



United States Nuclear Regulatory Commission

**Embrittlement Criteria for
Loss-of-Coolant Accidents
10 CFR 50.46**

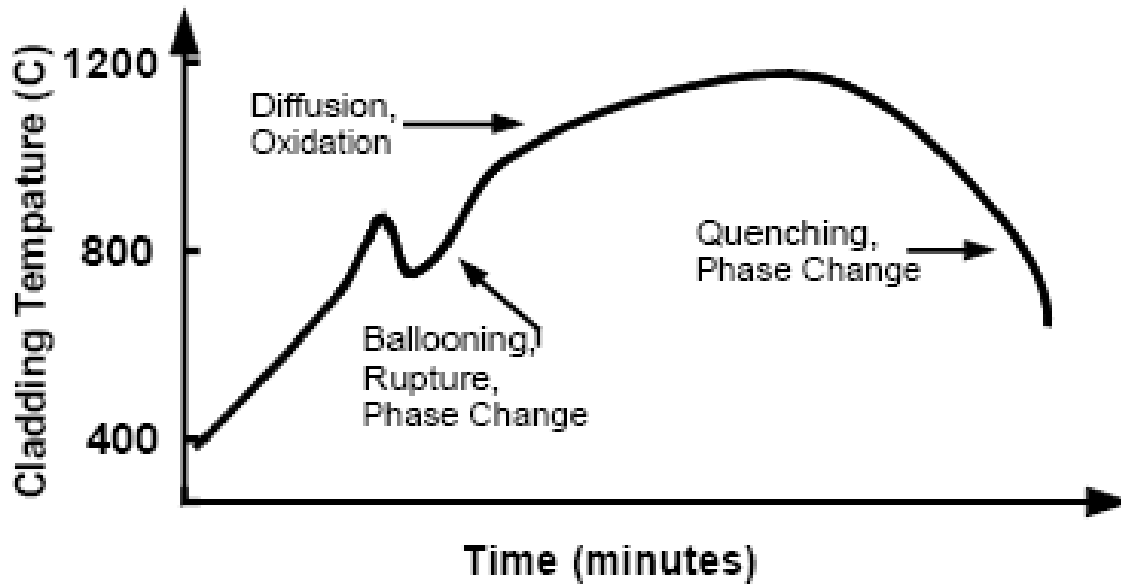
Ralph Meyer, RES

Regulatory Information Conference

March 14, 2007



Cladding Temperature During a LOCA





Current Embrittlement Criteria Specified for Zircaloy and ZIRLO Cladding Alloys (established in 1973)

Temperature Limit: 2200°F = 1204°C [50.46(b)(1)]

Time Limit: Corresponds to 17% Oxidation [50.46(b)(2)]

➡ ***ECR_{calculated} (percent oxidation) ≤ 17%***

Calculate ECR with a weight-gain equation

Assume 1-sided oxygen pickup except in balloon

Assume 2-sided oxygen pickup in balloon

IN-98-29 clarified 17% as Total Oxidation (i.e., Transient + Corrosion)



Cladding Alloys Tested in ANL Program

Element	Zircaloy-2 ^a	Zircaloy-4 ^a	ZIRLO ^{b,c}	M5 ^d	E110 ^e
Sn (wt%)	1.45	1.45	1.1	--	--
Nb (wt%)	--	--	1.1	1.0	1.0
Fe (wt%)	0.14	0.21	0.1	0.038	0.009
Cr (wt%)	0.10	0.10	--	--	--
Ni (wt%)	0.06	--	--	--	--
O (wt%) ^f	0.125	0.125	0.120	0.135	0.06
Zr	Balance	Balance	Balance	Balance	Balance

^aASTM B 811 [3]

^bR. Comstock et al. [4].

^cW. Leech [5].

