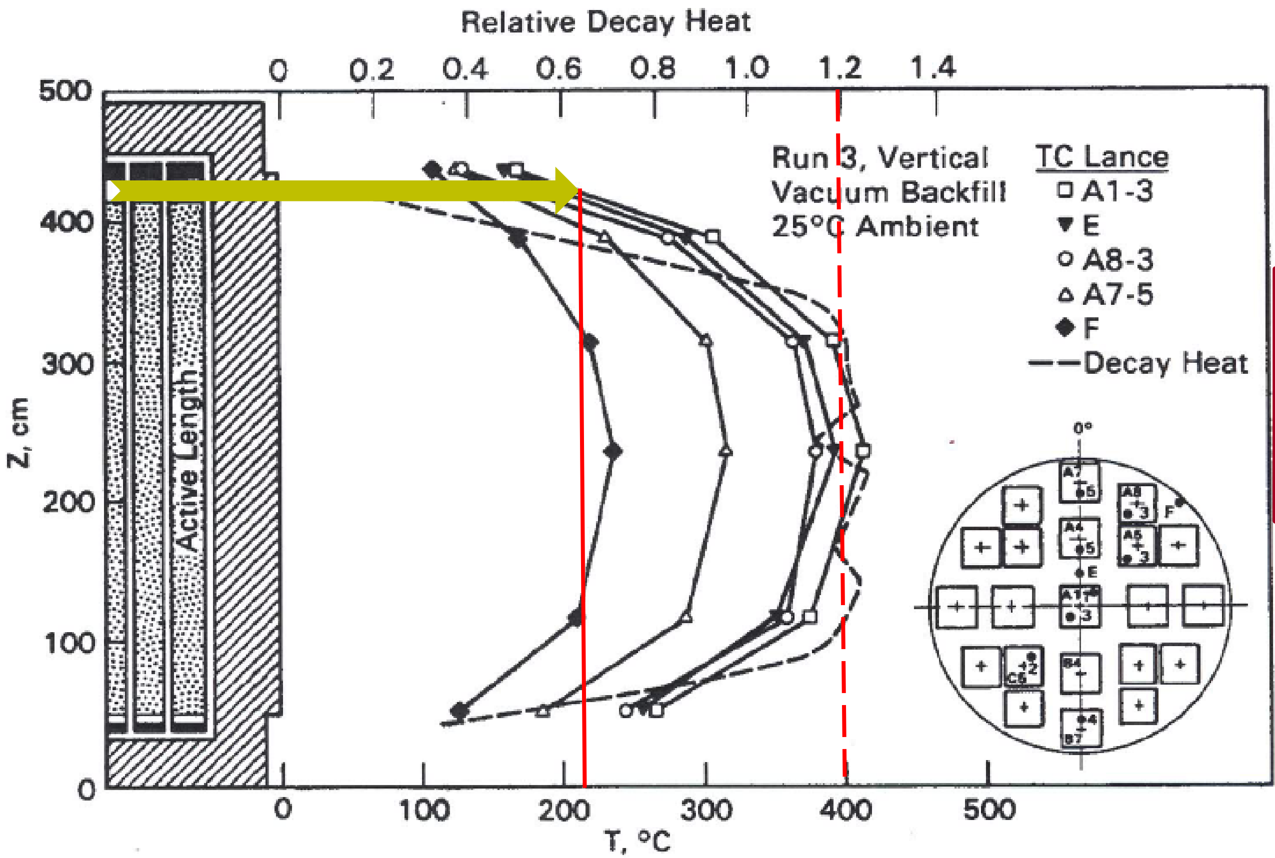


Figure 4-1.
Vacuum Test F

Assuming a temperature in the plenum of ~215°C – instead of 400°C – decreases stress by 27%

**Data**

***Plenum Temperature Benchmarks***

# Storage

# Calculated Hoop Stress at Re-precipitation (Peak Cladding Temperature = 400°C)

| EOL Internal Rod Pressure at 25°C [MPa] | Cladding wall thickness [%] | Hoop stress with plenum at 400°C & constant stress [MPa] | Hoop stress with plenum at 400°C & decreasing stress [MPa] | Hoop stress with plenum at 300°C [MPa] | Hoop stress with plenum at 250°C [MPa] |
|---|---|---|---|---|---|
| 3.89 | 100 | | 58 | 55 | 50 |
| 3.89 | 95 | 67 | 61 | 57 | 52 |
| 3.89 | 90 | | | 61 | 56 |
| 4.87 | 100 | | | | |
| 4.87 | 95 | | | | |
| 4.87 | 90 | | | | |
| 5.84 | 100 | 97 | 87 | 82 | 75 |
| 5.84 | 95 | 101 | 91 | | |
| 5.84 | 90 | 107 | 97 | 91 | 84 |

