Recent data on M5™ Alloy under LOCA Conditions (as compared to Zy-4 behavior)

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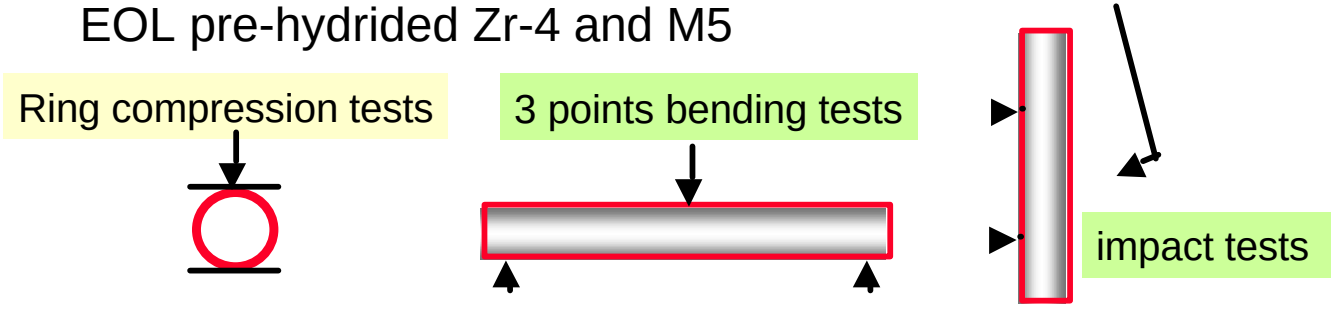
How does Nb-based alloys compare to Zr-4 under LOCA conditions ?

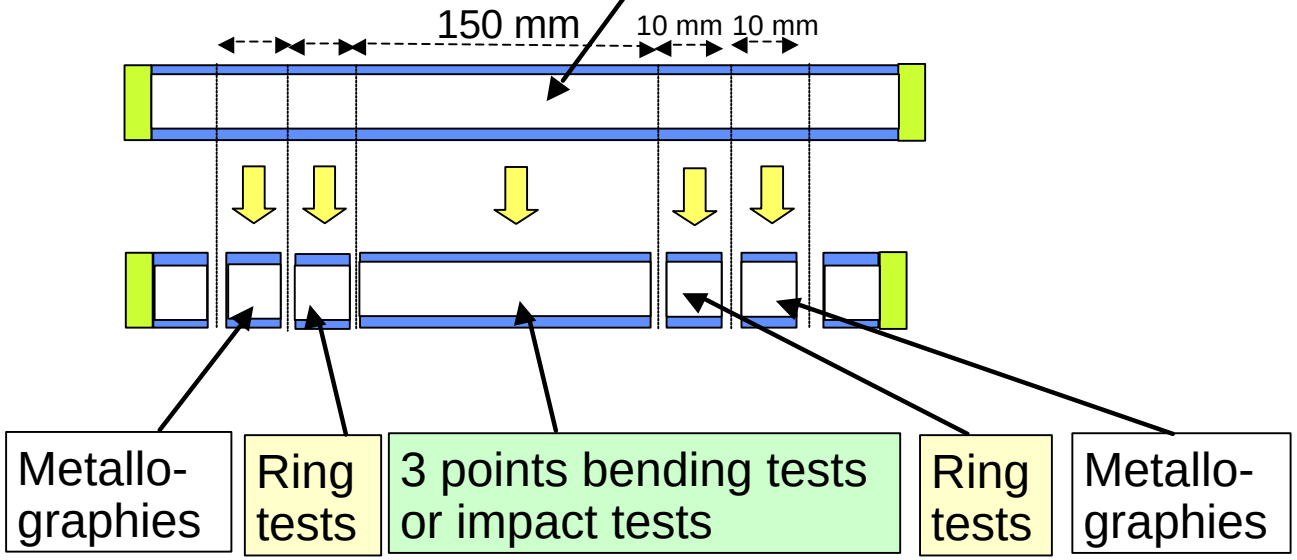
- Recent papers of experimental results on E110 cladding material suggested that all **Nb-based alloys may behave worse than Zr alloys** under LOCA conditions
  - Higher H pick up during high temperature oxidation
  - Lower post-quench residual ductility
- The purpose of this paper is to demonstrate that the Nb-based Alloy-**M5™** proposed by Framatome - behaves similar to (or better than) **Zr-4** under prototypical LOCA conditions

Current LOCA limits are based on post quench mechanical tests

- The LOCA limits are somewhat related to the **zero residual ductility** limit of the cladding measured **after** the LOCA transient, **at low temperature** using ring compression tests (Hobson 1970) or impact tests (Chung 1973)
  - »LOCA limits : ECR < 17% and PCT < 1204 °C
- To adopt the 1972 approach, *EDF*, Framatome-ANP and CEA and have performed a series of **post-quench mechanical tests** with as–received and prototypical EOL pre-hydrided Zr-4 and M5

