
**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 ?

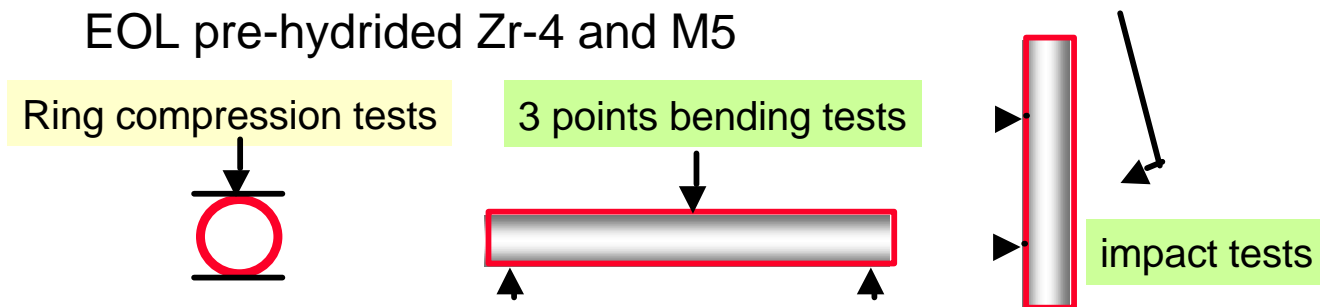
- Recent papers of experimental results on E110 cladding material suggested that all **Nb-based alloys may behave worse than Zr alloys** under LOCA conditions
 - Higher H pick up during high temperature oxidation
 - Lower post-quench residual ductility
- The purpose of this paper is to demonstrate that 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

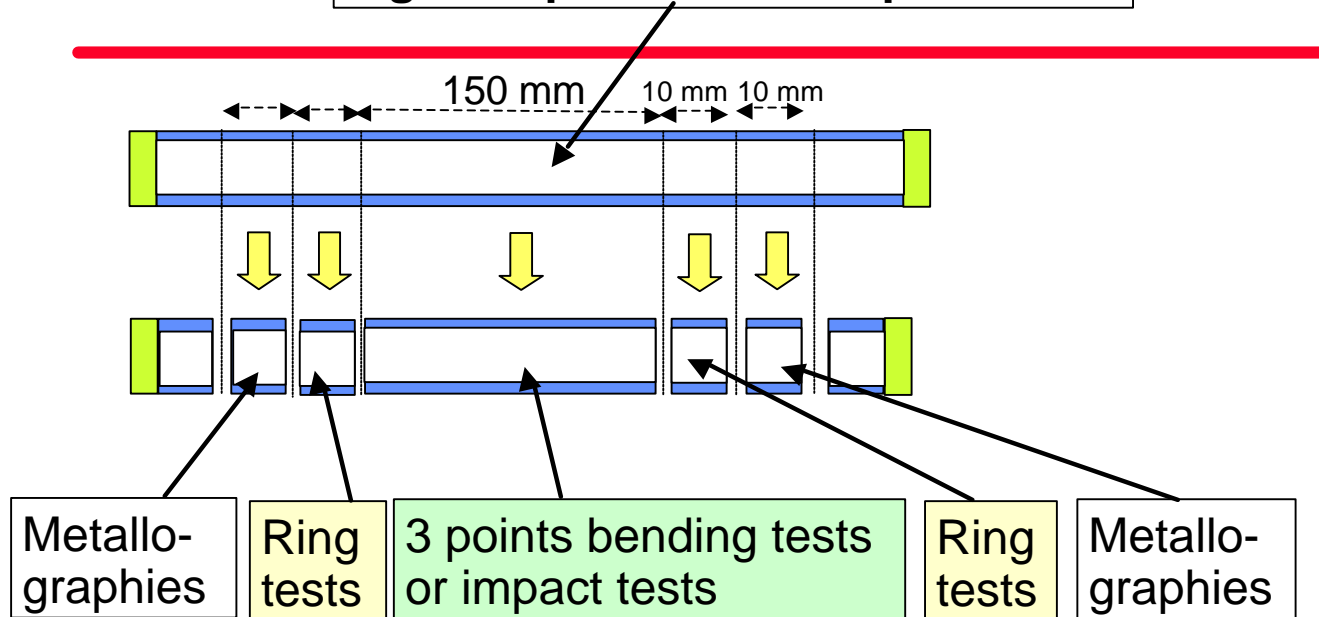
- The LOCA limits are somewhat related to the **zero residual ductility** limit of the cladding measured **after** the LOCA transient, **at low temperature** using ring compression tests (Hobson 1970) or impact tests (Chung 1973)

