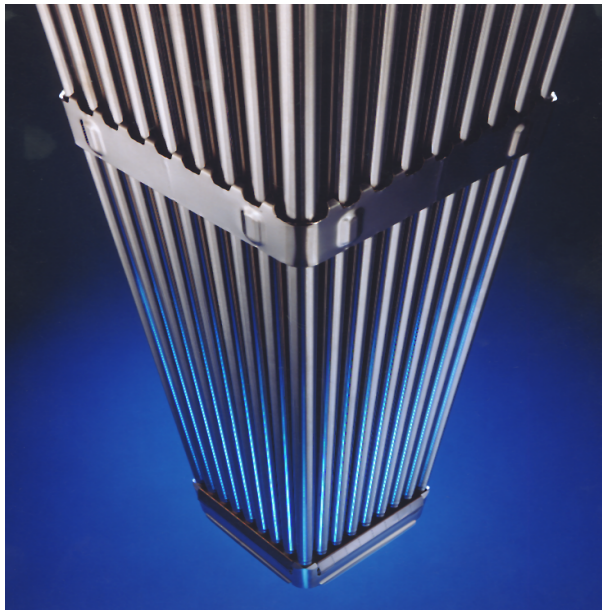
Global Nuclear Fuel
Americas

Proposed New LOCA Requirements



Performance based testing

Public Workshop September 2008

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Basis and assessment

NUREGCR-6967

- Technical basis for proposed new criteria
- Generally good quality work conducted over many years
- Contains significant information on aspects of Zr-based alloy behavior relevant to LOCA considerations (some issues with completeness, test procedures/criterion)

Performance-based testing

- Critical review of NUREGCR-6967 lead to conclusions different than proposed in RIL-0801
- Trace element effects not established by data
- Surface effects dominate and can be controlled through manufacturing controls

Performance-based testing

NUREGCR-6967 results indicate PQD variation with H is not strongly sensitive to alloy composition (including trace element) and manufacturing process based on similar behavior shown by Zircaloys, Zirlo and M5.

Use of prehydriding as surrogate for irradiation is justifiable since prehydrided unirradiated Zry4 show similar transition ECR as irradiated Zry-4, Zirlo and M5.

Russian E110 appears to be different and appears to be the driver for considering periodic testing for breakaway oxidation.

Periodic testing of as-fabricated cladding for PQD and breakaway oxidation

Rationale for periodic testing

- PQD variability concern appears to arise from apparent manufacturing variability.
- Breakaway oxidation concern appears to arise from surface condition effect and performance of E110.

Conclusion based on assessment of data in NUREGCR-6967:

Technical justification appears to be lacking for periodic testing for PQD and breakaway oxidation

Recommendation:

Identify and CONTROL parameters that affect PQD or HT oxidation.

PQD variability in as-fab cladding

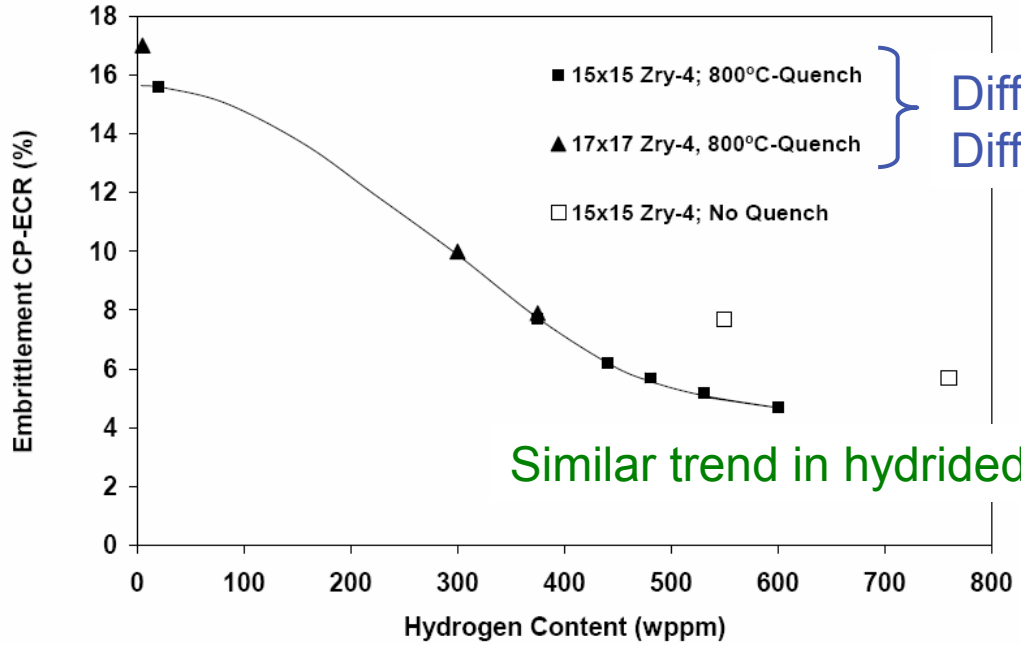
Table 77. Embrittlement Threshold (CP-ECR) for As-fabricated Cladding Alloys Oxidized at 1200°C, Cooled at 11-13°C/s to 800°C, Quenched at 800°C and Ring-compressed at 135°C. For CP-ECR values 1% higher than the embrittlement threshold, the alloys are classified as brittle. Results are rounded off to the nearest whole-number percent.

