Comments to the 10 CFR §50.46 Acceptance Criteria for ECCS for LWRs

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10 CFR §50.46 - Background

- The §50.46 (Acceptance Criteria for ECCS for LWRs) is going to be soon modified by NRC (High-burnup, New materials, **New Phenomena**).

- Goal of the §50.46: ... mainly to minimize the consequences of the Water-Metal Reaction during the postulated LOCA (Heat & Hydrogen release, Embrittlement / **Fragmentation** / Coolability).

- Rulemaking process: Discussions, …, questions, … :

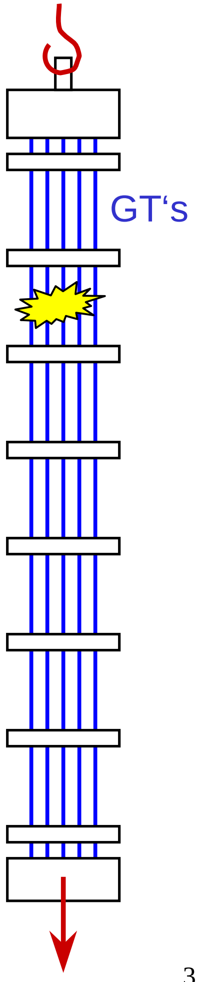
  ⇒ Is fuel rod the only concerned structure ? (… guide tube)

  ⇒ Role of hydrides in the embrittlement of Zr-alloys (cooling rate)

  ⇒ How to formulate a LOCA oxidation criterion ? (… methodology)

Post-LOCA Embrittlement of Oxidized Guide Tubes

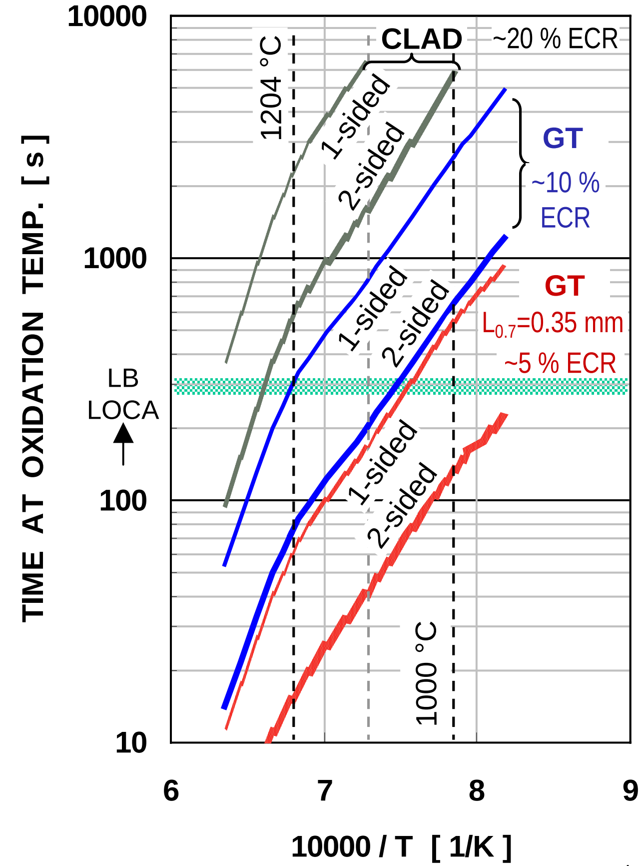
- § 50.46: No limit for the PWR GT oxidation
- Oxidation of GT should be limited to prevent its post-LOCA fragmentation (seismic, transportation).
- GT transient oxidation compared to claddings:
  - Temperature: GT < CL ($\Delta T < \sim 100$ ºC)
  - Wall thickness: GT < CL (~0.4 versus ~0.6 mm)
  - Axial & bending loads: GT > CL (to be analysed ...)
- Questions:
  - Is the GT embrittlement a safety-related problem ?
    (Embrittlement criteria for claddings - Chung-Kassner, …)
  - Oxidation inside GT: Stagnant steam conditions ?