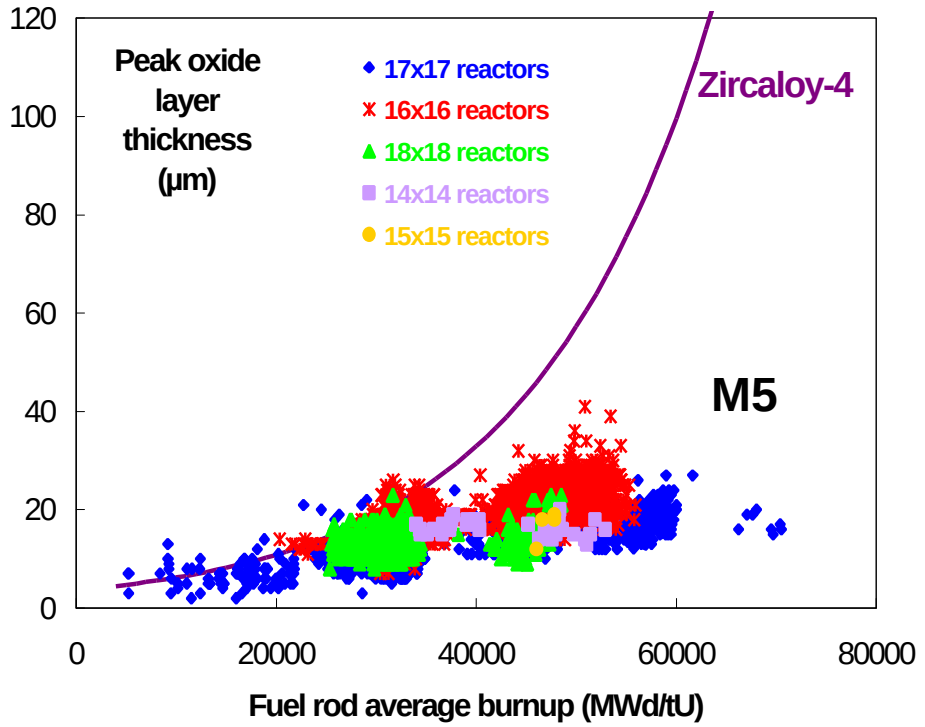


Closed-end specimen oxidized at high temperature then quenched

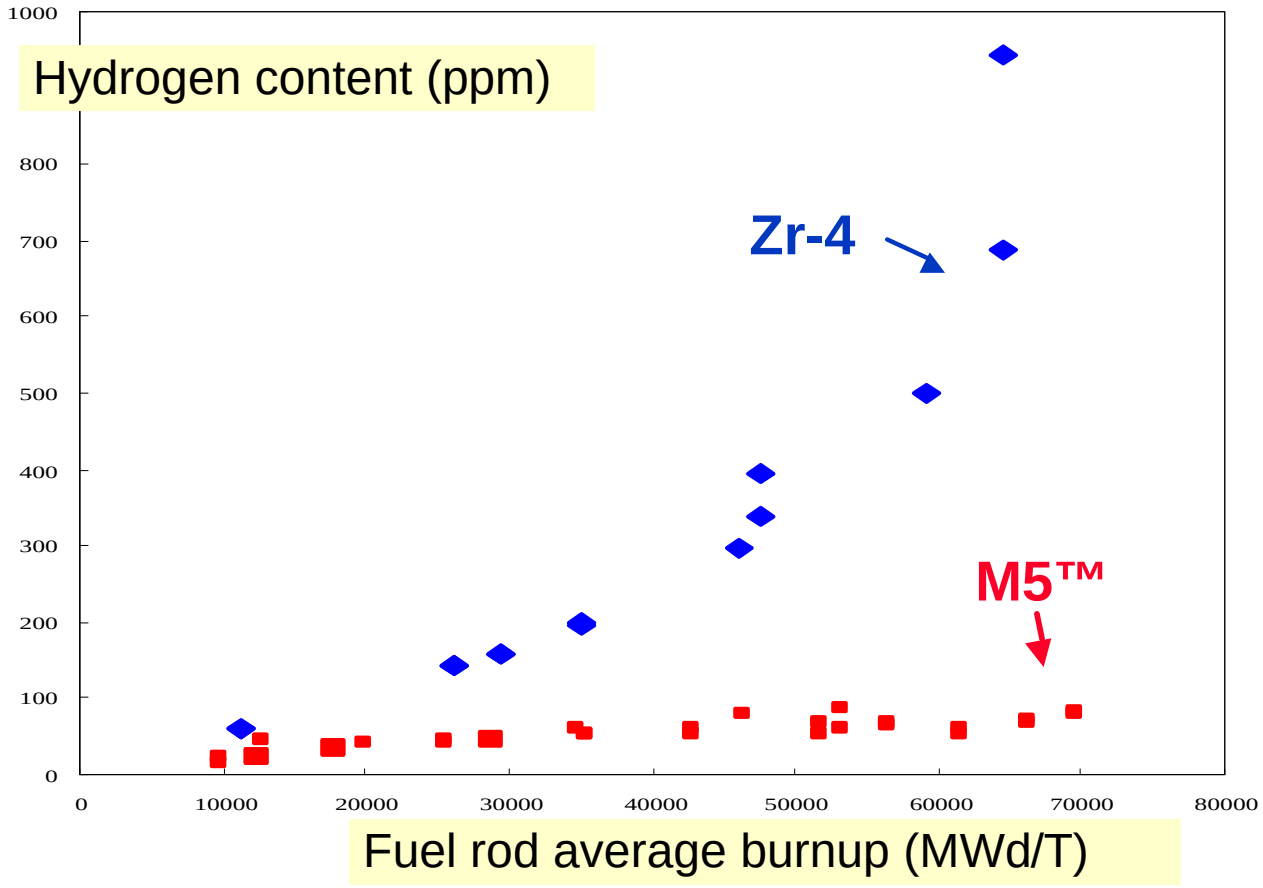


- 4 levels of oxidation temperatures : 1000 –1100 –1200 -1300ºC
- 4 levels of ECR
- Tests on **pre-hydrided** specimens (to simulate in-reactor corrosion)

