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**

  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:

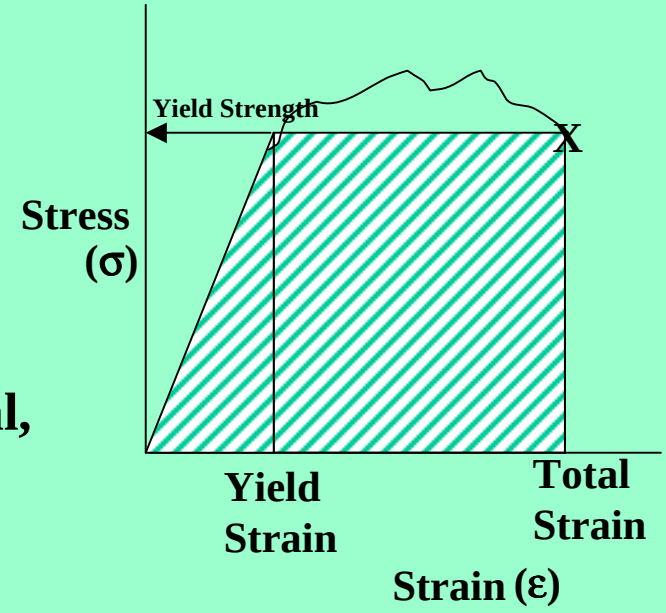
EPRI Report, 1001281, "Fracture Toughness Data for Zirconium Alloys – Application to Spent Fuel Cladding in Dry Storage", January 2001.

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:

$$K_{Ic}^2 = CU_c,$$

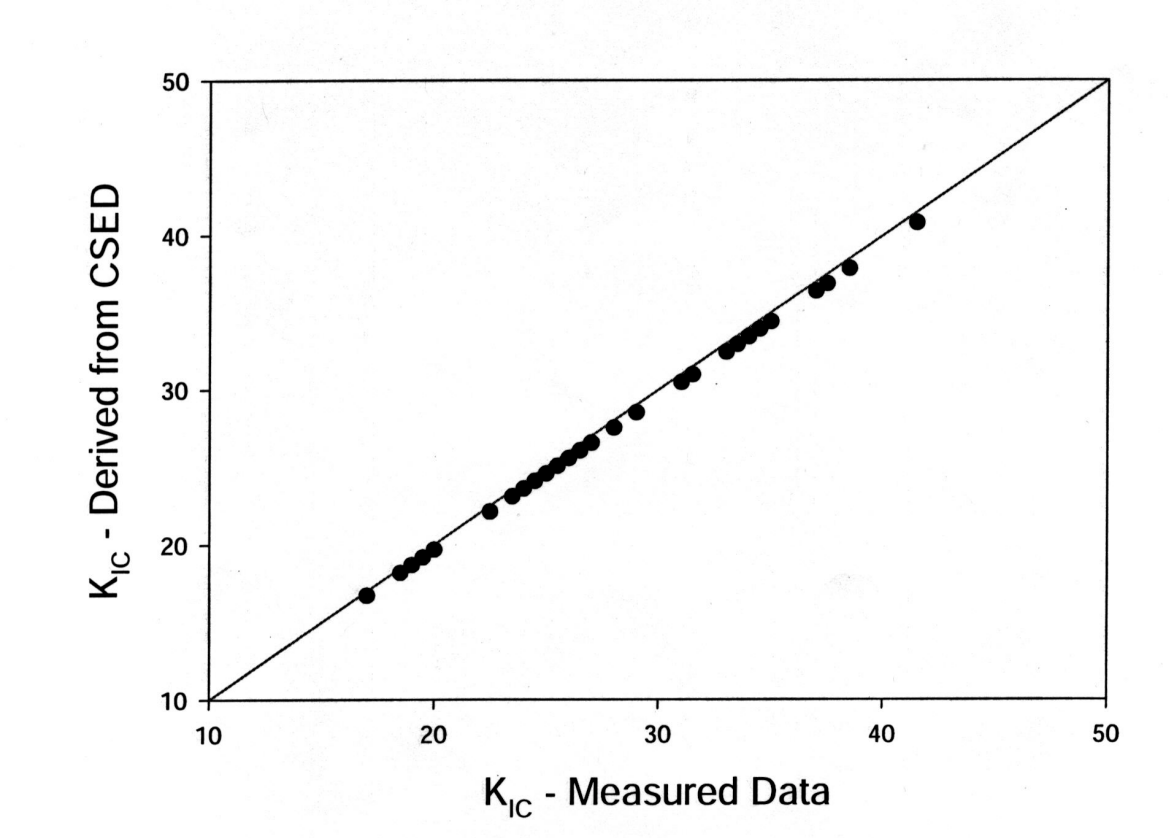
where, C is a material constant, depending up on crack properties and ductility of the material.