Post-LOCA Embrittlement of Oxidized Guide Tubes cont'd

- Chung-Kassner handling criterion
  [**ZRY** CLAD **0.635 mm**, **0.3 J** (300 K), NUREG/CR-1344]:
  $L\beta_{0.7\ wt\%\ O} > 0.3$ mm
  - Zry cladding (**0.6** mm WALL, **1200** °C):
    1-sided ~2200 s
    2-sided ~550 s — TO REACH $L\beta_{0.7}$
  - Zry guide tube (**0.4** mm WALL , **1100** °C):
    1-sided ~800 s
    2-sided ~200 s → WITHIN LB LOCA
- CH-K h. criterion applied to GT:
  → two-sided oxidation →
  small safety margin

Time calculated for Zircaloy to reach $L\beta_{0.7}$ = 0.3 & 0.35 mm



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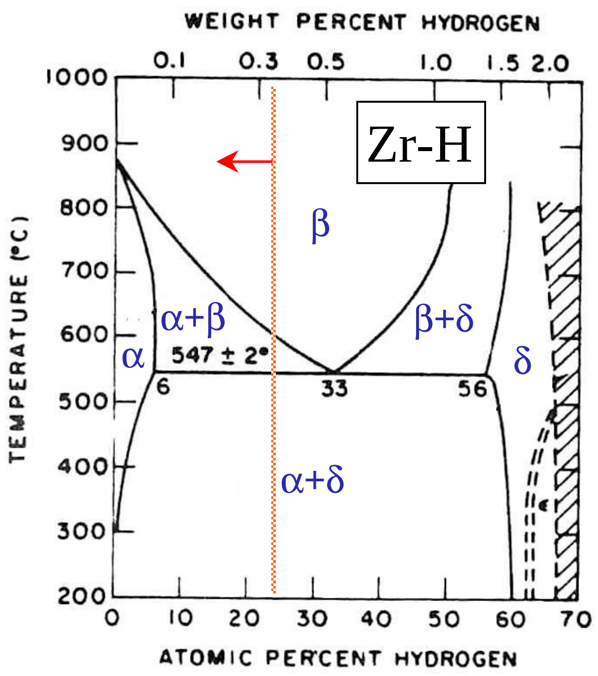
Post-LOCA Embrittlement of Oxidized Guide Tubes cont'd

- CH-K handling criterion - claddings:
  - Not axially and/or radially (pre)-loaded during the tests
- CH-K handling criterion applied to guide tubes:
  - Additional loads:
    - FA weight (handling & transportation)
    - Bending (fixed spacer grids - no slip, ...)
  - Stagnant steam inside GT ? $\rightarrow$ High hydrogen absorption ?
  - Experimental data for thin (~0.4 mm) GTs ?
- Question:

  Criterion for claddings - applicable also for GT ?

Role of Hydrides in the Embrittlement of Zr-Alloys

- β-Zr may dissolve > ~5000 ppm H above ~550 °C (eutectoid T)
- Necks at rupture: < ~3500 ppm H
- Intact cladding : << ~1000 ppm H
- Uetsuka 1981 (slow cooling <700 °C): δ-hydrides decrease the ductility
  J. Nucl. Sci. Tech. 18 [9],[10] (1981)
- Brittle failure depends on: Hydride distribution, spacing, …



- Question: Conditions for hydrides formation ?

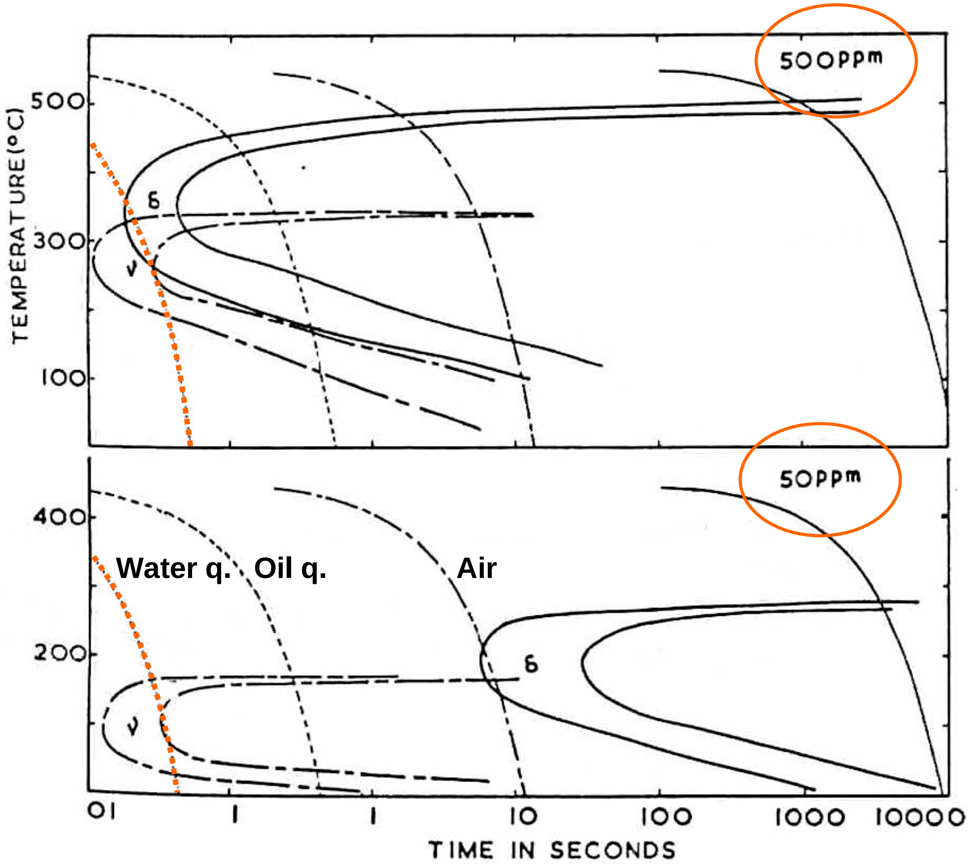
Role of Hydrides in the Embrittlement of Zr-Alloys cont'd