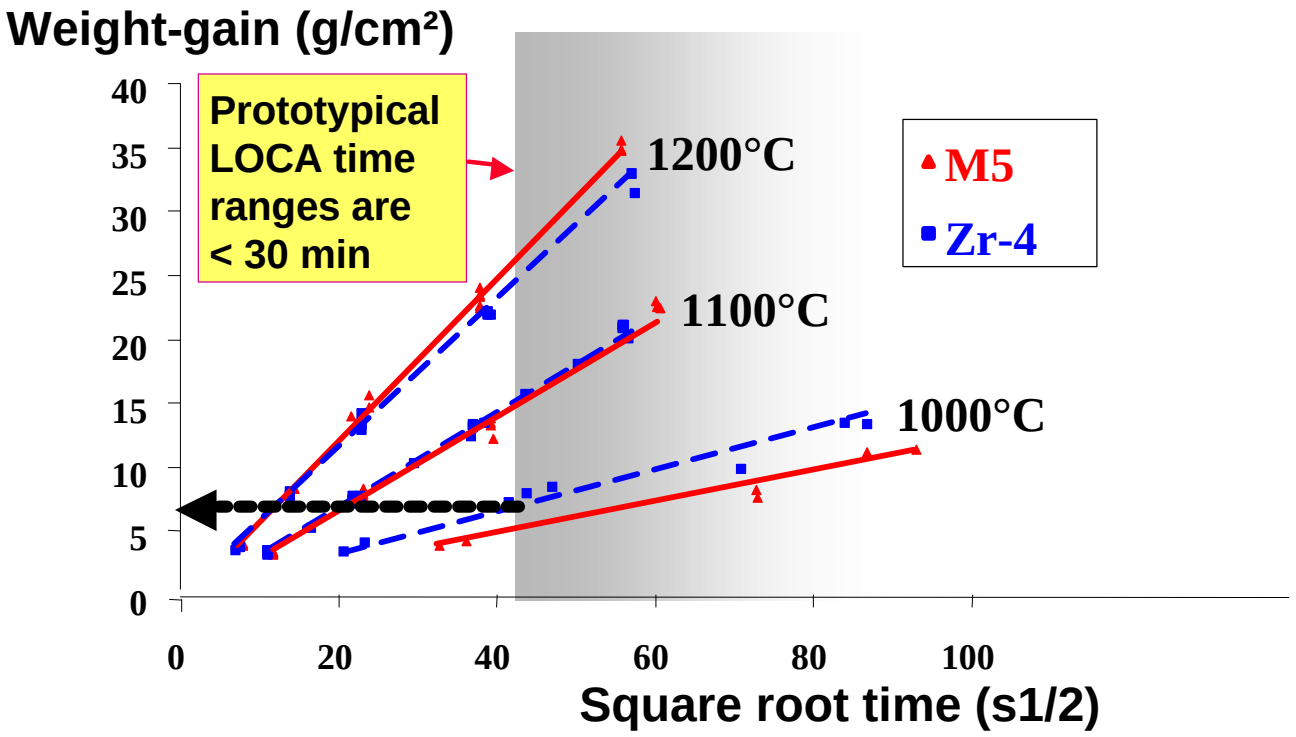
M5™ exhibits a much better in-reactor behavior than Zr-4



