High Burnup (HBU) Fuel Overview

U.S. Nuclear Regulatory Commission
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High Burnup (HBU) Fuel Overview

- December, 1999 NRC/NEI Meeting on Generic Issues
- HBU #1 on Generic Issues Priority List
- NRC/NEI Conducted Several Public Meetings
- Staff Revised ISG 11 in May 2000
- Staff Requested Additional Data to Support ISG Revision
- Staff Has Approved HBU > 45 Gwd/MTU. (One Under Review)
- NEI Submittals in December 1999 and January 2000
- Staff Feedback Needed to Determine Acceptability and to Determine What Next Steps Will Be Needed

NRC Staff Review of NEI/EPRI Reports On Creep And Fracture Toughness of High Burnup Zircaloy SNF Cladding

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NRC/NEI-Industry Meeting on High Burnup Fuel Dry Storage Issues

April 18, 2001

Strain Limit for Creep
Scope of Discussion

Reference:

1. *EPRI Report 1001207, "Creep As The Limiting Mechanism For Spent Fuel Dry Storage", December 2000.*

For high burnup zircaloy cladding, under dry storage (DS) conditions:

1. **What potential mechanisms can cause failure of the cladding?**
2. **What can be the allowable creep strain limit?**

Scope of the EPRI Creep Report

Zircaloy cladding may fail under dry storage conditions due to:

1. Stress Corrosion Cracking (SCC)
2. Delayed Hydride Cracking (DHC)
3. Creep
4. Failure From Pinhole

Stress Corrosion Cracking During Dry Storage

- **NEI/EPRI: SCC is not a factor**
  - **Determined using fracture mechanics**

- **NRC Staff Position:**
  - **Agrees that SCC is not an issue during DS.**

Delayed Hydride Cracking During Dry Storage

- **NEI/EPRI: DHC is not a factor**

  a) **Based on comparison of K_{IH} and calculated K_{ICSED} during dry storage**

  b) **Assumed maximum crack size**

  c) **Assumed maximum stress**

  d) **Assumed hydride re-orientation will not occur** (stress temperature)

  e) **If $K_{ICSED} < K_{IH}$, then no DHC and fracture.**

Delayed Hydride Cracking During Dry Storage of SNF

NRC Staff Position:

1) DHC cannot be ruled out.
2) Fracture toughness likely to be dependent on density and distribution of hydrides and degree of radial orientation.
3) CSED approach not validated against high burnup fracture data.
4) Fracture data, test temperature, and hydrogen levels not prototypical of high burnup fuel DS conditions.
5) Hydride reorientation may be possible.

Zircaloy Cladding Creep Data

NEI/EPRI: Data used to Support the Proposed 2% Creep Strain Limit

Data Source	Test Temperature, °C	Burnup, GWd/MTU	Stress, MPa	Hydrogen, ppm	Uniform Strain, %
Einzinger, et. al.	482 - 571	16 - 18	45 - 75	≤ 150	1.7 - 7
Goll, et. al.	300 – 370	60	320- 630	100 – 660	≥ 2.5 - ≅ 6.0
Bouffioux and Rupa	350 – 400	-	350 –386	215 – 1040	9 –12
Garde et. al.	40 – 400	45 – 63	≥ 480	110 – 730	0.05 – 3.0

Einzinger Creep Data

NRC Staff Position

Test data do not support a full range of applicability to high burnup fuel

- **Data are for low burnup fuel (16-18 GWd/MTU)**
- **Test temperatures are much higher than DS conditions.**
- **Test stresses are lower than DS conditions**

Goll Creep Data

NRC Staff Position

Test data do not support a full range of applicability to high burnup fuel (e.g., highly hydrided fuel)

- **Commercial high burnup fuel can have > 700 ppm hydrogen with spallation**
- **Test stresses are too high for DS conditions**

Bouffioux and Rupa's Creep Data

NRC Staff Position

Test data do not support a full range of applicability to high burnup fuel

- **Cladding not irradiated**
- **Cladding uniformly hydrided**
- **Test stresses too high**

Garde Creep Data

NEI/EPRI Assumptions in Data Interpretation

1. Used total strain (includes instability strain) rather than uniform
2. Factor of 2 increase in strain due to strain rate effects
3. Elastic strain capacity included

Garde Creep Data

NRC Staff Position

Test data do not support a full range of applicability to high burnup fuel

- Test stresses too high; however, test temperature, burnup, hydrogen levels are prototypical of high burnup fuel
- The use of uniform strain is more applicable to strain limit
- The factor of 2 increase in strain due to strain rate effect is not justified
- Application of elastic strain capability to plastic creep strain not justified

NRC Staff's Overall Assessment of NEI/EPRI's Creep Data

Test data do not support the proposed 2% creep strain limit for high burnup zircaloy fuel, because they are not prototypical of dry storage conditions.