For 'highly irradiated zircaloy':

$$K_{Ic} = 3.5\sqrt{U_c}.$$

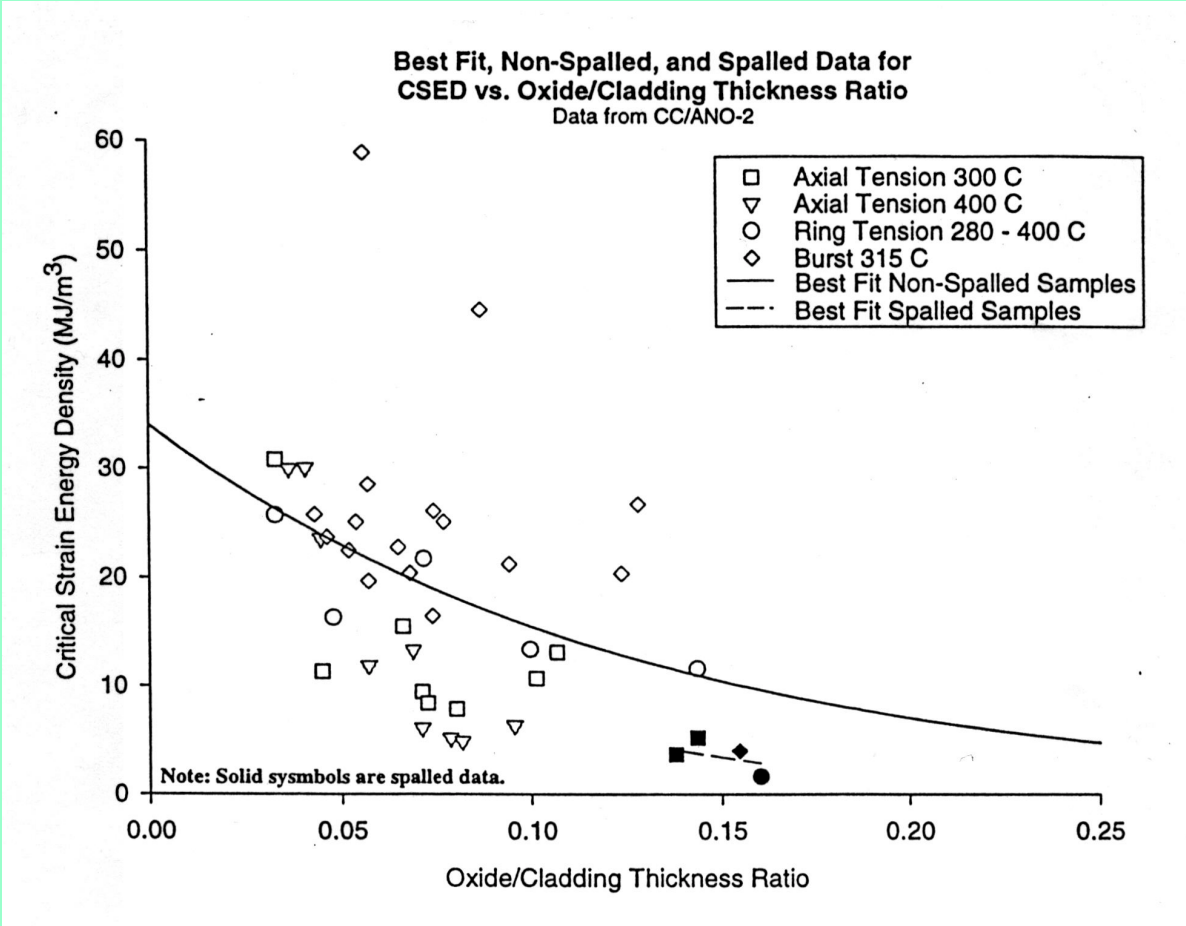
U_c represents the area under the stress-strain curve in an uniaxial or biaxial test.