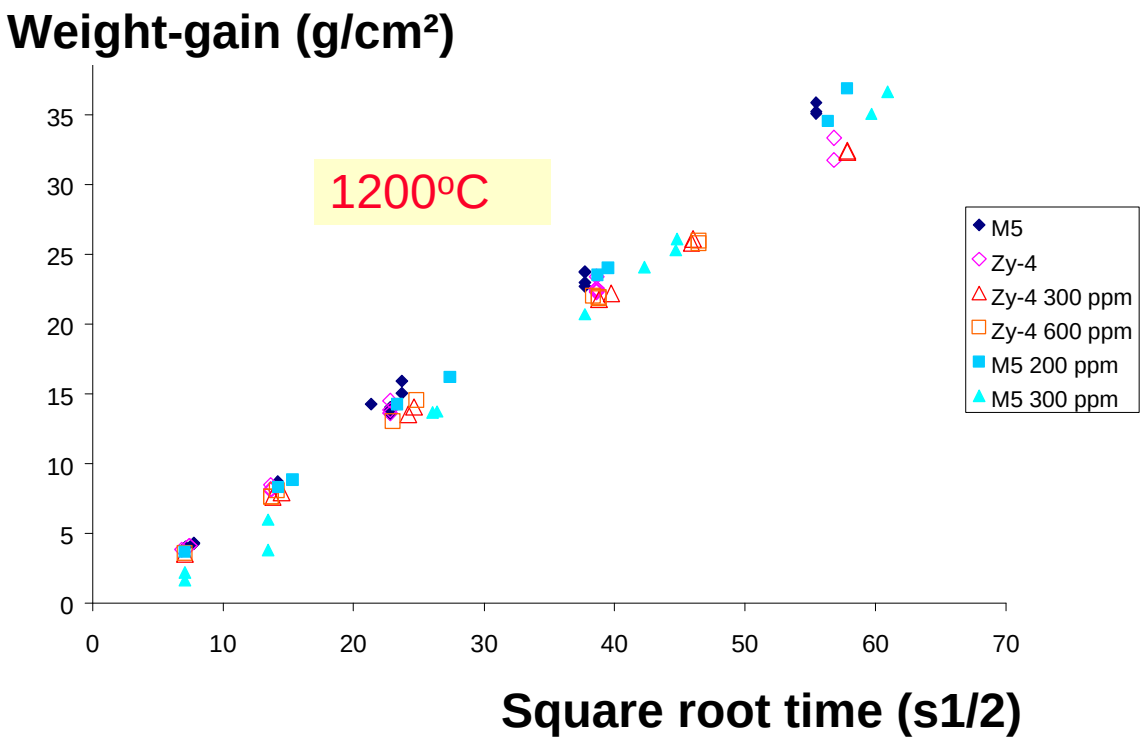
Hydrogen Uptake of M5™ is extremely low



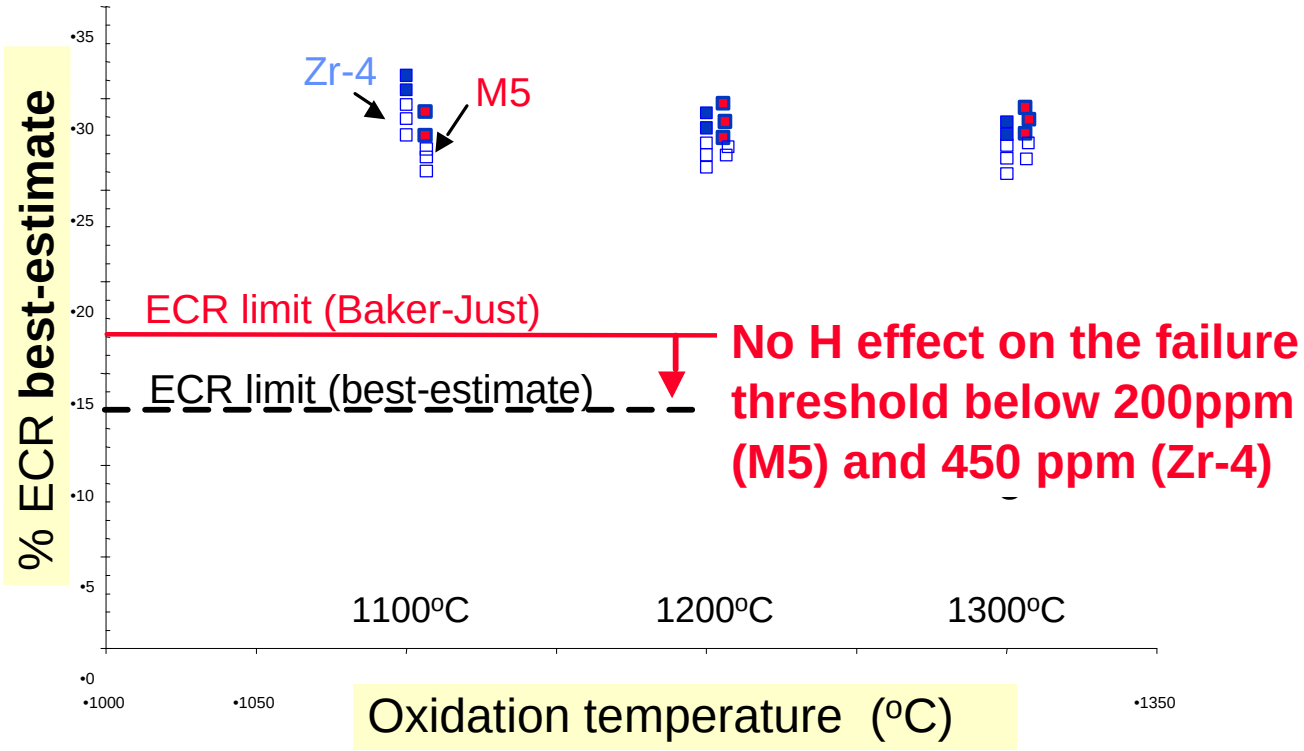
M5™oxidation kinetics are equivalent to Zr-4