»LOCA limits : $ECR < 17\%$ and $PCT < 1204\text{ }^{\circ}\text{C}$

- 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-hydrated Zr-4 and M5

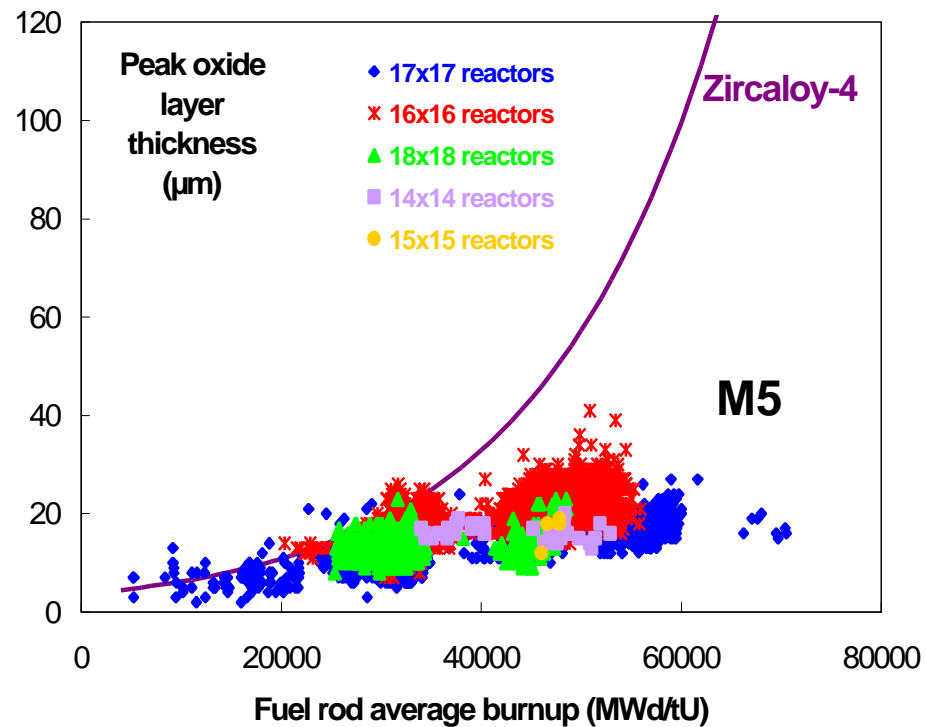


Closed-end specimen oxidized at high temperature then quenched

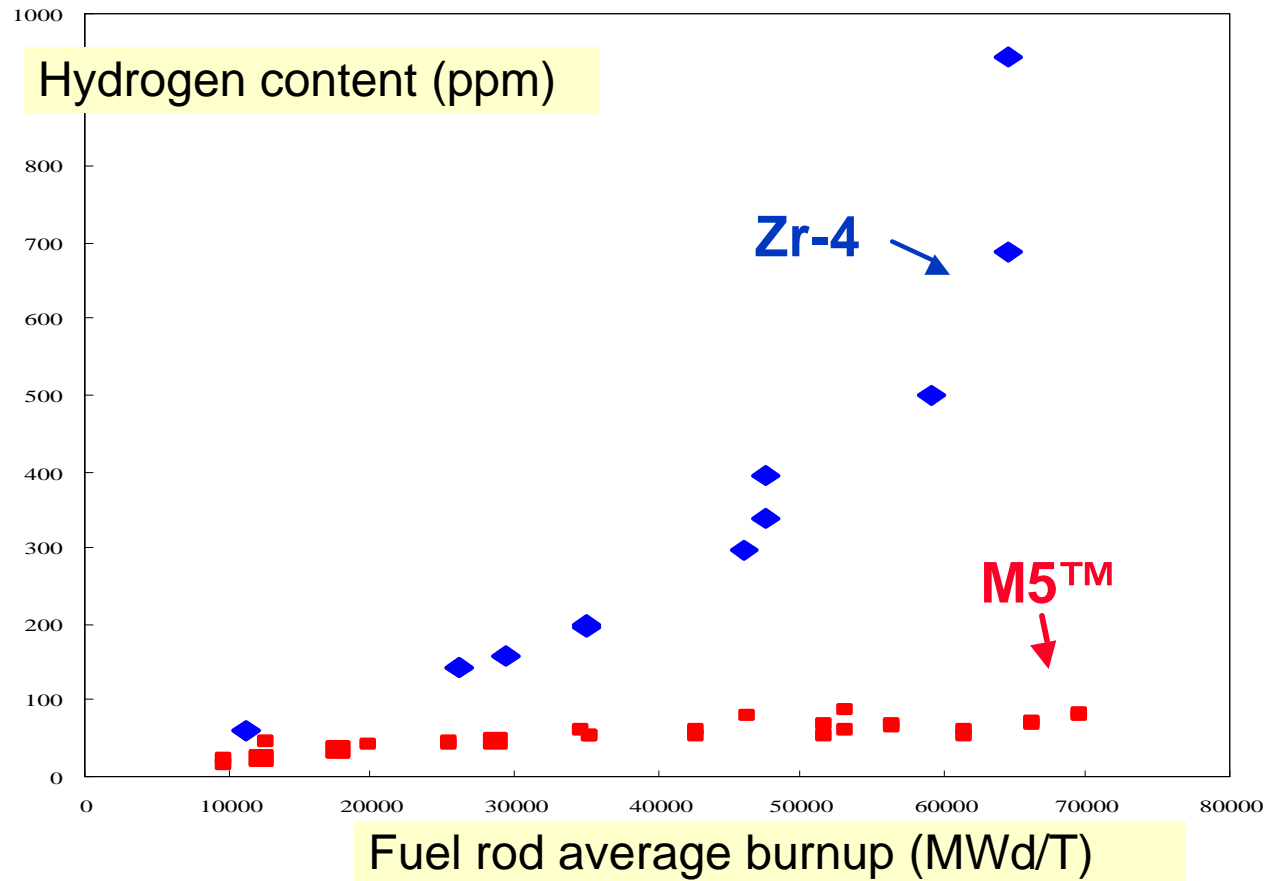