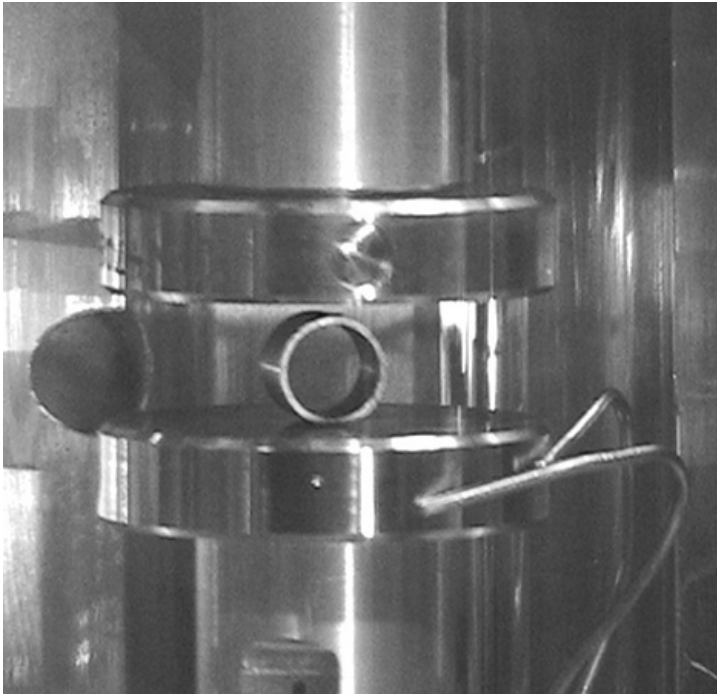
^dJ-P. Mardon et al. [6].

^eP. V. Shebaldov et al [7].

^fOxygen is considered an alloying element in these alloys.