No impact of H on oxidation kinetics for both alloys



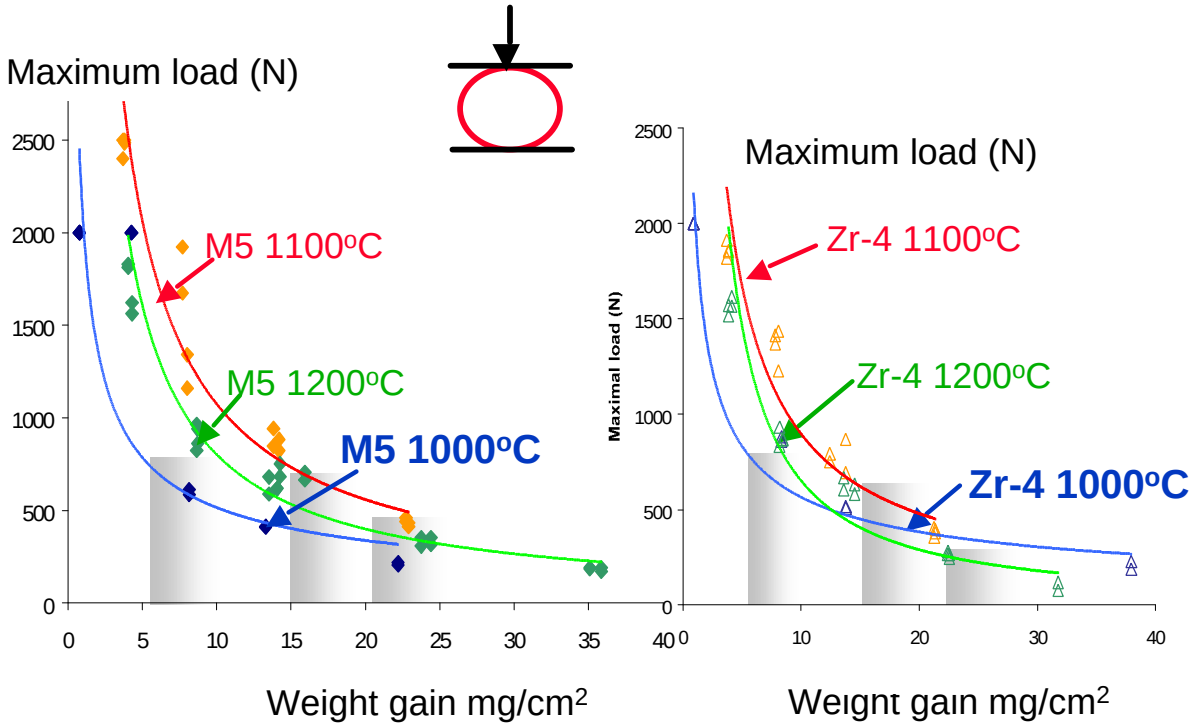
“Failure” upon quench is the same for Zr-4 and M5™-



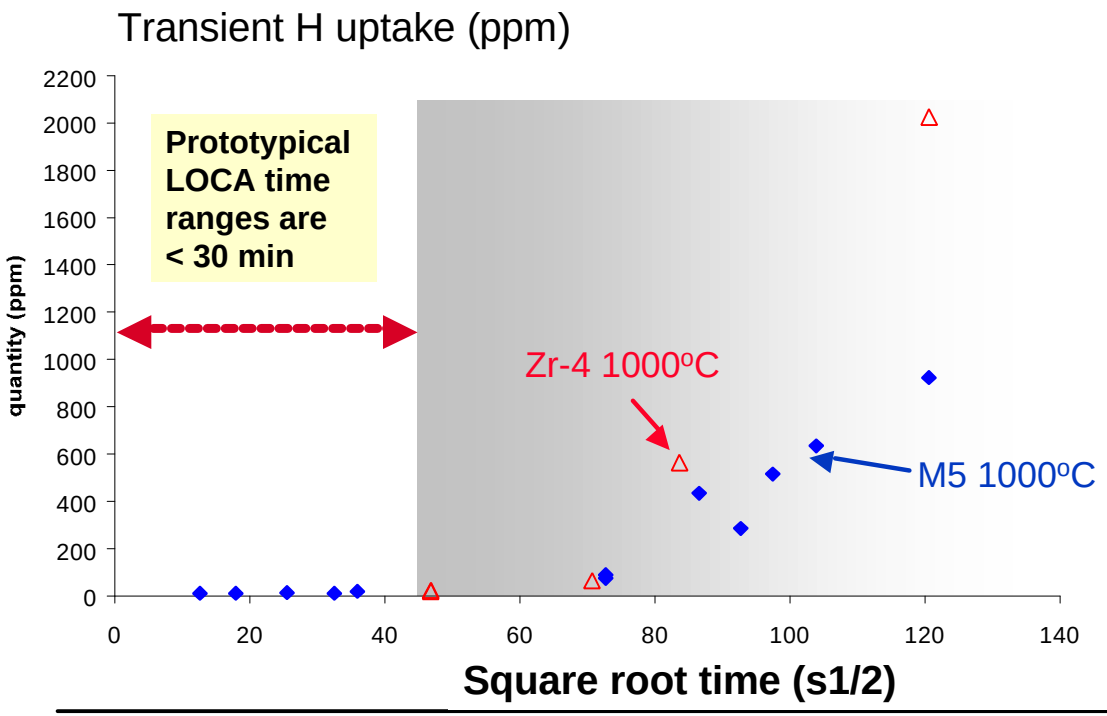
Behavior upon quench

- High temperature oxidation kinetics and quenching behavior are **equivalent for M5 & Zr-4**
- The failure thresholds of **pre-hydrided** M5™ and Zr-4 remain unchanged
- Negligible **transient hydriding** was observed after oxidation and quench (< 25 ppm)
- Time to failure upon quench at **1000°C** for fresh and pre-hydrided specimens are much longer than the time envisioned for LOCA