- 4 levels of oxidation temperatures : 1000 –1100 –1200 -1300°C
- 4 levels of ECR
- **Tests on pre-hydrided specimens** (to simulate in-reactor corrosion)

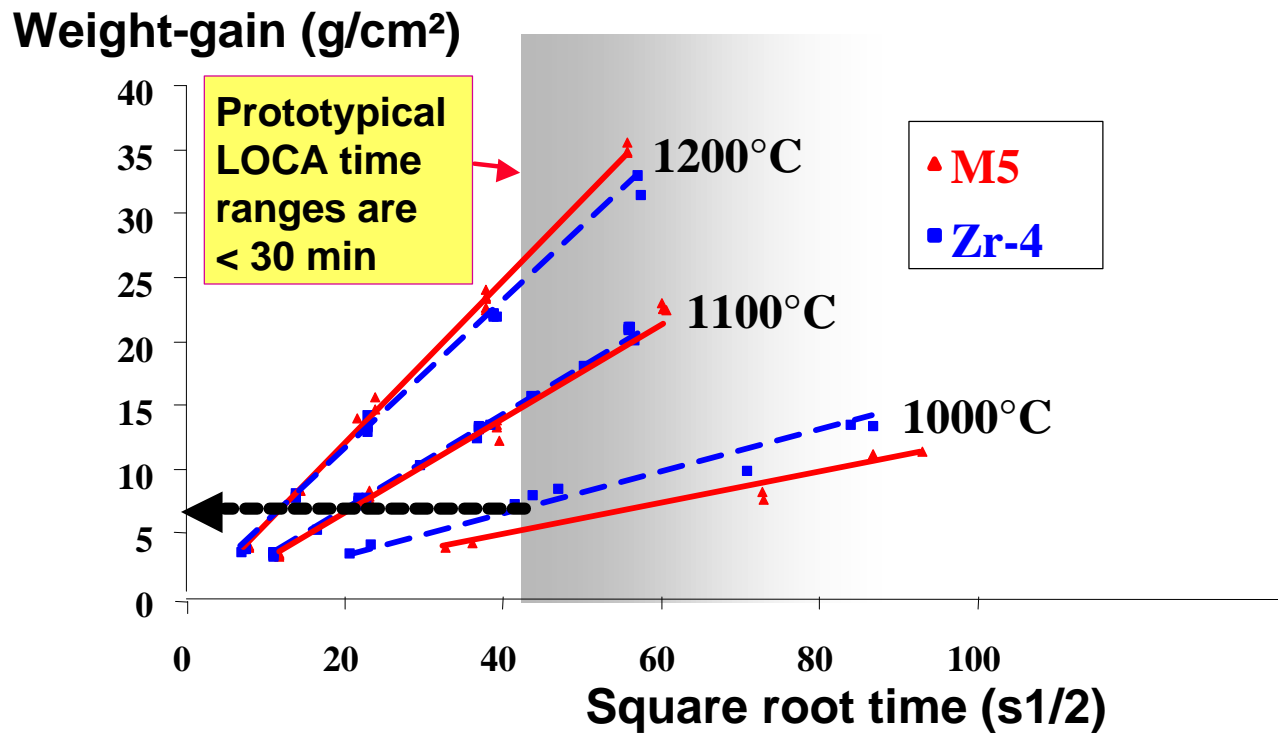
M5™ exhibits a much better in-reactor behavior than Zr-4