Alloy and Geometry	Manufacturer	Vintage	Embrittlement Threshold CP-ECR, %	Permanent (Offset) Strain, %
Zircaloy-4 15×15	Siemens	Old, Low Tin H.B. Robinson	16	1.1±0.4 (2.9±0.6)
Zircaloy-4 15×15	AREVA	Current Low Tin	19	1.5±0.3 (3.3±0.6)
Zircaloy-4 17×17	Westinghouse	Current Low Tin	17	1.1±0.4 (2.5±0.5
Zircaloy-2 10×10	Global Nuclear Fuel	Current ID Zr Liner	19	2.2 (3.3±0.4)
ZIRLO 17×17	Westinghouse	Current Standard Tin	19	1.1±0.1 (2.5±0.5)
M5 17×17	AREVA	Current	20	1.0 (3.5±0.4)

- > 16 – 20% when all alloys and variants considered
- > 17 – 20% when modern Zircaloy, Zirlo and M5 considered

PQD variability (17 – 20%) meets / exceeds the current 17% ECR criterion.

PQD variability



Different manufacturer
Different production date

Similar trend in hydrided state

Absence of manufacture variability
(recognized in NUREG/CR6967)

Figure 120. Embrittlement oxidation level (CP-ECR) vs. hydrogen content for 17×17 Zry-4 and 15×15 HBR-type Zry-4 oxidized at ≤1200ºC, cooled at 11-13ºC/s to 800ºC and quenched. Results for samples with large circumferential distributions in hydrogen content (±100 wppm) are not included in this figure because the limited database for these materials was insufficient to determine embrittlement CP-ECR.

- > Hydrogen effect on PQD is the main theme of proposed criteria.
- > Overall PQD test procedure consistent for assessing H effect.
- > Apparent PQD variability for as-fab cladding absent in hydrided state.

No evidence that benefits will result from periodic testing on as-fabricated cladding against variability above 17% ECR.

Surface roughness

Surface roughness affected both PQD and breakaway oxidation

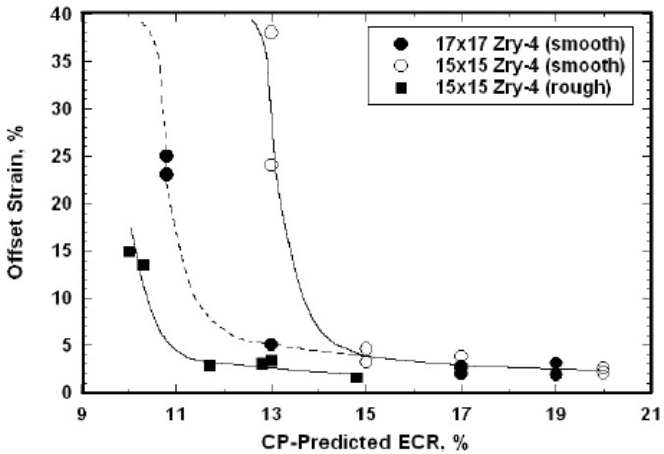


Figure 28. Offset strain vs. CP-ECR for 15×15 and 17×17 Zry-4 samples oxidized at 1200ºC, cooled at ≈11˚C/s to 800ºC, and quenched. Ring compression tests were conducted at 135ºC and 0.0333-mm/s displacement rate. Nominal offset strain for ductile-to-brittle transition ECR is 2%.

