United States Nuclear Regulatory Commission

RIC 2006

Session T1BC

Fuels – *Cladding Behavior for Regulatory Applications*

Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46

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Background

Embrittlement Criteria

10 CFR 50.46, §(b)(1) and §(b)(2)

- Peak Cladding Temperature limited to 2200°F (1204°C)
- Maximum Cladding Oxidation limited to 17% of thickness, with wall thinning accounted for

ECCS Models

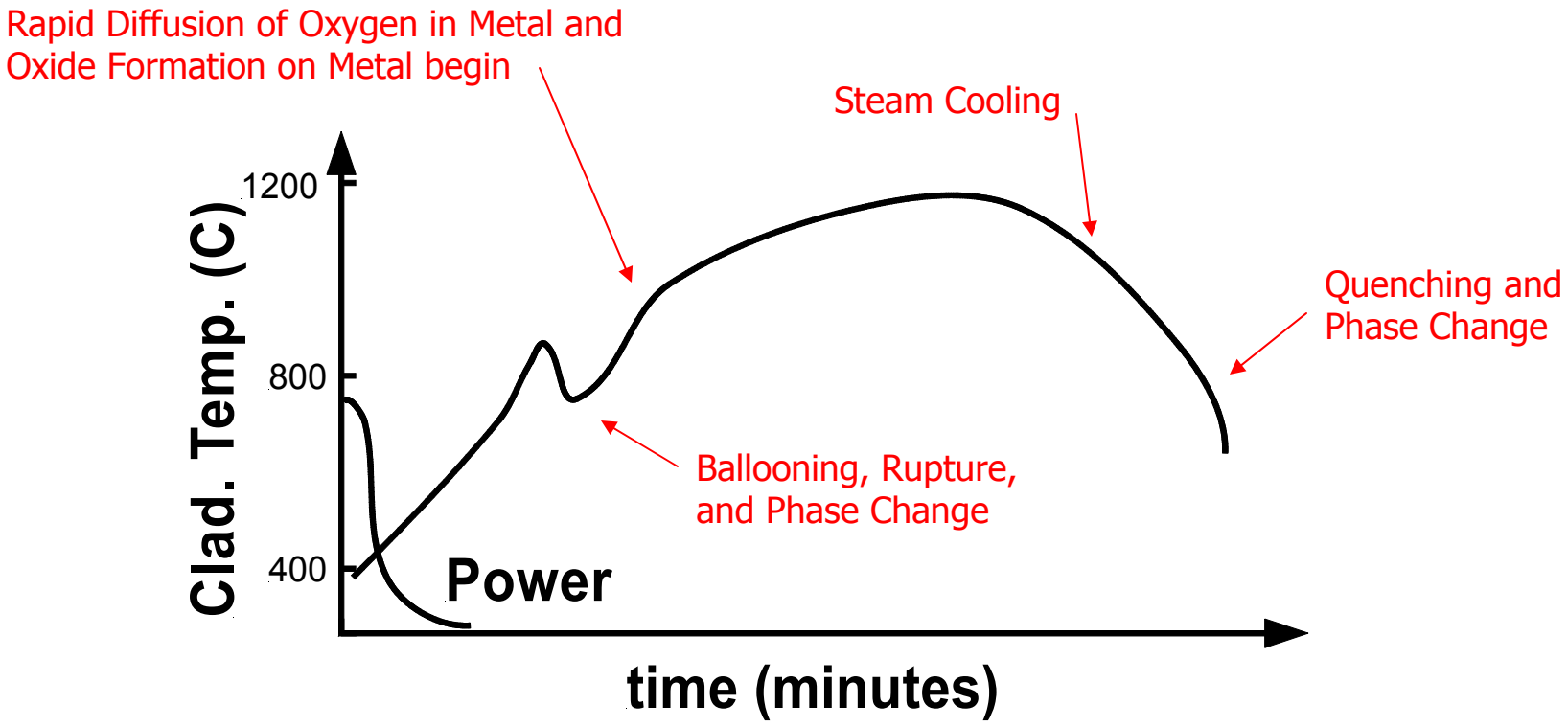
Appendix K, §I.5

- 2-sided Oxidation within 1.5 inches of rupture location

Information Notice 98-29

- Total Oxidation includes both pre-accident oxidation and oxidation occurring during a LOCA