Hydrogen Uptake of M5™ is extremely low

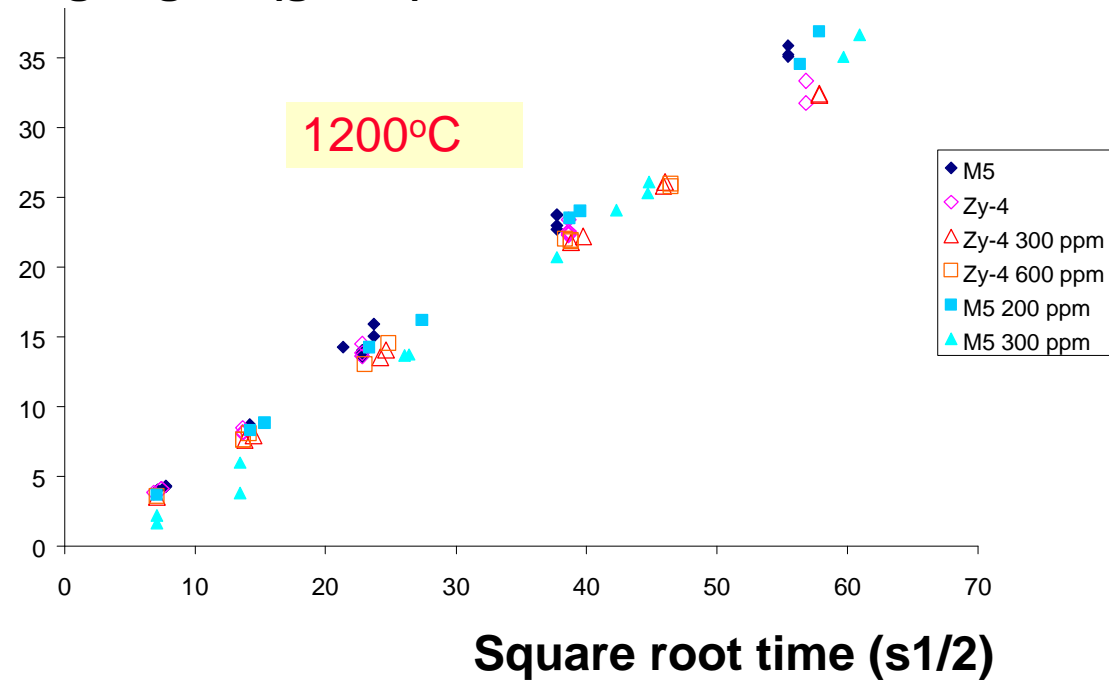


M5™ oxidation kinetics are equivalent to Zr-4

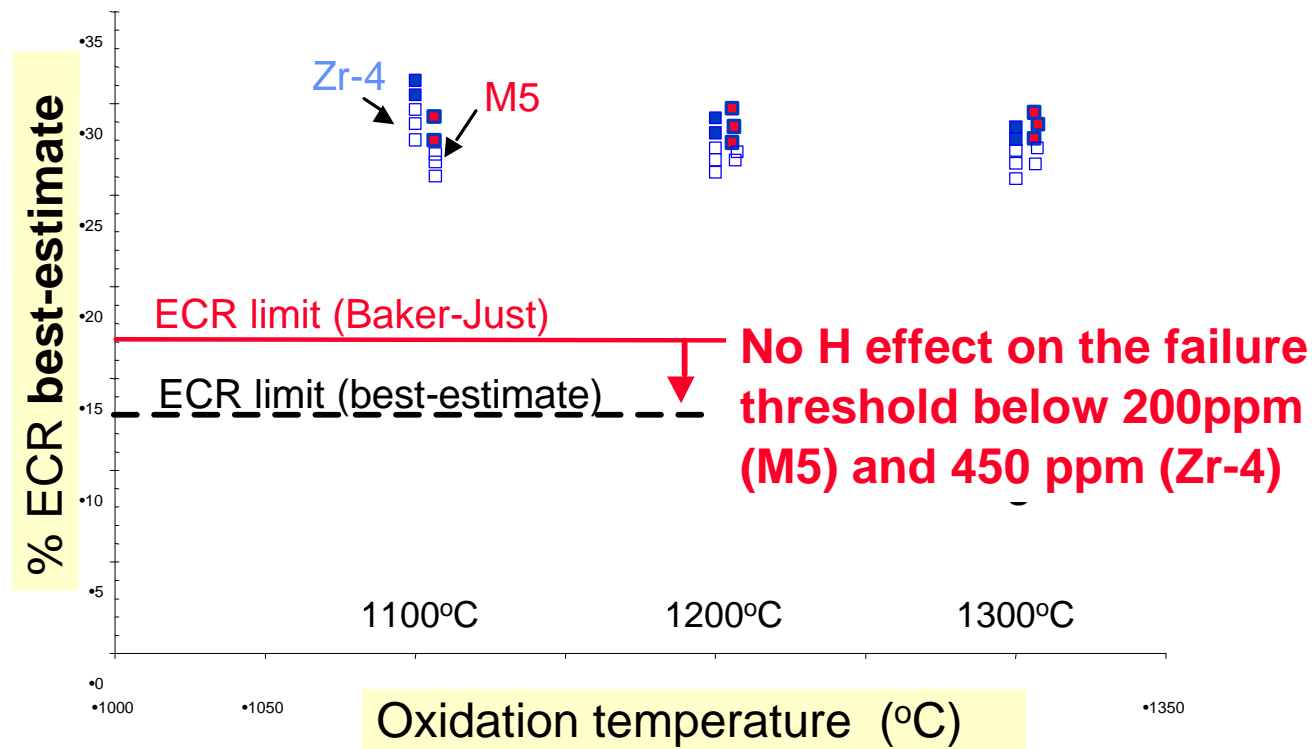