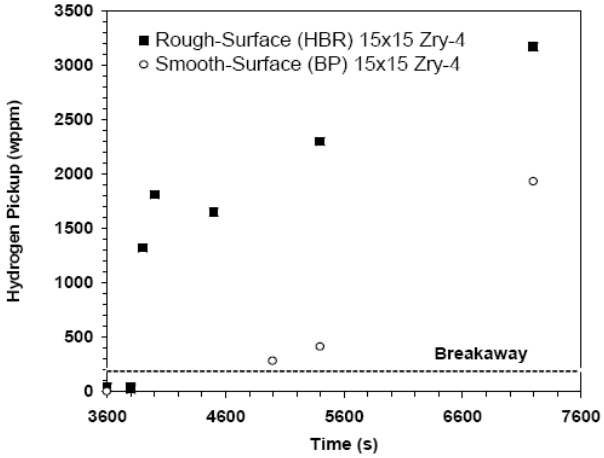


Figure 39. Breakaway-oxidation data for HBR-type (0.3-µm surface roughness) and belt-polished (0.1-µm surface roughness) 15×15 Zry-4 oxidized in the same apparatus at 985±12ºC. Based on the ANL 200-wppm-hydrogen-pickup criterion, breakaway oxidation time is ≈3800 s for HBR-type 15×15 Zry-4 and ≈5000 s for belt-polished (BP) 15×15 Zry-4.

Recommendation:

Control surface roughness to within qualified domain using manufacturing QA procedures

(rather than using PQD or breakaway oxidation for control)

Breakaway oxidation (hydriding)

- Concern is on **ductility** due to excessive H from **Breakaway Hydriding.**
- Current Kroll and belt finishing fabricated alloys provide sufficient time to breakaway oxidation
- E110 performs poorly – appears to drive concerns on breakaway oxidation and on trace element effect.

E110 and trace element effect

- Considerable effort assessing E110 at ANL
- Poor PQD related to poor HT oxidation behavior and appears to be related to surface conditions of E110
- Need to account for surface condition before trace element effect established
- E110 in as-fab condition is not compatible with current 17% ECR criterion

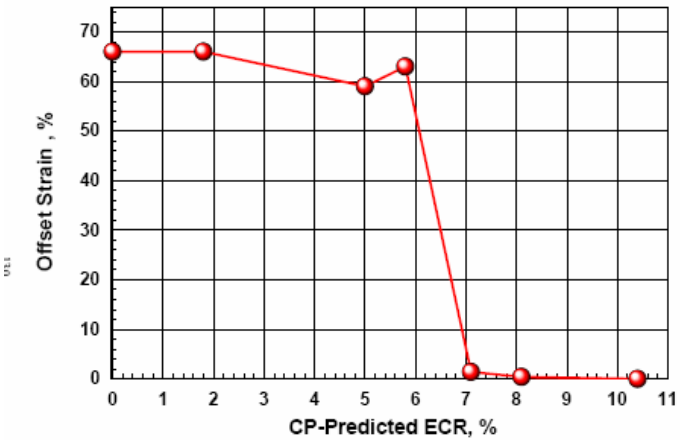
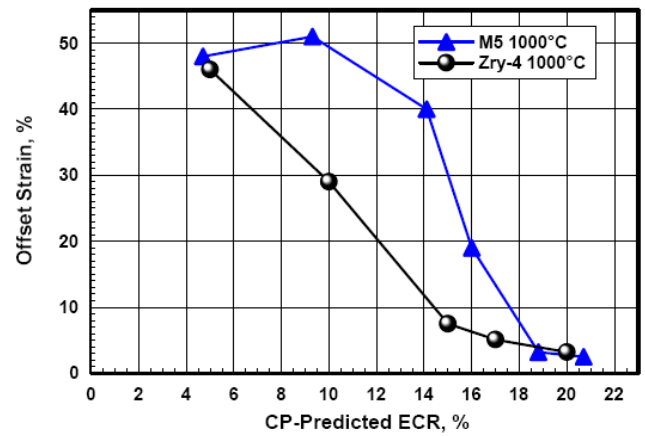


Figure 92. Room-temperature offset strain vs. CP-ECR for as-fabricated E110 tubing oxidized (two-sided) in steam at 1000°C for hold times of 0-825 s. Sample length is 8 mm, and displacement rate is 0.0333 mm/s. Embrittlement is due to excessive hydrogen pickup (>200 wppm).