General Cladding Behavior



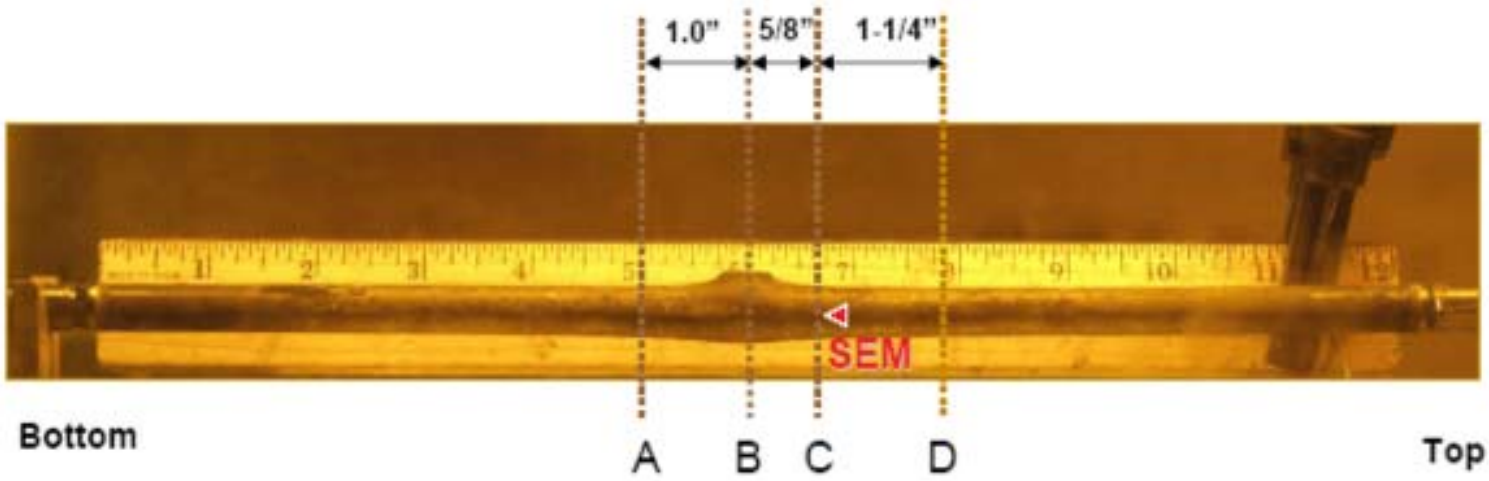
5 Mechanisms of Cladding Embrittlement

Two were known in 1973 when 10 CFR 50.46 was written.

One was discovered in 1980, but no action was taken.

Two were discovered in current NRC research at ANL and Kurchatov. One is sensitive to burnup, and the other is sensitive to alloy and fabrication.