No impact of H on oxidation kinetics for both alloys

Weight-gain (g/cm²)



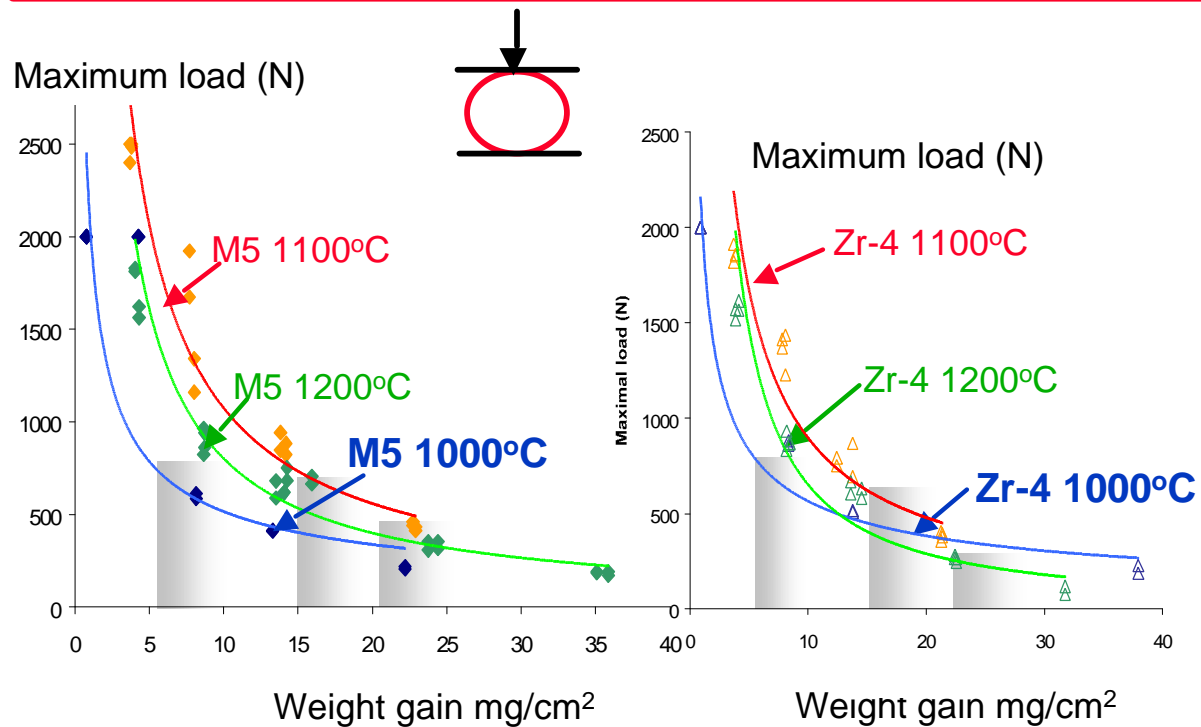
“Failure” upon quench is the same for Zr-4 and M5™.