- Contradictory data about the hydride formation:
  - Mishima 1968 … *The precipitation can occur under rapid cooling conditions such as quenching into ice water.* J. Nucl. Mater. 27 (1968)
  - Nath 1975 … *Stable δ-hydrides form on water-quenching (>1000 °C/s) at concentrations > ~500 ppm H.* J. Nucl. Mater. 58 (1975)
  - Chung 1980 … *Rapid cooling (~970 °C/s) through ~550 °C suppresses hydride precipitation (H < ~2000 ppm).* NUREG/CR-1344 (1980)
  - ANL 2001 → : *Integral test results: quenched x furnace-cooled ?*
- Questions:
  - Does a minimum cooling rate exist that suppresses hydrides ?
  - If yes: Cooling rate → Safety-related parameter for §50.46 ?

Role of Hydrides in the Embrittlement of Zr-Alloys cont'd

C-curves representing δ-hydrides formation in Zr-H (1.5 mm thick strips)

- … Stable δ-hydrides can hardly be avoided above ~500 ppm H …
- Metastable intragranular χ-hydrides form on water quenching even at ~50 ppm H ...



Nath et al: J. Nucl. Mater. 58 (1975)

Comments to the Development of an Oxidation Criterion

- SEGFSM TF on LOCA Test Methodologies
  - Difficult to find consensus: Missing complex view on the problem ?

- Purpose of the oxidation (embrittlement) criterion (PWR)
  - … to avoid fragmentation of the oxidized fuel assemblies (FA) due to thermal shock & post-LOCA loads.
- Concerned FA structures
  - Fuel rods (FR), Guide tubes (GT) (?), Grids (?)
- Listing & definition of the loads considered in FA
  - Thermal shock - Axial restraint & bending by grid spacers ? (slip allowed ?)
  - Post-LOCA loads - Seismic forces: Data available ?
    - Handling: Bending ? Tensile loads (GT) ?

Comments to the Development of an Oxidation Criterion

continued

- Listing of the critical elements / positions / phenomena
  - Stagnant steam oxidation
    - FR - burst position: outer/inner oxidation, wall thinning, hydridation, ...
    - FR - necks below/above the burst: hydridation, outer/inner oxidation, ...
    - (GT - inner surface: oxidation, hydridation ?)
  - Flowing steam oxidation
    - FR - intact: outer oxidation, pre-oxidized, pre-hydrided
    - (GT - outer surface: oxidation)

- Representative (and/or acceptable) oxidation method (inner / outer heating, T gradient through oxide, non-uniformities at burst …)
  - Heating: Resistance f., Infrared, DEH, Induction, Internal W-heater)
  - Oxidation conditions: Isothermal → transient
  - Exposed specimens: O & H content, layers, O-profile, hydrides, …

Comments to the Development of an Oxidation Criterion

continued

- Testing of the oxidized rods (FR, GT)
  - Representative specimens (length)
  - Quenching (partial axial restraint, bending, cooling rate, …)
  - Bending (empty FR ?), Impact-& Ring-compression tests, … ,
    - Room temperature ?
    - <u>Archive the load-deflection curve of each specimen</u> (future)
      (and also O & H content, layers, O-profile, hydrides, …)

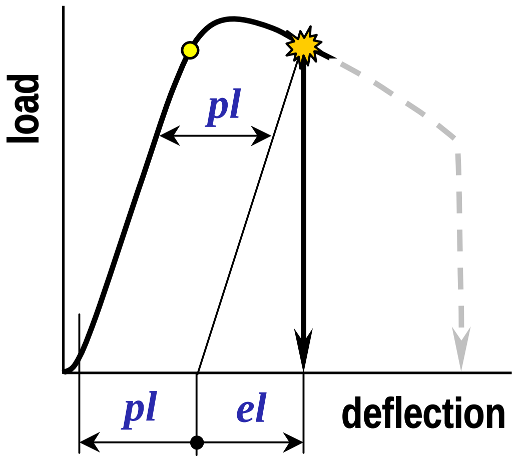
- Evaluation of the mechanical behavior of the oxidized rods
  - Thermal shock: Brittle fracture - Yes/No
  - Post-LOCA loads: What parameter is important in the tests ?
    - … deflection to failure, <u>plastic deflection to failure</u>, energy to failure, load at failure, … ?