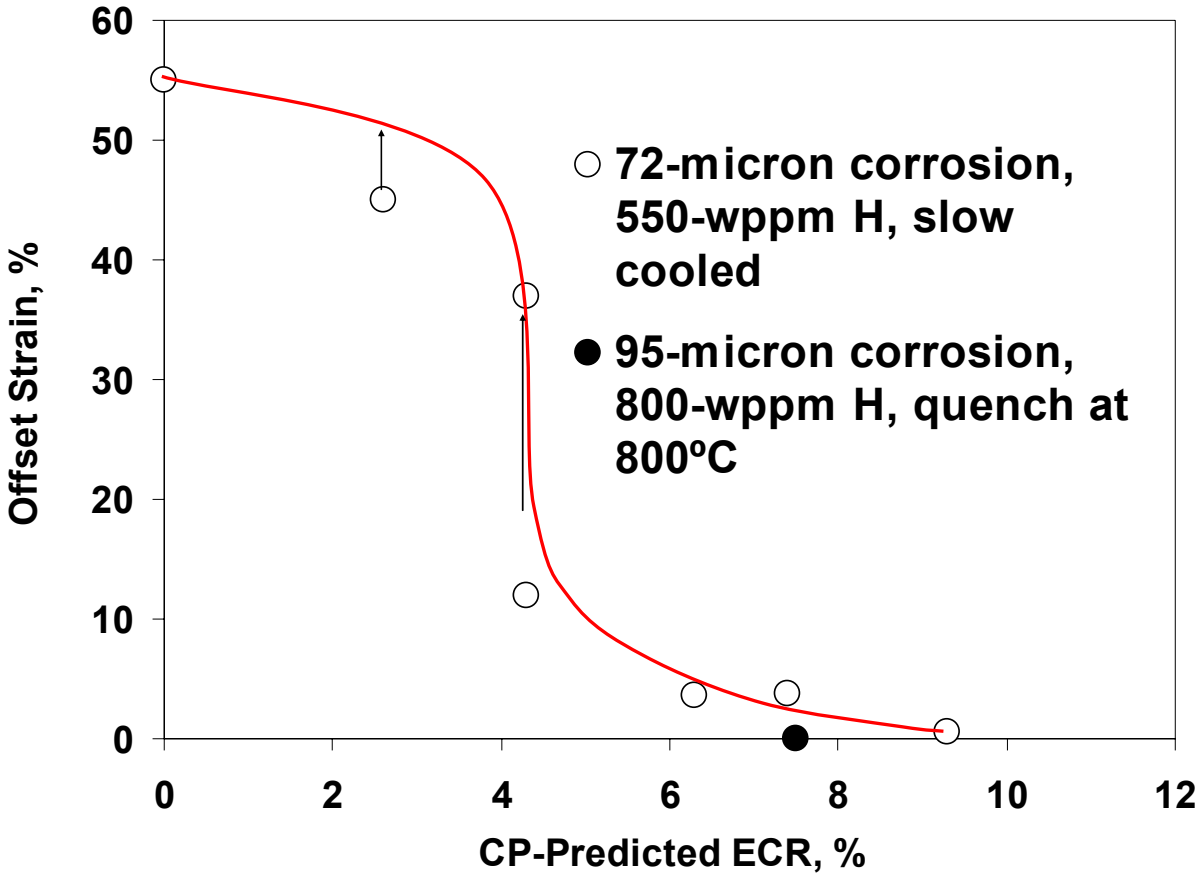
High-burnup BWR fuel rod after a simulated LOCA transient (ANL test ICL#3), showing locations A, B, C where the specimen broke during handling and D where it was sectioned for metallography.



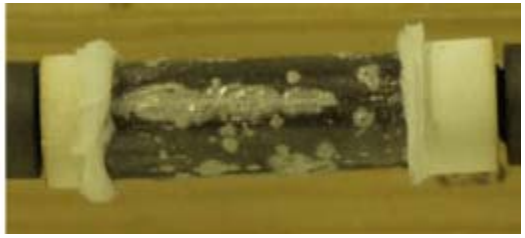
Disposition of the Ballooned Region (Mechanism #3)

- Retain requirement for 2-sided oxidation in balloon to protect as much of the ductile area as possible
- Brittle material often retains significant strength, and ruptured regions of cladding do not usually fracture during simulated LOCA transients, including quenching
- Fracturing that has been observed usually results in clean breaks rather than fragmentation.
- No significant offset of fractured rods is thought to be possible that would allow fuel pellets to fall out of the cladding tubes.
- Only a few inches of the 12 to 14-foot-long fuel rods are affected by ruptured balloons.