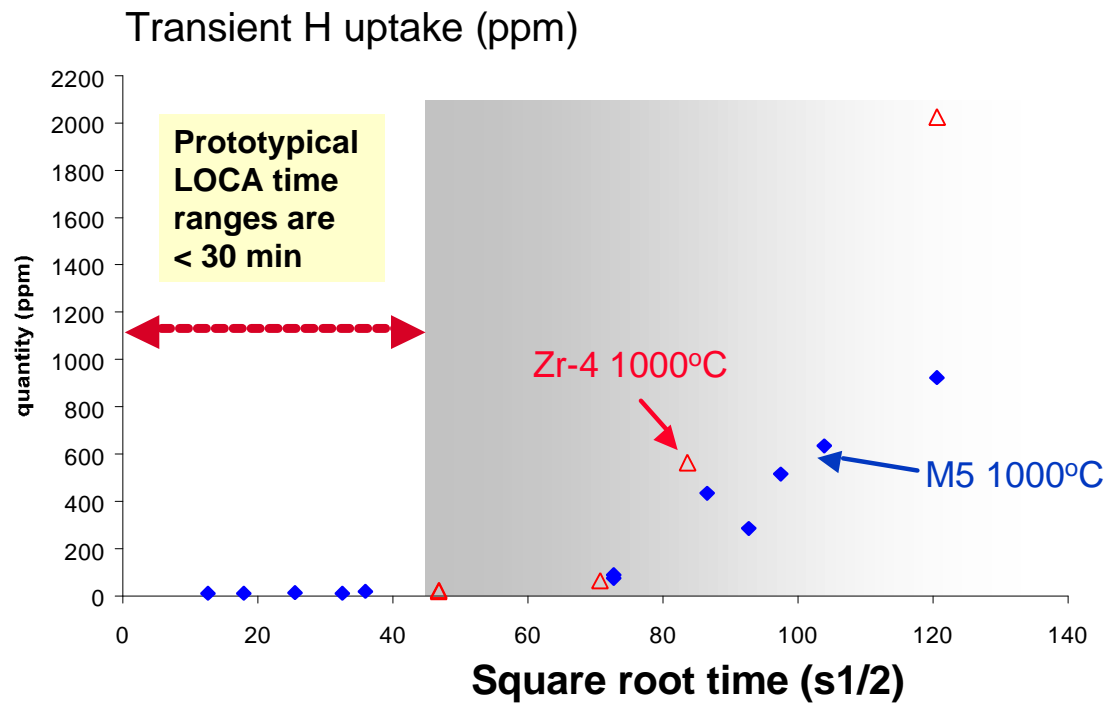
Behavior upon quench

- High temperature oxidation kinetics and quenching behavior are **equivalent for M5 & Zr-4**
- The failure thresholds of **pre-hydrided** M5TM 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

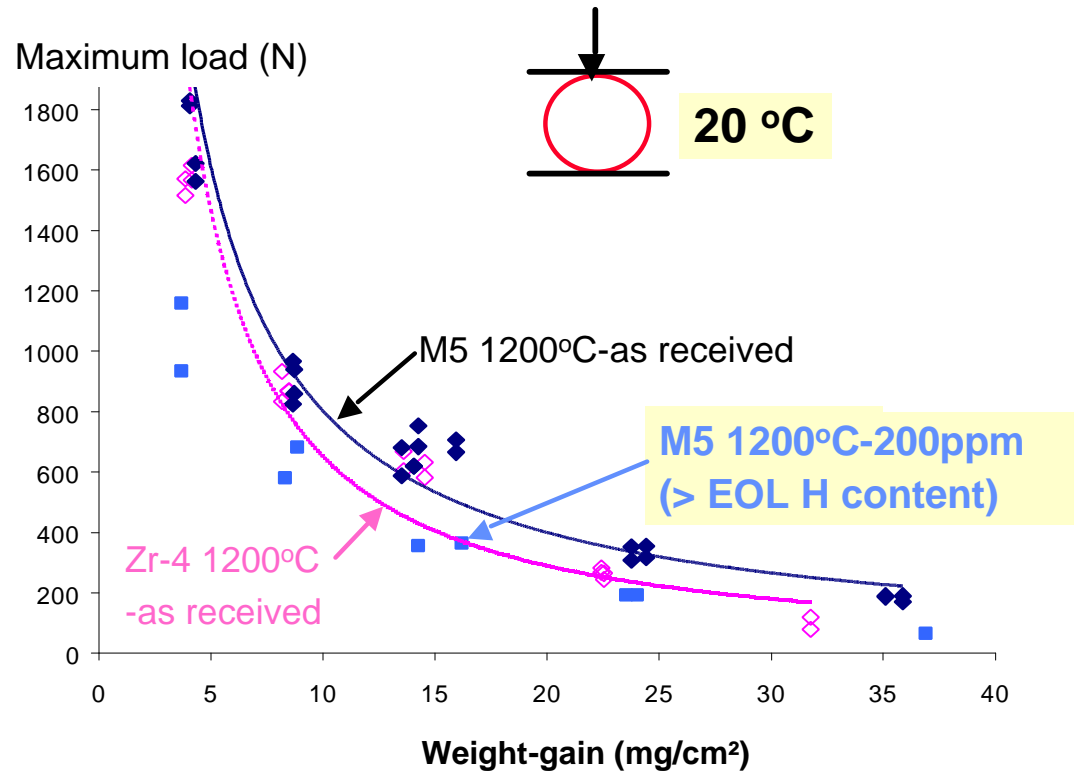
Post-Quench Ring Compression Tests at 20°C