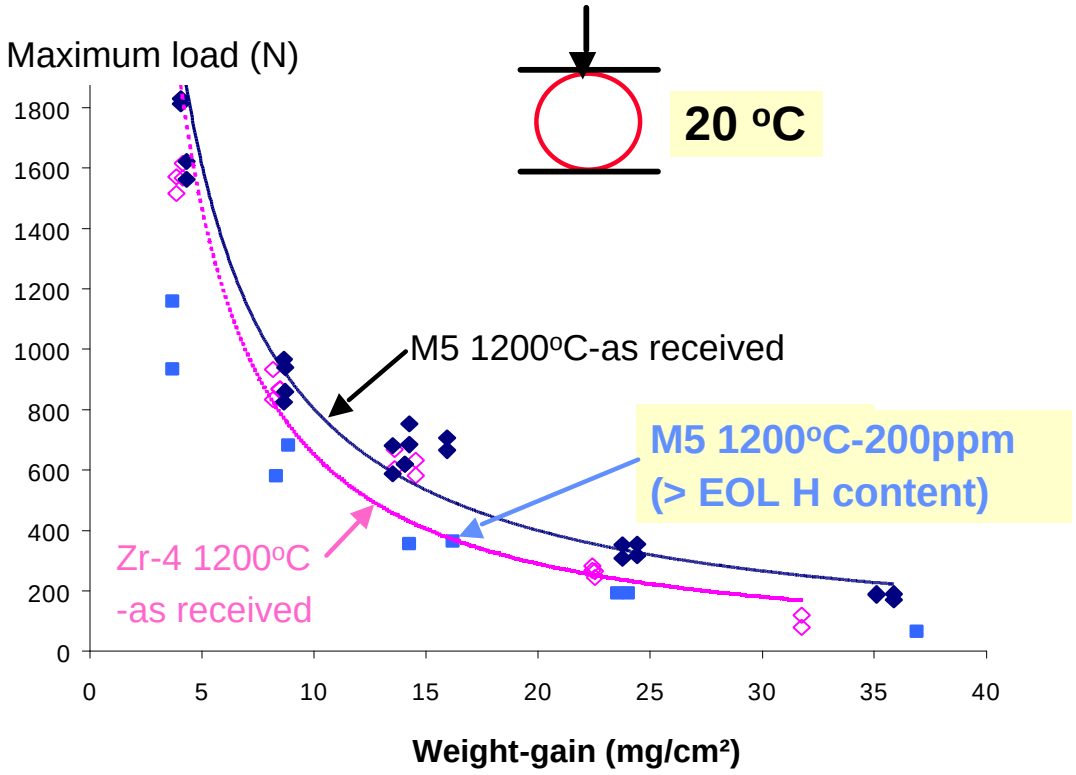
Post-Quench Ring Compression Tests at 20°C



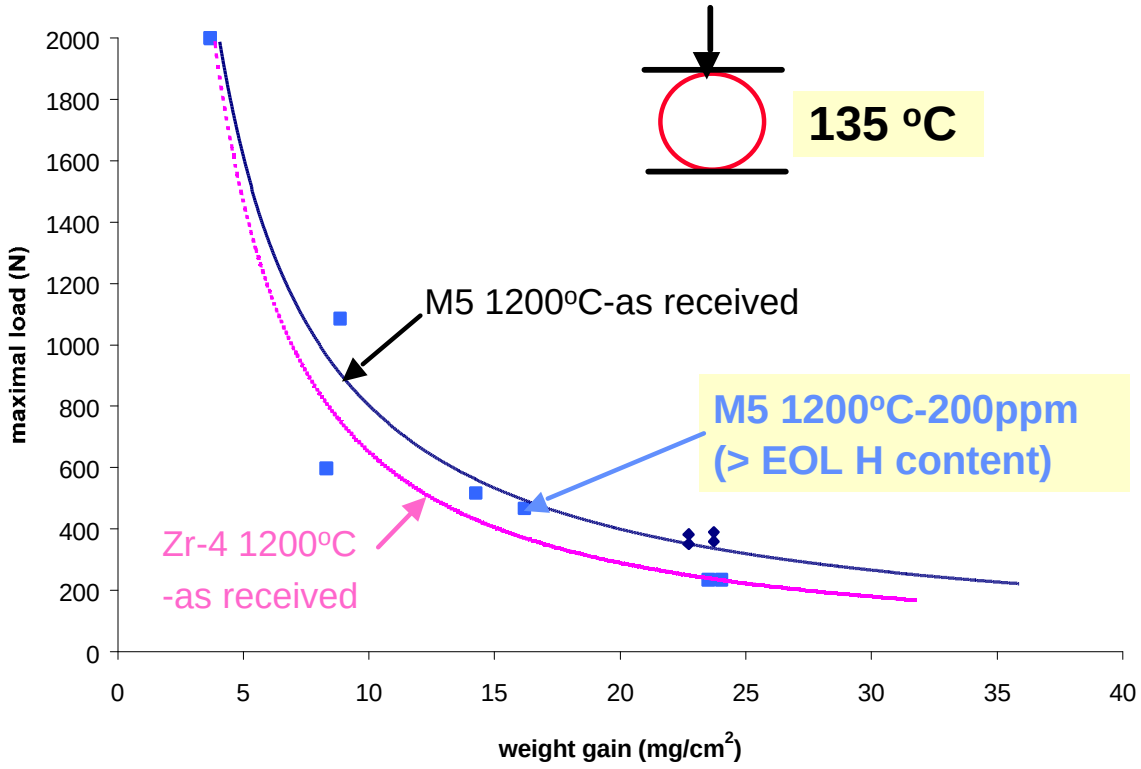
At 1000°C M5™ break-away H uptake is equivalent to Zr-4