EPRI Report Shows Excellent Correlation For Aluminum Alloys Using CSED

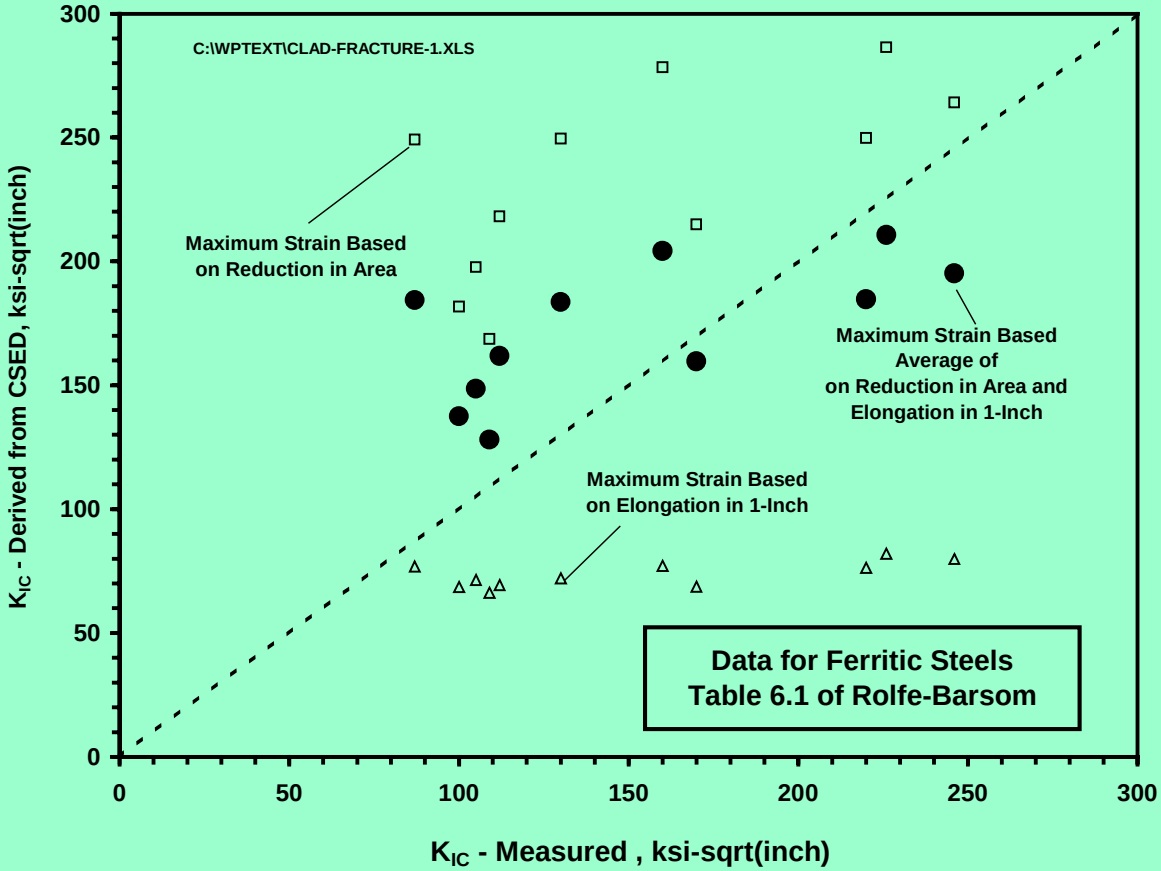


Does one obtain such good correlation for other materials?