Cladding Failure From Pinholes

NEI/EPRI

- Cracks, if initially present, will not propagate

NRC Staff Position

- Insufficient data and analysis to rule out crack propagation

NRC Staff Conclusion

Additional creep data for materials specific to high burnup cladding under temperatures, stresses, and hydrogen levels typical to dry storage are required to justify a new creep strain limit

EPRI Fracture Toughness Report
Scope of Discussion

Reference:

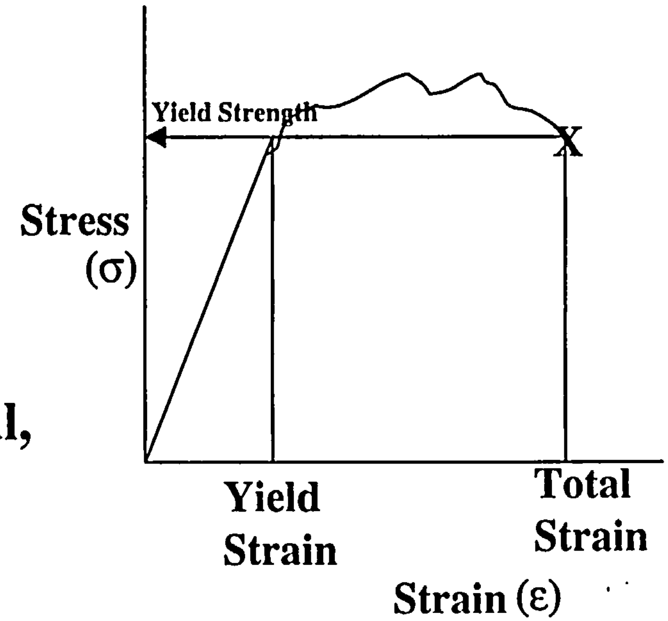
EPRI Report, 1001281, "Fracture Toughness Data for Zirconium Alloys – Application to Spent Fuel Cladding in Dry Storage", January 2001.

1. **Critical Strain Energy Density (CSED)**
   - Principles and Basics
2. **Applicability to High Burnup Zirconium Alloy Cladding**

Critical Strain Energy Density (CSED)

CSED is defined as the integral of the product of stresses and strains obtained in a test.

$$U_c = \sum_{0}^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij}$$



By equating the CSED of the LEFM material to the CSED of the actual material,

$$U_c = \frac{\sigma^2}{2E} = \sigma_y \varepsilon_{TE} - \frac{1}{2}\sigma_y \varepsilon_y .$$

(Eq. 8 of EPRI Report)

Critical Strain Energy Density (CSED)

EPRI report relates the CSED to K_{Ic} by:

$$K_{Ic}^{2} = CU_{c},$$

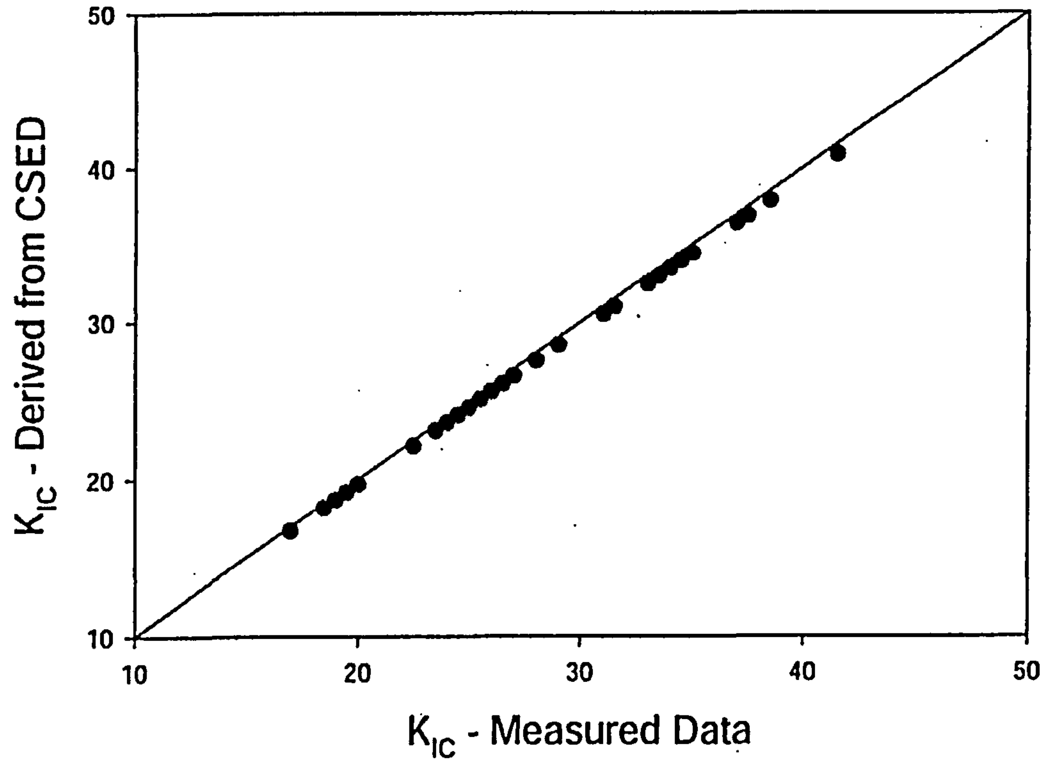
where, C is a material constant, depending up on crack properties and ductility of the material.

For 'highly irradiated zircaloy':

$$K_{Ic} = 3.5\sqrt{U_{c}}.$$

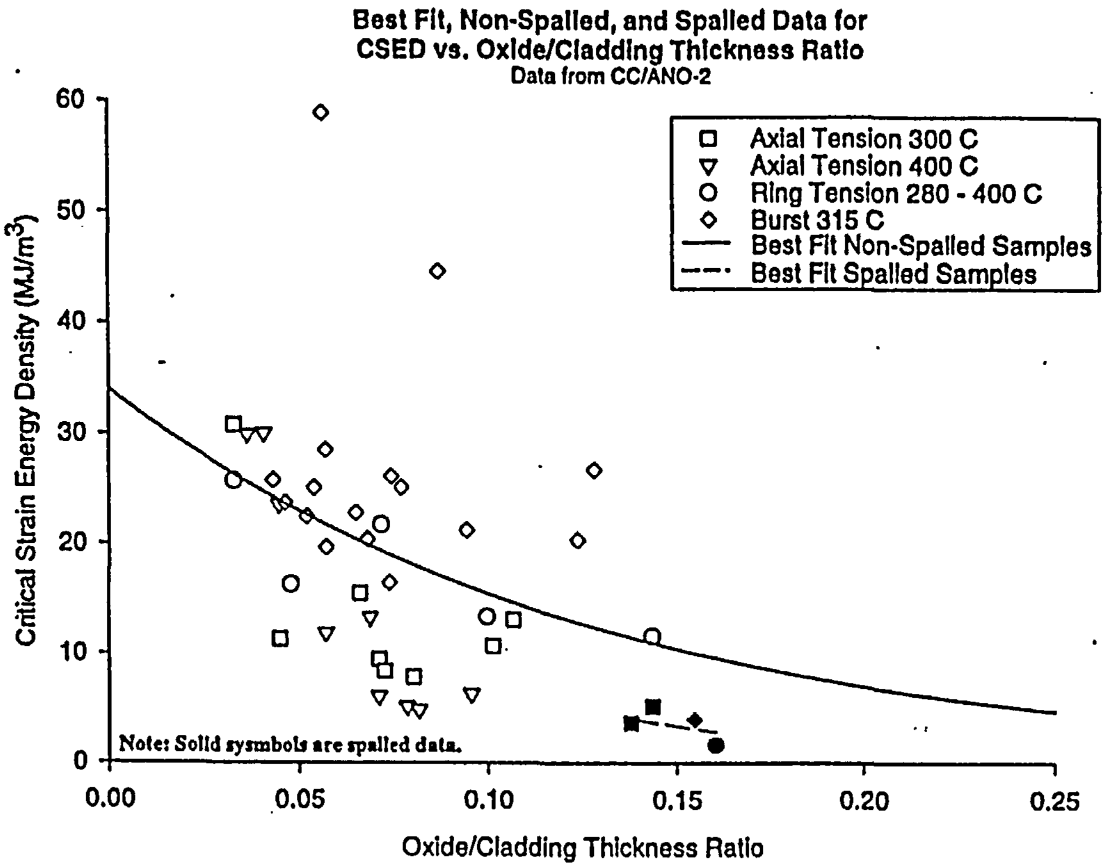
U_c represents the area under the stress-strain curve in an uniaxial or biaxial test.