Comments to the Development of an Oxidation Criterion

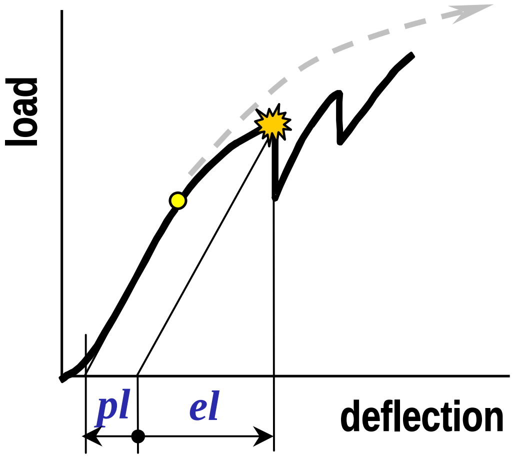
continued

- Formulation of an oxidation criterion
  - Approach of a <u>non-zero ductility</u> in the oxidized rods at failure: Failure "<u>far enough" from the ductile-to-brittle transition</u>.
  - The post-LOCA loads (to resist to), not quantified, will be covered by the always available ductile component.

BENDING TESTS



RING COMPRESSION TESTS



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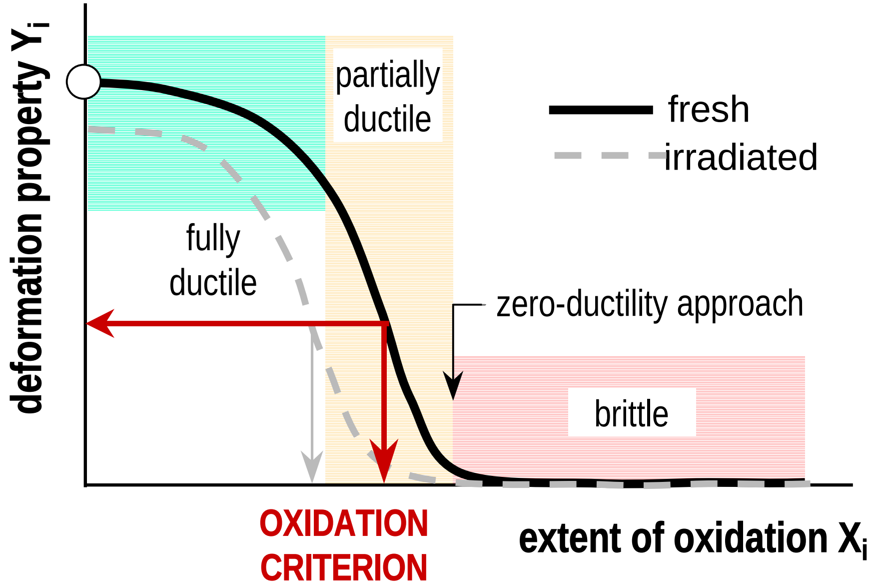
Comments to the Development of an Oxidation Criterion

continued

- The central part of the “partially ductile” transition zone determines both the maximum oxidation and the minimum plastic deformation.



Xi - ECR (≈ time at oxidation T),
Lβx%O,
O-weight gain,
centerline O-content in β-Zr,
H-content, hydride properties …

Yi - plastic deformation,
energy to failure,
load,
impact energy, ...

Conclusions

- Post-LOCA embrittlement of (thin) guide tubes
  - No limit for the GT oxidation in the current §50.46.
  - Two-sided oxidation may rapidly consume the available ductility.
- Impact of hydrides onto Zr-alloy embrittlement
  - May hydride formation be prevented on quenching ?
  - Is feasible to evaluate hydrides in the LOCA Test Methodology ?
- Comments to the oxidation criterion
  - Avoid to consider the indications on material toughness as an a priori failure criterion (prototypic conditions are difficult to simulate ...).
  - The uncertainties in the assessment of the post-LOCA loads may be covered by a required presence of a non-zero ductility.