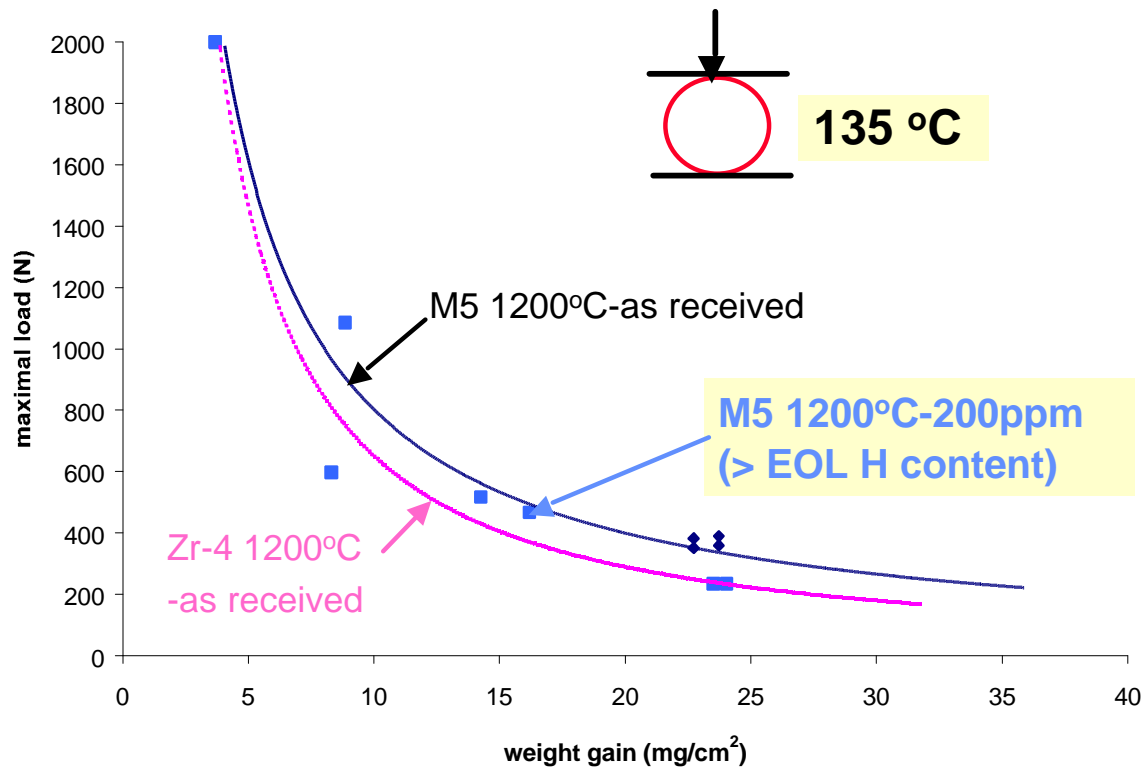
At 1000°C M5™ break-away H uptake is equivalent to Zr-4



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



At 135 °C the post-quench residual ductility of pre-hydrated 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

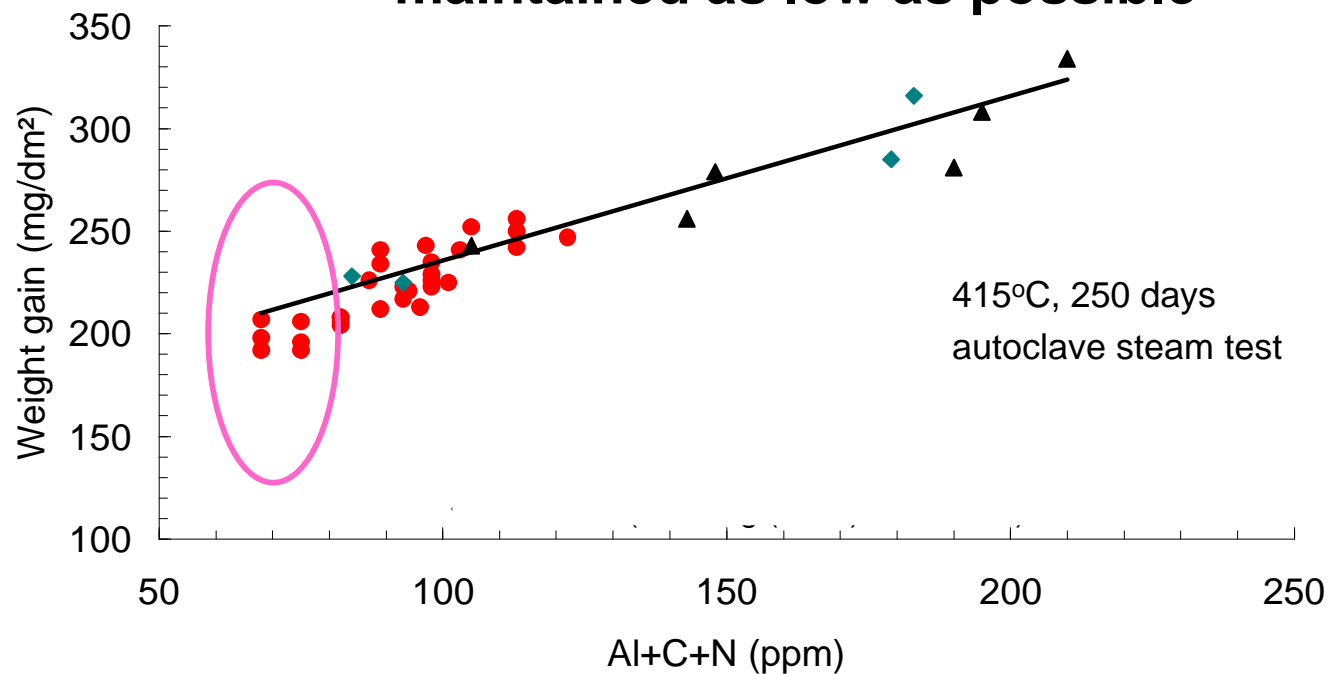
» Annealing temperatures » Number of pilgering steps