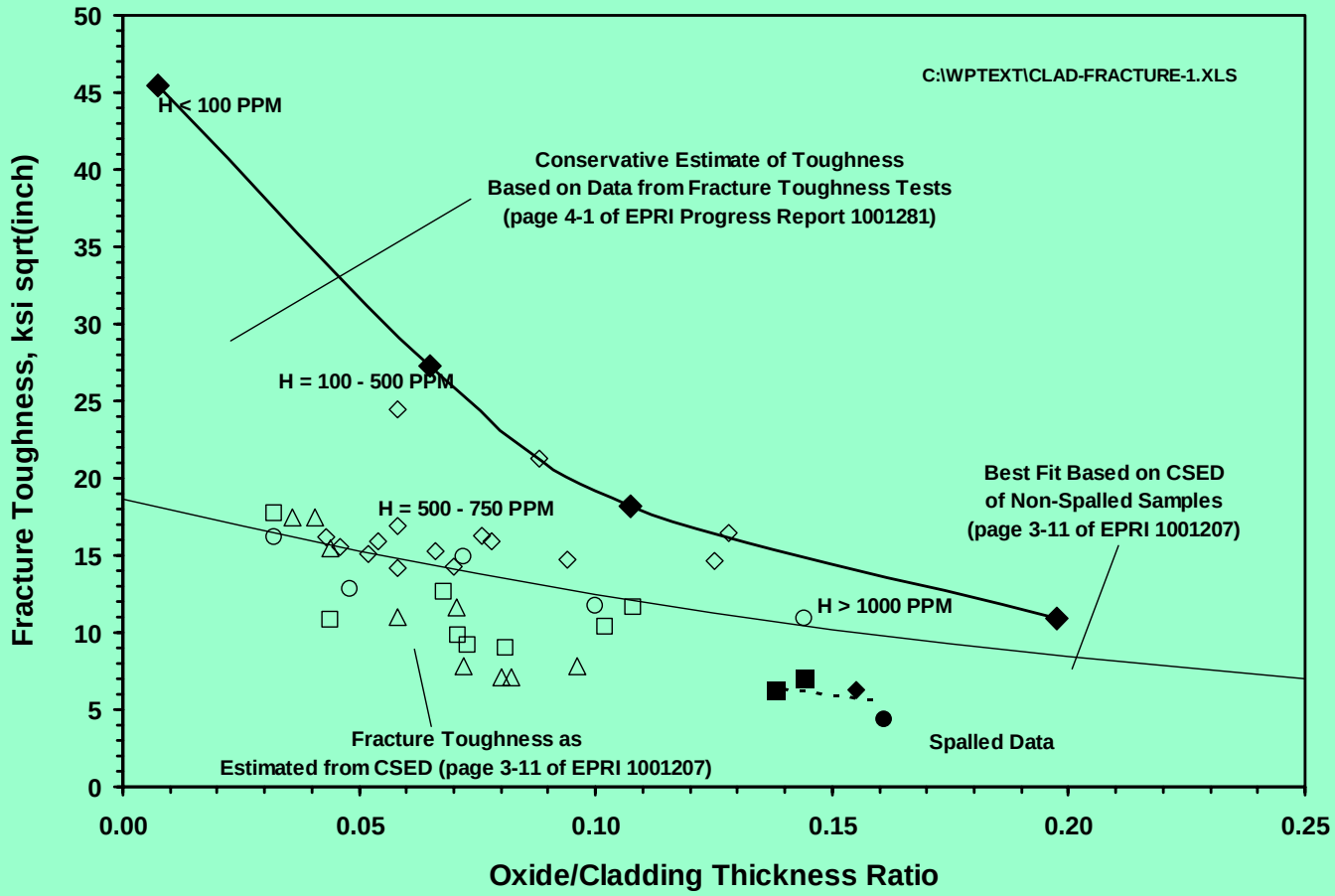
EPRI Data: CSED Shows Large Scatter In the Results for Hydrided Fuel Cladding



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.