Technical Basis for Revising 50.46(b) ECCS Acceptance Criteria

Regulatory Information Conference

March 12, 2009

Ralph Meyer
Division of Systems Analysis
Office of Nuclear Regulatory Research

1

Scope of NRC's LOCA Research

Determine the effect of burnup on the embrittlement criteria in 10 CFR 50.46 and provide the technical basis for their revision.

2200ºF Peak Cladding Temperature Limit (no change needed)

17% Maximum Cladding Oxidation (effort focused on this)

Several other fuel-related LOCA phenomena are under investigation or consideration in the NRC's research programs, but they are not needed to revise the criteria in the rule.

- Axial Fuel Relocation into a Balloon
- Loss of Fuel Particles through a Rupture Opening
- Ballooning and Flow Blockage (dimensions)
- Mechanical Behavior of Balloon

2

NRC-Sponsored LOCA Research Projects

- Argonne National Laboratory – funded by NRC with industry cooperation, NUREG/CR-6967*
- Kurchatov Institute – funded jointly by NRC and IRSN (France) with additional funding from TVEL (Russia), NUREG/IA-0211
- Halden Reactor Project – bilateral project funded by NRC, IFE/KR/E-2008-004

* ANL maintained close cooperation with Kurchatov, CEA, and JAEA. ANL hosted an OECD LOCA meeting with these and other international researchers.

3

Industry Cooperation on ANL Research Project

- Formal industry cooperation in ANL project since 1998
- EPRI has provided the high-burnup fuel rods used in this project
- Areva, GNF, and Westinghouse have provided unirradiated cladding for testing in this project
- Detailed (2-day) program review meetings have been held each year with industry representatives
- Non-industry representatives from international organizations have also participated in the program review meetings

4

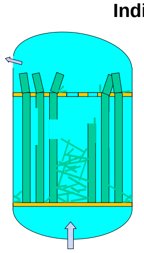
Background (next two slides)

This research was focused on the adequacy of the oxidation limit to prevent cladding embrittlement.

- Calculated cladding oxidation, which is a measure of time at temperature, is used as an indicator of embrittlement.
- Diffusion of oxygen into the metal (rather than oxide buildup on the surface) causes embrittlement.
- The cladding oxidation limit is thus very important – in fact, more important than the cladding temperature limit – because time at temperature (not temperature alone) determines embrittlement.

5

Extensive Cladding Oxidation Indicates Cladding Embrittlement



Collapse of fuel with severely oxidized (embrittled) cladding in low-flow incident in cleaning tank at Paks-2 plant in Hungary

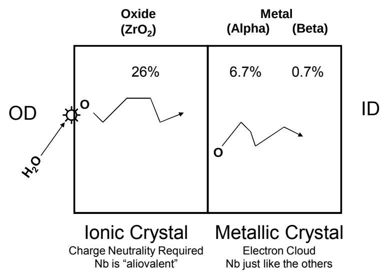
The oxidation limit in 50.46(b)(2) precludes this behavior by ensuring some residual ductility in the cladding.

Hozer at OECD meeting Studsvik 11/04

6

U.S.NRC

Diffusion of Oxygen controls both Oxidation and Embrittlement, but …



- Diffusion in oxide depends strongly on alloy.
- Diffusion in metal does not.

U.S.NRC

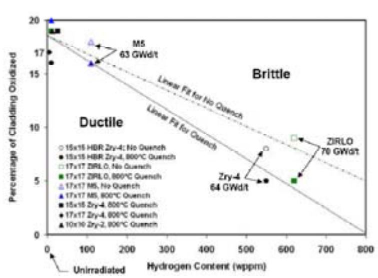
Research Finding #1 (next two slides)

Burnup-related processes reduce the oxidation limit below 17%.

- Hydrogen is absorbed in the cladding as a consequence of cladding corrosion during normal operation.
- Hydrogen accelerates the diffusion of oxygen in the cladding metal during a LOCA, thus speeding up embrittlement.
- Embrittlement during a LOCA therefore correlates with the hydrogen content from normal operation.