EPRI Report Shows Excellent Correlation For Aluminum Alloys Using CSED

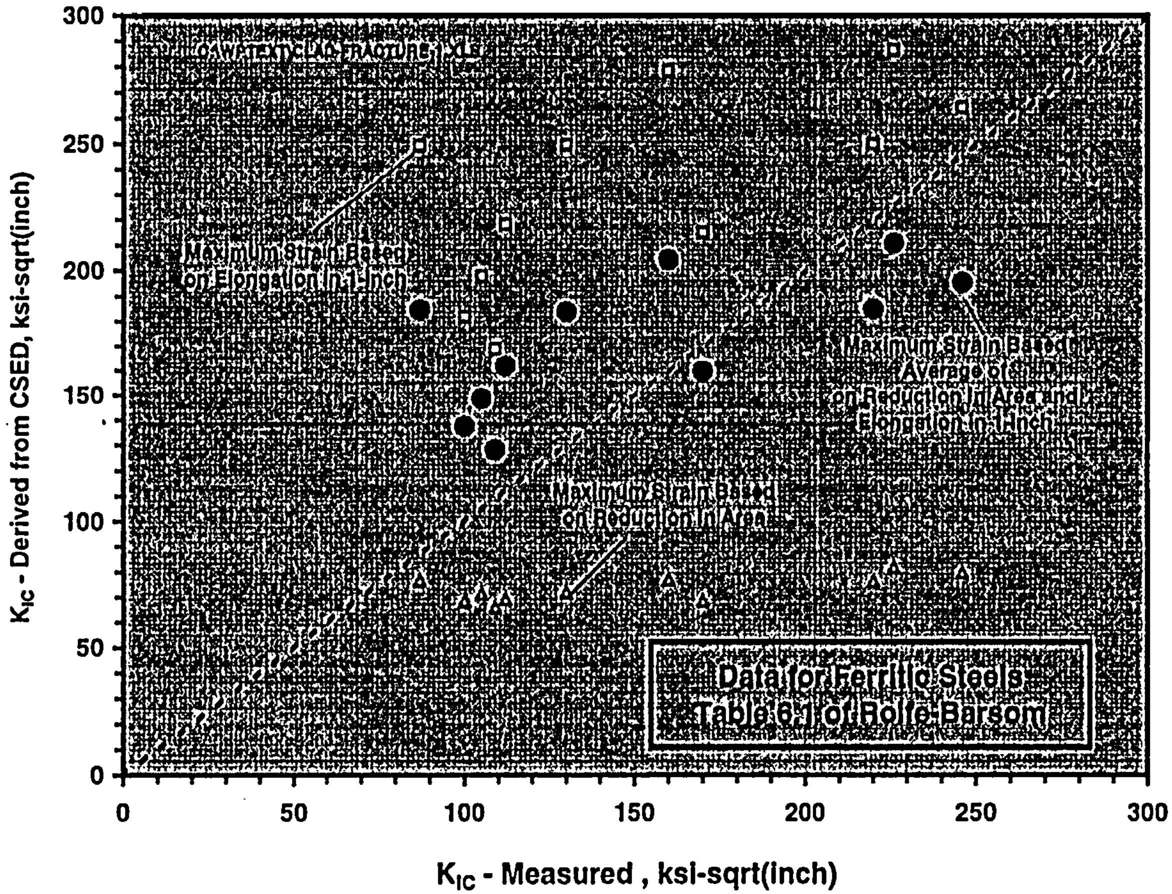


Does one obtain such good correlation for other materials?