Ring-compression Load Trains for Irradiated and Fresh Cladding Samples



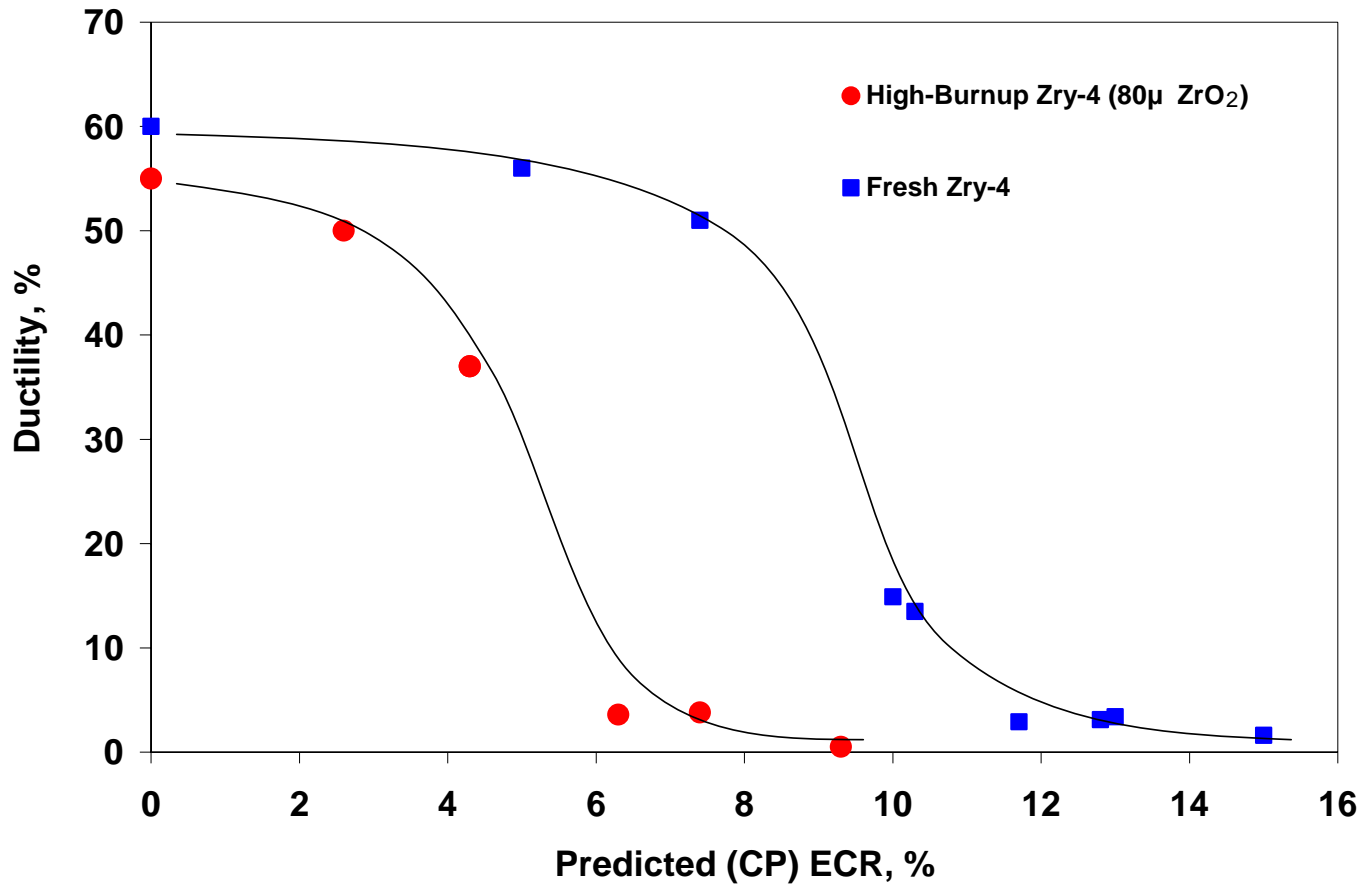
Instron 8511
Radiant Furnace
Glove Box



Instron 5566
Oven Heating



Ductility of High-Burnup and Fresh Zircaloy from H. B. Robinson


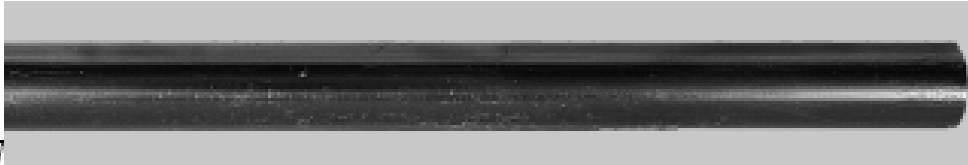




Earlier Russian-made Zr-1%Nb Cladding (E110) after Oxidation in Steam

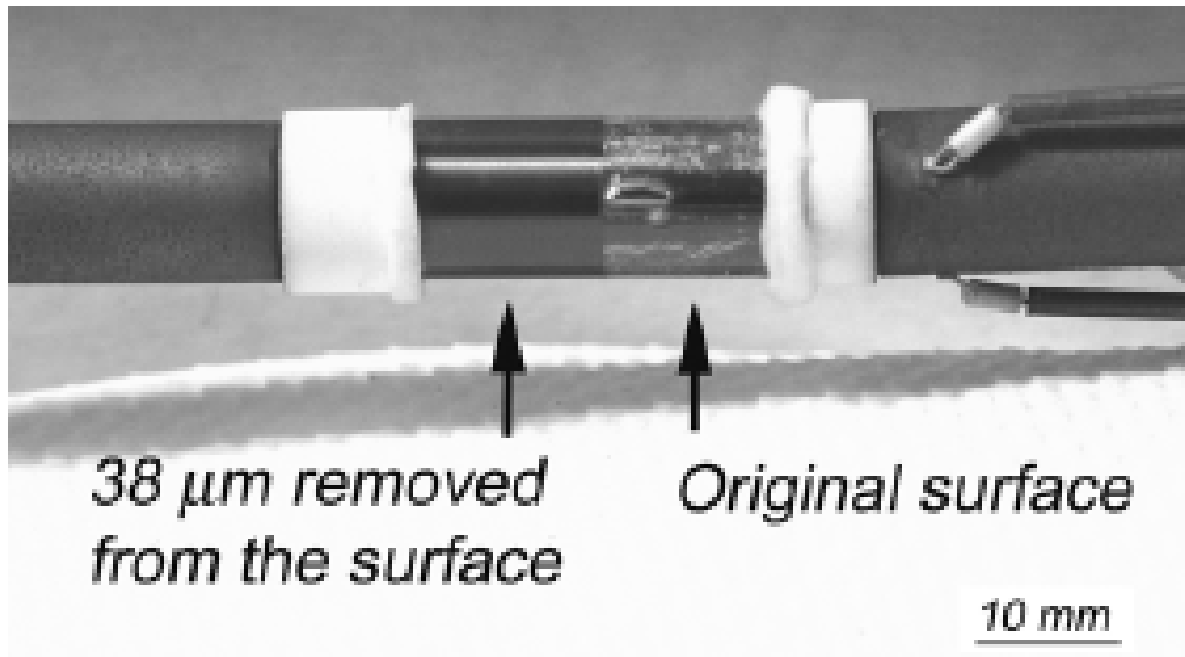


Effect of Ingot Processing on Breakaway

Cladding characterization		Oxidation duration	Cladding appearance	
E110 (standard)	ECR=6.7%	$t_{ef}=4804$ s	#131	
E110 _{G(3m)}	ECR=7.5%	$t_{ef}=14400$ s	#137	