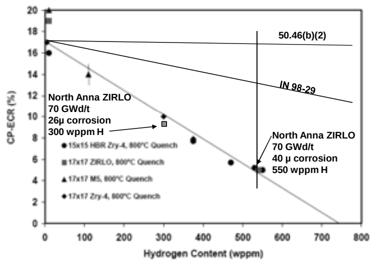
U.S.NRC

Embrittlement does not occur at a constant 17%, but on a sliding scale that is the same for all alloys tested.



RIL-0801

Measured Embrittlement Threshold and Licensing Limits: an Example



Recent data added

10

Research Finding #2 (next two slides)

Oxygen can enter the cladding metal from the ID as well as the OD in high-burnup fuel.

- This will nearly double the calculated oxidation in some analytical nodes.
- But 2-sided oxidation is already calculated in the rupture node so it may not create a more-limiting case.
- ID oxygen pickup will not occur in fresh fuel.

11

ID Oxygen Pickup Occurs at High Burnup

Oxygen source is present on both OD and ID

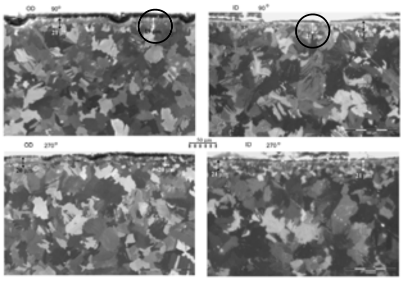
	OD	ID
Steam Oxide and Corrosion	Cladding	Bonding Layer and Fuel
Oxide	Metal	Oxide

► Bonding of oxide pellet and cladding forms by simple Diffusion Welding during normal operation.

► Equal amounts of Oxygen diffuse into cladding metal from OD and ID during a LOCA because cladding is approximately isothermal.

12

Halden LOCA Test confirms equal Oxygen Pickup from ID and OD



13

Research Finding #3 (next two slides)

Breakaway oxidation eventually occurs in all zirconium alloys and must be avoided because rapid embrittlement follows.

- Oxide crystal structure can change from tetragonal (protective) to monoclinic (cracked) in the LOCA temperature range.
- After breakaway, hydrogen is absorbed rapidly and promotes oxygen diffusion into the metal, thus reducing ductility.
- Breakaway is affected by surface finish and alloy impurities.
- Causal factors are not well known, so only way to make sure cladding has sufficient breakaway resistance is to test it.

14

Breakaway Oxidation is very Sensitive to Fabrication Processes

E110, 290 sec

E110, 1400 sec

M5, 2400 sec

Note that E110 and M5 are nominally the same alloy (Zr-1%Nb)

15

Breakaway occurs >2500 sec in Modern Cladding, but easy to change

- **Evolution of Zircaloys with Respect to Breakaway Oxidation**
  - 1970s rough surface (≈0.3 μm) and pickled Zry-4: 1800 s (L-S)
  - 1970s-1980s rough surface (≈0.3 μm) 15×15 Zry-4 : 3800 s (ANL)
  - Current wheel-polished (≈0.1 μm) 15×15 Zry-4: 5000 s (ANL)
  - Current belt-polished (≈0.1 μm) 10×10 Zry-2: >5000 s (ANL)
  - Current wheel-polished (≈0.1 μm) 17×17 Zry-4: ≈5400 s (CEA)
- **Comparison of Zr-1Nb Alloys Oxidized at 1000ºC**
  - Wheel-polished (≈0.1 μm) 17×17 M5: ≈6400 s (CEA)
  - Standard E110 tubing (≈0.4 μm); pickling
    - <300 s breakaway based on outer surface appearance
    - ≈600 s based on 200-wppm hydrogen pickup
- **Rationale for Breakaway Oxidation Performance Tests**
  - Alloys are optimized to improve performance under normal conditions
  - Breakaway oxidation under LOCA conditions is highly sensitive to many fabrication details, especially surface finish

16