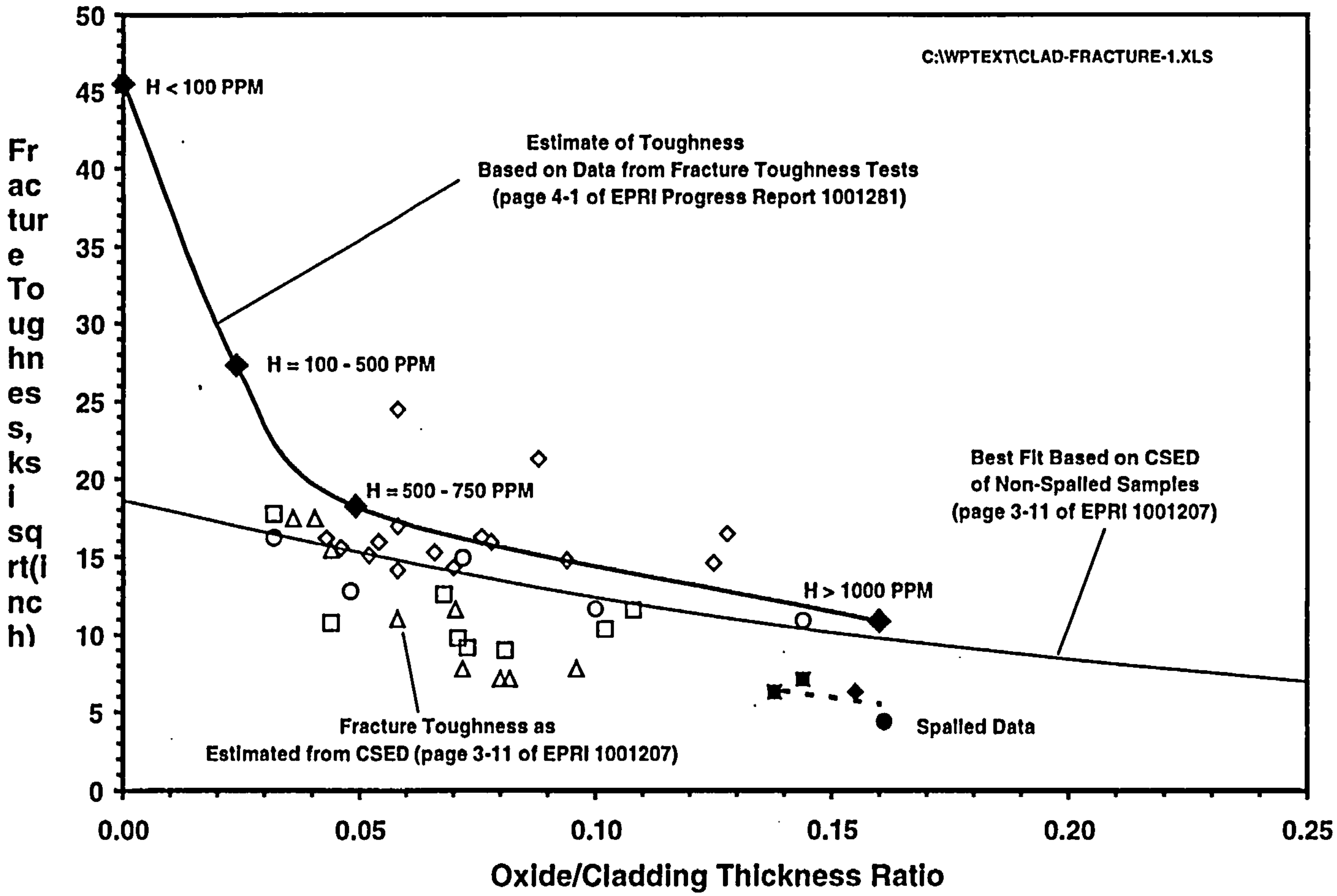
EPRI Data: CSED Shows Large Scatter In the Results for Hydrided Fuel Cladding



PNNL Analysis: For Ferritic Steels Large Scatter In The Predicted Vs. Measured Values Using CSED



PNNL Analysis: CSED Approach Indicates Persistent Large Uncertainty



Staff Conclusions

1. CSED validity to high burnup zircaloy cladding needs more confirmatory data.
2. A simplistic application of uniaxial (and biaxial) stress-strain behavior to creep and fracture phenomenon does not address the complexities in creep and fracture mechanisms.