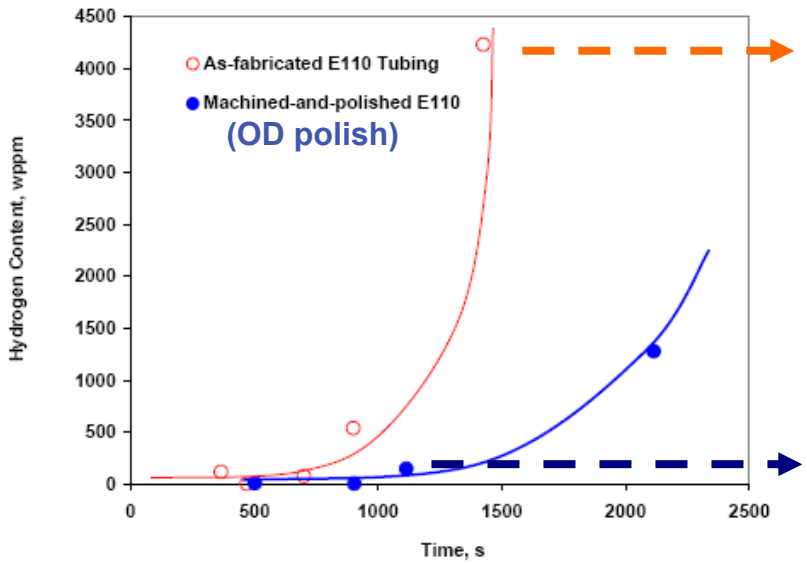
(b)

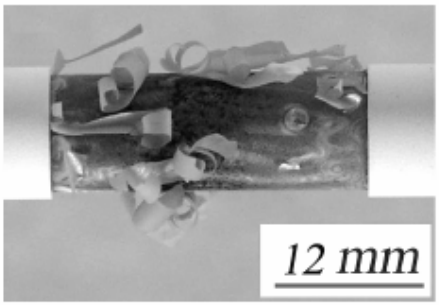
Figure 67. Post-quench ductility vs. measured (a) and CP-predicted (b) ECR for 17×17 M5 and Zry-4 oxidized in steam at 1000°C, cooled at ≈10°C/s to 800°C, and quenched. Offset strain was determined from results of ring-compression tests conducted at RT and 0.0333-mm/s displacement rate.

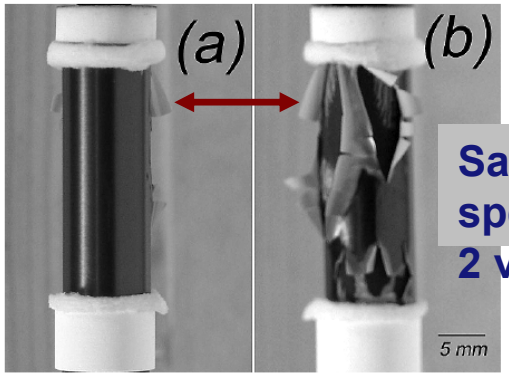
Current 17% ECR criterion is adequate in identifying poor performing material; additional breakaway oxidation requirement would be redundant.

E110 and trace element effect (2)

- Potential trace element effect appears to be confounded by surface condition
- ANL machine-and-polish appears to have been partially effective in eliminating surface condition effect
  - > 1100°C and 1200°C-oxidized machine-and-polished samples showed similar PQD as M5 and Zry4
  - > 1000°C-oxidized machine-and-polished samples still showed poorer breakaway oxidation behavior than M5 or modern Zircaloys – **surface condition effect NOT eliminated**
- ANL **machine-and-polish** means machine-and-polish on ID and **polish only** on **OD**.







Same specimen 2 views

Polish (OD) not as effective as machine+polish.
➔Expect more improvement with OD machining.