Yegorova et al., NUREG/IA-0211

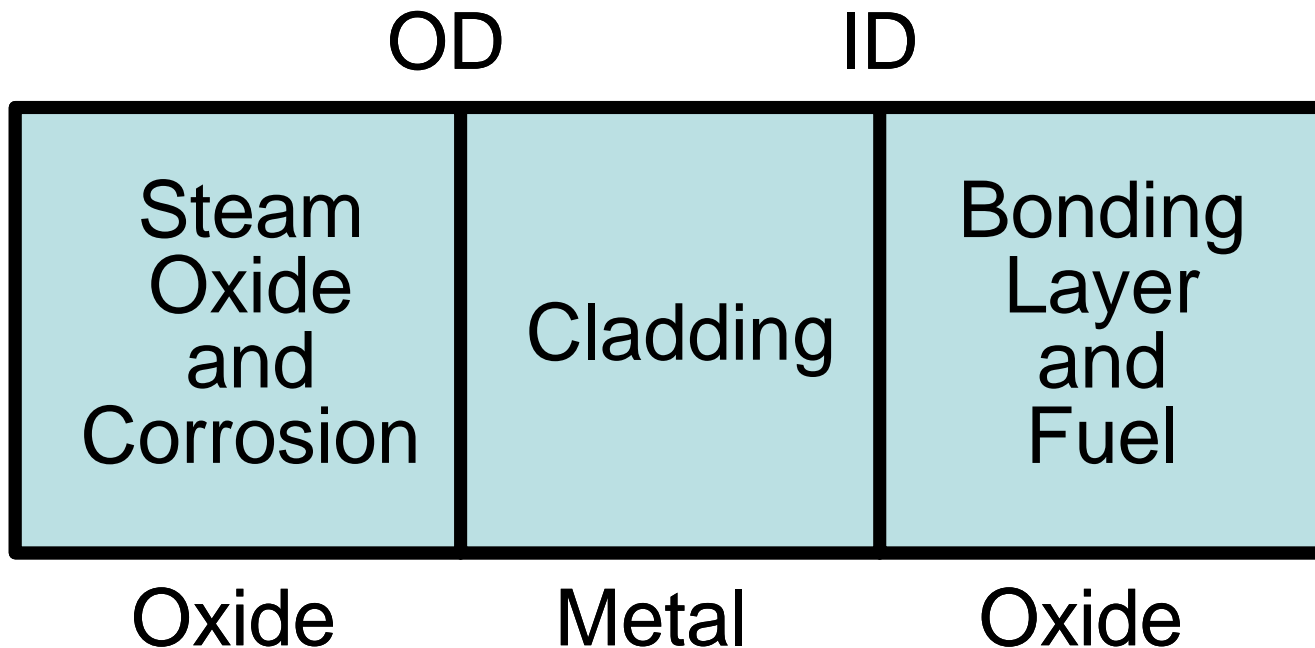
Effect of Surface Condition on Breakaway



E110 following oxidation at 1000°C for 290 seconds



Diffusion-Couple Character of Oxygen Sources and Cladding Metal for High-Burnup Fuel





Performance-based Embrittlement Criteria Appropriate For All Zirconium Cladding Alloys

(research result, not yet subjected to public comment or adopted in regulations)

Temperature Limit: 2200°F = 1204°C [50.46(b)(1) no change]

Time-based Limit: From Tests for each Material [50.46(b)(2) new]

$$\Rightarrow ECR_{\text{calculated}} \text{ (percent oxidation)} \leq ECR_{\text{unirradiated}} - F_{CR} ECR_{\text{corrosion}}$$

$ECR_{\text{calculated}}$ = Cathcart-Pawel weight-gain equation

$ECR_{\text{unirradiated}}$ = embrittlement threshold at 1200°C

F_{CR} = 1.0-1.6 depending on LOCA cooling rate

$ECR_{\text{corrosion}}$ = corrosion thickness from burnup

Always assume 2-sided oxygen pickup

(No embrittlement calculation in balloon)

$$\Rightarrow t \text{ (above } 650^{\circ}\text{C)} \leq \text{measured minimum breakaway time}$$