# Cladding Performance during Dry Storage

- Explicit cladding material performance requirements
  - "… spent fuel cladding must be protected during storage against degradation that leads to gross ruptures …"
  - " … degradation of the fuel during storage will not pose operational safety problems with respect to its removal from storage."
- Additional consideration: Risk information
  - Extremely low risks associated with dry storage
- Expect good performance of cold-worked stress-relieved cladding
  - Zircaloy-4
  - ZIRLO

# Transportation

# Cladding Performance during Transportation

- Explicit cladding material performance requirements
  - Hypothetical accident conditions
    - None
  - Normal conditions
    - “A package used for the shipment of fissile material must be so designed and constructed and its contents so limited that under the tests specified in § 71.71 …

      (2) The geometric form of the package contents would not be substantially altered;



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# PWR Failure Probabilities – Regulatory Transport (Source: SAND90-2406)

| Assembly Loading Condition | Drop Angle | End Plate Tensile Strain (%) | End Plate Pinch Load (N) | End Plate No. Per Rod | Spacer Grid Support Tensile Strain (%) | Spacer Grid Support Pinch Load (N) | Spacer Grid Support No. Per Rod | Midspan Between Spacer Grids Tensile Strain (%) | Midspan Between Spacer Grids Pinch Load (N) | Midspan Between Spacer Grids No. Per Rod | Failure Probability Per Rod: Longitudinal Slit PCI Part-Wall Crack | Failure Probability Per Rod: Transverse Pinhole Rupture | Failure Probability Per Rod: Rod Breakage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B&W 15 x 15 PWR | | | | | | | | | | | | | |
| 9.0-m End Drop | 90 | 2.5 | 0 | 1 | 1.04 | 84.5 | 2 | 2.02<br>0.844 | 0<br>2345 | 1<br>1 | 8.E-10 | 7.E-06 | 8.E-07 |
| 9.0-m Corner Drop (Initial Impact) | 84 | 2.6 | 0 | 1 | 0.971 | 72.9 | 2 | 2.08<br>0.546 | 0<br>3006 | 1<br>1 | 2.E-09 | 9.E-06 | 1.E-06 |
| 9.0-m Corner Drop (Slapdown) | 2 | 3.47 | 0 | 1 | 1.37 | 9728 | 2 | 1.02 | 0 | 3 | 2.E-05 | 2.E-04 | 2.E-05 |
| 9.0-m Side Drop | 0 | 3.3 | 0 | 2 | 1.3 | 9265 | 6 | 0.97<br>1.2 | 0 | 5<br>2 | 2.E-05 | 2.E-04 | 5.E-05 |
| 0.3-m Normal Drop (Side Drop) | 0 | 1.00 | 0 | 2 | 0.66 | 3560 | 6 | 0.72 | 0 | 7 | 3.E-08 | 3.E-07 | 2.E-08 |
| Fire | n/a | 0.8 | 0 | a | 0.8 | 0 | a | 0.8 | 0 | a | 1.E-11 | 0.0[b] | 0.0[b] |
| Normal[c] Transport | n/a | 0.252 | 0 | 1 | 0.1 | 79.2 | 2 | 0.203 | 0 | 2 | 0.0[d] | 2.E-07 | 2.E-12 |

[a] Fire analysis stress is based on part-wall crack in fuel with probability of 1 in 10,000.
[b] These failure modes are not applicable to regulatory fire conditions.
[c] Normal transport is due to shock and vibration loading.
[d] Stress intensity factor is less than threshold value.

# Summary – Potential R&D Topics

- Laboratory
  - New claddings
    - pRXA and RXA cladding with no liner
  - Recovery of ductility with temperature
- Confirmatory Demo
  - Positives, such as lower than generally assumed state of stress in cladding
  - Absence of negatives, such as any synergy between degradation mechanisms
- More extensive operational data
  - Distribution of EOL rod internal pressure
  - Plenum temperature (demo project)

# 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://mydocs.epri.com/docs/public/00000000000abcdefg.pdf

in which "abcdefg" represents the 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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