Post-quench RT ring compression tests on M5™ and Zr-4



At 135 °C the post-quench residual ductility of pre-hydrided M5™ is restored



Post-quench ductility

- **No** runaway oxidation and related embrittlement was observed up to 1400°C during prototypical LOCA time frame (<30 min)

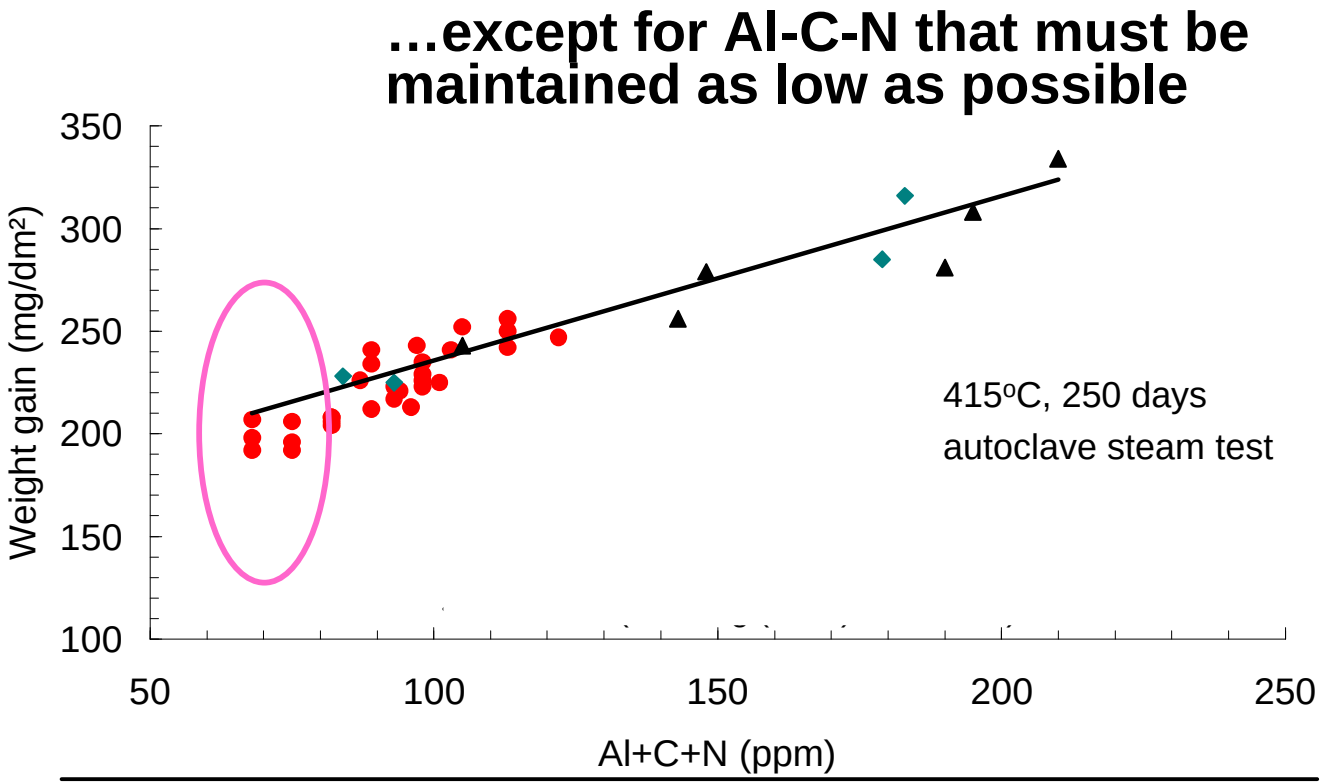
- **In-service oxidation/hydriding has NO or little effect** on the oxidation, the quench behavior or the post quench ductility of M5™

- Contrary to E110, the **post-quench mechanical properties** of M5™ are similar to (or better than) those of Zr-4

Why M5™ is different from other Nb Alloys ?