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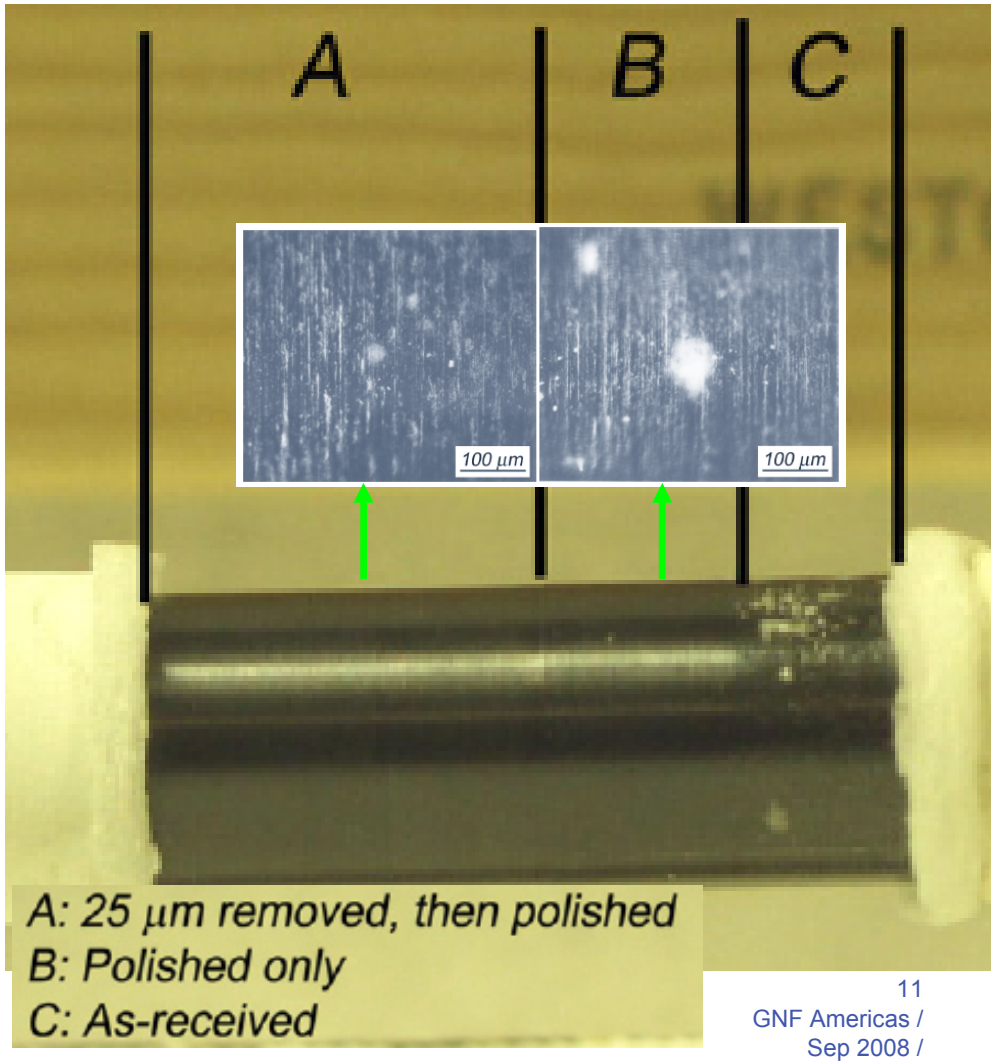
E110 and trace element effect (3)

- Trace element effect (sponge vs. electrolytic) is established only **IF** poor performance of E110 persists after surface condition effect has been eliminated.

- OD polish NOT as effective as machine+polish
- Results for 1000°C-oxidized E110 ANL M+P samples is consistent with insufficient OD surface removal.
- Trace element effect not established from ANL results. **Consistent with NUREG/IA-0211**
- Surface condition effects possibly reflected in corrosion behavior



Recommendation:

Evaluate use of corrosion testing to control surface condition (contamination).

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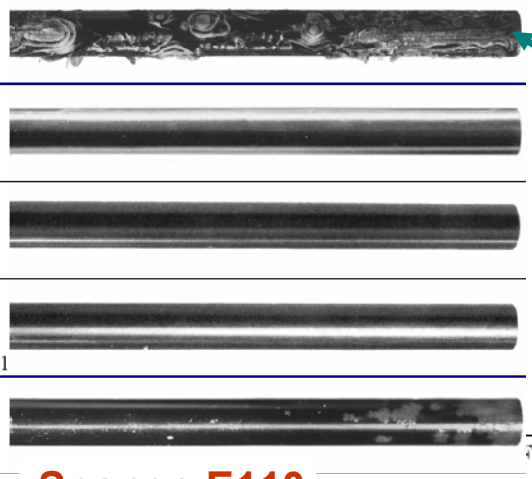
Trace Element Effect – **E110**

(NUREG/IA-0211)