Example of Criteria for M5

$ECR_{unirradiated} = 20\%$ (we measured this for 17x17, belt-polished, M5)

$ECR_{corrosion} = 4\%$ (arbitrary case, 40 microns)

**$CP\text{-}ECR \text{ (limit)} = 15.2\%$
[current limit 13%]**

**Use 2-sided analysis
[currently done in balloon]**

**$t \text{ (above } 650^{\circ}\text{C)} \leq 6,000 \text{ seconds (measured)}$
[no current limit]**



Example of Criteria for ZIRLO

$ECR_{unirradiated} = 19\%$ (we measured this for 17x17, belt-polished, std. ZIRLO)

$ECR_{corrosion} = 4\%$ (arbitrary case, 40 microns)

**$CP\text{-}ECR$ (limit) = 14.2%
[current limit = 13%]**

**Use 2-sided analysis
[currently done in balloon]**

**t (above 650°C) ≤ 3,000 seconds (we measured it)
[no current limit]**



Example of Criteria for Zircaloy-2

$ECR_{unirradiated} = 19\%$ (we measured this for 9x9, Zirc-2 with a Zr liner)

$ECR_{corrosion} = 1.8\%$ (arbitrary case, 20 microns)

**$CP\text{-}ECR$ (limit) = 17%
[current limit 15.2%]**

**Use 2-sided analysis
[currently done in balloon]**

**t (above 650°C) ≤ 5,000 seconds (we measured it)
[no current limit]**



Example of Criteria for Modern 17x17 Zircaloy-4 (Westinghouse)

$ECR_{unirradiated} = 17\%$ (we measured this for 17x17, belt-polished, low-tin Zirc.)

$ECR_{corrosion} = 10\%$ (defacto regulatory limit, 100 microns)

**$CP\text{-}ECR$ (limit) = 5%
[current limit 7%]**

**Use 2-sided analysis
[currently done in balloon]**

**t (above 650°C) ≤ 5,000 seconds (we measured it)
[no current limit]**



Example of Criteria for Modern 15x15 Zircaloy-4 (Areva)

$ECR_{unirradiated} = 19\%$ (we measured this for 15x15, belt-polished, low-tin Zirc.)

$ECR_{corrosion} = 9\%$ (defacto regulatory limit, 100 microns)

**$CP\text{-}ECR$ (limit) = 8.2%
[current limit 8%]**

**Use 2-sided analysis
[currently done in balloon]**

**t (above 650°C) \leq 5,000 seconds (we measured it)
[no current limit]**



Example of Criteria for Old 15x15 Zircaloy-4 (Areva)

$ECR_{unirradiated} = 14\%$ (we measured this for 15x15 rough surface Zirc-4)

$ECR_{corrosion} = 9\%$ (defacto regulatory limit, 100 microns)

**$CP\text{-}ECR$ (limit) = 3.2%
[current limit 8%]**

**Use 2-sided analysis
[currently done in balloon]**

**t (above 650°C) ≤ 3,800 seconds (we measured it)
[no current limit]**



Example of Criteria for Old Russian E110

$ECR_{unirradiated} = 12\%$ (Kurchatov measured this for standard E110)

$ECR_{corrosion} = 0.5\%$ (Kurchatov measured 5 microns at 50 GWd/t burnup)

CP-ECR (limit) = 11.4%
[current limit 16.5%]

Use 2-sided analysis
[currently done in balloon]

t (above 650°C) ≤ 500 seconds (we measured it)
[no current limit]



Conclusions

Current operating reactors have adequate margin:

- Temperature limit of 2200°F is not exceeded
- Corrosion is being subtracted from 17%
- 17% is conservative at lower temperatures
- 2-sided analysis in a balloon gives about same result as high-burnup ID oxygen pickup away from the balloon

There is a need to revise 50.46(b) now:

- Current rule, without care, might not ensure ductility
- M5 and Optimized ZIRLO now require license exemptions
- Poorly performing variations of present alloys are possible and would not be identified by the present rule
- 50.46(b) criteria desired before 50.46(a) is moved forward

There are sufficient data to revise the rule now:

- Transfer of rulemaking basis from RES to NRR scheduled for March 31, 2007, as a Research Information Letter