» Quenching modes » Final annealing temperature

» Number of meltings » Surface finish

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

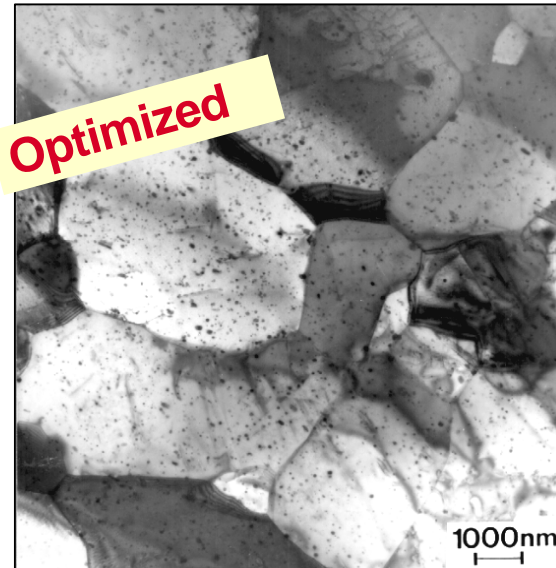
...except for Al-C-N that must be maintained as low as possible



The Final Annealing Temperature has a major impact

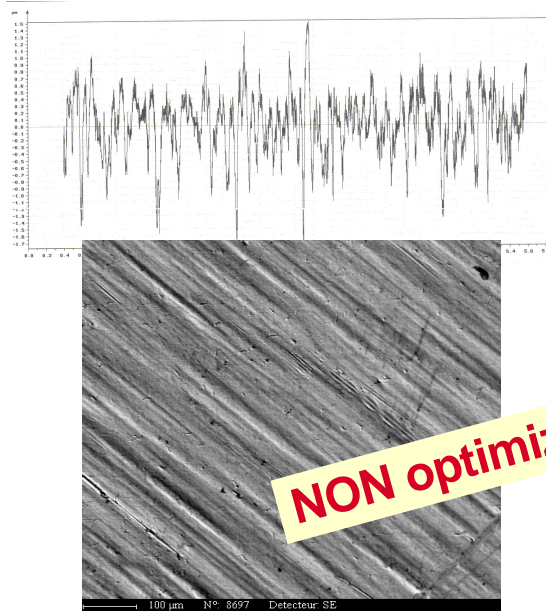


High T process
(β -Zr, β -Nb) alignments // to the rolling direction
→ heterogeneous corrosion

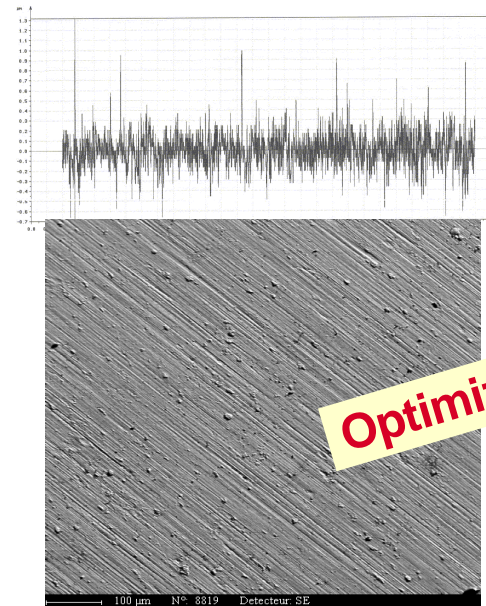


M5™ “low temperature” process
 β -Nb uniformly distributed - No β -Zr
→ stable microstructure

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
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