- Recent studies suggest impurities, SPPs size and distribution or the surface finish may impact the Nb based alloys behavior under LOCA conditions
- During the M5™ optimization process, potential effect of many parameters variability have been investigated
  - **Chemical composition**
    - »Alloying elements (Nb Fe Cr Ni V O…)
    - »Impurities (Ca Mg Sn Si Zn Al N H S …)
  - **Manufacturing process**
    - » Annealing temperatures
    - » Quenching modes
    - » Number of meltings
    - » Number of pilgering steps
    - » Final annealing temperature
    - » Surface finish

Variations of the main addition elements within the specified ranges have little impact…

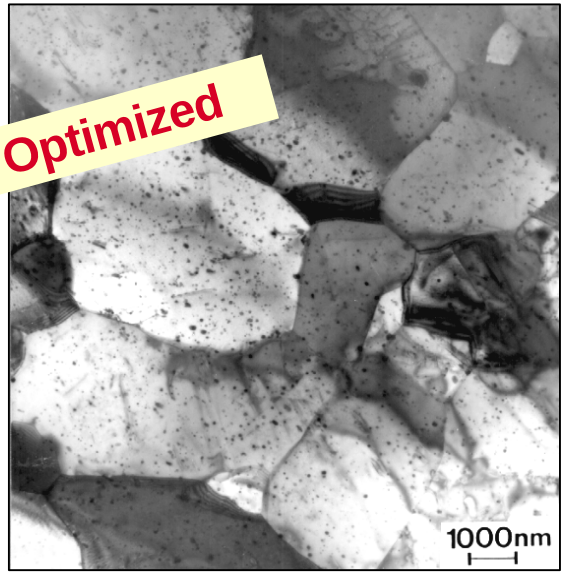


The Final Annealing Temperature has a major impact

High T process

(ß-Zr, ß-Nb) alignments // to the rolling direction

→heterogeneous corrosion

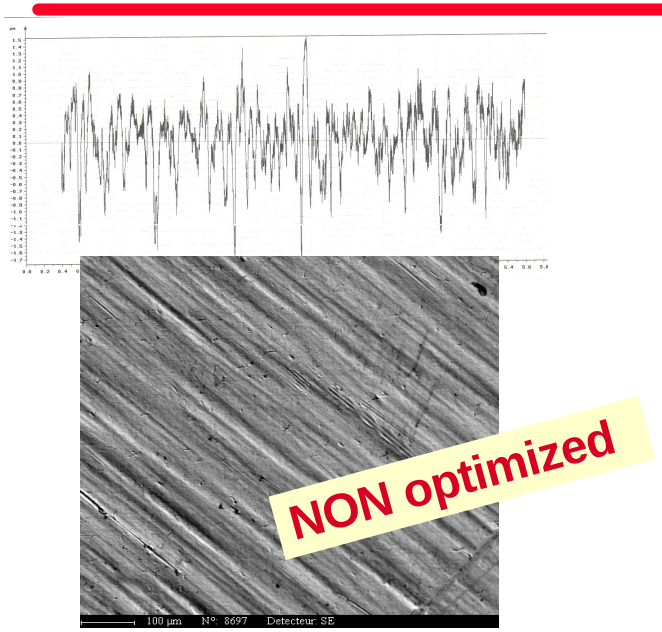


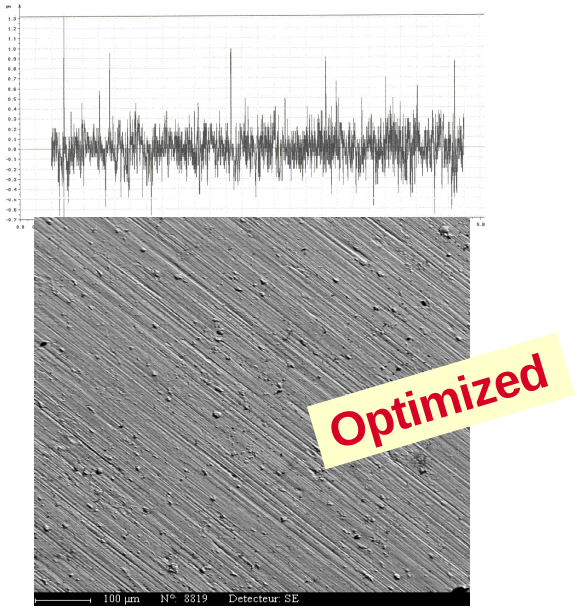
M5™ "low temperature" process

ß-Nb uniformly distributed - No ß-Zr

→ stable microstructure

OD surface finish strongly impacts the oxidation behavior





High OD surface roughness
→higher oxidation kinetics

OD Standard M5™ process : mechanical polishing →low surface roughness and low fluorine contamination→excellent oxidation behavior

Conclusions

- Contrary to other Nb alloys, the **post-quench mechanical properties** of prototypically pre-hydrided M5™ are similar to (or better than) those of Zr-4
- M5™ behavior under LOCA conditions is **fairly robust** regarding
  - –The chemical composition variations within the spec
    - »Only Al+C+N has to be controlled and as low as possible
  - –The manufacturing process variants
    - »The last annealing temperature has to be lower than the eutectoid temperature and the OD surface has to be smooth
- The LOCA criteria (PCT<1204°C and ECR<17%) are fully justified and can be used for M5™ conservatively