Corrosion During Burnup Reduces Ductility (Mechanism #4)

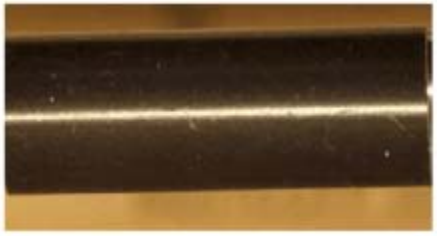


Breakaway Oxidation Reduces Ductility (Mechanism #5)



E110, 290 sec

E110, 1400 sec



M5, 2400 sec

Summary of Possible Criteria

Step 1 Short segments of unirradiated cladding of the alloy of interest could be oxidized in steam at 1200°C and subsequently tested at 135°C to determine the **oxidation level** (expressed as a percent of the cladding thickness) at which ductility is lost.

Step 2 Additional segments of this unirradiated cladding could be oxidized in steam at appropriate temperatures in the range of 800-1200°C to determine the **time** required to initiate breakaway oxidation.

Step 3 Pre-accident **corrosion** (oxide) could be determined and expressed as a percent of the cladding thickness for the fuel rods and burnups of interest.

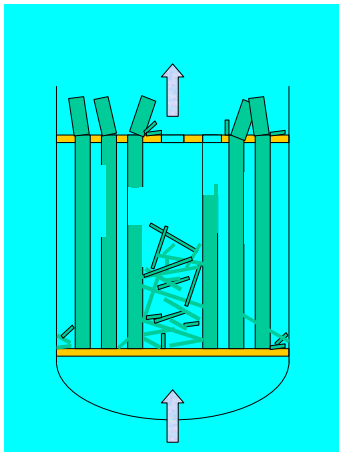
cont'd

Summary of Possible Criteria

Step 4 The **calculated cladding oxidation** during a LOCA should not exceed the oxidation level determined in Step 1 minus the pre-accident corrosion determined in Step 3.

Step 5 The **calculated time** spent above any temperature should not exceed the time required to initiate breakaway oxidation at that temperature, as determined in Step 2.

Step 6 Cladding oxidation should be calculated with the **Cathcart-Pawel** correlation at all temperatures for testing and analysis to provide a uniform time measure for all cases.



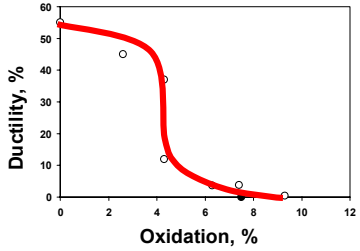
FUEL RESEARCH ON *LOCA* CRITERIA, 10 CFR 50.46(b)

Avoid Core Collapse by Maintaining Cladding Ductility

Research

Alloy Effects
(this cladding not used in the U.S.)

Burnup Effects



Local Effects

Precision

1973 Criteria

Zircaloy & ZIRLO (prescriptive)

- 2200°F Limit Cladding Temp.
- 17% Limit Cladding Oxidation

Proposed Criteria

All Zirconium Alloys (performance based)

- 2200°F Limit, Clad. Temp.

Measure:
- Embrittlement Onset
- Oxide Breakaway Time
- Corrosion from Burnup

- Limit on time at temperature based on measured values.

Conclusions

1. No safety problem has been found for operating reactors with modern fuel that has been analyzed using the current practice of a limit of 17% minus the corrosion thickness and the C-P (or B-J) oxidation correlation.
2. No reanalysis of operating reactors is expected because the current practice is consistent with the criteria that have been outlined.
3. No ECCS models should have to be revised if the criteria as outlined were adopted.
4. Such criteria would be applicable to small-break and large-break LOCAs, but they are especially appropriate for small breaks with lower temperatures at which breakaway oxidation might occur.
5. Such criteria should remain valid for modest burnup extensions (e.g., to 75 GWd/t) because corrosion (not fluence) is the major variable and has been studied over a wide range.
6. The criteria as outlined are performance-based and should apply to all zirconium-based cladding materials.