Cladding characterization		Oxidation duration	Cladding appearance
E110 (tradi-tional)	ECR=7.7%	t_{ef}=865 s	#44
$E110_{G(fr)}$	ECR=6.5% (28 ppm of H content)	t_{ef}=2016 s	#91
$E110_{G(3ru)}$	ECR=6.9% (16 ppm of H content)	t_{ef}=2519 s	#98
$E110_{G(3ru)}$	ECR=8.9% (11 ppm of H content)	t_{ef}=5028 s	#101
$E110_{G(fr)}$	ECR=8.5% (12 ppm of H content)	t_{ef}=5013 s	#93



Sponge E110

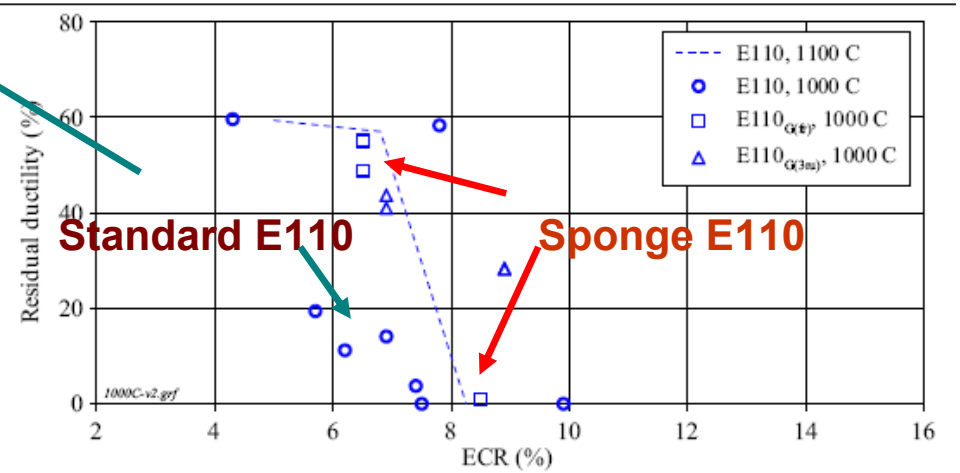


Fig. 4.12. The appearance and mechanical properties of different E110 cladding after the oxidation at 1000 C

P 4.16

Besides, the obtained data allow to formulate one new problem: for oxidation at 1000 C, the critical measured ECRs corresponded with the zero ductility thresholds of standard and sponge ECR claddings are similar to both types of the cladding but the oxidation duration differs approximately six times. In the context of this

Trace element effect (electrolytic vs. sponge) for E110 appears to be NOT evident for ductility but evident for oxidation.

Trace Element Effect – **E635**
(NUREG/IA-0211)

P 4.21

The results obtained during this research confirm the important role of iron in the cladding oxidation behavior. This thesis is based on the fact that sponge types of the E110 cladding with the higher content of iron demonstrate the better corrosion behavior than the standard E110 alloy with low Fe content as well as on the fact that the results of oxidation tests of the E635 cladding (iodide/electrolytic) with a very high content of iron have shown that the oxidation behavior of the standard E635 cladding is somewhat better than that of the standard E110 cladding. Though, in this case the absence of a general difference in the oxidation behavior of the standard E635 and sponge E635 impels to involve additional test data to continue the analysis of this and other issues connected with the chemical composition of Zr-Nb alloys. The interesting scope of investigations was recently performed in the VNIINM (Russia) [25].

P 5.16

the oxidation and mechanical tests of the E635 cladding with a very high iron content in the cladding material (0.34–0.4% by weight) showed that the oxidation behavior and embrittlement threshold of iodide/electrolytic E635 was somewhat better than that for the iodide/electrolytic E110 but the sponge variant of E635 had practically the same embrittlement characteristics as iodide/electrolytic E635. And

Trace element effects on HT oxidation and embrittlement from electrolytic / sponge Zr comparison appears to be NOT generic.

Summary: Periodic PQD and breakaway oxidation testing

- PQD variability: Above current 17% criterion and absent in hydrided state.
- Surface roughness can affect PQD and HT oxidation. Recommend apply QA control within qualified domain.
- Breakaway oxidation concern dominated by E110 surface condition. Trace element effect is not established from test data. Recommend evaluate use of corrosion testing to monitor surface condition or contamination.

Conclusion:

Technical justification appears to be lacking for periodic testing for PQD and breakaway oxidation

Recommendation:

Identify and CONTROL parameters that affect PQD or HT oxidation.